Modelling of temperature changes during transport of fresh fish products

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Mechanical Engineering

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Abstract

Temperature control is a critical parameter to retard quality deterioration of perishable foodstuff, such as fresh fish, during distribution from processing to consumers. This thesis is aimed at analysing and improving the temperature management in fresh fish chill chains from processing to market by means of experiments and numerical heat transfer modelling. Ambient and product temperatures are mapped in real multi-modal distribution chains, which are both sea and air based. The results serve as a basis for simulation experiments, in which different packaging units and solutions are compared with respect to thermal insulation and product quality maintenance and more optimal ones are proposed. The experimental results are used to validate 3-D heat transfer models of chilled or superchilled whitefish, packaged in single boxes or multiple boxes assembled on a pallet, under thermal load.

Much more severe temperature control problems are measured in air transport chains, especially in passenger airplanes, compared to sea transport. However, space for improvement in sea transport chains has also been discovered. The results underline the importance of precooling whitefish products before packaging for air freight and applying well distributed cooling packs inside the packaging. The results imply that product temperature differences of up to 10.5 °C can occur in a non-superchilled fresh fish pallet load and the storage life difference between the most and the least sensitive boxes on a full size pallet in a real air transport chain can exceed 1–1.5 days. It is demonstrated that even though a widely used expanded polystyrene (EPS) box design with sharp corners offers better thermal insulation than a corrugated plastic (CP) box, the sharp-corner design can be significantly improved. Such design improvement has been accomplished by developing a numerical heat transfer model in ANSYS FLUENT resulting in a new 5-kg EPS box currently manufactured by the largest EPS box manufacturer in Iceland. Other temperature-predictive models of products, developed and validated in this thesis, consider a cooling pack on top of superchilled cod packaged in two types of EPS boxes, compared to chilled fish packaged in a CP box without a cooling pack. Finally, models are developed for pallet loads of different sizes containing either chilled or superchilled fish. The models are used to confirm the temperature-maintaining effect of precooling and estimate the effect of pallet stack size.

KEYWORDS: fish, temperature, heat transfer modelling, packaging, transport, precooling.

Ágrip

Hitastýring í flutningi ferskrar matvöru frá vinnslu til markaðar hefur afgerandi áhrif á skemmdarferla vörunnar. Ferskar fiskafurðir eru dæmi um slíkar afurðir. Markmið þessarar ritgerðar er að greina og bæta hitastýringuna í kælikeðjum ferskra fiskafurða frá vinnslu til markaðar með tilraunum og stærðfræðilegum varmaflutningslíkönum. Niðurstöður umhverfis- og vöruhitamælinga í raunverulegum flug- og sjóflutningsferlum eru notaðar til hönnunar á flutningshermitilraunum, þar sem mismunandi pakkningalausnir eru bornar saman með tilliti til einangrunargildis og gæða fiskafurða, sem þær innihalda. Niðurstöður hermitilraunanna eru notaðar til að sannreyna niðurstöður þrívíðra varmaflutningslíkana af ferskum og/eða ofurkældum hvítfiski pökkuðum í staka kassa eða kassastafla á bretti undir hitaálagi.

Niðurstöður benda til töluverðra vandamála í hitastýringu í flugflutningi, einkum í tilfelli farþegaflugvéla, en síður í gámaflutningi með skipum. Þó er enn þörf fyrir endurbætur í sumum sjóflutningskeðjum. Sýnt er fram á mikilvægi forkælingar fyrir pökkun til að viðhalda réttum fiskhita í flutningi, einkum í flugi. Það sama á við um frosnar kælimottur, sem ráðlagt er að dreifa sem mest kringum fiskflök eða -bita í pakkningum og jafna þannig kæliáhrif þeirra. Mælingar gefa til kynna að búast megi við allt að 10,5 °C hitastigsmun innan heillar brettastæðu af ferskum flökum í illa hitastýrðum flugflutningi. Gera má ráð fyrir að þessi hitamunur valdi því að geymsluþol afurða í horn-kössum brettastæðunnar verði allt að 1–1,5 dögum styttra en afurða í miðju stæðunnar.

Einangrunargildi frauðkassa (EPS, expanded polystyrene) er hærra en sambærilegra kassa úr bylgjuplasti (CP, corrugated plastic). Í verkefninu er þrívítt líkan af horn-rúnnuðum (kringdum) frauðkassa þróað í ANSYS FLUENT hugbúnaðinum með bætta einangrun kassa og afurðagæði að markmiði. Greining með líkani er grunnur nýs 5 kg frauðkassa, sem nú er framleiddur af stærsta framleiðanda frauðkassa á Íslandi. Önnur varmaflutningslíkön, sem þróuð hafa verið í verkefninu, eru m.a. af kælimottu ofan á ofurkældum þorskhnökkum í tveimur gerðum EPS-kassa og kældum flökum í CP-kassa án kælimottu. Enn fremur eru þróuð líkön af brettastæðum með kældum eða ofurkældum fiski til að rannsaka áhrif staðsetningar á bretti, stærðar brettastæða og forkælingar á þróun fiskhita undir hitaálagi.

LYKILORÐ: fiskur, hitastig, varmaflutningslíkön, pakkningar, flutningur, forkæling.

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Nomenclature

B	unfreezable water as kg per kg dry solids
c_p	specific heat capacity, $\mathrm{J\,kg^{-1}\,K^{-1}}$
CFU	colony forming unit
Co	corner of box/pallet
CP	corrugated plastic
DT	dynamic storage temperature
EPS	expanded polystyrene
h_{conv}	convective heat transfer coefficient,$\mathrm{W\,m^{-2}\,K^{-1}}$
h_{rad}	radiative heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
k	thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
L	length, m
L	temperature data logger/position
LC	liquid cooling
m	mass, kg
Mi	middle of box/pallet
n	number of time steps
N	new box
NC	non-superchilled
O	old box
P	position
q	number of temperature data loggers
R	thermal contact resistance, $\mathrm{m^2\,K\,W^{-1}}$
Ra	Rayleigh number, dimensionless
RH	relative humidity, %
SC	superchilled/SuperChiller
ST	steady storage temperature
t	time, s
T	temperature, °C, K
$T_{\mathrm{f,init}}$	initial freezing point, °C, K
V	volume, $\mathrm{m^3}$
W	width, m
x	characteristic length, m
X	relative material content in foodstuff
X_{I}	ice content
X'_{w}	unfreezable water content
$X^{\mathrm{o}}_{\mathrm{w}}$	total water content
$X_{\mathrm{w,u}}$	unfrozen water content
ΔT	temperature difference, °C, K
ΔV	partial volume, $\mathrm{m^3}$

Greek symbols

ϵ	emissivity, dimensionless
ρ	density, $\mathrm{kg\,m^{-3}}$
σ	Stefan-Boltzmann's constant, ($5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$)

Subscripts

amb	ambient
b	box
bot	bottom of box/pallet stack
f	fish
init	initial
I	ice
out	outside
side	side of box/pallet stack
stack	pallet stack
top	top of box/pallet stack
w	wall

Acknowledgements

This work was supported by the EU-project *CHILL-ON* (project no. FP6-016333-2) and the Icelandic research project *Thermal modelling of chilling and transport of fresh fish ("Hermun kæliferla").* The latter one was funded by AVS R&D Fund of Ministry of Fisheries in Iceland (project no. R 037-08), Technology Development Fund (project no. 081304508) and University of Iceland Research Fund. The financial support is gratefully acknowledged. My superiors at Matís during the last years, Arnljótur Bjarki Bergsson, Guðjón Þorkelsson, Sigurjón Arason, Sjöfn Sigurgísladóttir and Sveinn Margeirsson, are thanked for their trust and for realising the importance and novelty of the thesis subject.

I would like to express my gratitude to my doctoral committee as a whole for their support, expertise and instructive guidance during the thesis research. Special thanks to my main supervisor, Halldór Pálsson, for all his help in preparing the heat transfer models and interpreting the experimental and simulated results. Likewise, I'd like to express my heartfelt appreciation to Sigurjón Arason, for initiating the project (and talking me into all this!), his multi-disciplinary expertise during this work and in other related projects and finally, endless enthusiasm. Also, Magnús Þór Jónsson and Sjöfn Sigurgísladóttir for their constructive criticism at different stages of the thesis research and making me realise that I could probably not model the whole world ... not this time at least. Viktor Popov at the Wessex Institute of Technology in Southampton, UK, is thanked for the educative cooperation in the *CHILL-ON* project, especially in building the first versions of a single box heat transfer model and useful advices throughout the thesis work.

Sincere thanks go to Radovan Gospavic at the Wessex Institute of Technology for his valuable assistance, in particular in developing the first models during my visit to WIT in January 2009 and excellent cooperation in writing our papers. I'm grateful to Hélène L. Lauzon for her extremely valuable contribution to paper V and Mai Thi Tuyet Nga is gratefully thanked for superb collaboration in writing paper I. My other colleagues at Matís in the *CHILL-ON* project, Emilía Martinsdóttir, Eyjólfur Reynisson, Hannes Magnússon, Kolbrún Sveinsdóttir, Kristín Anna Þórarinsdóttir, Lárus Þorvaldsson and María Guðjónsdóttir are acknowledged for an enjoyable and productive collaboration. Furthermore, I offer my regards to the University of Iceland-*CHILL-ON* team, Tómas Hafliðason, Sveinn Víkingur Árnason, Einir Guðlaugsson, Guðrún Ólafsdóttir and Sigurður Grétar Bogason. Many thanks to Kristín Líf Valtýsdóttir and Sæmundur Elíasson for their good work on their MSc projects, which both have contributed to the current thesis. Special thanks to my sister, Rakel Heiðmarsdóttir, for proofreading the thesis. The author would like to acknowledge all the collaborating companies in the R&D project *"Hermun kæliferla"* for fruitful cooperation, in particular Promens Tempra and Samherji.

Last but far from least, I thank my wife, Rakel Ingólfsdóttir, for being the love of my life and our wonderful daughter, Arna, for making the latter half of this thesis work even more enjoyable than the first half.

Chapter 1

Introduction

Temperature is in general known to be one of the most important parameters for the quality and safety of fresh food. Fresh products from whitefish, such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), are examples of such temperature-dependent perishables and are also among the most valuable seafood exported from Iceland. Insufficient temperature control in fresh fish supply chains will inevitably cause quality deterioration, decreased product safety, more product waste and depreciated product value. On the other hand, prolonged storage life can assist in avoiding consignments being rejected by the buyer on arrival and enhance customer satisfaction and market share. The relative loss of perishable foods through a lack of refrigeration has been estimated as 20% worldwide and as high as 9% for developed countries (IIR, 2009). This implies that much can be earned by optimising temperature control in the fresh fish chill chain from processing to the consumer.

The annual export volume of fresh fish fillets and portions (mainly loins) from Iceland has increased during the last two decades despite a reduction between 2006 and 2010 (Statistics Iceland, 2012), as seen in Figure 1.1. This reduction between 2006 and 2010 was mainly due to decreased air freight since the volume of containerised sea freight was rather stable between 2006 and 2010.

The total annual export value of Icelandic fresh fish loins and fillets was between 13.3 and 15.6 million ISK FOB (free on board) between 2006 and 2010, which is equivalent to around 82 to 96 million EUR (as at February 14, 2012). The mean price each year for the air transported products was around 30 to 50% higher than for the sea transported products between 2006 and 2010. This implies that the preferred transport mode for the highest value fresh fish products from Iceland has been by air, despite the two- to three-fold higher transport cost according to Geirsson (2009). The main advantage of the air transport compared to the sea transport is shorter transport time. As an example, the transport time is around three to six days shorter by air than by sea from Iceland to UK or France. However, the main advantage of containerised sea transport chains is fewer interfaces with uncontrolled ambient conditions.

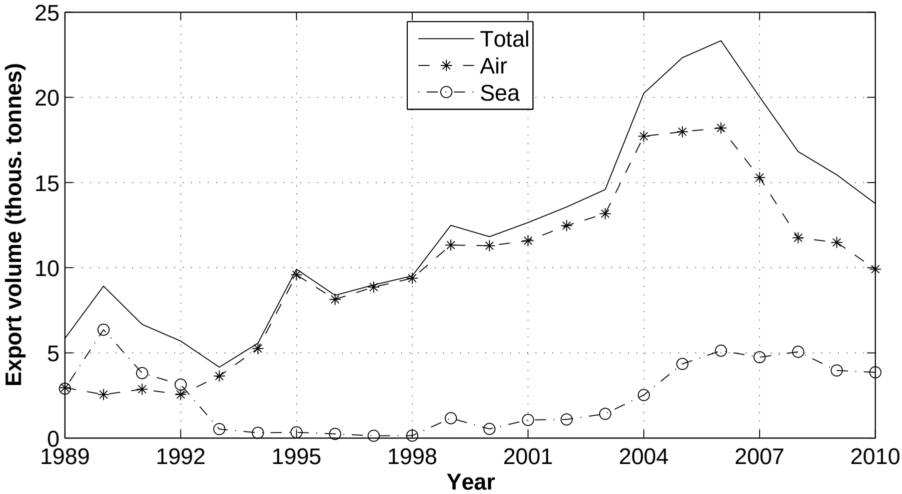

Figure 1.1: Export of fresh fish loins and fillets from Iceland by transport mode in the years 1989–2010 (Statistics Iceland, 2012).

According to the second law of thermodynamics, heat always flows from a hot body to a cold body. Thus, prolonged ambient thermal load will eventually affect the product temperature. The fish temperature during transport and storage in the chill chain is affected by different factors, such as the initial fish temperature (level of precooling during processing), thermal properties of the foodstuff, interaction of ambient conditions (e.g. temperature, air flow, solar radiation, humidity) and time. Insulative inner and outer (master) packaging can also play an important role in protecting the perishables against abusive temperature conditions. All those factors make the task of predicting and controlling temperature changes during transport of fresh fish a very challenging task.

The thesis is a part of the national research project *"Hermun kæliferla" (e. Thermal modelling of chilling and transport of fresh fish)* and the EU Integrated project *CHILL-ON*. The national project was ongoing from 2008 to 2011 in cooperation with the food research company Matís ohf., University of Iceland, the packaging manufacturer Promens Tempra ehf., the shipping company Eimskip hf. and the fisheries companies Brim hf., Festi ehf. and Samherji hf. The current PhD study was funded by AVS R&D Fund of Ministry of Fisheries and Agriculture (project no. R 037-08), Technology Development Fund (project no. 081304508) and University of Iceland Research Fund.

Two masters theses are also connected to the work presented here. The emphasis of the first one is on the effects of different precooling techniques and improved packaging design on fresh fish temperature control (Valtýsdóttir, 2011b). The aim of the second one is to analyse the effects of seasonal variations and palletisation patterns on temperature distributions inside different reefer containers used for fresh fish export (Elíasson, 2012) (unpublished).

The main aim of the EU integrated project *CHILL-ON* was to improve the quality and safety, transparency and traceability of the chilled/frozen supply chain. Within *CHILL-ON*, the responsibility of Matís was mainly comparison of cooling techniques as well as design and validation of chilling protocols for fresh fish, described in a work package lead by Emilía Martinsdóttir at Matís, and participation in field trials. The thesis author contributed to these tasks as a member of Matís research group (Guðjónsdóttir et al., 2008; Margeirsson and Arason, 2008a,b; Lauzon et al., 2010a,b; Mai et al., 2010; Magnússon et al., 2009a; Margeirsson et al., 2010a,b,c; Martinsdóttir et al., 2010; Valtýsdóttir et al., 2010; Þorvaldsson et al., 2010; Lauzon et al., 2011; Margeirsson et al., 2011; Valtýsdóttir et al., 2011a) and furthermore, collaborated with Dr. Viktor Popov's research group at the Wessex Institute of Technology, whose task was to improve packaging design, transport and storage of fresh fish.

1.1 Scope of the study

The overall aim of the PhD work is to analyse and improve temperature control during processing and transport of fresh fish. The specific objectives of the work are to:

- Assess the need for improved temperature control during air- and sea freight.
- Investigate the effect of dynamic ambient temperature on packaged fresh fish products with regard to product temperature variations and quality deterioration.
- Investigate the effect of precooling and using different packaging solutions (including cooling packs) on maintaining the correct temperature during transport.
- Explore the applicability of heat transfer modelling to predict temperature of packaged products under dynamic ambient temperature conditions.
- Improve the design of insulated wholesale fish boxes by applying numerical heat transfer modelling combined with optimisation.

The results provide valuable information on hazardous steps with regard to thermal loads during transport of fresh fish products. This allows for easier selection of transport modes for the processors and increases quality management in the chain, leading to increased value of exports. Increased knowledge of the effect of precooling fresh fish further decreases the waste of such products.

The aim of the numerical modelling is to provide a necessary basis for improvements in the design of thermally insulated packaging. The results from the current study can be extended to other fresh food chains in order to further secure and increase storage life and value of food products, fresh fish in particular.

1.2 Structure of the thesis

The thesis consists of a synopsis, outlining the main topics considered and the combined results and conclusions. This is accompanied by the following papers, which will be referred to in the text by their respective Roman numerals:

Journal articles

I Mai, N., Margeirsson, B., Margeirsson, S., Bogason, S., Sigurgísladottir, S., Arason, S., 2011. Temperature Mapping of Fresh Fish Supply Chains-Air and Sea Transport. Journal of Food Process Engineering. doi: 10.1111/j.1745-4530.2010.00611.x.

The thesis author was responsible of the experimental design, performing all temperature measurements and pre-processing of data for this paper and participated in interpreting the results.

II Margeirsson, B., Gospavic, R., Pálsson, H., Arason, S., Popov, V., 2011. Experimental and numerical modelling comparison of thermal performance of expanded polystyrene and corrugated plastic packaging for fresh fish. International Journal of Refrigeration, 34(2):573–585.

The thesis author was the main author of this paper. He was responsible of the experimental design along with the co-authors and conducted all experiments for this paper. The thesis author performed most of the numerical simulations and was solely responsible for the comparison between experimental and numerical results.

III Gospavic, R., Margeirsson, B., Popov, V., 2012. Three-dimensional mathematical model for estimation of the temperature variation in chilled packaging units. International Journal of Refrigeration. In press.

The thesis author was responsible of the experimental design along with the co-authors, conducted all experiments and was partly responsible of the numerical modelling for this paper.

IV Margeirsson, B., Pálsson, H., Popov, V., Gospavic, R., Arason, S., Sveinsdóttir, K., Jónsson, M.Þ., 2012. Numerical modelling of temperature fluctuations in superchilled fish fillets packaged in expanded polystyrene and stored at dynamic temperature conditions. International Journal of Refrigeration. In press. doi: 10.1016/j.ijrefrig.2012.03.016.

The thesis author was the main author of this paper. He had the main responsibility of the experimental design, conducted the experiments (excluding sensory evaluation) and performed all numerical modelling and comparison to experimental results for this paper.

V Margeirsson, B., Lauzon, H.L., Pálsson, H., Popov, V., Gospavic, R., Jónsson, M.Þ., Sigurgísladottir, S., Arason, S., 2012. Temperature fluctuations and quality deterioration of chilled cod (*Gadus morhua*) fillets packaged in different boxes stored on pallets under dynamic temperature conditions. International Journal of Refrigeration, 35(1):187–201.

The thesis author was the main author of this paper. He was responsible of the experimental design along with the co-authors and conducted all experiments and data processing (excluding quality data) for this paper.

VI Margeirsson, B., Pálsson, H., Gospavic, R., Popov, V., Jónsson, M.Þ., Arason, S., 2012. Numerical modelling of temperature fluctuations of chilled and superchilled cod fillets packaged in expanded polystyrene boxes stored on pallets under dynamic temperature conditions. Revised manuscript has been submitted to Journal of Food Engineering.

The thesis author was the main author of this paper. The thesis author performed all the numerical simulations and was solely responsible for the comparison between experimental and numerical results.

In conference proceedings

VII Valtýsdóttir, K.L., Margeirsson, B., Arason, S., Pálsson, H., Gospavic, R., Popov, V., 2011. Numerical Heat Transfer Modelling for Improving Thermal Protection of Fresh Fish Packaging. In: 6th International CIGR Technical Symposium. 18–20 April 2011, Nantes, FRA.

The thesis author had the main responsibility of the experimental design and was solely responsible of the conduction of the experiments and supervising the MSc student and the first author of the paper, Ms. Kristín Líf Valtýsdóttir, in the numerical modelling for this paper.

The research topics of the original papers are presented in Table 1.1.

Table 1.1: Research topics in papers I–VII.

Paper No.	Temperature mapping in real chill chains	Heat transfer modelling	Packaging comparison	Single packages	Multiple packages	Pre-cooling
I	x				x	x
II		x	x	x		
III		x		x		
IV	x	x	x		x	x
V			x		x	
VI		x			x	x
VII		x	x	x		

1.3 Study design

The thesis is based on seven studies described in papers I–VII (Figure 1.2). Mapping of both ambient and product temperatures in real air and sea multimodal transport chains is described in paper I. The results from these real transport chains are used for simulating air transport conditions in the rest of the papers. It should be noted that the dynamic temperature conditions applied there are only used to represent the temperature conditions during air transport, not sea transport. The thermal performance of different packaging solutions are studied experimentally and numerically for single boxes in papers II and III, where an analytical model for a single EPS package is validated with experimental and numerical results. Paper IV describes numerical modelling of temperature fluctuations in superchilled fish fillets in two EPS box types, including a comparison between the two box types by the means of temperature monitoring and sensory evaluation. One EPS box type is an improved box version designed by further developing a heat transfer model from paper II with the aim of minimising the maximum product temperature during thermal load. The redesigning process is discussed in paper VII.

Temperature variations and quality deterioration of packaged fish fillets, as influenced by the box type used and their position on pallets, are studied in paper V. In paper VI the results from the temperature measurements presented in paper V are used to develop and validate a 3-D heat transfer model of thermally loaded, chilled and superchilled fish fillets packaged in EPS boxes and assembled on a pallet. Finally, the effect of precooling on product temperature maintenance during transport is covered in papers I and VI.

The combined structure of the study with respect to a complete transport chain is shown in Figure 1.2.

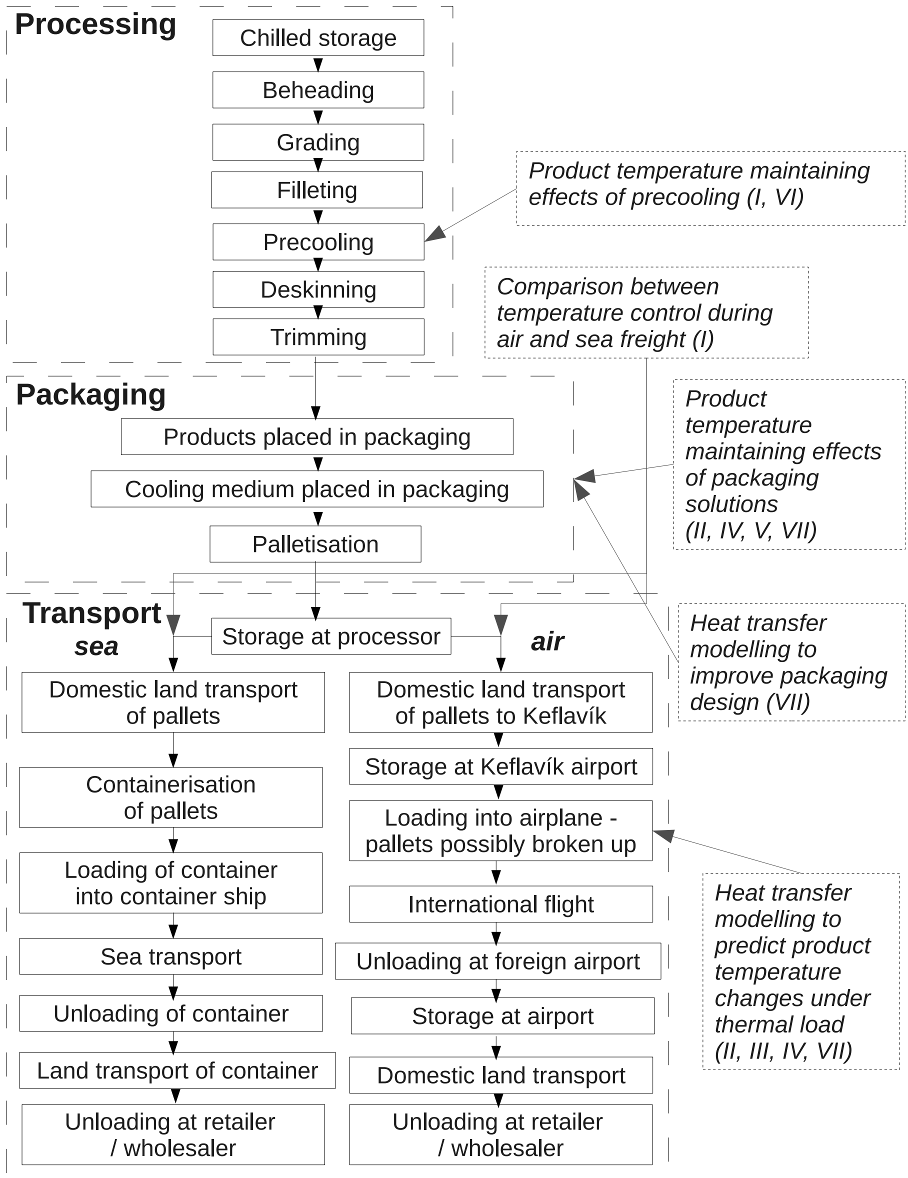

Figure 1.2: Overview of the study design. Each research topic is shown in relation to the appropriate links in typical Icelandic fresh fish chill chains through processing, packaging and transport. Paper numbers are shown in parentheses.

1.4 Scientific contribution

The thesis' main contribution to science is related to temperature control in fresh fish chill chains from processing to market. The study aims at assessing and improving weaknesses of chill chains with experiments and numerical heat transfer modelling.

Comparison between temperature control during air and sea transport of fresh whitefish products from processing to market is the scientific contribution of paper I. The thesis also includes both experimental (I) and numerical investigations (VI) of the temperature-maintaining effect of precooling fresh fish products, which are subjected to thermal load during distribution. Such elaborative comparison is new in the field of fish transport and provides core information needed for further studies as well as valuable information for the industry.

Numerical heat transfer models, which have resulted from this research, are described in several papers (II, III, IV, VI). In these papers, product temperature distributions inside whole packages and whole pallet loads of fresh and superchilled fish products under time dependent thermal load are introduced for the first time. The numerical predictions are verified against experimental results, obtained in the current study, which also include comparison between thermal performance of different packaging solutions, such as expanded polystyrene boxes, corrugated plastic boxes and cooling packs. The good agreement between simulations and experiments verifies the potential usage of numerical models in the design of packaging and transport methods.

Extensive temperature measurements in an air transport simulation study (V) show that product temperature differences of up to 10.5 °C can occur in a non-superchilled fresh fish pallet load during transport from processing to market. The results from the same study show that the storage life difference between the most and the least sensitive boxes on a full size pallet in a real air transport chain can exceed 1 to 1.5 days, depending on the level of ambient thermal load. Product temperature and storage life variations within a single pallet load of fresh fish products under thermal load have not been described as extensively before.

Finally, the process of utilising a numerical heat transfer model to improve the design of thermally insulated wholesale fish box (VII), is presented for the first time. This has resulted in a round corner 5-kg box currently manufactured by the largest fish packaging manufacturer in Iceland, Promens Tempra in Hafnarfjörður.

Chapter 2

Background

The purpose of this chapter is to provide a scientific background to the research. Initially, cold chain management and its effect on storage life of fresh fish is discussed. Secondly, precooling and different means to precool fresh fish are presented. Thirdly, thermophysical properties of whitefish and possible methods to model them are covered. Finally, the different available packaging solutions for fresh fish products are presented with an overview of relevant heat transfer modelling studies.

2.1 Cold chain management and storage life

Storage life of air-stored cod products processed from fresh raw material (processed less than 4 days post-catch) is usually between 10 and 14 days at 0 °C (Huss, 1995; Magnússon and Martinsdóttir, 1995). Storage life is the time elapsed from processing until a Torry score of 5.5 out of 10 is reached (Shewan et al., 1953; Martinsdóttir et al., 2001). This score has been used as the limit for consumption at Matís (Martinsdóttir et al., 2001). Similarly, the time elapsed from processing until a Torry score of seven is reached is called the freshness period. Factors influencing the freshness period and the storage life include raw material quality and age, seasonal variations, processing treatments and levels of bacterial contamination.

Because of the well known fact that both the quality deteriorating enzymatic and microbiological activity are greatly temperature-dependent, the freshness period and storage life of fresh fish is highly temperature-dependent (Huss, 1995; Lauzon et al., 2010b). This implies that even a short-duration thermal load can considerably shorten the freshness period and storage life of fish products. An increase in mean product temperature by 0.5 °C may reduce the freshness period and/or the storage life of processed fish by one day (Lauzon et al., 2010b). This emphasises the importance of protecting fresh fish products from thermal abuse during distribution.

Because of the importance of temperature control during distribution of fresh foods, almost all countries in Europe, USA as well as many other countries have signed the ATP - Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (ATP, 2010). According to the ATP, fish temperature should be as close to 0 °C as possible without freezing the products. However, the recommended transport temperature in the ATP could be decreased without any freezing because the initial freezing point of cod is −0.91 °C according to Rahman (2009a). James et al. (2006) noted that most transport containers are not designed to extract heat from the load but only to maintain the temperature of the load. This emphasises the importance of precooling the products before distribution, see Section 2.2.

As the fastest transport mode, air freight is very common for perishable fresh fish products (Sharp, 1988; Stera, 1999; James et al., 2006). During a five-year period, the volume of temperature-sensitive cargoes transported by air increased at an annual rate of 10–12%, to reach 4.4 million tonnes in 1998 (Stera, 1999). The main disadvantage of air transport is an unavoidable break in the cold chain caused by fluctuating or very high/low temperatures during the flight itself and while the airplane is loaded, refuelled, cargo transshipped or unloaded (Stera, 1999; Brecht et al., 2003; James et al., 2006). Upon arrival at the destination, the product can be held for several hours for quarantine checks or be subjected to fumigation before being released to the importer (Bollen et al., 1997). It has been estimated that up to 80% of the relatively short transport time involves waiting on the tarmac and transport to and from the airport (Sharp, 1988; James et al., 2006). According to James et al. (2006), air temperatures between 15 and 20 °C can be expected in the aircraft hold during flight, which is in good agreement with the results of Sharp (1988) and Bollen et al. (1997).

What further increases the diversity of possible ambient conditions encountered by perishables in air transport chains is the fact that around 60% of these cargo is transported in cargo holds of passenger planes, which have a limited space (Stera, 1999). The corresponding ratio for Icelandic fresh fish products has been increasing from around 20% to around 30% during the last decade according to Grétarsson (2011). In order to maximise volume exploitation of small cargo holds, pallets are frequently broken up before being loaded on board the passenger planes (Grétarsson, 2011), which further increases the thermal load on the cargo. Yet another risk for perishables in passenger aircrafts is excessively cold and dry air because the holds are pressurised and continuously ventilated with fresh outside air with temperatures as low as −56.5 °C (Stera, 1999).

In order to protect temperature-sensitive foodstuff from the expected thermal load during air freight, insulated packaging, polystyrene slabs, insulation blankets/lining can be used with or without cooling media such as dry ice and ice packs (Stera, 1999; James et al., 2006). Even more sophisticated solutions include standard baggage type containers made of aluminium and lined with mineral wool blanket or polystyrene slab insulation. These containers can be equipped with a small compartment for ice or dry ice or even with a mechanical refrigeration unit (Stera, 1999). Because of the aforementioned space limitations, some of these insulating devices are not applicable in small passenger aircrafts. Thus, perishables often have to rely on only the thermal protection of the packaging during air transport (Stera, 1999; James et al., 2006; Grétarsson, 2011).

Another mode of fresh fish transport is sea freight where the product is stored in either porthole containers (insulated containers) or integral refrigerated containers (commonly called "refrigerated containers" or "integral containers"). A fundamental drawback of sea transport as compared to air transport is the longer transport time, which causes quality deterioration even at optimal storage conditions (Pawsey, 1995). Another fundamental difference between air and sea transport chains should be noted: The portability of the containers, which are closed and sealed after loading and are to be kept closed throughout the voyage. This results in fewer interfaces between different links in the chain where serious ambient thermal load is to be expected, compared to air transport chains.

The porthole containers are not equipped with their own refrigeration unit and thus are reliant on an external supply of cold air while the integral containers are equipped with an integrated refrigeration unit which is secured one end of the container. This unit is normally operated using three-phase electric power (Wild et al., 2005). James et al. (2006) stated that close temperature control is very easily achieved in insulated containers that are placed in insulated holds and connected to the ship's refrigeration system. The maximum difference between delivery and return air can be less than 0.8 °C when the containers are fully loaded and the cooled air is forced uniformly through the space surrounding the container load. James et al. (2006) also described that integral containers are often carried on deck when shipped because of problems in operating the refrigeration units within closed holds. On the deck, much higher ambient temperatures accompanied by solar radiation can result in significant spatial- and temporal temperature variations inside the container. Tanner and Amos (2003a,b); Moureh and Flick (2004); Giannakourou et al. (2005); Punt and Huysamer (2005); Wild et al. (2005); Rodríguez-Bermejo et al. (2007); Jedermann et al. (2009) have all published studies showing that maintaining stable and homogeneous temperature distribution inside containers can be a difficult task. Despite this, a growing preference to use marine containers for transport of perishables over the long distances has been such that the size of the world reefer (fully refrigerated ship) fleet slightly declined in the 1990's (Stera, 1999).

According to Seafish and Humber Seafood Institute (2010), the two main product categories of fresh Icelandic cod and haddock exports to the United Kingdom are the following:

- Whole (head-on gutted) fresh fish, which is primarily transported in containers to Humberside auction markets.

- Fresh fillets or specially cut portions, such as cod loins, which are either transported by air or by container vessel directly to retail or foodservice customers; sometimes though with a short stop for repackaging in the United Kingdom.

Air transport is still the more common transport mode for Icelandic fresh fish fillets and portions, according to the statistics in Figure 1.1 and Seafish and Humber Seafood Institute (2010). However, in recent years an upward trend in the volume of sea freight has been observed due to technical developments (Seafish and Humber Seafood Institute, 2010) and difference between transport cost by air and sea (Geirsson, 2009).

None of the aforementioned studies has covered temperature mapping and comparison between air and sea transport of fresh whitefish products from processing to market. Such a study is necessary to assess the need for improved temperature control during air- and sea freight and facilitate the choice of transport mode for Icelandic fish processors, with regard to both economical benefits and product quality.

2.2 Precooling

Superchilling is a preservation method for foodstuff, which implies partial freezing, i.e. lowering the food temperature to no more than 1–3 °C below the initial freezing point, $T_{\mathrm{f,init}}$ (Aune, 2003; Magnussen et al., 2008; Kaale et al., 2011; Stevik and Claussen, 2011). The initial freezing point of most fresh food is around -1 °C (Pham, 1996) and the initial freezing point of cod is specified by Rahman (2009a) as -0.91 °C. The term "superchilling" is actually also used when chilling a product to a temperature between the initial freezing point of the product and 0 °C (Aune, 2003; Ando et al., 2004). Studies have shown that superchilled storage of both fresh cod and other foods such as salmon, prawn and pork is effective in delaying microbial growth, maintaining freshness and prolonging storage life (Aune, 2003; Ando et al., 2004; Martinsdóttir et al., 2005; Olafsdottir et al., 2006; Duun, 2008; Magnussen et al., 2008; Kaale et al., 2011).

The process of precooling has been defined as the removal of field heat (prior to transport and storage) thus slowing deteriorative processes and thus maintaining a high level of quality that ensures customer satisfaction (Brosnan and Sun, 2001). For years, the fresh fish industry has precooled the fish fillets and loins before shipping, either by applying a short-duration treatment using a special precooling equipment before packaging or by storing the palletised fish boxes for a few hours in a frozen storage room. Precooling also protects the foodstuff against thermal load during distribution (Sharp, 1988, 1998; James et al., 2006), especially if the food is precooled to a superchilled temperature below the initial freezing point, causing partial freezing and build-up of a cold reservoir in the product. This means that extra energy is needed for melting the partly frozen water in the product so that the superchilled, packaged products can withstand more severe thermal load than non-superchilled products in similar packaging. Comparison between the results of storage life studies by Magnússon et al. (2009a) and Gao (2007) verifies this clearly.

One of the newest techniques available is the ”SuperChiller” cooling technique by Marel (Garðabær, Iceland) but liquid cooling (LC) and slurry ice cooling (SIC) are widely used. Each precooling method aims to effectively lower the temperature of the fresh fish and should be applied as close to packaging as possible to avoid re-heating of the products. Stevik and Claussen (2011) have compared the ”SuperChiller” to a similar precooling equipment alternative, the ”Impingement Advantec Lab Freezer” by JBT Foodtech (Helsingborg, Sweden), in which the fish fillets are superchilled at −37 °C for 45 seconds followed by temperature equalisation at 9 °C for 10 minutes. Lesser gaping and risk of freezing was obtained for the fillets superchilled in the ”SuperChiller” but the relatively short processing time and low labour demand were noted as advantages of the latter method.

2.2.1 Liquid cooling and slurry ice cooling

Liquid cooling of fresh fish is a precooling technique which consists of immersing the fresh fish into cooled brine (1.0–2.5% NaCl). Slurry ice cooling is a similar technique except that a two-phase slurry ice (mixture of ice crystals and brine) is used as a cooling medium. Numerous studies have shown that slurry ice yields a significantly higher chilling rate than ice and can be used for many applications other than chilling fish (Piñeiro et al., 2004; Kauffeld et al., 2005, 2010; Digre et al., 2011). The fish is usually dropped from a conveyor belt into a tank containing the cooling medium and transported via an underwater conveyor belt or a turning spiral (Valtýsdóttir et al., 2010). Margeirsson et al. (2010b) concluded that the temperature difference between the cooling medium and initial product temperature is the most important factor for the cooling rate during liquid cooling of fish fillets. Margeirsson et al. (2010b) measured a cooling rate of 0.12 to 0.20 °C min^{-1}, or 0.03 °C min^{-1} per °C difference between initial product and medium temperature when cooling cod fillets in a liquid or slurry ice medium. Normally, the salt content of fresh Atlantic whitefish (cod and haddock) is around 0.2–0.3% (Þórarinsdóttir, 2010). Studies have shown that during liquid cooling in lightly salted water or slurry ice with a salinity of around 1.0–2.5% for 6 to 15 min, the salt content of fish flesh increases to 0.3–0.5% (Magnússon et al., 2009a,b; Margeirsson et al., 2010a; Valtýsdóttir et al., 2010).

However, it has proven to be difficult in practice to maintain the lowest possible temperature of the brine cooling medium in order to achieve the most efficient cooling of fish. In general, a temperature decrease of only 1–2 °C has been observed in liquid cooled fish products (Magnússon et al., 2009b; Valtýsdóttir, 2011b). The main problems relating to this technique include poor temperature control of the liquid over the processing day and ease of bacterial contamination, encouraging the growth of fish spoilage bacteria in the brine (Lauzon et al., 2010a). Extended holding time in the liquid cooler will therefore lead to higher bacterial contamination on the fillets. Valtýsdóttir et al. (2010) noted that the salt content required in a cooling medium to reach a suitable cooling temperature is higher for a one-phase brine compared to a two-phase slurry ice. This fact makes slurry ice better suited for precooling than brine because a lower salt concentration results in a lower salt uptake in the fish muscle. Furthermore, because of the latent heat of slurry ice it is easier to maintain its required low temperature than in a brine cooling medium. This is advantageous for fish cooling and improves temperature control in the cooling process.

2.2.2 Combined blast and contact cooling technique

The "SuperChiller" precooling technique (formerly referred to as combined blast and contact (CBC) cooling technique by Skaginn Ltd., Akranes, Iceland) involves superchilling the fillets by transporting them through a freezer tunnel with the skin touching a Teflon-coated aluminium conveyor belt (Figure 2.1) at a temperature of approximately −8 to −6 °C and simultaneously blasting cold air over the fillets (Valtýsdóttir et al., 2010). Before the combined blast and contact cooling in the SuperChiller, fish fillets are conveyed through a liquid- or slurry ice cooler for about 8 to 10 min with salinity of approximately 1.0–2.5%. This prevents excessive freezing of the fish flesh in the SuperChiller. Measurements have shown that only around 8 to 10 min are required to reduce the fillet temperature from around 1 to 4 °C to temperatures between −1.0 and −0.5 °C with the air temperature in the SuperChiller set at −8 °C (Gao, 2007; Valtýsdóttir et al., 2010; Stevik and Claussen, 2011).

Figure 2.1: Precooling of whitefish fillets in a SuperChiller (Valtýsdóttir, 2011b). Fillets are subjected to both blast and contact cooling as they are transferred with the skin down on an aluminium belt while cold air is blown above them (left). Superchilled fillets exit the SuperChiller (right) before being transferred on another conveyor belt to deskinning and trimming.

In addition to the effective cooling, this superchilling technique facilitates further handling of the fillets, in particular deskinning, leading to higher fillet yield and more valuable products (Martinsdóttir et al., 2004). The cooling technique has been shown to contribute to a slower quality degradation at an early stage, leading to an extension of the freshness period and storage life of both fillets under steady and dynamic temperature storage (Martinsdóttir et al., 2005; Olafsdottir et al., 2006; Gao, 2007; Magnússon et al., 2009a).

The temperature-maintaining effect of precooling are demonstrated in Figure 2.2 and Table 2.1. The figure presents fish fillet and ambient temperatures during dynamic temperature storage in a storage life study (Magnússon et al., 2009a). The precooling (LC+SC) clearly decreased the temperature rise caused by the ambient thermal load as compared to the non-superchilled fillets (NC). The results for the freshness period, storage life and mean temperature until the end of storage life are presented in Table 2.1. The difference in mean product temperature between non-superchilled and superchilled fish resulting after the thermal load applied, further demonstrates the better capability of superchilled products to withstand temperature abuse.

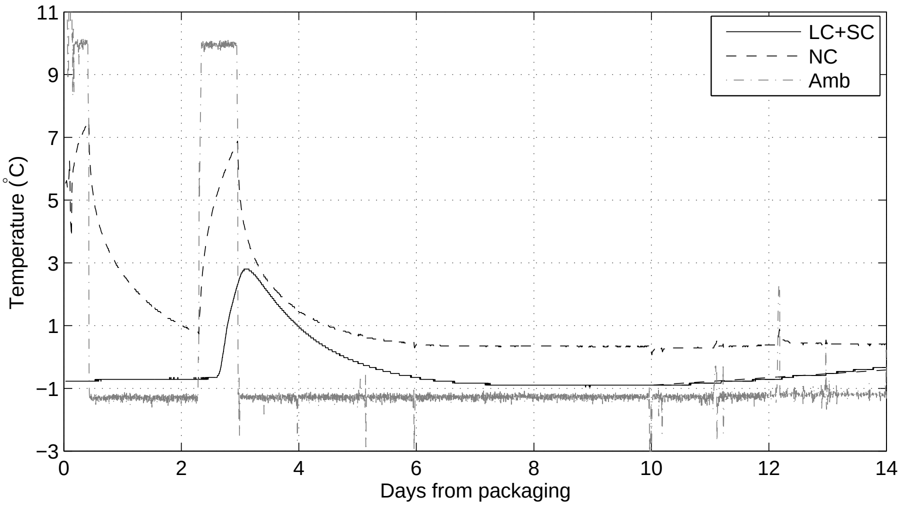

Figure 2.2: Cod fillet and ambient temperatures during dynamic temperature storage. Amb: ambient, LC+SC: Fillets precooled in a liquid cooler and a SuperChiller, NC: Non-superchilled fillets (adopted from Magnússon et al. (2009a)).

Cooling of whole cod fish in a SuperChiller weighing around 1 kg (typical fillet weight is 0.4–0.6 kg) has been temperature monitored by Gao (2007). The effects of precooling on quality of the whole fish were not investigated. The results show that a much larger cooling load, either by increased airflow or more importantly longer holding time or lower temperature in the SuperChiller, is needed in order to decrease the whole fish temperature to −1 °C.

Table 2.1: Freshness period and storage life according to sensory evaluation. LC+SC: Fillets precooled in a liquid cooler and a SuperChiller, NC: No cooling of fillets during processing (Magnússon et al., 2009a).

Group	Freshness period	Storage life	Mean temperature (°C)
LC+SC	4–6	12–13	−0.4 (13 days)
NC	3–6	6–10	1.1 (10 days)

2.3 Thermal properties of whitefish

Many mathematical models have been developed in order to predict thermal properties of foodstuffs. Jowitt et al (1983), Choi and Okos (1986), Harðarson (1996), Pham (1996), Fikiin (1998) and Rahman (2009b) are among the authors that have reported different models, the first and the latest providing a broad overview of available models and tabulated data. Difficulties in estimating the ratio of frozen water (ice content, X_{I}) in the food and the importance of the initial freezing temperature ($T_{\mathrm{f,init}}$) of the food substance for the phase change, are among the problems encountered in the modelling work. The temperature dependency of the specific enthalpy and ice content are shown in Figure 2.3 using salmon with lower water content and higher fat content than whitefish as an example.

Products with no sharply defined phase change region, such as fish, can in general cause complications in numerical heat transfer modelling (Pham, 1995; Harðarson, 1996; Pham, 2006). For problems solved with fixed grid methods, such as apparent heat capacity methods, the complications can be related to the sharp peak in the apparent heat capacity of the food (Figure 2.4), which is due to the latent heat. Other methods for dealing with phase change of foodstuffs, such as enthalpy methods and Pham's quasi-enthalpy method, were reviewed by Pham (2006).

The thermophysical properties of foodstuffs are in general known to be much influenced by the water content of the food. Due to this, the known seasonal variations of the water content of whitefish (Huss (1995), chapter 3) causes a certain variability in the thermophysical properties of the raw material and the resulting fish products. The water content (X_{w}) of cod can range from 78 to 83% (Murray and Burt, 2001). As an example of the large variability in the predicted thermophysical properties, using an equation by Sweat (1986) to estimate the thermal conductivity (k) of cod results in values between 0.40 and $0.43\,\mathrm{W\,m^{-1}\,K^{-1}}$. On the other hand, different equations reported by Miles et al. (1983) yield values between 0.30 and $0.50\,\mathrm{W\,m^{-1}\,K^{-1}}$.

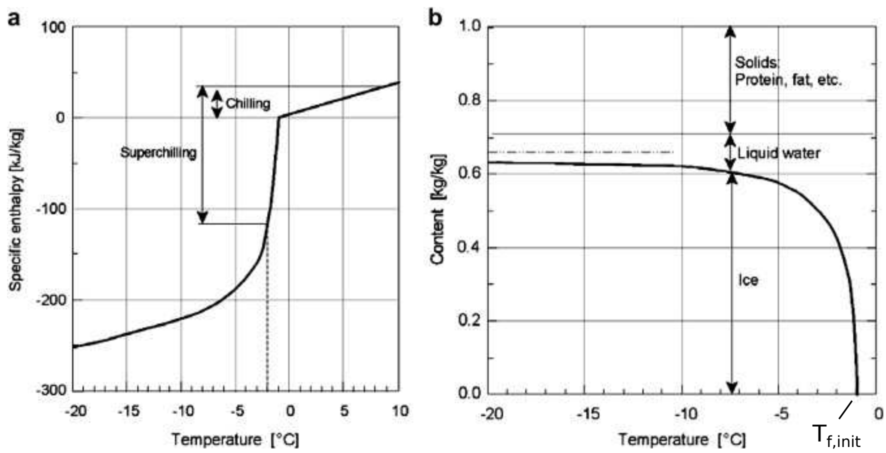

Figure 2.3: Energy (a) and ice content (b) in salmon fillet dependent of temperature (adopted with permission from Magnussen et al. (2008) and Harðarson (1996)).

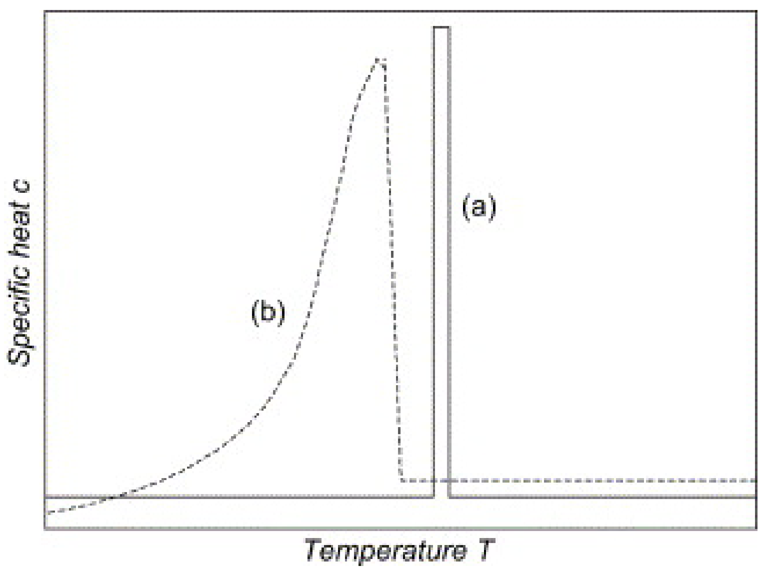

Figure 2.4: Apparent specific heat for (a) a material with sharp phase change, (b) a material with gradual phase change (Pham (2006), with permission).

2.4 Wholesale packaging solutions

The quality deteriorating impact of ambient temperature fluctuations during distribution of perishables can be dampened by thermal insulation of the packaging. Other characteristics of packaging which can influence the quality of the products include cost (disposal or recycling), strength and space. Here, space includes both internal space for cooling packs or ice and space required for storage. Expanded polystyrene (EPS) boxes have traditionally been utilised for export of Icelandic fresh fish products up to this date (Margeirsson et al., 2009; Þóroddsson, 2010). EPS boxes are usually white, manufactured from moulded polystyrene beads, resulting in a material with up to 98% of the volume consisting of air pores. The air decreases the density and increases the insulation performance but decreases strength and of course increases the required storage volume for the boxes.

Another type of wholesale fresh fish packaging has been receiving increased international attention because of environmental and economic reasons, i.e. corrugated plastic (CP) boxes. In the United Kingdom, usage of EPS and CP boxes as wholesale fresh fish boxes has been estimated at 14 and 0.6 million boxes, respectively (Seafish, 1996), but the ratio between these two box types may change in the future, bearing the aforementioned environmental and economic reasons in mind. The most popular wholesale fish box aimed at suiting the needs and preferences of processors, distributors and buyers (wholesalers/retailers) have a storage capacity of 3 to 6 kg (Seafish, 1996; Þóroddsson, 2010), but the size is normally decided by the buyer (Þóroddsson, 2010). The CP boxes are produced from extruded corrugated plastic (polypropylene) sheets which are 2.0 to 3.3 mm in thickness. The CP boxes can be flat packaged when not in use, which can save valuable storage space but they have poor strength relative to the EPS boxes (Seafish, 1996) and studies have indicated that the insulation of CP boxes is worse than for EPS boxes (Anyadiegwu and Archer, 2002; Margeirsson et al., 2009). The ambient temperature profile applied in the study by Anyadiegwu and Archer (2002) was aimed at simulating an airfreight distribution chain but according to several results of studies mentioned in Section 2.1 and paper I, more severe thermal load can be expected in case of airfreight. Margeirsson et al. (2009) used an air temperature profile similar to the temperature profiles during air transport described in paper I to compare the thermal insulation of EPS to that of CP boxes but neither numerical heat transfer modelling nor sensory evaluation were performed.

Since the CP packaging is relatively new, more emphasis has been put on investigating thermal insulation of EPS. Froese (1998) examined insulating properties of EPS boxes containing live fish immersed in water being chilled by low ambient temperature. Burgess (1999) calculated and compared thermal resistance (R-value) of different insulating packaging by letting regular ice inside the packaging melt when stored in a constant temperature environment. Further comparison between different packaging solutions was performed by Singh et al. (2008), also using ice-melt tests. The authors not only calculated R-values for different packaging solutions but also melting point and latent heat (thereby cooling capacity) of 12 different gel packs and PCMs (phase change materials), whose purpose is to maintain required product temperature. The authors state that the thermal resistance is a property of the whole package including the product, i.e. not just a property of the insulating material. This suggests that the most reliable way to compare thermal performance of different wholesale fresh fish packaging is to actually test the packaging while containing fish under challenging, dynamic temperature conditions. Cooling capacity of gel packs and phase change materials was studied experimentally by Labranque and Kacimi (2007), Elliott and Halbert (2005). Zalba et al. (2003) reviewed a number of studies on application of phase change materials in conservation and transport of temperature-sensitive materials and describe a number of commercial PCMs as well as potential materials to be used as PCMs, along with their wide-ranging thermophysical properties.

Other available packaging types for fresh fish transport, described by Seafish (1996), include solid or corrugated fibreboard boxes, returnable high-density polyethylene boxes and bulk modified atmosphere packs.

2.5 Heat transfer modelling

James et al. (2006) noted that models aimed at predicting heat and mass transfer during transport of perishables can generally be divided into two groups: 1) models that consider the environment within the transport unit (usually with regard to airflow), 2) models that concentrate on the product temperature. In order to simulate real conditions during storage and transport of fresh fish, these models should preferably be able to take into account variable ambient conditions, which can occur because of door openings, poor temperature control in a chilled storage, product transfer to unrefrigerated conditions, etc. The known temperature control problems (see Section 2.1) in multi-modal transport chains have increased the interest in the effects of transport conditions on microbial growth, storage life and food safety. Almonacid-Merino et al. (1993) coupled a numerical heat transfer model with a microbial growth model to develop a storage life prediction model able to estimate storage life. The model inputs were dynamic ambient temperature, location of food filling a rectangular container and packaging characteristics. The results show that even when the ratio of the total storage time at an undesirable ambient temperature is rather short (2–3%), the storage life reduction can be significant (20–30%). Amos and Bollen (1998) developed a storage life model for asparagus by combining a heat transfer model and an empirical correlation for the remaining shelf life as a function of integral of heat units (degree-hours above 0 °C). Their model was used to predict the performance of insulating blankets and to determine the mass of ice required in eutectic blankets.

The focus of the modelling work in this thesis is on heat transfer inside packaged food, i.e. neither on coupling of heat transfer models nor on modelling of the product environment inside transport units. However, because the heat transfer models of the product environment are sometimes combined with models of the packaged food, a reference should be made to the studies of Hoang et al. (2000), Foster et al. (2002), Moureh et al. (2002a), Foster et al. (2003), Rizzi (2003), Moureh and Flick (2004), Nahor et al. (2005), Delele et al. (2009) and the review papers of Xia and Sun (2002), James et al. (2006) and Smale et al. (2006).

A considerable number of investigations have been conducted to study the effects of temperature abuse on refrigerated food and to relate product temperature changes to abusive ambient conditions and thermal properties of the food and packaging solutions. Both experimental and numerical methods have been used to show that the temperature distribution in single packages and in pallet loads exposed to thermal load is in general inhomogeneous, with highest temperatures at the corners of the packages/loads and the most stable temperatures at their centre (Dolan et al., 1987; Almonacid-Merino et al., 1993; Moureh and Derens, 2000; Moureh et al., 2002b; Tanner et al., 2002a,b; Stubbs et al., 2004; Laguerre et al., 2008). Because of this temperature heterogeneity inside the same packaging unit, the relevant quality and safety parameters of the food product will depend on its relative location within the unit.

Verboven et al. (2006) gave a review of mathematical approaches to predicting transport phenomena in food bulks, packages and stacks during refrigeration processes, taking into account airflow as well as heat and mass transfer. Analytical heat transfer models are in general less complex and require less computational power than CFD models. Zuritz and Sastry (1986) developed an analytical solution for one-dimensional temperature distribution in food packaging without taking into account its three-dimensional structure. A generalised methodology for mathematical modelling of heat transfer and testing was presented by Tanner et al. (2002a,b). Chen and Ramaswamy (2007) reported a simulation package using Microsoft Visual Basic for modelling thermal processes in food based on a scheme combining numerical and some simple analytical approaches.

Moureh and Derens (2000) developed a three-dimensional CFD model using the CFD software PHOENICS to predict temperature rises in pallet loads of frozen fish under thermal load. In order to validate the numerical results, experiments were performed with pallets loaded with 11 levels of frozen fish packages (height: 14 cm) both on a shaded dock in February (at 4 °C, 80% RH) and on an open dock in July (at 21.6 °C, 50% RH). The product temperatures were −25 °C and −20 °C in February and July, respectively, and the pallet loads were covered with a plastic film. In order to map the temperature evolution at various locations in the pallet, the most temperature-sensitive cartons located at the top, medium and bottom corners of the pallet were instrumented with temperature-recording sensors. It should be noted that the sensors were placed at the centre of the most external portions in each carton, but not at the most critical positions which are found at the outer corners of the cartons.

The model predicted the maximum product temperature to rise over 25 min by 2.7 °C and 6.4 °C in the February and July simulations, respectively. Largest temperature rises were obtained both experimentally and numerically at the top level, which is in good agreement with the results of Sillekens et al. (1997), who studied temperature changes of cut flowers during flight and the results of Raab et al. (2008), who studied land based transport of poultry.

To relate the results of Moureh and Derens (2000) to real transport conditions, according to the ATP (2010), p. 69, a brief temperature rise at the surface of frozen fish above the maximum allowed temperature of −18 °C is limited to 3 °C. The maximum temperature rise over only 25 min in the study of Moureh and Derens (2000) exceeds this limit severely in the summer situation and almost in the winter situation as well. Fresh fish is more sensitive to temperature fluctuations than frozen fish and thus, even more emphasis should be put on minimising temperature fluctuations of the fresh one.

Investigations of the effectiveness and applicability of insulated covers for pallet loads reach at least as far as to the 1980's (Sharp, 1988). The combined heat transfer and storage life model of Amos and Bollen (1998) was used to evaluate the effect of pallet wrapping on temperature control and quality deterioration of asparagus during air freight. Applying either insulated blankets or eutectic blankets (containing ice) increased the storage life by 0.5–0.7 days and 2–3 days, respectively. The results showed that using eutectic blankets across only the top of the pallet, yields little additional benefit over using pallet covers alone, which is in good agreement with the experimental results of Bollen et al. (1997).

Moureh et al. (2002b) presented a three-dimensional CFD model, which can be seen as an extension of the model of Moureh and Derens (2000). Moureh et al. (2002b) studied three types of pallet covers, and by replacing the actual heterogeneous composition of products and packaging within a pallet by an equivalent homogeneous thermally equivalent medium (as in Moureh and Derens (2000)), a domain including a large number of pallets could be simulated. The time needed for the product temperature to rise to 24 °C proved to be around two-fold when an insulated cover was used as compared to the corresponding time without a cover. The authors also noted that due to solar radiation, the outside surface temperature of a food pallet load can become larger than the ambient air, which was also observed by Dolan et al. (1987).

Because of the frequent break up of pallets (Grétarsson, 2011), temperature distributions inside single and/or a few packages under thermal load are also relevant research topics. Burgess (1999) reported a simple analytical model used for calculating thermal resistance (R-value) of insulated boxes but a more sophisticated analytical heat transfer model of a single box was developed by Choi and Burgess (2007). The model could amongst other things be used to predict ice requirement and changes in product mean temperature. The model could however not be used to predict the temperature distribution inside the insulated box.

Stubbs et al. (2004) used an in-house general-purpose software to develop a numerical heat transfer model in order to study temperature distribution in chilled cheese packaged in an EPS box under thermal load. Gel refrigerant was applied at different surfaces (top, bottom, sides) inside the EPS box. As would be expected, distributing the cooling capacity of the gel refrigerant was found to be beneficial with regard to minimising product temperature rises.

More recently, East and Smale (2008) and East et al. (2009) reported how zone based heat transfer modelling (based on Tanner et al. (2002a,b)) could be combined with a genetic algorithm in order to optimise the design of a thermally insulated box with regard to cost. Also, in a temperature-predictive model of an insulated box loaded by chilled products and a refrigerant (referred to as phase change material) developed by Laguerre et al. (2008), the product temperature evolution at a given position in the box was assumed to be a linear response of the initial temperature of the load and the ambient temperature. The authors considered conduction to be the main heat transfer mechanism in the box partly because the small air space above the product would not allow for significant natural convection. The results showed that the model was applicable for both constant and variable ambient temperature as long as the PCM was not completely melted.

None of the aforementioned studies covered a numerical heat transfer model of fresh (chilled or superchilled) fish either in single, free standing packages or packages assembled on pallets.

Chapter 3

Materials and methods

This chapter gives an overview of the necessary prerequisites for performing the research presented in this thesis, both involving material properties, measurement procedures and modelling theory. The experimental and heat transfer modelling procedures are described in more details in the original papers I–VII.

3.1 Whitefish and packaging materials

In all experiments, either cod (*Gadus morhua*) or haddock (*Melanogrammus aeglefinus*) fillets or loins are used. The experiments are carried out in different seasons of the year implying small differences between the thermophysical properties of the fish in different experiments. The thermal properties adopted in the heat transfer models (II, III, IV, VI, VII) are covered in Section 3.3.1. The time of catch, handling on board the fishing vessels and the processing operations applied are described in details in the original papers.

The dimensions and thermal properties of the wholesale fish box types used in the comparative thermal load experiments are presented in Tables 3.1 and 3.2, respectively. The research is limited to EPS and CP, which are by far the most popular packaging types for export of Icelandic fresh fish products.

Table 3.1: Dimensions of fish boxes.

Box type	Used in paper	Inner dim. L x W x H (mm)	Outer dim. L x W x H (mm)
5-kg EPS	II, III, VII	355.5 x 220 x 85	400 x 264.5 x 135
5-kg EPS (new)	IV, VII	355.5 x 220 x 90	400 x 264.5 x 135
6 to 7-kg EPS	IV	355.5 x 220 x 109	400 x 265 x 159
3-kg EPS	V, VI	355.5 x 220 x 71	400 x 264.5 x 121
5-kg CP	II, V	370 x 230 x 80	395 x 247 x 85

Figures 3.1 and 3.2 show how whitefish products are often packaged in wholesale boxes. The fish is either put inside a plastic bag inside the box or a thin plastic (polyethylene) film is put on top of the fish as shown in Figure 3.1. The shape of the fish pile inside the boxes should be noted. The thickest part

Table 3.2: Thermal properties of fish boxes.

Box type	Used in paper	m (g)	ρ (kg m^{-3})	c_p (kJ kg^{-1} K^{-1})	k (W m^{-1} K^{-1})
5-kg EPS	II, III, VII	181	23[a]	1.28 ± 0.05[b]	0.0345[a]
5-kg EPS (new)	IV, VII	183	23[a]	1.28 ± 0.05[b]	0.0345[a]
6 to 7-kg EPS	IV	205	25[d]	1.28 ± 0.05[b]	0.031–0.036[c]
3-kg EPS	V, VI	171	23[a]	1.28 ± 0.05[b]	0.0345[a]
5-kg CP	II, V	178	116–164[e]	1.894 ± 0.002[e]	0.0184–0.0350[e]

[a] Gudmundsson (2009); [b] Al-Ajlan (2006); [c] Al-Ajlan (2006); Holman (2002); BASF (2001); [d] Baldursson (2008); [e] Calculated in the current study, see paper II

of the pile is normally seen in the middle of the box as a result of fast actions during packaging.

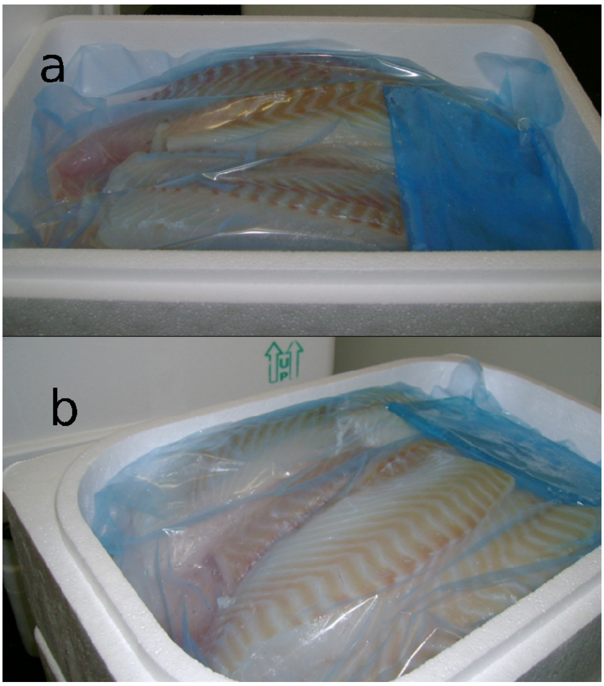

Figure 3.1: Cod loins with a thin plastic (polyethylene) film and a gel pack on top of the loins in an old EPS box type (a) and in a new EPS box type with rounded corners designed in the current study (b).

In the packaging comparison studies, both ice packs (II, III) and gel packs (IV) are used. The ice packs are manufactured by Promens Tempra (Hafnarfjörður, Iceland), contain only water (ice), weigh 252 ± 1 g and have the dimensions 310 x 175 x 13 mm. The gel packs (Figure 3.1) are manufactured by Ísgel (Blönduós, Iceland), weigh 125 ± 2 g and have the dimensions 160 x 125 x 6 mm.

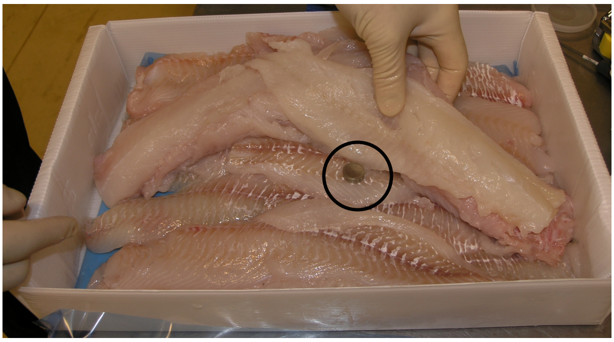

Figure 3.2: Haddock fillets in a CP box. Also shown is an Ibutton temperature logger used for monitoring temperature in between fillets.

3.2 Temperature measurements

All thermal load simulation experiments for comparison of packaging solutions or validation of numerical heat transfer models (II–VII) are conducted in temperature-controlled air climate chambers from Celsius (Reykjavík, Iceland). Temperature measurements for mapping and assessing fresh fish transport chains (I) are all performed in real conditions, i.e. in fresh fish processing plants and during real transport from processor to market.

3.2.1 Measurements devices

The specification of the different measurement devices used is presented in Table 3.3. Ibutton temperature loggers (type DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) are used to monitor all product temperatures. This includes the temperature inside the insulated boxes during real transport (I, IV) and in the packaging and transport simulation studies (II, III, IV, V, VI, VII).

Outside surface and ambient temperatures are either measured with the Ibutton loggers or Tidbit v2 temperature loggers from Onset Computer Corporation (Bourne, MA, USA). All temperature loggers are factory calibrated and re-calibrated by the authors in a thick mixture of fresh, crushed ice and water. Relative humidity is monitored with HoBo U12 temperature and relative humidity loggers from Onset Computer Corporation. Finally, air velocity is measured with Thermo-Anemometer Datalogger (model 451126) from Extech Instruments (Waltham, MA, USA).

3.2.2 Placement/configuration of measurement devices

In the cold chain mapping trials (I, IV), temperature recorders are put at 3–4 different positions inside boxes at different locations in a pallet load. This is done to grasp the temperature differences both within each package and within

Table 3.3: Specification of measurement devices.

Device	Resolution	Range	Accuracy
Ibutton	0.0625 °C	−40 to 85 °C	±0.5 °C [a] at −15 to 65 °C
Tidbit v2	0.02 °C	−20 to 70 °C	±0.2 °C at 0 to 50 °C
HoBo U12	0.03%	5 to 95%	±2.5%
Thermo-Anemometer logger	$0.01\,\mathrm{m\,s^{-1}}$	0.3 to $45\,\mathrm{m\,s^{-1}}$	$\pm(3\,\% + 0.1)\,\mathrm{m\,s^{-1}}$

[a] equal to the allowed deviation from the set point by standards for food distribution (BS EN 12830, 1999)

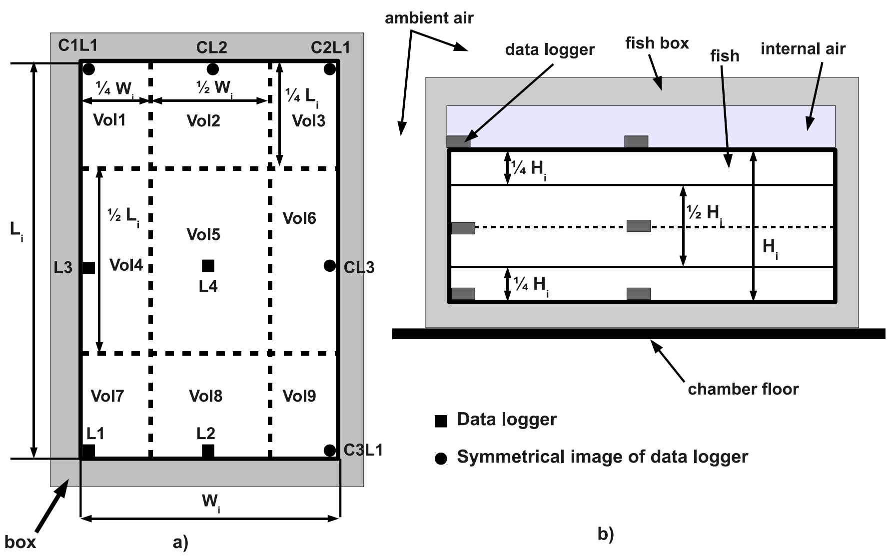

Figure 3.3: Positions of product temperature loggers inside fish boxes along with corresponding copies of the product temperature loggers: a) in horizontal plane, b) in vertical plane (II, III).

each pallet load. In order to map the ambient thermal load during distribution, the surface temperature is also measured at few different positions on each pallet.

In the transport simulation studies (II–VI) the product temperature is measured at four (IV, V, VI) or twelve (II, III) different positions inside each box. In paper II the product temperature is measured at four positions at the bottom, four positions at mid-height and four positions at top of the fillets. The positions in each of the three horizontal planes are shown in Figure 3.3a and in a vertical cross section in Figure 3.3b. The configuration of temperature sensors in papers V and VI is presented in Figures 3.4 and 3.5.

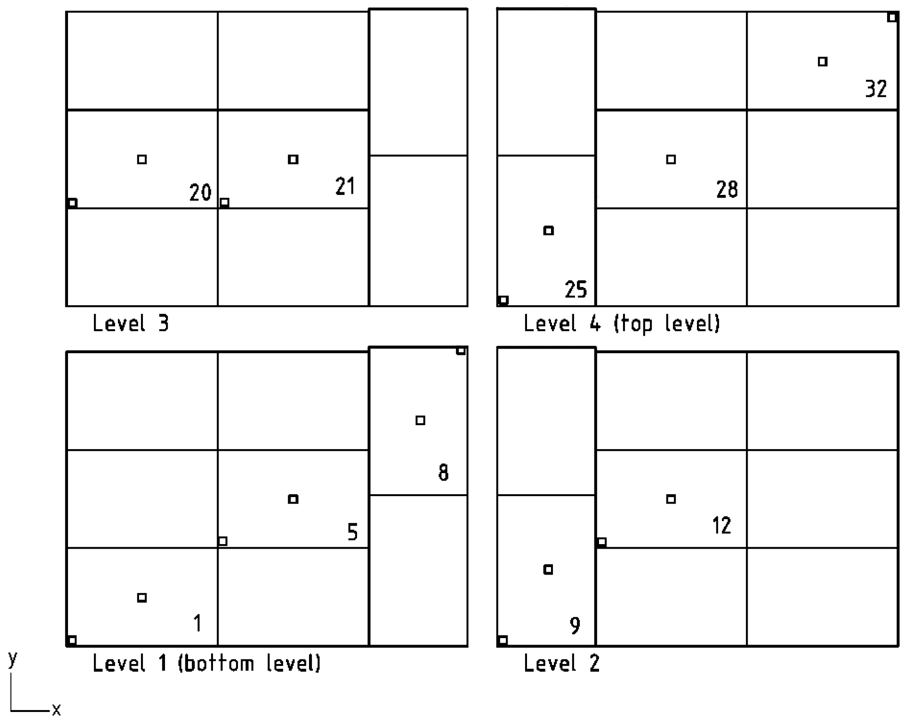

Figure 3.4: Configuration of fish boxes and numbering of ten temperature-monitored EPS boxes and four CP boxes (circled numbers) at the four layers on each pallet. Small squares represent the horizontal positions of temperature data loggers (V, VI).

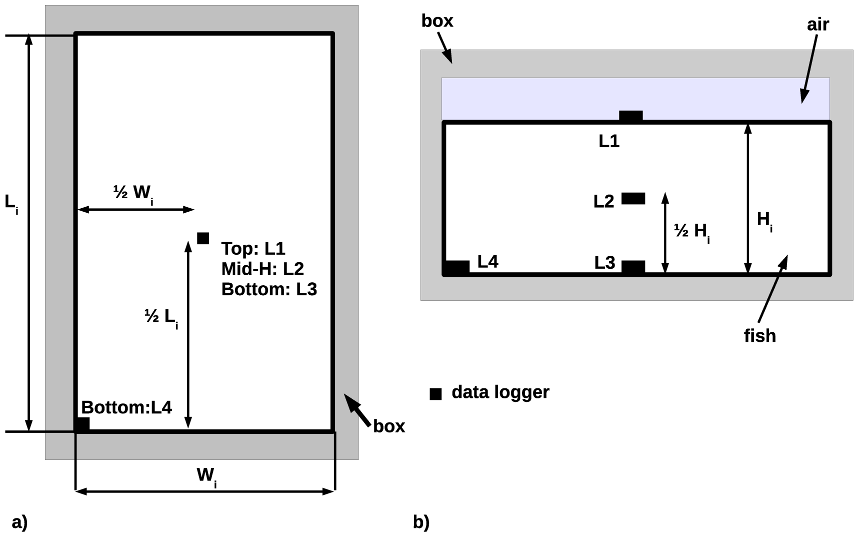

Figure 3.5: Positions of product temperature loggers in nine out of ten temperature-monitored EPS boxes and four CP boxes: a) in horizontal plane, b) in vertical plane. Product temperature in the bottom corner (L4) is not monitored in EPS box no. 28, see Figure 3.4 (V, VI).

Calculation of mean product temperature

The mean product temperature is calculated as a volume weighted mean temperature according to:

$$T_{\text{mean}} = \frac{1}{V}\int_V T \cdot dV \tag{3.1}$$

$$T_{\text{mean}} = \frac{1}{V}\sum_{\text{whole domain}} T_{\text{i}} \cdot \Delta V_{\text{i}} \tag{3.2}$$

where V and ΔV_{i} represent the volume of the whole domain and partial volume, respectively. A calculation of the mean temperature in case of twelve product temperature loggers is performed in paper II, where it has been assumed that the product temperature distribution is symmetric in each horizontal plane and symmetric images of corresponding loggers (black circles in Figure 3.3a) are used to calculate the mean product temperature, according to Eq. 3.2.

3.3 Numerical heat transfer modelling

Three dimensional finite volume heat transfer models are developed using the Computational Fluid Dynamics (CFD) software FLUENT for the following domains/cases under temperature-abusive conditions:

- single 5-kg EPS box containing chilled fish (II).

- single 5-kg CP box containing chilled fish (II).
- single 5-kg EPS box with round corners containing chilled fish (VII) or superchilled fish and a cooling pack (IV).
- partly loaded pallet with 32 3-kg EPS boxes containing chilled or superchilled fish (VI).
- fully loaded pallet with 96 3-kg EPS boxes containing chilled fish (VI).

In the first two models developed (II), the computational domain is limited to a single box containing fish fillets distributed evenly at the bottom of the box with air above the fillets. As in the rest of the models, the airflow outside the boxes is not modelled and is taken into account by using a convection coefficient and ambient temperatures, which are both steady (VII) and dynamic (II, III, IV, VI). The same limitation of the computational domain is valid for the round corner EPS box design (VII). The model of the same box type containing superchilled fish and a cooling pack (IV) takes into account the uneven fish distribution inside the boxes (Figure 3.6) in the experiment conducted.

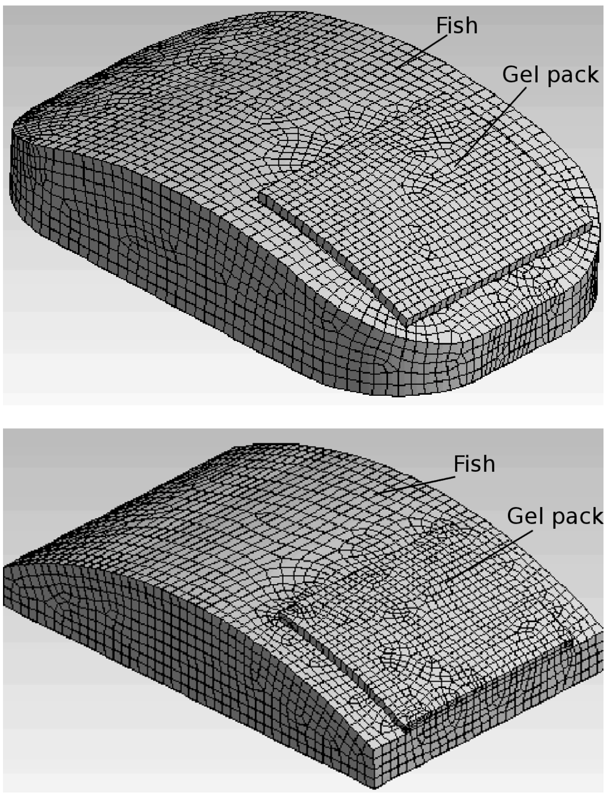

Figure 3.6: Computational mesh for fish and gel pack inside a new box type (above) and an old box type (below) (IV).

In order to develop the models of 32 packages assembled on a pallet (VI), the model for single EPS boxes (II) is extended in order to take into account an increased number of fish boxes. These pallet boxes have their height reduced by 14 mm and a volume capacity of 3 kg instead of 5 kg, see Table 3.2. Finally, after comparison to experimental results the model with 32 packages (4 box layers) is further scaled up by increasing the number of box layers to 12, representing a fully loaded pallet (VI).

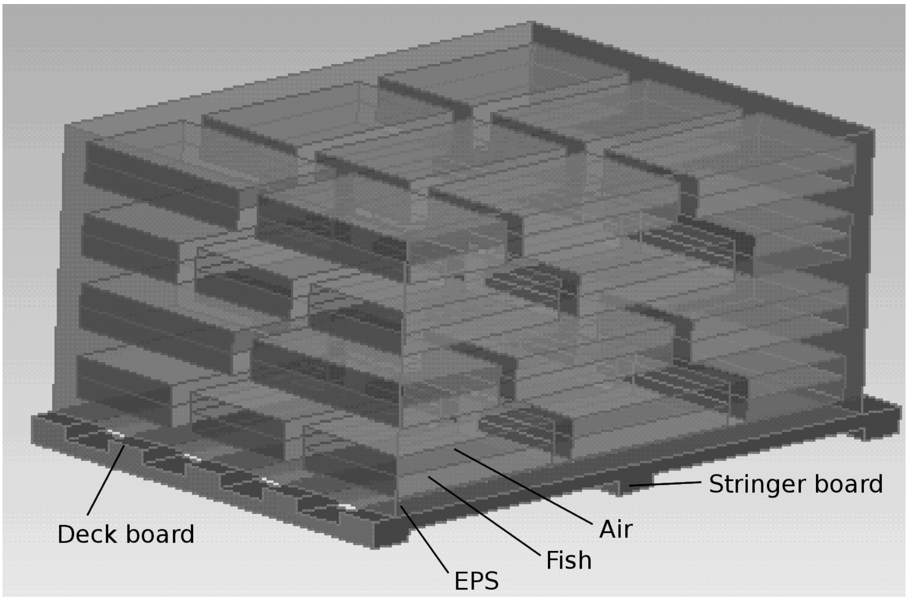

Figure 3.7: Computational domain comprising an upper part of a Europallet and 32 3-kg EPS boxes containing fish and air (VI).

In all the models, inside the fish fillets heat is transferred only by conduction described by the following partial differential equation:

$$\rho_{\mathrm{f}} c_{p,\mathrm{f}} \frac{\partial T_{\mathrm{f}}}{\partial t} = \nabla \cdot (k_{\mathrm{f}} \nabla T_{\mathrm{f}}) \tag{3.3}$$

The air layer above the fish fillets in each box is assumed to be static in all models, implying that heat transfer in the air is conductive, according to Eq. 3.3, and radiative, modelled with a Surface-to-Surface (S2S) radiation model, see Siegel and Howell (1992). The emissivity adopted for the inside surface of fish boxes (both EPS and CP) and the fish is 0.9 according to Earle and Earle (2004). The assumption of no convection above the fish fillets can be explained by the fact that the fish is maintained at lower temperature than the inside of the box lid. This causes higher-density air to be trapped below lower-density air in the enclosed space above the fish fillets and thus no gravity driven convection takes place.

3.3.1 Thermal properties of whitefish

In the models with non-superchilled fish (II, III, VI, VII), the following non-temperature dependent thermal properties are adopted:

- $\rho = 1054\,\mathrm{kg\,m^{-3}}$ (see Zueco et al. (2004))
- $c_p = 3.73\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$ (mean value between 4 and 32 °C, see Rao and Rizvi (1995)
- $k = 0.43\,\mathrm{W\,m^{-1}\,K^{-1}}$ (applies both at 0 °C and 10 °C according to Zueco et al. (2004))

In the models with superchilled fish (IV, VI), temperature dependent thermal properties are assumed. According to Rahman (2009b), the different types of water found in frozen foods are usually defined as total water (X_w^o), ice (X_I), unfreezable water (X'_w, which can not be formed as ice even below −40 °C) and unfrozen water (X_w^u). The total water content can be expressed as

$$X_\mathrm{w}^\mathrm{o} = X_\mathrm{w}^\mathrm{u} + X_\mathrm{I} + X'_\mathrm{w} \tag{3.4}$$

The following relationship from Rahman (2009b) is adopted for calculating the ice content of the fish as a function of temperature (T):

$$X_\mathrm{I} = (X_\mathrm{w}^\mathrm{o} - X'_\mathrm{w})(1 - \frac{T_\mathrm{f,init}}{T}) \tag{3.5}$$

The initial freezing point of cod ($T_\mathrm{f,init}$) is listed by Rahman (2009b) as −0.91 °C but is taken as −0.92 °C in the FLUENT models because of better fit with the experimental data (IV). The initial freezing point is lower than the freezing point of pure water because of dissolved substances in the moisture within the foodstuff. The un-freezable water content is estimated as 5.3% according to the following equation by Rahman (2009b):

$$X'_\mathrm{w} = B(1 - X_\mathrm{w}^\mathrm{o}) \tag{3.6}$$

where $B = 0.278$ (Fikiin, 1998) is the bound water as kg per kg of dry solids and $X_\mathrm{w}^\mathrm{o} = 0.803$ (IIR, 1986; Fikiin, 1998) is the total water content. The generic model by Choi and Okos (1986) is used for estimating linearly temperature dependent apparent specific heat capacity (c_p, both accounting for sensible and latent heat) of cod as shown in Table 3.4. Both a constant density of $1054\,\mathrm{kg\,m^{-3}}$ and values for thermal conductivity are adopted from Zueco et al. (2004) assuming a sharp change at $T_\mathrm{f,init}$.

Table 3.4: Linearly temperature dependent thermal properties of cod (IV, VI).

T (°C)	−1.00	−0.92	−0.9	−0.85	0	15
c_p ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$)	189.4	223.0	3.679	3.679	3.675	3.755
k ($\mathrm{W\,m^{-1}\,K^{-1}}$)	1.302	1.302	0.43	0.43	0.43	0.43

3.3.2 Boundary conditions

Mixed convection and external radiation boundary conditions are applied to the top and the sides of the single boxes (II, IV, VII) and the pallet stacks (VI) in addition to the bottom of the pallet stacks (VI). The convective heat transfer coefficient outside the pallet stack (h_{conv}) is estimated from well known correlations, for laminar natural convection in air (Ra $< 10^9$ (Holman, 2002)), as follows:

- Box/pallet stack top (horizontal plane):

$$h_{\text{conv,top}} = 1.32 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{3.7}$$

- Pallet stack bottom (horizontal plane):

$$h_{\text{conv,bot}} = 0.59 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{3.8}$$

- Box/pallet stack sides (vertical planes):

$$h_{\text{conv,side}} = 1.42 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{3.9}$$

  where $\Delta T = T_{\text{amb}} - T_{\text{w,out}}$ ($T_{\text{w,out}}$: outside box/pallet stack wall temperature) and x is the characteristic length.

In order to estimate h_{conv} at the top and vertical sides of the single boxes, the results from outside surface temperature loggers are used for representing $T_{\text{w,out}}$ in Eqs. 3.7 and 3.9. For the pallet stacks (VI), the results from the single-box study (II) are used to estimate ΔT with a constant value of 3 K because less precise surface temperature measurements are conducted in the multiple-box study (VI). It should be noted that in all these experiments (II, IV, VI), the surface and ambient temperatures are time dependent, which makes it even harder to estimate ΔT. In addition to this, the surface temperature of each box/pallet stack plane is not uniform as discussed by Moureh and Derens (2000). However, it should be noted that according to Eqs. 3.7–3.9, h_{conv} is proportional to $(\Delta T)^{1/4}$ and thus not very sensitive to ΔT. The estimated values for the $h_{\text{conv,top}}$ range between 2.1 and 2.3 W m^{-2} K^{-1} for the single boxes (II, III, IV) and is 1.8 W m^{-2} K^{-1} for the pallet stacks (VI). Similarly, the estimated values for the $h_{\text{conv,side}}$ are between 3.0 and 3.5 W m^{-2} K^{-1} for the single boxes and between 1.7 and 2.2 W m^{-2} K^{-1} for the pallet stacks.

The time dependent temperatures measured around 0.1–0.3 m above the single boxes (II, III, IV) and the pallet loads (VI) are adopted as the free flow (external) temperature for the convective and radiative boundary conditions at the box/pallet load top and sides. Similarly, the ambient temperature measured at the chamber floor is adopted as the free flow temperature for the convective and radiative boundary conditions at the bottom of the pallet stack. For the single boxes, on the other hand, the time dependent temperature measured at the chamber floor is used as the floor (external) temperature.

The radiative heat transfer coefficient outside the boxes/pallet loads (h_{rad}) can be expressed according to the following relation (Moureh and Derens, 2000):

$$h_{\mathrm{rad}} = \frac{\sigma}{\frac{1}{\epsilon_{\mathrm{amb}}} + \frac{1}{\epsilon_{\mathrm{b,out}}} - 1} \left(T_{\mathrm{b,out}}^2 + T_{\mathrm{amb}}^2\right)\left(T_{\mathrm{b,out}} + T_{\mathrm{amb}}\right) \tag{3.10}$$

An emissivity of 0.9 is adopted for both the outside surface of EPS/CP boxes and the chamber walls according to The Engineering Toolbox (2010) and Holman (2002).

3.3.3 Thermal contact resistance

Non-ideal surface contact is assumed between different solid materials in the numerical heat transfer models and consequently thermal contact resistances (R) between the adjacent surfaces of the materials are estimated, see Table 3.5. The recommendation by BASF (2001), along with the results of Cleland and Valentas (1997) for plate freezing applications and those of Novikov (1970); Shojaefard and Goudarzi (2008) for pressure dependence of R are taken into account to estimate R. It should be noted that estimating R without experimental studies can be a challenging task as discussed in Holman (2002), p. 54–55.

Table 3.5: Estimated thermal contact resistance between different adjacent surfaces.

Surfaces	Paper no.	R ($\mathrm{m^2\,K\,W^{-1}}$)
fish, EPS box	II, III, IV, VI	0.05
fish, CP box	II	0.05
EPS box, plywood floor	II, III	0.1
fish, gel pack	IV	0.1
EPS box, gel pack	IV	0.1
EPS box, wooden pallet	VI	0.1

3.3.4 Initial conditions

In all the heat transfer models developed and validated by experimental results (II, III, IV, VI), the experimental results for the mean fish temperature are used to define uniform initial conditions throughout the whole computational domain. This is a simplification of the real conditions because in the experiments, product temperature differences inside the computational domains between 0.2 °C (IV) and 0.9 °C (VI) are measured in reality.

Chapter 4

Summary of results and discussion

The goal of this chapter is to summarise and discuss the results from the experiments and heat transfer modelling summarised in Chapter 3 and described in more details in papers I–VII.

4.1 Temperature control in chill chains

The main conclusion from the temperature mapping of different air and sea transport chains is that temperature control in containerised sea transport is, in general, much better than in multi-modal air transport chains (I). Furthermore, efficient superchilled processing is very important for the product temperature control during transport and storage, especially for air freight. The critical thermally abusive steps in air transport chains described earlier by Stera (1999), Brecht et al. (2003) and James et al. (2006) are also noted in the current study (I). Ambient thermal load is especially prominent in passenger transport and the critical steps include the flight itself, loading and unloading operations and storage under un-chilled conditions at the airports. The results in this section are mainly based on results from paper I but some results on sea transport have not been published before.

4.1.1 Air transport

An air transport chain, which was mapped in September 2007, is taken here as an example. The ambient and product temperatures are shown in Figures 4.1 and 4.2, respectively. The transport is carried out in a cargo airplane and the product is cod loins packaged in 5-kg EPS boxes assembled on two pallets. Table 4.1 presents the logistics activities carried out in the chain and the mean ambient temperatures (with standard deviations) at each step for the two studied pallets.

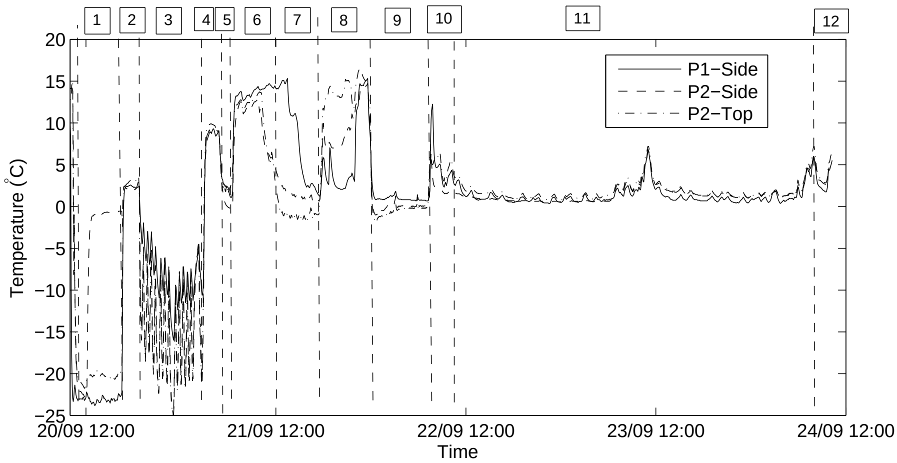

Figure 4.1: Surface temperatures of two pallets (P1 and P2) during air cargo transport from Iceland to UK in September 2007 (adopted from paper I).

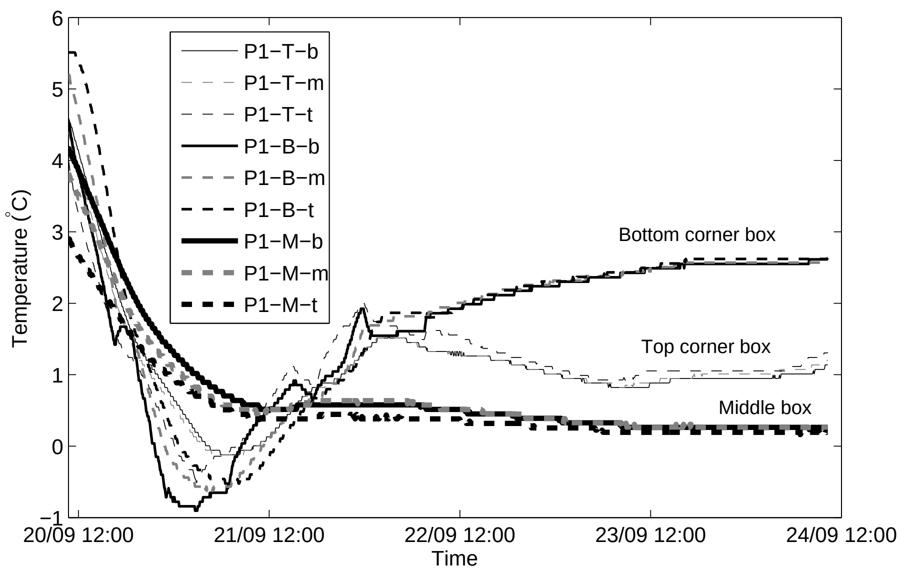

Figure 4.2: Product temperatures in three 5-kg EPS boxes in pallet load no. 1 during air cargo transport from Iceland to UK in September 2007 (adopted from paper I). P: pallet; T: top corner box; B: bottom corner box; M: middle level box at the side of the pallet stack; t: top-height middle position inside box, m: mid-height middle position inside box, b: bottom middle position inside box.

Table 4.1: Logistics steps and mean ambient temperatures (°C) in a cargo air transport chain in September 2007 (adopted from paper I). SD: standard deviation.

Step	Description	Duration (hours)	Amb. temp. of pallet 1 (mean±SD)	Amb. temp. of pallet 2 (mean±SD)
1	Frozen storage post-packaging at processor in North-Iceland	6.0	-22.5 ± 3.3	-13.0 ± 9.6
2	Chilled storage at processor	2.0	2.3 ± 0.3	2.5 ± 0.5
3	Domestic transport in a refrigerated truck	8.3	-8.1 ± 3.5	-14.4 ± 5.9
4	Unloading and loading in Reykjavík (RVK)	2.0	8.4 ± 1.1	8.7 ± 1.3
5	Transport from RVK to Keflavík airport (KEF, IS) in a chilled truck	1.3	2.2 ± 0.7	1.3 ± 1.1
6	Un-chilled storage at KEF airport	5.3	13.3 ± 2.0	10.3 ± 3.0
7	Chilled storage at airport + loading	6	8.1 ± 5.3	0.5 ± 1.6
8	Flight KEF–Humberside (HUY, UK) + un-chilled storage at HUY	6.3	6.4 ± 4.8	11.7 ± 3.1
9	Storage at HUY and road transport to Carlisle (UK)	7.3	1.0 ± 0.4	-0.2 ± 0.6
10	Unloading + unchilled storage at wholesaler in Carlisle	3.0	4.7 ± 2.7	3.6 ± 1.7
11	Chilled storage at wholesaler	45.8	1.3 ± 1.0	1.7 ± 1.1
12	Distribution to retailer	2.2	3.0 ± 1.2	4.0 ± 1.2
Total		4.0 days	0.7 ± 8.0	0.5 ± 7.6

High temperature variations and several abuses are observed during loading/unloading processes (steps 4 and 10), interim storage at the airports and the wholesaler (steps 6 and 10), and the flight (step 8). The pallets are exposed to un-chilled conditions (up to 15 °C) for more than 16.5 hours, which equals about 17% of the total logistics time from the processor to the retailer. These ambient thermal loads cause a temperature increase of the product inside the boxes in steps 6–8 and high product temperature at delivery as shown in Figure 4.2. The product temperature variations can obviously be related to the location of boxes on the pallet since less fluctuation is experienced in the middle boxes than at the bottom and top of the pallet. This is in good agreement with earlier investigations (Sillekens et al., 1997; Moureh and Derens, 2000; Moureh et al., 2002b; Raab et al., 2008; Jedermann et al., 2009). Interestingly, larger temperature rise is obtained in the bottom corner box than in the top corner box contrary to the results of Sillekens et al. (1997), Moureh and Derens (2000), Moureh et al. (2002b) and Jedermann et al. (2009). It should be noted that the temperature data loggers are positioned at three different levels in the middle of the studied fish boxes but not in the corners of the boxes. Judging from the results of the remaining papers in the current PhD work, higher temperature rises are expected in the outer corners than in the middle of the corner boxes, implying that the absolute maximum product temperature is not monitored in this trial. The product temperature variations are not as large on pallet no. 2 (results shown in paper I), which shows that the effect of abusive temperature conditions can vary not only within each pallet but also between different pallets in the same shipment. This can depend on the location of each pallet with regard to other cargo, cooling equipment and doors of the transport unit etc.

In two other air transport chains, mean ambient temperature was measured as 3.0 ± 5.2 °C, (duration: 1.7 days) and 8.7 ± 5.6 °C (duration: 2.2 d), i.e. higher than in the September 2007 trial (0.7 ± 8.0 and 0.5 ± 7.6 for the two pallets). The frozen storage at the processor right after packaging (step 1) and the frozen land transport (step 3), which are not considered among the best precooling methods (see Section 4.1.3), are the main reason for the lower mean ambient temperature in this trial. Without taking those two steps (no. 1 and 3) into account, the mean ambient temperature is around 3 °C. The results from temperature mapping of air transport chains in the current study emphasise the need for both applying effective precooling of products (see Section 4.1.3) and improving the thermal protection of the wholesale packaging used for air transport (see Section 4.3.2).

4.1.2 Sea transport

In September 2008, temperature control during sea transport from the same processor in Iceland as in the September 2007 trial was investigated in three separate shipments (I). The main conclusion is that the ambient temperature was more stable and considerably lower than in the air transport chains, i.e. -0.2 ± 0.5 °C (duration: 4.8 days), -0.7 ± 2.8 °C (duration: 5.9 days) and -0.7 ± 0.2 °C (duration: 6.7 d).

In September 2009, the ambient and product temperatures during sea transport from a producer located ca. 50 km from the international airport in Keflavík, Iceland, to Boulogne-sur-Mer, France, were monitored as is shown in Figures 4.3 and 4.4, respectively. The wholesale packaging material applied is EPS as in the earlier chain mapping trials. The different steps in the chain are illustrated in Table 4.2 along with the calculated mean ambient temperature at each step. The temperature measurements are conducted in a similar way as in paper I, i.e. with temperature data loggers positioned both inside the packaging and at its outside surface.

The results from the September 2009 trial are in good agreement with the results from paper I regarding the stable ambient temperature during the actual sea transport steps no. 5 and 7. However, for possible improvement of this particular cold chain, the unchilled and perhaps unnecessary delays both at the processor and at the transporter before containerisation should first be considered. Secondly, a thermal load period is experienced a few days later during transfer between containers, partly under unchilled conditions, in Immingham UK. As can be seen in Figure 4.4, the product temperature in the insulated EPS boxes is inevitably affected by the temperature fluctuations as in other parts of this work (I, II, III, IV, V, VI, VII).

More recently, a chain temperature mapping performed in January 2010 em-

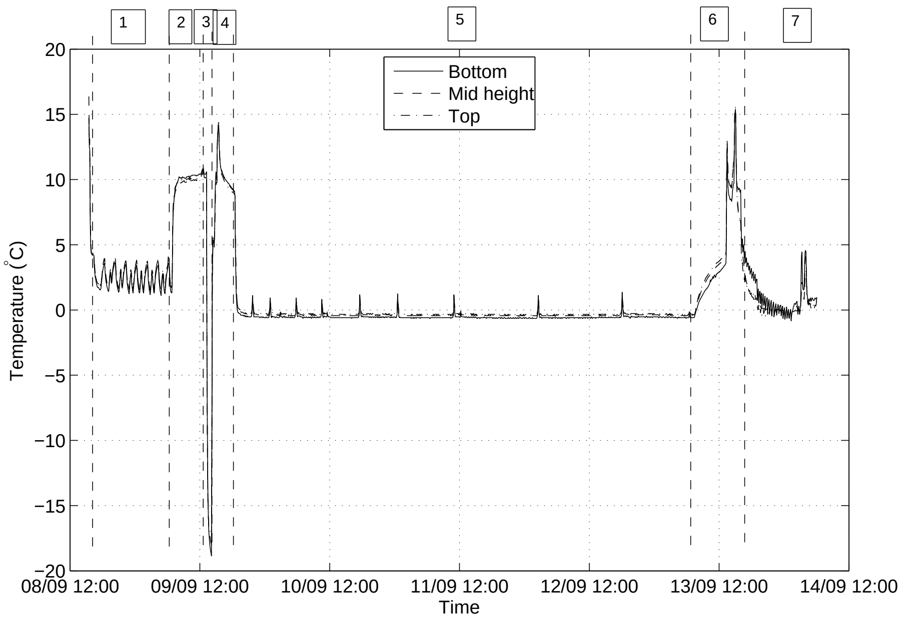

Figure 4.3: Surface temperatures of one pallet in a sea transport chain from Iceland to France in September 2009.

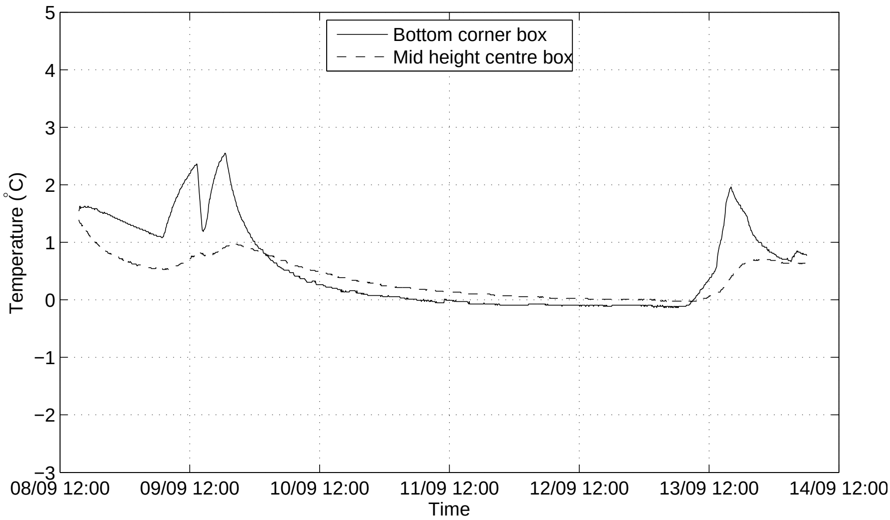

Figure 4.4: Product temperatures in two 5-kg EPS boxes on the same pallet in a sea transport chain from Iceland to France in September 2009.

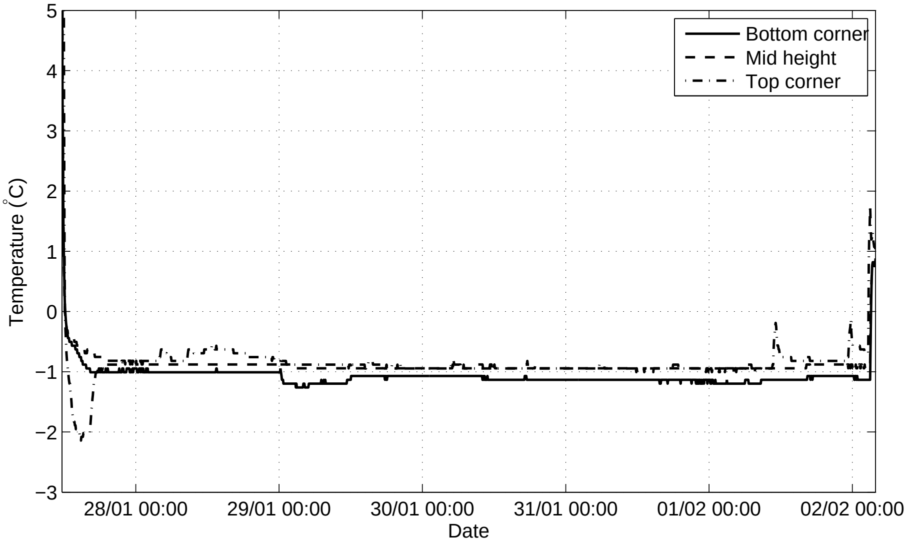

Figure 4.5: Ambient temperatures during containerised sea transport from processor in North-Iceland to Boulogne-sur-Mer, France.

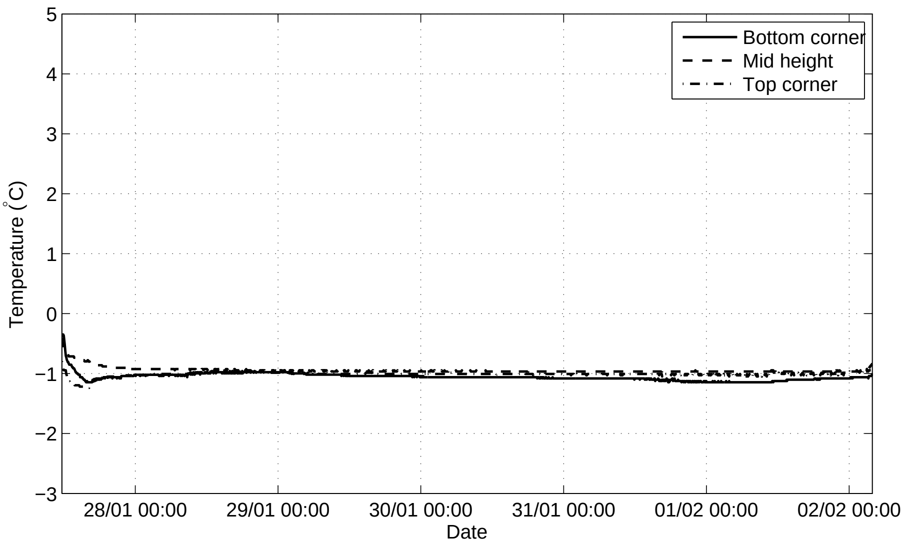

Figure 4.6: Product temperatures during containerised sea transport from processor in North-Iceland to Boulogne-sur-Mer, France.

Table 4.2: Logistics steps and mean ambient temperatures (°C) in a sea transport chain in September 2009. SD: standard deviation.

Step	Description	Duration	Amb. temp. (mean±SD)
1	Chilled storage at processor in Southwest-Iceland	15.4 h	2.8 ± 1.7
2	Un-chilled storage at transporter + handover to transporter	6.3 h	10.0 ± 0.6
3	Transport from processor to a warehouse centre in Reykjavík in a refrigerated truck	1.0 h	-14.5 ± 4.7
4	Storage and containerisation at transporter in Reykjavík	4.4 h	9.5 ± 2.3
5	Sea transport from Reykjavík to Immingham, UK	3 d 18.6 h	-0.2 ± 0.8
6	Transfer between containers in Immingham, UK, partly unchilled environment	3.6 h	8.6 ± 3.3
7	Sea transport from Immingham to Boulogne-sur-Mer, FR	13.3 h	1.3 ± 1.0
Total		5 d 14.6 h	1.1 ± 3.5

phasises the importance of an unbroken cold chain eliminating any unwanted thermal load at intermediate steps. The studied cold chain Iceland-France, from the same processor as in the September 2007 air transport trial, deals with the export of fresh whitefish loins as in the other trials, but in this case 12-kg CP boxes are used instead of EPS boxes in the other studies. The remarkably stable ambient (-0.9 ± 0.4 °C) and product (-1.0 ± 0.1 °C) temperatures are displayed in Figures 4.5 and 4.6, respectively. Apart from the stable temperature during the whole transport, it is interesting to see how the temperature control during processing has been greatly improved since 2007, relying on the installation and fine tuning of a "SuperChiller" precooling equipment (see Section 2.2.2) at the processing plant under consideration. The undesirable transfer between containers identified in the sea transport chain in September 2009 is not experienced in this trial, thereby not causing any undesirable deviations from the superchilled storage temperature around -1 °C. Thus, comparison between the results from the studied sea transport chains demonstrates that differences can be found in the temperature control between different sea transport chains. Finally, it should be noted that the lesser insulation of CP boxes (see Section 4.2 and paper II) is not a matter of concern in such a well temperature-controlled chill chain implying that other factors than temperature control can be emphasised when choosing the packaging type.

4.1.3 Precooling

The ambient and product temperatures during transport of precooled haddock fillets in July 2008 from a processor in Southwest-Iceland to Plymouth, UK, are illustrated in Figure 4.7 (I). The mean ambient temperature is 8.7 ± 5.6 °C implying much more severe thermal load than during the transport of the non-precooled fish in the September 2007 trial (0.7 ± 8.0 and 0.5 ± 7.6 for the two pallets, see Figure 4.1). It should be noted that the aircraft used is a passenger plane and problems regarding temperature control are in general more common in such aircrafts than in cargo airplanes (Stera, 1999; Grétarsson, 2011).

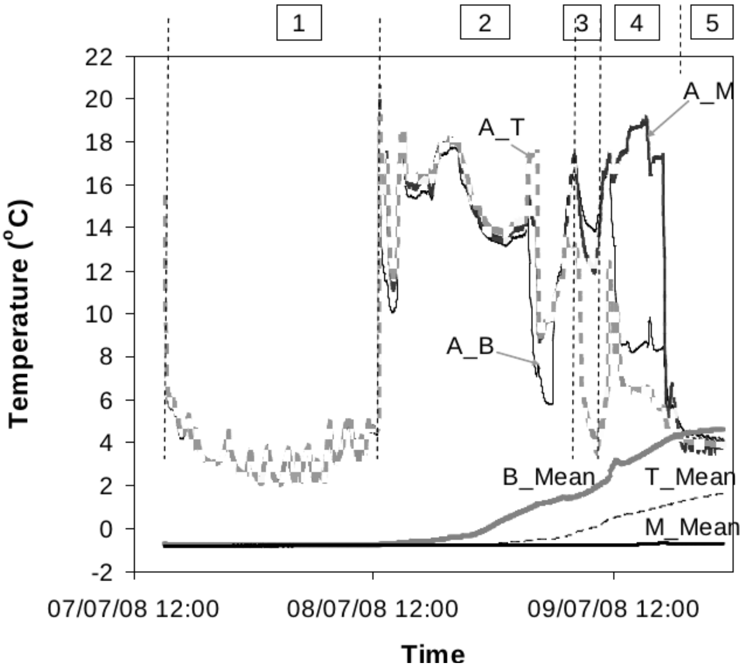

Figure 4.7: Ambient and product temperatures of precooled haddock fillets in a passenger air transport chain from Southwest-Iceland to Plymouth, UK. Numbers in boxes refer to the different steps of the chill chain: 1: Chilled storage at processor post-packaging; 2: Road transport and storage at Keflavík airport; 3: Flight Keflavík-London Heathrow; 4: Storage at Heathrow, Road transport to Plymouth. A: ambient; T: top corner box; B: bottom corner box; M: middle level box (I).

The initial product temperature, $-0.8\,^{\circ}$C, is measured in the middle of all the three studied boxes, which are located at the bottom corner, top corner and mid-height of a single pallet load (Figure 4.7). Despite the high thermal load, the product temperature in the middle of the mid-height box (with one side facing the ambient air) only increases to $-0.7\,^{\circ}$C while the corresponding temperatures in the bottom corner and top corner boxes increase to $4.9\,^{\circ}$C and $2.2\,^{\circ}$C, respectively. The temperature-maintaining effect of precooling, shown in this study, has been noted earlier by Sharp (1988), Sharp (1998) and James et al. (2006). The higher temperature rise in the bottom corner box than in the top corner box is again worth noting since it is not in good agreement with the results of Sillekens et al. (1997), Moureh and Derens (2000), Moureh et al. (2002b) and Jedermann et al. (2009). The trend of highest temperature rise in the bottom corner box is already seen before the loading of the aircraft. However, the likely break-up of the pallet during loading of the aircraft (Grétarsson, 2011) can influence this comparison for the rest of the transport.

Comparison between the results of the two trials conducted in September 2007 and in July 2008 is also interesting with regard to the chilling rate during precooling. The haddock fillets in July 2008 were effectively precooled in a "SuperChiller" precooling equipment (see Section 2.2.2), which requires only around 8 to 10 min to decrease the fillet temperature down to between −1 and −0.5 °C (Gao, 2007; Valtýsdóttir et al., 2010). On the other hand, the cod loins in the trial in September 2007 were subjected to a more primitive precooling method, which comprised storage in a frozen storage room (at around −20 °C) after packaging in insulated EPS boxes. This resulted in slow cooling of the fresh fish; during the 6 hours inside the frozen room, the product temperature on pallet no. 1 only decreased from 3–5 °C to 2–3 °C. Rapid cooling is recommended, especially for cooling below the initial freezing point of the product (superchilling) because in case of very slow freezing, relatively large ice crystals can form inside the fish flesh causing textural damages to it and increase drip (IIR, 1986; Singh and Heldman, 2001). The thermal resistance effect of precooling has also been confirmed with a numerical heat transfer model of a 4-level pallet load (VI), see Section 4.3.3.

4.2 Packaging measurements

The main objective of the comparison between packaging solutions was to investigate the thermal insulation of different packaging types and the cooling effect of cooling packs. The investigated fish boxes include four EPS box types and one CP box type (see Section 3.1). The EPS and CP boxes are both compared in single-box trials (II) and in a trial with 4-level pallet loads (V).

4.2.1 EPS vs. CP packaging

The temperature evolution in four thermal load trials comparing EPS and CP is shown in Figure 4.8 (II). The mean product temperature is calculated from temperature in twelve different locations at three levels of each box, according to Eq. 3.2 and Figure 3.3. The differences between the fillet temperature fluctuations using the four packaging solutions studied are similar in all four trials. As an example, fillet temperature fluctuations in Trial 1 are analysed and presented in Table 4.3. The results clearly demonstrate that the insulating performance of expanded polystyrene is significantly better than of corrugated plastic since the fillet temperature increase is considerably faster in the CP boxes, independent of usage of cooling packs. This is in good agreement with the results of Anyadiegwu and Archer (2002) and Margeirsson et al. (2009). The better insulation of the expanded polystyrene boxes make this type of packaging more suitable for the case of chilled chains with insufficient control. Lesser insulation of CP implies that the fish is chilled faster in the CP boxes during periods when the ambient temperature is lower than the product temperature.

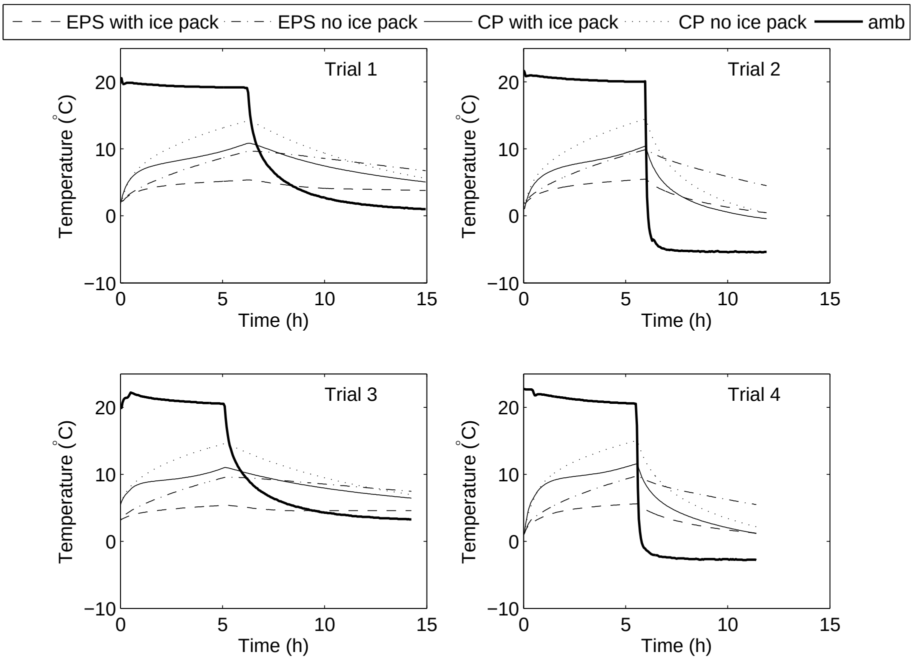

Figure 4.8: Evolution of ambient temperature (amb) and mean product temperature during four temperature abuse trials with haddock fillets in free standing wholesale fresh fish boxes (II).

This illustrates that less insulation can actually be preferable at some stages of broken chill chains. However, assuming that proper initial product temperature is reached with efficient precooling during processing, better insulation of the packaging is always preferred to protect the product against both too low and too high temperatures. Finally, as has been discussed in Section 4.1, there is not much need for well insulated packaging in well temperature-controlled chill chains.

Table 4.3: Product temperature changes in Trial 1, with mean ambient temperature of 19.4 °C and warm up time of 6.1 hours (II). IP: ice pack.

Packaging solution	Temp. before warm up (°C)	Temp. after warm up (°C)	Temp. increase during warm up (°C)	Mean rate of temp. increase (°C h^{-1})
EPS1 = EPS with IP	2.2	5.4	3.2	0.51
EPS2 = EPS no IP	2.1	9.6	7.5	1.21
CP1 = CP with IP	2.1	10.8	8.7	1.41
CP2 = CP no IP	1.9	14.1	12.2	1.97

Thermal insulation is not important for the inner boxes of an unbroken pallet load since they are protected by the outer boxes of the load. This can be noted by comparing the results from thermal load trials on pallet loads (V) presented in Section 4.2.4 to the single box trials (II) presented in Figure 4.8. In case of the pallet loads, the relatively good insulation of the EPS box is of greatest importance for the boxes in contact with the warm surrounding air compared to the inner (centre) boxes on the pallets. Only small differences are obtained between the temperature evolution at different points in the best protected centre boxes on the EPS and CP pallets during dynamic temperature periods. However, a clear upward trend is observed throughout the entire trial (comprising two major thermal load periods) for the centre CP boxes while the temperature in the corresponding EPS boxes is relatively stable.

4.2.2 Cooling packs

Figure 4.8 illustrates that applying frozen cooling packs in fish boxes reduces the mean product temperature rise during temperature abuse (II). According to those results, an EPS box without an ice pack maintains similar mean product temperature during temperature abuse as a CP box with an ice pack. It should be noted that only one cooling pack is positioned on top of the fillets in those trials but distributing the cooling capacity of the cooling packs has been found advantageous with regard to the mean product temperature maintenance in Stubbs et al. (2004) and Valtýsdóttir et al. (2010). The results from paper II also imply that the danger of localised freezing of fresh fish fillets as a result of using ice packs is not substantial, at least when the ice pack size is moderate (252 ± 1 g with 3 kg of fish in the present study).

The product temperature distribution inside the two 5-kg EPS boxes ("New" and "Old") containing a gel pack on top of superchilled cod loins in one end of each box (IV, see Section 4.3.1), clearly demonstrates how the cooling effect of the cooling pack is strongest for the fish loins near it. The same trend is seen in the results of paper II, see Figure 4.9. The results of this PhD work thus confirm the results of Stubbs et al. (2004) and Valtýsdóttir et al. (2010), that a higher number of smaller cooling packs distributed within the boxes better protect the fish against ambient thermal load. However, the demand of fast packaging operations in fresh fish processing plants may influence how well the cooling effect of the cooling packs can be distributed.

4.2.3 Temperature distribution inside single packages

Heterogeneous temperature distributions have been recorded inside both single EPS and CP boxes during warm up periods as is illustrated in Figure 4.9 (II). Due to the higher insulation of EPS and the cooling effect of the cooling pack, the temperature at the centre of the EPS box without an ice pack (4.9b) is lowest (8.1 °C) at the end of the warm up period, compared to 10.9–11.0 °C at the corners (both at the bottom and top). The same trend in temperature distribution is clearly seen in case of the CP box without an ice pack, see Figure 4.9d. After the warm up, the minimum temperature inside the CP box without ice pack, 12.2 °C, is found at the mid-height centre compared to the maximum temperature of 16.1 °C found at the mid-height corner of the CP box (not shown in the figure) and 15.7 °C at the bottom corner. The higher temperature difference experienced inside the CP box (3.9 °C) compared to the EPS box (2.9 °C) can be explained by low thermal diffusivity, i.e. thermal resistance of the fish fillets and poorer insulation of the CP relative to EPS.

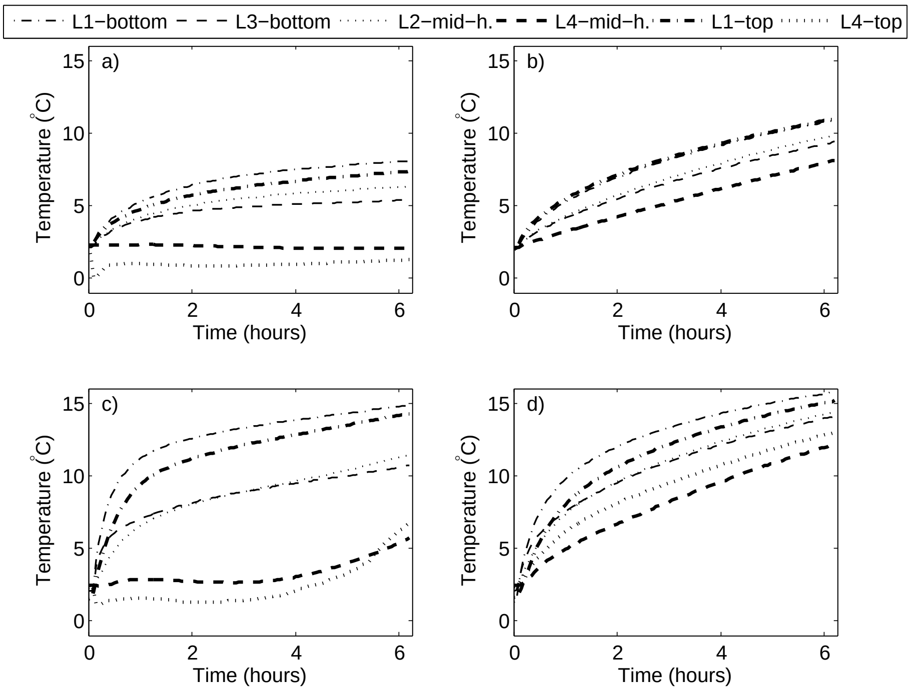

Figure 4.9: Temperature evolution at different positions (see Figure 3.3) inside wholesale boxes containing haddock fillets during 6.1-hour temperature abuse with mean ambient temperature 19.4 °C in Trial 1: a) EPS with ice pack, b) EPS without ice pack, c) CP with ice pack, d) CP without ice pack (II).

Heterogeneous temperature distributions in superchilled cod loins packaged in two types of EPS boxes with a cooling pack on top of the loins have also been predicted with a numerical heat transfer model and obtained by measurements, see Section 4.3.2 (IV).

4.2.4 Temperature distribution inside pallet loads

The heterogeneous temperature distributions found in single pallet loads during real air transport (I) are investigated experimentally in more details in 4-level pallet loads, comprised of both EPS and CP boxes containing 3 kg of non-precooled cod fillets, in air climate chambers (V). The temperature monitoring is a part of a storage study, which aim is to study temperature variation and quality deterioration of packaged cod fillets and relate the deterioration to dynamic storage temperature conditions, product temperature changes, packaging type used and position of packages within a pallet load (V). Evolution of ambient temperature around the two pallets during the whole storage period is presented in Figure 4.10. The figure shows that the dynamic ambient temperature profile applied, represents a rather well controlled air transport chain with two main thermal loads, no more hazardous than is reported in paper I (up to 20 hours at mean ambient temperature of 10 to 15 °C). Similarly, the mean ambient temperature of −0.4 °C for the steady storage reference group represents a well temperature-controlled, containerised sea transport according to the results in paper I.

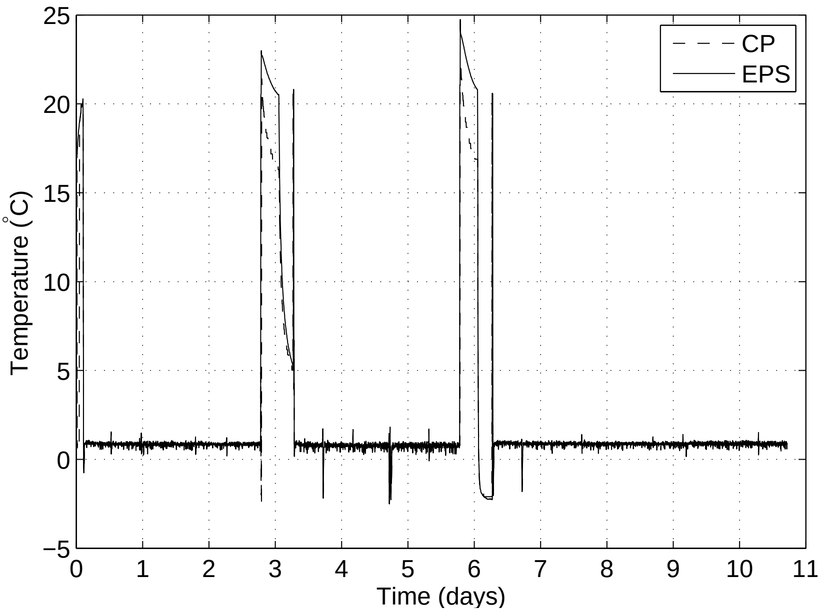

Figure 4.10: Ambient temperature evolution at 0.8 to 0.9 m height during storage of cod fillets packaged in EPS and CP boxes palletised separately (V).

The initial maximum product temperature differences in the second dynamic period are 1.8 °C and 0.6 °C on the EPS and the CP pallet, respectively. The ambient thermal load and thermal inertia of the fish and packages cause the maximum product temperature differences in the pallet at a given time to rise to 8.5 °C for the EPS boxes compared to 10.5 °C for the CP boxes. These product temperature differences are the absolute maximum temperature differences found on the pallets, i.e. the temperature differences between the most sensitive position L4 in the bottom corner boxes (no. 8, shown in Figure 4.11) and the least sensitive position L2 of the centre boxes in the mid-layer (no. 12 and 21, shown in Figure 4.12). Those maximum temperature differences inside pallet loads can be compared to the results of Margeirsson et al. (2009), who recorded maximum product temperature differences of 6–8 °C in a similar study on EPS and CP boxes, but with air blast during longer (24 h) warm up time with lower ambient temperature (around 10 °C) as compared to the study in paper V.

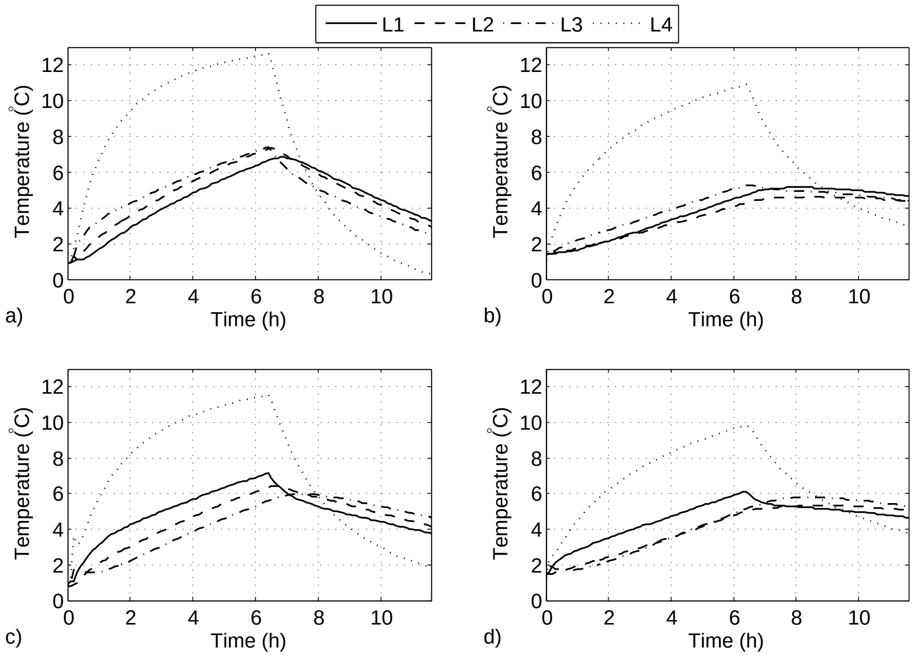

Figure 4.11: Product temperature evolution in two of the most temperature sensitive boxes on each pallet during the second dynamic period with air blast chilling: a) Box CP-8 at bottom corner, b) Box EPS-8 at bottom corner, c) Box CP-32 at top corner, d) Box EPS-32 at top corner, see box configuration in Figure 3.4 (V).

The samples for sensory evaluation are taken towards the mid-height centre position (L2). The product temperature evolution for this particular centre position during the dynamic periods is shown in Figure 4.13. The maximum centre temperatures (L2) in the top corner boxes EPS-25/32 are 0.5 to 1.2 °C higher than in EPS-1/8. The largest temperature rise in the top corner boxes is in good agreement with the results of Moureh and Derens (2000), who recorded temperature at the centre of the outermost frozen fish portions only at top, medium and bottom corners of a pallet stack. However, the overall maximum temperatures of the EPS pallet in the current study are experienced at L4 in the bottom corner boxes EPS-1/8 but not the top corner boxes EPS-25/32. This can be explained by the lack of temperature monitoring at the top corners above L4 in the top corner boxes, which should be the hottest positions according to Sillekens et al. (1997), Moureh and Derens (2000), Moureh et al. (2002b) and Jedermann et al. (2009).

The maximum centre temperature differences recorded between boxes (2.9–

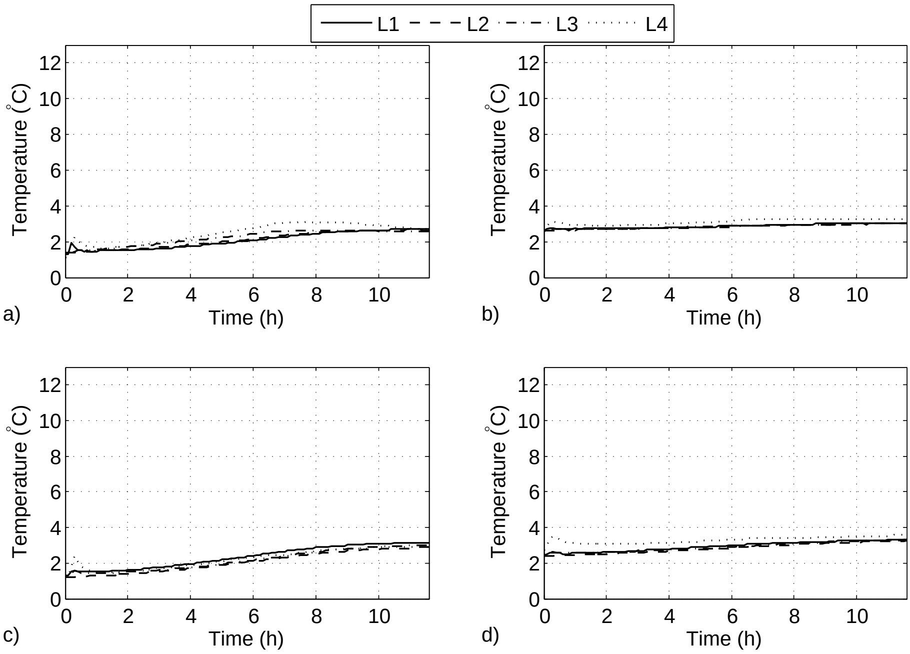

Figure 4.12: Product temperature evolution in the two least temperature sensitive boxes on each pallet during the second dynamic period with air blast chilling: a) Box CP-12 at centre of layer 2, b) Box EPS-12 at centre of layer 2, c) Box CP-21 at centre of layer 3, d) Box EPS-21 at centre of layer 3, see box configuration in Figure 3.4 (V).

3.9 °C for EPS and 4.8–5.2 °C for CP during the two dynamic periods) are less than the temperature differences measured inside the corner boxes (up to 6.7 °C in EPS-8 and 6.9 °C in CP-8). This implies that the largest temperature gradients are found close to the boundaries of the pallet load and that larger quality variation can be expected inside the corner boxes than between different box positions on the pallets. This also emphasises the bigger risk for the outside boxes of the pallet and the accompanying need for master packaging solutions such as pallet covers, which have been proven to be thermally protective in both experimental and numerical studies (Sharp, 1988; Bollen et al., 1997; Amos and Bollen, 1998; Moureh et al., 2002b).

Sensory data reveals that the storage life of the products stored under steady mean temperature of −0.4 °C (simulating well-controlled, containerised sea transport) is estimated to 11 days (Table 4.4). The higher and more fluctuating storage temperature (simulating air transport) results in a storage life reduction of 1.5–3 days as compared to the simulated sea transport conditions. The large temperature changes in the boxes positioned at corners result in faster quality deterioration and microbial growth than at the centre of each pallet. The results from the current study thereby suggest that the storage

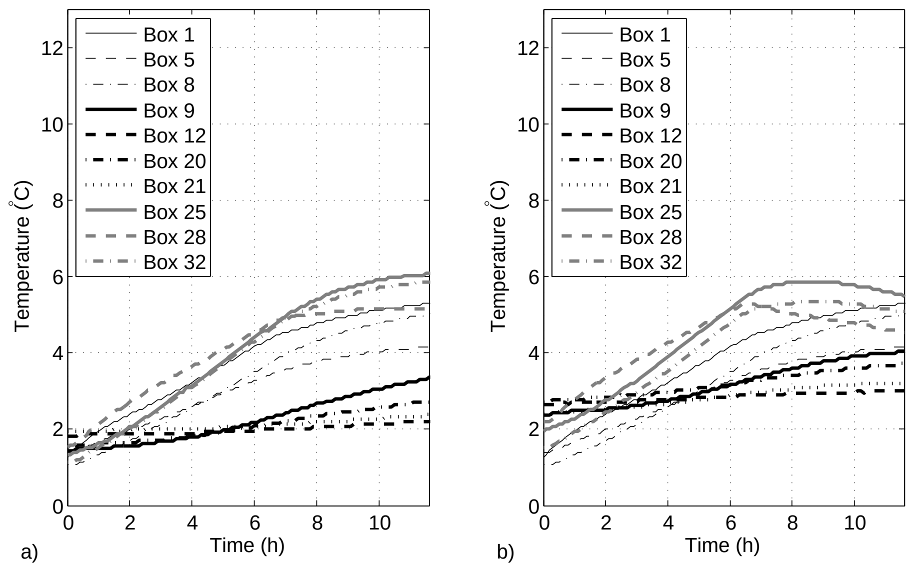

Figure 4.13: Product temperature evolution at the mid-height centre (L2) in all ten EPS boxes during the dynamic periods: a) First dynamic period on day 3 with no air blast chilling, b) Latter dynamic period on day 6 with air blast chilling (see box configuration in Figure 3.4).

life difference between the most and the least sensitive boxes on a full size pallet in a real air transport chain can exceed 1–1.5 days, depending on the level of ambient thermal load. Due to the temperature dependency of quality deterioration of perishables, storage life uniformity can be improved by using insulated pallet covers. As an example, Amos and Bollen (1998) noted a storage life increase of asparagus of up to 1.0 day and a reduction of the storage life range from 0.5 days to 0.2 days, resulting from using insulating pallet covers.

Table 4.4: Storage life of cod products determined by sensory or microbial analysis. ST: Steady storage temperature, DT: dynamic storage temperature, Mi/Co: samples taken from boxes at the middle/corners of the pallet stack. Product temperature was calculated from box centres (L2) and tops (L1) (V).

Group	Storage life (days)	Prod. temp. at L2 until end of storage life mean±std. dev. (°C)	Mean prod. temp. at L1 and L2 until end of storage life mean±std. dev.(°C)
EPS-ST	11^a	0.3±0.7	0.2±0.8
EPS-DT-Mi	9^b	2.7±0.5	2.8±0.5
EPS-DT-Co	8^b	2.5±1.2	2.5±1.3
CP-ST	11^a	0.4±1.0	0.3±1.1
CP-DT-Mi	9.5^b	2.1±0.7	2.1±0.7
CP-DT-Co	8^b	1.9±1.6	1.9±1.5

^{a} based on sensory evaluation; ^{b} based on microbial limit of log 7.5 CFU g^{-1} for counts of *Photobacterium phosphoreum*. CFU: colony forming unit

4.3 Heat transfer modelling of packaged fish

4.3.1 Single packages

Good agreement is obtained between experimental results and numerical results with the heat transfer models of the free standing EPS and CP boxes without ice pack, see Table 4.5 (II). The mean and maximum absolute errors and overall mean absolute errors in the table are calculated using the following relations:

$$\text{Mean abs. error} = \frac{1}{n}\sum_{i=1}^{n}|T_{\text{exp,i}} - T_{\text{numerical,i}}| \tag{4.1}$$

$$\text{Overall mean abs. error} = \frac{1}{q \cdot n}\sum_{j=1}^{q}\sum_{i=1}^{n}|T_{\text{exp,i,j}} - T_{\text{numerical,i,j}}| \tag{4.2}$$

where the number of time steps was $n = 120$ (3 minutes intervals between measurements) and the number of positions (temperature sensors) was $q = 6$. This implies that the models give valuable information on the temperature distributions inside a thermally loaded free standing EPS and CP packages. The overall absolute error of the numerical model for the EPS box (homogeneous material) is lower (0.4 °C) than the corresponding error of the numerical model for the non-homogeneous CP box (0.7 °C). The errors can be explained by possible inaccurate placement of the temperature sensors and the simplification of adopting a steady, uniform convective heat transfer coefficient for each outside surface of the boxes. The higher mean error of the model of the CP box can be attributed to the inaccuracy resulting from the estimation of the equivalent thermal parameters of the CP box (Choi and Burgess, 2007).

Table 4.5: Mean absolute error (°C) during the first 6 hours of warm up in Trial 1 of results obtained by the FLUENT software for 6 data loggers in two packaging types without ice packs (II).

Position	CP	EPS
L2-bottom	0.5	0.6
L3-bottom	0.6	0.4
L2-mid-height	1.0	0.1
L3-mid-height	0.7	0.1
L4-mid-height	0.8	0.2
L1-top	0.4	0.8
Overall	**0.7**	**0.4**

4.3.2 Design of new improved EPS boxes

The results from paper II confirm that the corners are the most sensitive positions in fresh fish boxes under thermal load. This is actually a natural result of basic heat transfer theory and the geometry of the box, as the corners have three surfaces for heat exchange with the ambience (see Moureh and Derens (2000) in case of a pallet stack). Bearing the weakness of the corners in mind, the heat transfer model of the original 3-kg EPS box in paper II is further developed with the aim of re-designing the original 5-kg EPS box with regard to minimising the maximum product temperature rise in the box under thermal load (VII). By thickening the box walls at the corners (Figure 4.14) the insulation of the box is enhanced and to counterbalance the weight of the new box, the walls are made thinner further away from the corners. By focusing on the radius of curvature of the box corners, the reference box is optimised in a step-by-step procedure using a "trial and error" method. This has been done in close cooperation with Promens Tempra, the largest manufacturer of EPS boxes in Iceland, also taking into account the advice and requirements of Icelandic fresh fish processors on outer dimensions and volume capacity of the box.

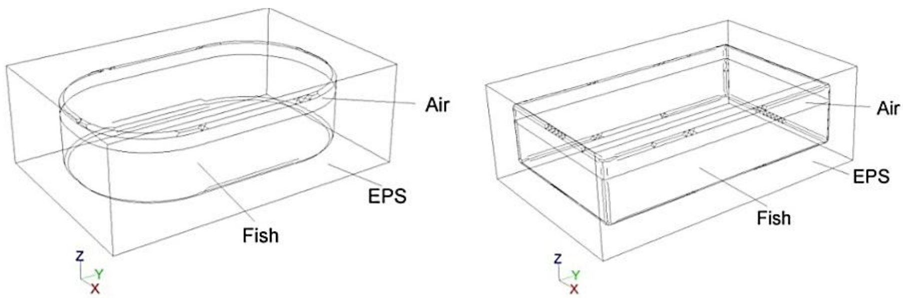

Figure 4.14: Geometries of an improved box design "C" (left) and the original 5-kg EPS box (right), each containing fish fillets and an air layer above the fish (VII).

Using the CFD software ANSYS FLUENT to develop a model, which is basically built up in the same way as the 3-kg model in paper II apart from the different geometry, the effects of rounding the corners are evaluated, see Figure 4.15. The temperature contour plot (Figure 4.15) illustrates that the fish positioned at the corners of the original, sharp-corner box is replaced by packaging material (EPS) in the new box. This leads to 1.5–2 °C (mainly depending on the radius of curvature of the different designs tested) lower predicted maximum fish temperature in the new box design compared to the original box, assuming an initial fish and packaging temperature of 1 °C and an ambient temperature of 15 °C for 4 hours.

The performance of a new 5-kg box design (currently manufactured by Promens Tempra) in protecting superchilled fish is experimentally and numerically compared with an old box design with a capacity of 6–7 kg (IV). The difference in the capacity of the boxes is mainly due to a height difference of 24 mm, resulting in a 12% higher box weight and more air space above the 5-kg fish pile in case of the old box. The thicker air layer in the old box implies a higher thermal resistance between the top of the box and the fish pile. Thus,

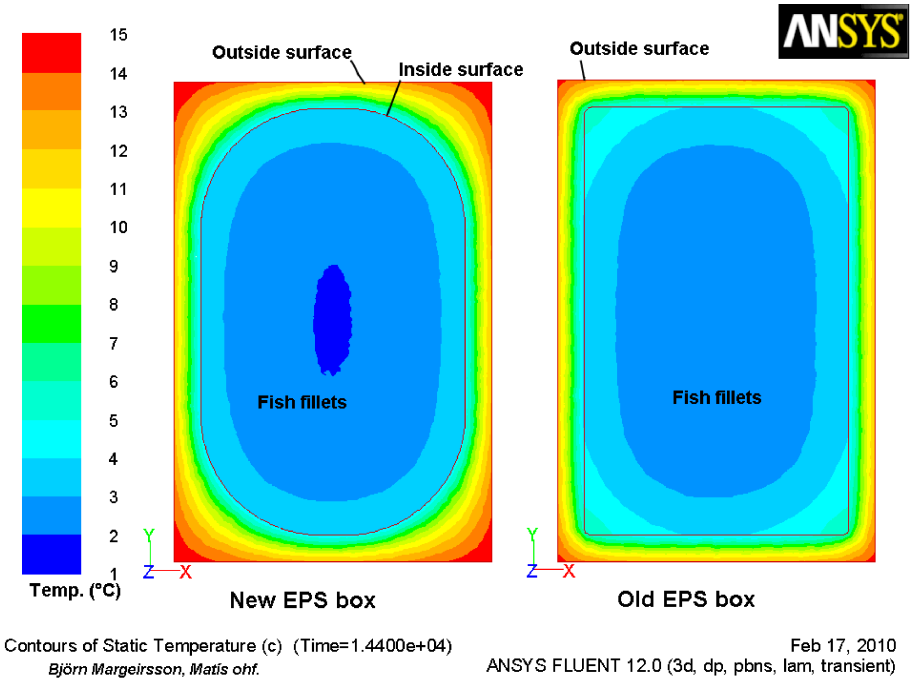

Figure 4.15: Temperature contours in a horizontal section through an improved box design "C" (left) and the original box (right) at mid-height of fillet pile after 4 hours at $T_{\text{amb}} = 15\,^{\circ}\text{C}$ and $T_{\text{init}} = 1\,^{\circ}\text{C}$ (VII).

the larger capacity of the old box does not give the new box an advantage in the comparison.

The ambient temperature during the whole storage time is presented in Figure 4.16 and the results from FLUENT and experiments are compared in Figure 4.17 at four different positions inside the two box types. The predicted temperature distributions in a vertical cross section through the new box at three time steps are also shown in Figure 4.18. The results show that the ambient thermal load obviously causes very heterogeneous temperature distributions inside the boxes which can be seen by the large temperature increase at the bottom corners (P1 and P2) compared to the very stable temperature at the middle of the box (P3). This is in good agreement with the results of paper II for single packages, not including gel packs. The cooling effect of the gel pack is also obvious in Figure 4.18.

Comparison of both the experimental (EXP) and simulated (FLUENT) results indicates that the rounded corners design of the new box offers better thermal protection with regard to maximum product temperature. This is true despite the thicker, insulative air layer above the fish in the old box. Furthermore, the results indicate that more homogeneous product temperature

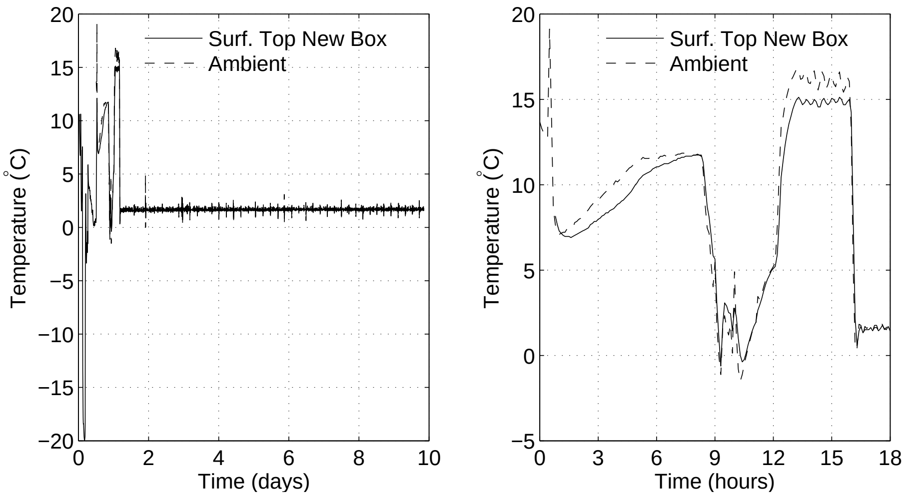

Figure 4.16: Environmental temperature. Left: during the first 10 days post-packaging, right: zoom-up of the dynamic temperature period in air climate chambers starting around 12 h post-packaging (IV).

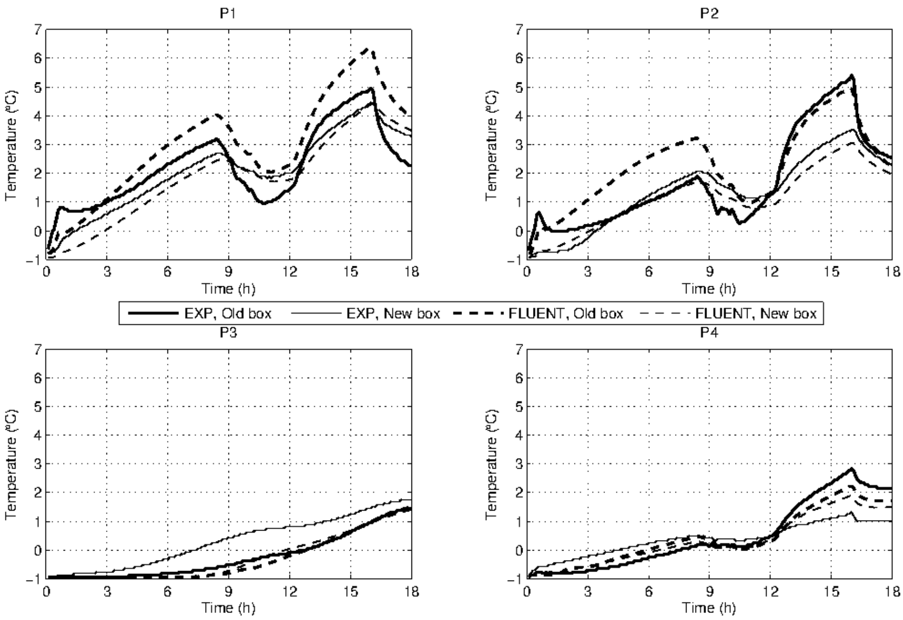

Figure 4.17: Comparison between numerical results obtained with FLUENT and experimental results (EXP) for four selected positions inside the old and new boxes during the dynamic temperature period (IV).

distribution can be expected during dynamic temperature storage in the new

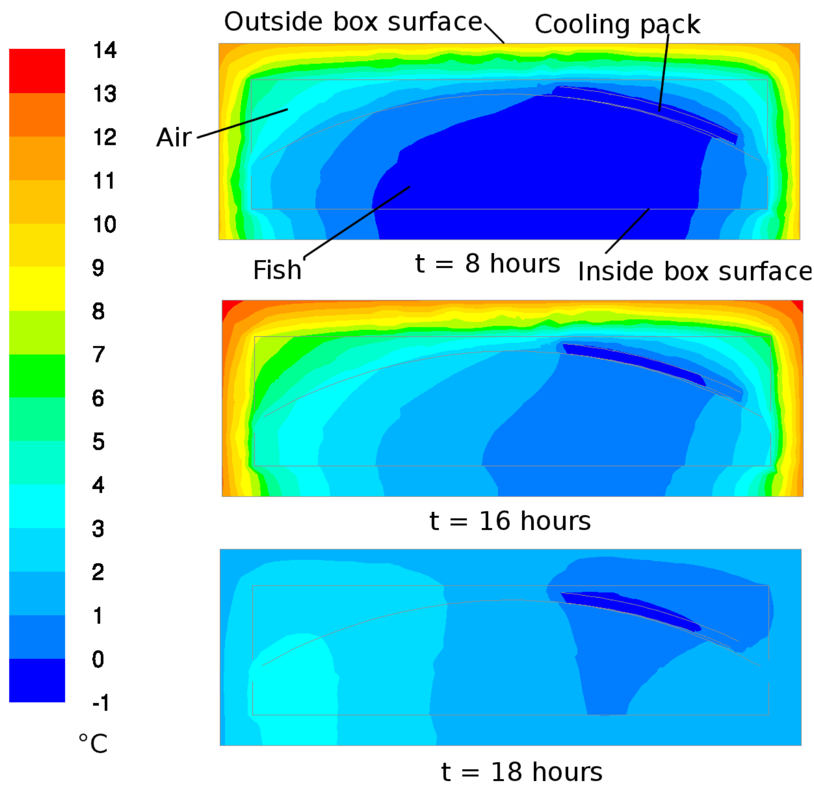

Figure 4.18: Temperature contours in a vertical longitudinal section through the middle of the new EPS box 8 h (top), 16 h (middle) and 18 h (bottom) after the beginning of the dynamic temperature period (adopted from paper IV).

box type compared to the older box type. This means that more even product quality and safety can be ensured inside each package by using the new boxes in chill chains with a relatively high thermal load.

Table 4.6: Mean absolute error (°C) of numerical results at four positions inside two box types (IV).

Position	Old box	New box
P1	0.9	0.3
P2	0.7	0.3
P3	0.1	0.6
P4	0.3	0.3

Table 4.6 shows that the mean absolute errors (calculated with Eq. 4.1) for the numerical results are below 1 °C for all positions inside the two boxes (IV). The overall mean absolute errors (calculated with Eq. 4.2) are 0.5 °C and 0.4 °C for the old and the new box, respectively. These values should be compared to

the accuracy of the temperature data loggers, which was ±0.5 °C, i.e. similar to the overall mean absolute errors. The positioning of the temperature loggers and the shape of the fish pile in each box can be mentioned as a possible source of error in the heat transfer models. It should also be noted that the numerical models are found to be very sensitive to the initial freezing point adopted for the fish, which is in good agreement with the results of Pham (1995), Harðarson (1996) and Pham (2006). Methods better suited for dealing with phase change of foodstuffs, such as enthalpy methods described by Pham (2006), are not applied in the current study. The fact that the cod fillets are immersed in lightly salted water (salinity around 2%) for around 12–15 min before precooling in a "SuperChiller" is likely to increase the salt content of the fish muscle from the natural value of 0.2–0.3% (Þórarinsdóttir, 2010) to 0.3–0.5% (Magnússon et al., 2009a; Valtýsdóttir et al., 2010), which lowers the initial freezing point.

The performance of the two boxes is also evaluated by means of sensory evaluation. Figure 4.19 shows how the Torry freshness score changes with storage time (IV). A Torry score around seven indicates that the fish has lost most of its freshness odour and flavour characteristics and has a rather neutral odour and flavour (Shewan et al., 1953). The time elapsed from processing until a Torry score of seven is obtained is called the freshness period. This score is reached after 2–3 days for O-Co (old box, corner samples) and after 5–6 days for both N-Co (new box, corner samples) and N-Mi (new box, middle samples). The Torry scores for N-Co and N-Mi are significantly higher than for O-Co both on day 6 and on day 10. When the mean Torry score is around 5.5, most of the sensory panellists detect spoilage attributes and this score has been used as the limit for consumption at Matís (Martinsdóttir et al., 2001). According to this, the storage life of the O-Co group is six days and around eight days for the N-Co and N-Mi groups. Thus it can be concluded that the storage in the new boxes results in approximately 2–3 days longer freshness period and about two days longer storage life. Furthermore, the sampling location within the new boxes does not affect the sensory quality significantly.

4.3.3 Pallet loads

Paper VI describes a numerical heat transfer model which is developed to simulate the product temperature distribution inside the temperature abused, four-level EPS pallet load. As in the other numerical studies conducted here, a three-dimensional time dependent heat transfer model is developed using ANSYS FLUENT. The numerical heat transfer model of a single EPS box described in paper II is extended in order to take into account an increased number of fish boxes (see Figure 3.7) and 14 mm lower boxes with capacity of 3 kg instead of 5 kg. To validate the model, numerical results are compared with the experimental results presented in Section 4.2.4.

Table 4.7 shows that the mean absolute errors are below 0.6 °C for all four levels. The overall mean absolute error of the four levels is 0.3 °C. In this context, the accuracy of the temperature sensors, ±0.5 °C, should be noted again.

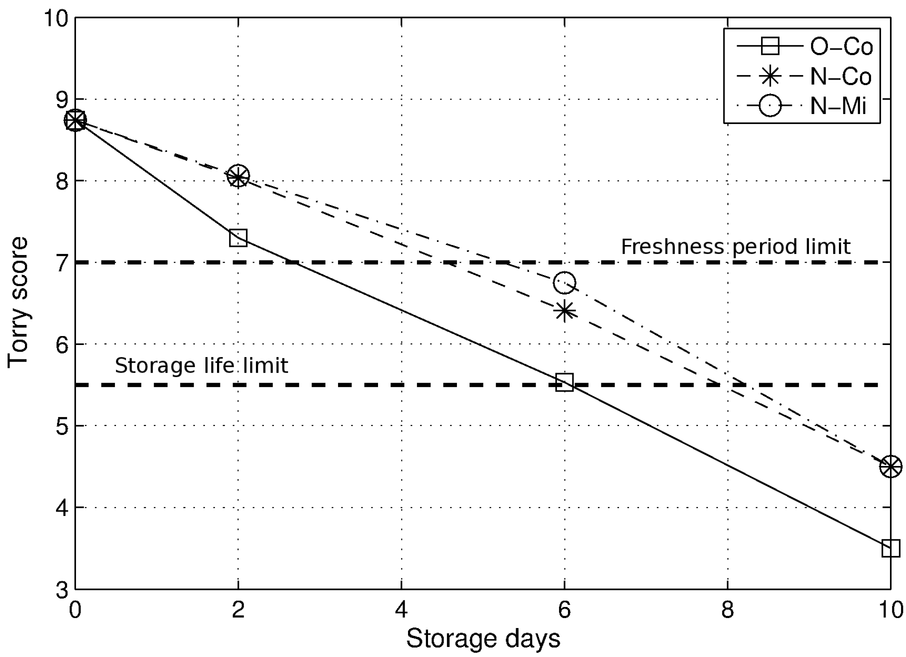

Figure 4.19: Mean Torry scores. O: Old box, N: New box, Co: Corner samples, Mi: Middle samples (adopted from paper IV).

As before, the errors are calculated with Eqs. 4.1 and 4.2. The largest mean error in each level are written in boldface in Table 4.7 and it can be concluded that the largest error is found for position L4 (bottom corner), especially in the outer boxes (B1, B8, B9, B20, B25, B32) as compared to lower errors at the centre positions (L1, L2, L3) and especially in the the middle boxes (B12 and B21). Also, the higher mean absolute error at the bottom level (no. 1) compared to the other levels is noticeable (0.5 °C vs. 0.2–0.3 °C).

Temperature contours in a vertical cross-section of the four-level pallet are presented in Figure 4.20. The cross-section is taken 2.5 cm from the wall inside the boxes at the left side of the pallet stack (boxes no. 1, 17, etc. in Figure 3.4), i.e. close to the most vulnerable positions near the outside surfaces of the stack. Very inhomogeneous temperature distributions are noticed in Figure 4.20, where large temperature gradients are found close to the outside surfaces of the pallet, as opposed to the relatively stable temperature in the centre of the pallet stack (results shown in paper VI). These results further emphasise the temperature sensitivity of the corner boxes already pointed out in the current work and by others (Dolan et al., 1987; Almonacid-Merino et al., 1993; Moureh and Derens, 2000; Moureh et al., 2002b; Tanner et al., 2002a,b; Stubbs et al., 2004; Laguerre et al., 2008).

In order to investigate the effect of pallet stack height, the model of the

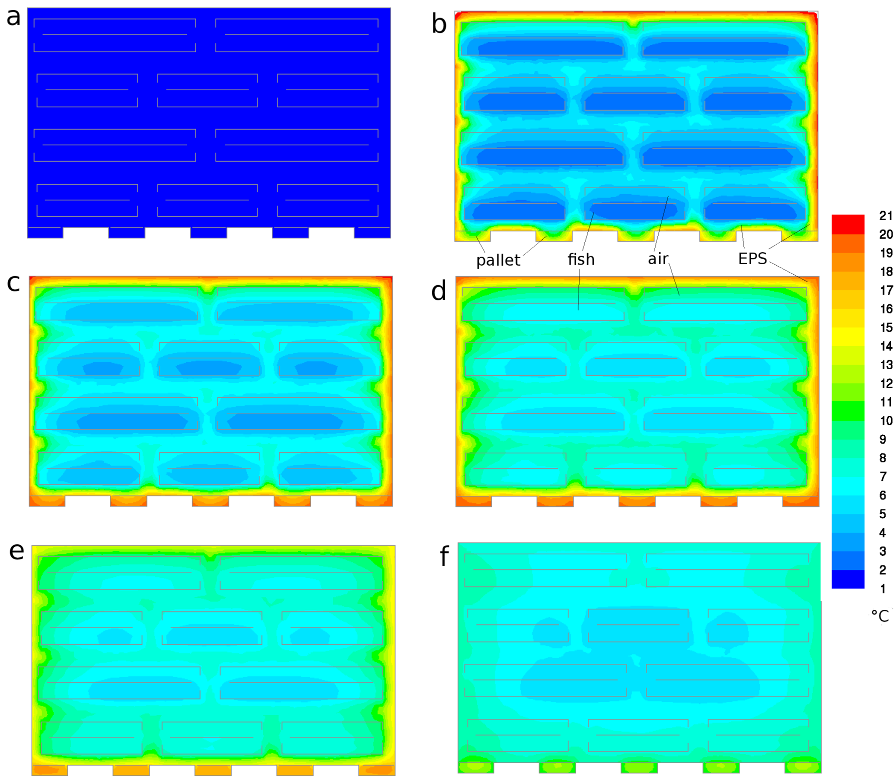

Figure 4.20: Numerical results: temperature contours in a vertical section 2.5 cm from the wall inside the boxes at the left side of the four-level pallet during dynamic temperature storage a) at the beginning of thermal load and after b) 1 h, c) 3 h, d) 6 h, e) 7 h, f) 9 h of thermal load (VI).

Table 4.7: Mean absolute errors (°C) of numerical results during 9 hours of dynamic temperature storage (VI).

Level 1		Level 2		Level 3		Level 4	
Position	Error	Position	Error	Position	Error	Position	Error
B1-L1	0.5	B9-L1	0.2	B20-L1	0.1	B25-L1	0.2
B1-L2	0.3	B9-L2	0.3	B20-L2	0.1	B25-L2	0.2
B1-L3	0.3	B9-L3	0.2	B20-L3	0.1	B25-L3	0.3
B1-L4	**2.1**	B9-L4	**0.9**	B20-L4	**1.5**	B25-L4	**0.4**
B5-L1	0.5	B12-L1	0.1	B21-L1	0.2	B28-L1	0.3
B5-L2	0.4	B12-L2	0.1	B21-L2	0.2	B28-L2	**0.4**
B5-L3	0.3	B12-L3	0.1	B21-L3	0.1	B28-L3	0.1
B5-L4	0.6	B12-L4	0.1	B21-L4	0.1	B28-L4	
B8-L1	0.2					B32-L1	0.3
B8-L2	0.6					B32-L2	0.1
B8-L3	0.2					B32-L3	0.2
B8-L4	0.3					B32-L4	**0.4**
Mean	**0.5**	Mean	**0.2**	Mean	**0.3**	Mean	**0.3**

4-level pallet load is expanded to take into account a 12-level pallet under the same dynamic temperature conditions. The effect of additional box levels is seen by comparing the simulated temperature contours in Figure 4.21 (12 levels) to the ones in Figure 4.20 (4 levels). The comparison indicates that the additional levels in the 12-level stack should result in a slower temperature rise in the middle of the pallet stack. This can be explained by the higher thermal resistance between the core and the surface in the higher pallet stack.

The effect of pallet stack size can further be observed in Figure 4.22, which illustrates the maximum, minimum and mean product temperatures for the two pallet stack sizes. The additional box levels have very limited effect on the maximum temperature rise (Figure 4.22a) because the fish at the most sensitive positions (corners of corner boxes) are still similarly exposed to the ambient thermal load despite the increased number of box levels. The minimum temperature at the middle of the pallet load is slightly more affected by the load height, resulting in a 0.5 °C lower minimum temperature for the higher pallet load after a 9-hour thermal abuse, see Figure 4.22b. These small differences indicate that similar absolute maximum temperature differences should be expected for the two pallet stack sizes and further justify the use of only 4 box levels for representing a whole pallet in the storage life study in paper V. The results from the this study thus indicate that similar maximum storage life difference between the most and the least sensitive boxes are to be expected for a full size pallet under simulated air transport temperature conditions, as was obtained in paper V, i.e. 1 to 1.5 days.

The largest effect of the added box layers is seen in the mean temperature shown in Figure 4.22c. The mean temperature after a 9-hour thermal load is 1.0 °C lower in the 12-level pallet, which implies that a more even product

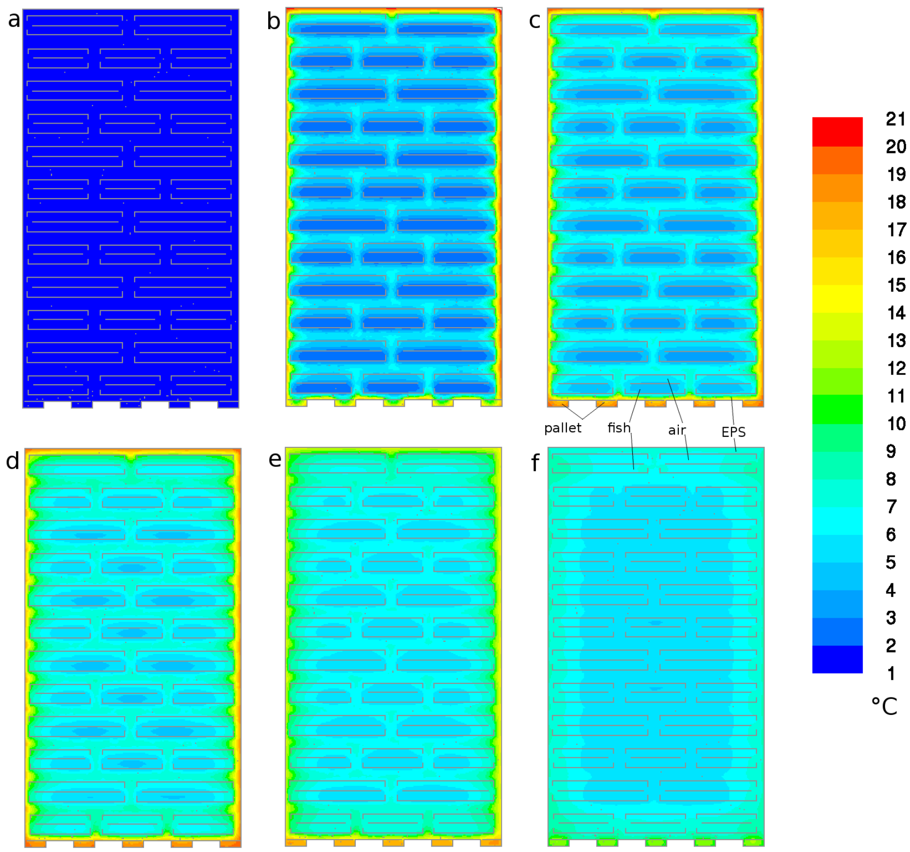

Figure 4.21: Numerical results: temperature contours in a vertical section 2.5 cm from the wall inside the boxes at the left side of the 12–level pallet during dynamic temperature storage a) at the beginning of thermal load and after b) 1 h, c) 3 h, d) 6 h, e) 7 h, f) 9 h of thermal load (VI).

quality is to be expected for a full size pallet than in case of a 4-level pallet. It should be noted that this does not contradict the prediction of similar maximum storage life differences for the two pallet load sizes. More even product quality on the full size pallet can be expected because the mean temperature is closer to the minimum temperature (resulting in maximum storage life) meaning that a higher ratio of fish boxes on the full size pallet will have temperature close to the minimum temperature of the pallet.

Figure 4.22 also demonstrates the positive, temperature maintaining effect of precooling the fish to the superchilled (SC) temperature of −1 °C before the thermal load. The latent heat of the partially frozen water in the superchilled fish (initial freezing point taken as −0.92 °C in the model) causes a slower fish temperature rise than in case of the non-superchilled (NC) fish at the initial temperature of 1.4 °C (despite the fact that the temperature difference between fish and ambient air is higher for the superchilled fish, which increases heat transfer from the ambience to the fish). The initial mean temperature difference between the NC-fish and the SC-fish is 2.4 °C. The numerical models predict that this temperature difference will rise to 4.8 °C during the 9-hour dynamic temperature period while the difference between the maximum temperatures of NC and SC-fish is predicted to be around 3.5–4.5 °C throughout most of the 9-hour period. The results of Gao (2007), Magnússon et al. (2009a) and paper V show that minimising temperature rises in fresh fish products under thermal load is important for maximising storage life and the results of the current work demonstrate that precooling is one possible way to do this.

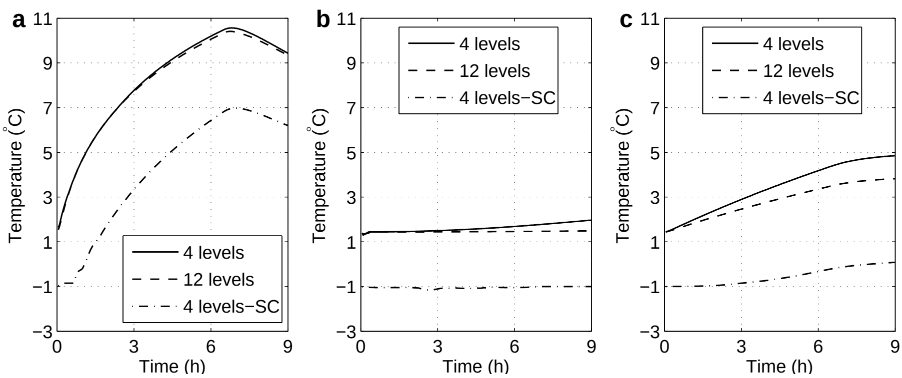

Figure 4.22: Numerical results: product temperature evolution in 4-level pallet vs. 12-level pallet during 9-hour dynamic storage. a) maximum temperature, b) minimum temperature, c) mean temperature. SC: fillets superchilled at −1 °C at the beginning of thermal load (VI).

Chapter 5

Conclusions and future perspectives

During this thesis work, experiments in real and simulated conditions and numerical simulations have been carried out to study spatio-temporal temperature changes during transport of fresh fish products. The numerical modelling is limited to temperature predictions within different packaging units (containing chilled or superchilled fish and possibly cooling packs) but the experimental results also provide valuable information on the ambient conditions during storage and transport of fresh fish products from processors in Iceland to the European market.

The main conclusion from the temperature mapping of air and sea based transport chains is that temperature control in containerised sea transport is in general much better than in multi-modal air transport chains (I). Even more severe demand for better temperature control has been identified in passenger air freight than in cargo air freight of perishables. More detailed knowledge is needed on the difference between the ambient thermal load on passenger and cargo air freight and more importantly, the effect of thermal load on the spatio-temporal product temperature changes, which is the main focus of this PhD study. But analysing only the weaknesses in the distribution chains of temperature-sensitive foodstuffs is not adequate to improve the value of the perishables. The advantages of each transport mode (the relatively short transport time for air vs. the relatively low cost and stable transport temperature for sea) must be investigated more thoroughly to further facilitate the choice between the two transport modes. More emphasis must be placed on educating different people involved in the chill chain about the weaknesses, the importance of perfect product temperature control and possible ways to approach it. Despite that air transport will probably continue to be the natural choice of transport mode for the highest-value products, the better temperature-controlled and less expensive, containerised sea transport may further increase its share in Icelandic fresh fish export in the coming years.

Improving the insulation of packaging is one possible way to improve the product temperature control. The effects of dynamic ambient temperature on packaged fresh fish products have been studied for different packaging units both using single units (II, III, IV, VII) and multiple units assembled on a pallet (I, V, VI). Experimental results revealed heterogeneous temperature distributions both inside single boxes and in pallet loads. The insulating performance of EPS boxes was found to be significantly better than the insulating capacity of comparable CP boxes (II). The importance of packaging insulation is decreased by assembling the wholesale boxes on pallets but studying single packages is still of importance because pallets are frequently broken up before loading onboard passenger airplanes. Applying frozen cooling packs on top of fresh fish fillets also proved to be advantageous for minimising the effect of too high ambient temperature. The cooling capacity should also be distributed throughout the packaging as much as possible.

The temperature variations in a 4-level pallet load in a storage life study simulating conditions during air transport resulted in a storage life reduction of 1.5–3 days, depending on the position within the pallet load, compared to fish stored under steady mean temperature of $-0.4\,^{\circ}\mathrm{C}$ (simulating well-controlled, containerised sea transport, see paper V). Judging from those results, the storage life difference between the most and the least sensitive boxes on a full size pallet in a real air transport chain can exceed 1–1.5 days, depending on the ambient thermal load experienced. More research effort in this area would facilitate the choice of transport mode and even packaging for different fresh fish products whereas profitability must depend on not only the transport cost but also the quality and safety of the product, environmental and sustainability aspects of the transport mode and the packaging.

Efficient superchilled processing of fresh fish has proven to be very important for the temperature control during transport and storage, especially for air freight. This was investigated both by means of temperature monitoring during real transport (I) and heat transfer modelling (IV, VI). As Kaale et al. (2011) have discussed, numerical heat transfer modelling is likely to become useful in the nearest future to further improve the function of various superchilling units with regard to temperature, holding time and air velocity inside the superchilling unit. Superchilling of whole fish with combined blast and contact cooling technique on board fishing vessels could also be applied to possibly maintain the raw material quality even further than is currently done by storage in water ice or slurry ice.

The findings of this thesis demonstrate that numerical heat transfer modelling is a valuable tool to cost effectively predict whitefish temperature changes under thermal load with sufficient accuracy for industrial applications. This conclusion has been strengthened by the fact that it has been used to improve the design of a commercial 5-kg EPS box type with regard to thermal insulation (VII) resulting in a new box type, which currently is the most popular in its size category in Iceland. The models developed could, in conjunction with a product temperature-storage life prediction model, be used to estimate the storage life of thermally loaded whitefish pallets of different sizes and with different initial product temperatures. The models could also be used to predict spatio-temporal temperature changes and improve temperature control for other food products, such as salmon or meat, by simply adopting the correct thermophysical properties of the product. The simulations could also be expanded in order to consider the whole chill chain from processing to market in addition to the broken down portions of the chain as is the case in the current work. This would, however, require some adjustments of the current models to take the storage and transport conditions into account, e.g. by adopting different surface heat transfer coefficients. Finally, the gained knowledge on the applicability of heat transfer modelling to improve thermal insulation of food packaging could be transferred to other packaging applications, outside the food industry.

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Paper I

TEMPERATURE MAPPING OF FRESH FISH SUPPLY CHAINS – AIR AND SEA TRANSPORT

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ABSTRACT

Temperature history from three air and three sea freights of fresh cod loins and haddock fillets in expanded polystyrene boxes from Iceland to the U.K. and France were analyzed to find out the effect of different factors on the temperature profile and predicted remaining shelf life (RSL) of the product. It was also aimed to pinpoint hazardous steps in the supply chains. Significant difference ($P < 0.001$*) was found in: the temperature at different locations inside a certain box; mean product temperature between boxes of a certain shipment; and the boxes' surface temperature at different positions on a pallet for the whole logistics period. The predicted RSL depends on the time and temperature history of the product, shortest for sea transportation and longest for an air shipment with precooled product. Several critical steps were found in air freighting: the flight itself, loading/unloading operations and holding storage at unchilled conditions.*

PRACTICAL APPLICATION

The paper strengthens fundamental understandings on logistics of fresh fish by air and sea in EPS boxes using ice or gel mats as coolants, with

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particular contribution of information related to mode of transportation, box–pallet arrangement and location, time–temperature and precooling effects. It is proposed to precool products before packing to better stabilize the temperature of product during abusive period(s). It is also suggested to group the products based on the time–temperature history and/or positions on the pallets for better management in further handling of the fish.

INTRODUCTION

The consumption of fresh fish has been growing while other forms of fish products have remained the same or even declined (Vannuccini 2004; FAO 2009). This makes the supply of fresh fish increasingly important. The world production of fresh seafood has gradually grown from about 30,000,000 tons in 1994 to 50,000,000 tons in 2002 (Vannuccini 2004).

Temperature is considered as the main factor that affects the quality and safety of perishable products. Abusive and/or fluctuating temperature accelerates rapid growth of specific spoilage microorganisms as well as pathogens (Jol *et al.* 2005; Raab *et al.* 2008), thus may cause economic losses and safety problems.

It is well known that fresh fish is often stored and shipped at melting ice temperature (Pawsey 1995; ATP 2007) or even below 0C, at superchilled temperature (Olafsdottir *et al.* 2006b) to keep it good and safe for a certain period. However, the fresh fish supply chains may face certain hazards when the requirements are not fulfilled.

The transportation of perishable products such as fresh fish is very common by air as it is very fast. However, during loading, unloading, truck and air transportation, storage and holding the product is normally subjected to temperature abuse at unchilled conditions (Brecht *et al.* 2003; Nunes *et al.* 2003), which means that much of its journey is unprotected (James *et al.* 2006). Even fluctuation and/or high temperature for short time was reported to cause the rejection of a whole strawberry load (Nunes *et al.* 2003). Results from a study on chilled modified atmosphere packaged Pacific hake have shown that even a small fraction of storage time (4.3%) at abusive temperature caused a significant reduction in shelf life (25%) of the product (Simpson *et al.* 2003).

Another means of transporting fresh fish is by sea where the product is containerized in refrigerated containers to maintain the required low temperature for the whole voyage. This mode of transportation, however, takes much longer time compared with air freighting where time is known as a main factor in reducing the quality of perishables even at optimum conditions of handling (Pawsey 1995).

There are several studies about the effect of different factors in the cold chains on the temperature distribution and/or quality of food products such as fresh-cut endive (Rediers *et al*. 2009), strawberry (Nunes *et al*. 2003), asparagus (Laurin 2001), chilled chicken breast (Raab *et al*. 2008), frozen fish (Moureh and Derens 2000), chilled gilthead seabream (Giannakourou *et al*. 2005) and so forth. However, there is still no scientific publication on the temperature mapping and comparison for a real supply chain of fresh cod loins or haddock fillets from processing to market by air and sea transportation.

Shelf-life models are very useful to assess the effects of temperature changes on product quality (Jedermann *et al*. 2009). The data set of time–temperature history can be fitted to predict RSL by using available models such as the square root model for relative rate of spoilage (RRS) of fresh seafood (DTU-Aqua 2008).

The aim of this work was to investigate the temperature changes of fresh cod loins and haddock fillets packed in EPS boxes, as well as of the environment around the product during the logistics from producers in Iceland to markets in the U.K. and France by air and sea freights, and from that, to pinpoint critical steps in the supply chains. The study was also aimed to compare the effect of different factors such as product locations inside each box, box positions on a pallet, logistics units (i.e., master boxes, pallets or containers), precooling and modes of transportation on the temperature profiles of product and box surface, and to compare the effect of these factors on the predicted RSL of product based on the time–temperature records from the shipments.

MATERIALS AND METHODS

Temperature Mapping

The temperature mappings were performed for three air and three sea trips of the fresh fish supply chains from the processors in Iceland (IS) to the markets (distributors, retailers or secondary processors) in the U.K. and France (FRA) in September 2007 and June, July and September 2008. Descriptions of the logistics of these chains are shown in Table 1.

Product Profile for the Shipments. Products of all the studied trips, except for the one in July 2008, were fresh cod loins from a processing company in Dalvik (North – Iceland). In July 2008, they were fresh haddock fillets from another company in Hafnarfjordur (South West – Iceland).

The cod was caught east of Iceland. Onboard, it was bled, gutted, washed and iced in insulated tubs. The fish to ice ratio was about 3:1, and the fish was packed in four to five layers alternatively with ice above and below each fish layer. The preprocessed whole fish was stored in the tubs in the refrigerated

TABLE 1.
DESCRIPTIONS ON THE LOGISTICS OF THE STUDIED CHAINS

Freight	Step	Description	Duration	Ambient temperature	Ambient temperature of pallet 1	Ambient temperature of pallet 2
				Mean ± STDEV (C)	Mean ± STDEV (C)	Mean ± STDEV (C)
Air_ Sep 2007 (Freighter)	1	Frozen storage at producer after packing (Dalvik, IS)	6 h	−16.2 ± 9.2	−22.5 ± 3.3	−13.0 ± 9.6
	2	Chilled storage at producer	2 h	2.5 ± 0.5	2.3 ± 0.3	2.5 ± 0.5
	3	Transportation from Dalvik to Reykjavik (RVK, IS) in a refrigerated truck	8 h 20 min	−12.3 ± 6.0	−8.1 ± 3.5	−14.4 ± 5.9
	4	Unloading and loading in a chilled truck in RVK	2 h	8.6 ± 1.3	8.4 ± 1.1	8.7 ± 1.3
	5	Transportation from RVK to Keflavik airport (KEF, IS) in a chilled truck	1 h 20 min	1.6 ± 1.1	2.2 ± 0.7	1.3 ± 1.1
	6	Unchilled storage at KEF airport	5 h 20 min	11.3 ± 3.0	13.3 ± 2.0	10.3 ± 3.0
	7	Chilled storage at KEF airport	6 h	3.1 ± 4.9	8.1 ± 5.3	0.5 ± 1.6
	8	Flight from KEF to Humberside airport (HUY, U.K.) and unchilled storage at HUY	6 h 15 min	9.9 ± 4.5	6.4 ± 4.8	11.7 ± 3.1
	9	Storage at HUY and transportation to Carlisle (U.K.)	7 h 15 min	0.2 ± 0.8	1.0 ± 0.4	−0.2 ± 0.6
	10	Unloading/unchilled storage at wholesaler in Carlisle	3 h	3.9 ± 2.1	4.7 ± 2.7	3.6 ± 1.7
	11	Storage in Carlisle	45 h 45 min	1.5 ± 1.1	1.3 ± 1.0	1.7 ± 1.1
	12	Distribution to retailers	2 h 12 min	3.7 ± 1.3	3.0 ± 1.2	4.0 ± 1.2
	Total	3.9 d at distributor; or 4 d at retailers		0.6 ± 7.7	0.7 ± 8.0	0.5 ± 7.6
Air_June 2008 (Freighter)	1	Cold storage after packing at producer (Dalvik)	2 h	−6.8 ± 8.2	−11.5 ± 6.0	−2.2 ± 7.4
	2	Loading truck and transportation to RVK	9 h 35 min	−0.3 ± 2.9	−2.4 ± 2.8	1.7 ± 1.1
	3	Unchilled storage over night in RVK	10 h 10 min	8.8 ± 2.5	10.5 ± 1.7	7.1 ± 2.0
	4	Transportation in refrigerated truck to KEF	2 h 15 min	3.4 ± 2.8	4.5 ± 2.5	2.2 ± 2.7
	5	Chilled storage at KEF airport	2 h 45 min	1.2 ± 1.0	1.9 ± 0.7	0.5 ± 0.6
	6	Loading at KEF and flight from KEF to Nottingham (U.K.)	5 h 30 min	4.6 ± 3.0	3.6 ± 2.6	5.6 ± 3.2
	7	Transportation from processors storage	7 h 55 min	1.7 ± 2.3	1.0 ± 2.6	2.3 ± 1.8
	Total		1.7 d	3.0 ± 5.2	2.6 ± 6.3	3.5 ± 3.7

TABLE 1. *CONTINUED*

Freight	Step	Description	Duration	Ambient temperature	Ambient temperature of pallet 1	Ambient temperature of pallet 2
				Mean ± STDEV (C)	Mean ± STDEV (C)	Mean ± STDEV (C)
Air_July 2008 (Passenger)	1	Chilled storage at the producer in Hafnarfjordur (IS) after packaging	21 h 30 min	3.6 ± 1.3		
	2	Transport from Hafnarfjordur to some storage at KEF	19 h 10 min	14.4 ± 2.8		
	3	From taking off to landing	3 h 5 min	12.1 ± 4.2		
	4	Storage at London Heathrow airport (LHR, U.K.)	7 h 15 min	10.7 ± 5.0		
	5	Land transport in refrigerated truck to secondary producer in Plymouth (U.K.)	5 h	4.2 ± 0.4		
	Total		2.3 d	8.7 ± 5.6		
Sea_18–23Sep 2008		Handling and transportation in refrigerated container: trucked from producer to habor Reydarfjordur (IS); shipping to Rotterdam habor (the Netherlands); and land transportation until final destination (Boulogne sur mer, FRA)	4 d 19 h 45 min (4.8 d)	–0.2 ± 0.5		
Sea_23–29 Sep 2008	1	Cold storage at the producer (Dalvik)	3 h 35 min	–11.6 ± 5.5		
	2	Loading into container and transportation to RVK	8 h 30 min	–2.8 ± 2.1		
	3	Partly chilled hold in RVK	4 h 50 min	3.5 ± 4.3		
	4	Transportation and handling in refrigerated container: trucked from producer to RVK; shipping to Immingham (U.K.); and land transportation till final destination (Grimsby, U.K.)	5 d 3 h 30 min	–0.4 ± 1.5		
	Total		5.9 d	–0.7 ± 2.8		
Sea_24 Sep–1 Oct 2008		Handling and transportation in refrigerated container: trucked from producer (Dalvik) to RVK; shipping to Immingham (U.K.); and land transportation till final destination (Grimsby, U.K.)	6 d 16 h 35 min (6.7 d)	–0.7 ± 0.2		

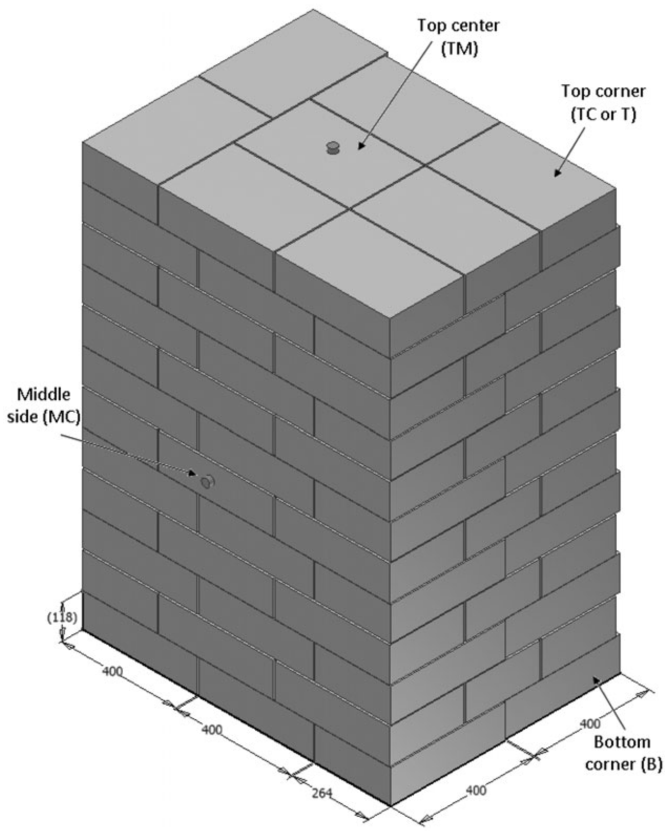


FIG. 1. COMMON LOADING PATTERN OF 3-KG EXPANDED POLYSTYRENE BOXES ON A PALLET
Round buttons on top and side of the pallet illustrate the surface loggers.

ship's hold until landing approximately 2–4 days from catch. After landing, it was transported in unrefrigerated trucks to the processing plant located only a few hundred meters away from the harbor. The catch was processed the following day after a chilled storage overnight.

For the products aimed to air transportation, the fish was headed, filleted, skinned and cut into portions (approximate size: $26 \times 5 \times 2.3$ cm, approximate weight: 0.32 kg). After processing, the cod loins were immediately packed in EPS boxes (outer dimensions: $400 \times 264 \times 118$ mm), which contained about 3 kg of cod loins with two frozen gel – mats (September 2007) or one gel mat of 125 g (June 2008) lying on top of the loins, and with a plastic film in between. The EPS boxes were loaded on Euro pallets ($1,200 \times 800$ mm) with eight boxes in each row and 12 rows high (Fig. 1), and the palletized boxes wrapped in a thin plastic sheet for protection.

For the products aimed to sea transportation, the processing steps include heading, filleting, liquid cooling, combined blast and contact (CBC) cooling, skinning and trimming. After processing, the cod loins of the same size as for air shipments were immediately packed in EPS boxes (400 × 264 × 135 mm) which contained 5 kg of cod loins. The boxes were equipped with drainage holes at the bottom in order to drain melting ice which was put on top of a thin plastic sheet above the loins. The amount of ice utilized in each box was about 0.3–0.5 kg. The boxes were palletized on Euro pallets (1,200 × 800 mm) with nine boxes in each row and 12 rows on each pallet. A few layers of thin plastic film were wrapped around the palletized boxes before they were containerized.

The haddock was caught north of Iceland by a line vessel in July 2008. On board, it was bled, washed, packed and stored with ice in insulated tubs until landing in North Iceland. Fish tubs were transported in a refrigerated truck approximately 400 km to the processing plant in Hafnarfjordur. The raw material was stored in the plant's chilled storage room (ambient temperature about 2 to 4C) overnight. The fish was about 1 day old from catch when the processing started the following morning. The different steps in the processing include gutting, washing, filleting, trimming, liquid cooling (10–15 min in ice slurry at −1 to 1C), CBC cooling (10–11 min at about −10 to −8C), skinning and trimming, followed immediately by packaging into EPS boxes (600 × 400 × 147 mm). Each box contained 12 kg of haddock fillets, without any ice or gel packs as a cooling medium since the CBC treatment decreases the fillet temperature to around –0.5C. Twenty-eight boxes (seven rows with four boxes in each row) were palletized on each Euro pallet (1,200 × 800 mm) and the pallet load wrapped with layers of thin plastic sheet.

Logger Configurations. Based on previous studies (Moureh and Derens 2000; Moureh *et al*. 2002) and own preliminary studies, it was observed that the temperature at different positions of product and packages is often not homogeneous during thermal load. Loggers were configured in the way that temperature changes at different positions inside a box and on box surface, and at different positions of boxes on a pallet could be sufficiently monitored.

Loggers for the temperature mapping were placed in the product during packaging and on the box surface before or during palletizing. Logger configurations are the following:

In September 2007, measurements were carried out with two pallets (P1, P2): four boxes for each pallet: at top center (TM), top corner (TC), bottom corner (B) and in the center of middle row (M) of the pallets; 3 loggers inside each box: on top (t), in the middle (m), and at the bottom (b) of product. Three outside loggers to measure box ambient temperature (A) were attached to the middle side (MC) boxes of P1 (P1_A_MC), P2 (P2_A_MC) and to the top corner box of P2 (P2_A_T). The box positions and outside loggers are shown for one pallet in Fig. 1. At the end, two inside loggers of P2, which were the top loggers inside the center–middle row box (P2_M_t) and the top center box (P2_TM_t), got lost.

In June 2008, measurements were conducted with two pallets (P1, P2): three boxes for each pallet: at top corner (T), bottom corner (B) and middle height (M); 3 loggers inside each box (t, m and b). Four outside loggers were placed on top (P1_A_T, P2_A_T) and side (P1_A_MC, P2_A_MC) of the two pallets. However, two inside loggers of P2, which were at the bottoms in the bottom corner box (P2_B_b) and the top corner box (P2_T_b), failed to record. Therefore, the data sets are just available for nine inside loggers of P1, seven inside loggers of P2 and four outside loggers.

For the air shipment by a commercial passenger flight in July 2008, one pallet was investigated: three boxes (T, B and M) with two loggers inside (m and b) and one on the surface of each box (A_T, A_B and A_M).

In the sea freight study September 18–23, 2008, measurements were done with one pallet: three boxes (T, B and M) with three loggers inside (t, m and b) and one on the surface of each box (A_T, A_B and A_M). However, all the inside loggers were lost; two outside loggers stopped working before the shipment started, only one outside logger on the middle box (A_M) worked properly.

In the sea freight September 23–29, 2008, a study was carried out for one pallet with only three surface loggers on top corner, bottom corner and middle boxes (A_T, A_B and A_M, respectively).

Lastly, in the sea trip September 24 to October 1, 2008, the temperature mapping was done on one pallet: three boxes (T, B and M) with three loggers inside (t, m and b) and one on the surface of each box (A_T, A_B and A_M). One inside logger (B_t) was lost.

It should be noticed that in all the sea trips and in the air freight July 2008, the middle boxes (M) also means middle side (MC) as they have one free side on a pallet side. Furthermore, the middle box in July 2008 had two free sides as it was located at the corner of the middle row.

In general, each mapped box was equipped with three loggers inside (one at the bottom, one in the middle height of product and another on top of product) and a logger on the box surface (top or side). This gives the actual temperature history of product at different positions inside a box, as well as the actual temperature changes on the box surface.

Types of Loggers. The iButton temperature loggers are small and relatively cheap devices with wide range of operation temperature, high precision and sufficient memory for data storage (up to 4,096 data points, e.g., recording continuously for 14 days at 5 min interval or 28 days at 10 min interval). They can function during contact with food, water or ice and can be easily set.

DS1922L temperature loggers iButton were used for mapping the temperature inside the boxes, with temperature range: –40C to 85C; resolution: 0.0625C; accuracy: ±0.5C and ±1 min/week. Recording intervals were set at 2 (Air_July 2008), 4 (Air_September 2007), 5 (Sea_24September 2008) or 10 (Air_June 2008) min.

TBI32-20+50 Temp Data Loggers were used for the measurement of ambient temperature on the box surfaces, with temperature range: −20C to +50C; resolution: 0.3C; accuracy: ±0.4C and ±1 min/week. Recording intervals were set at 1 (Sea_23–29September 2008, Sea_24September 2008), 2 (Air_July 2008), 4 (Air_September 2007) or 5 (Air_June 2008, Sea_18–23September 2008) min.

All loggers were calibrated in thick mixture of fresh crushed ice and water before use.

Data Analysis

Multivariate analysis was performed using the Unscrambler version 9.0 (CAMO Process AS, Norway). The main variance in the data set was studied using PCA with full cross validation. Data were preprocessed by autoscaling prior to the PCA, i.e., first centered by subtracting the column average of elements from every element in the column, and then each element was scaled by multiplying with the inverse standard deviation (1/STDEV) of the corresponding variable, to handle the model offsets and to let the variance of each variable be identical initially (Bro and Smilde 2003).

One-way repeated measures analysis of variance was applied to the data using the software SPSS version 16.0 (released September 2007) (SPSS Inc., Chicago, IL) in order to study the effect of some factors such as product locations, box positions and chain steps on the temperature of product and box surface. The null hypothesis was that the analyzed factors have no influence on the temperature. Bonferroni correction was used in confidence interval adjustment for multiple comparisons of locations. Tukey's multiple comparison test was used to determine the statistical difference between steps. All tests were performed with significance level of 0.05.

Microsoft Excel 2003 was used to calculate means, standard deviation and range for all measurements and to generate graphs.

The Seafood Spoilage and Safety Predictor (SSSP) software version 3.0 (DTU Aqua, Denmark) was used to predict the effect of time–temperature combination on the RSL based on the recorded temperature profile. Recorded data of cod loins and haddock fillets from different positions inside boxes were separately fitted into a square root model for RRS of fresh seafood from temperate water. In SSSP, RRS at T °C has been defined as the shelf life at a reference temperature T_{ref}, which normally is 0C, divided by the shelf life at T

°C (Dalgaard 2002), where shelf life was determined by sensory evaluation. The SSSP uses the concept of accumulative effects of time and temperature. The SSSP is based on growth kinetics of specific spoilage organisms and empirical RRS secondary models (Dalgaard *et al*. 2002). A reference shelf life of 9 days (from catch) stored at 1.5C for fresh cod loins in EPS boxes (Wang *et al*. 2008) was used in this study. A shelf life of 12 days (from catch) at 0C was applied for fresh haddock fillets in EPS boxes (Olafsdottir *et al*. 2006a). In order to enable the comparison of the effect of different logistics practices on the RSL, it was assumed that all fish batches had undergone 3 days from catch of the same conditions before the temperature mapping started. Therefore, 3 days were subtracted from the SSSP's RSL outputs based on the temperature history during logistics to get the final RSL. The mapping data for haddock fillets in July 2008 were also used for cod loins, assuming that the product was cod, to compare the RSL between the shipments.

RESULTS AND DISCUSSION

Temperature Mapping

Air Freight in September 2007. Figure 2a reveals some hazardous parts of the chain because of the ambient temperature rise. The two most abusing steps were the flight followed by unchilled storage at the arrival at Humberside airport (step 8) and the unchilled storage at the departure at Keflavik airport (step 6), which caused the rise of temperature inside boxes in steps 6–8 (Fig. 2b). Unloading and reloading activities (steps 4 and 10) were also notable but with shorter durations (approximately 2 h in step 4, and 3 h in step 10). In total, the pallets were exposed to unchilled conditions (up to 15C) for more than 16.5 h, accounting for about 17.4% of the total time from processor to retailers.

In step 1, the temperature on the side of pallet 2 (P2_A_MC) was considerably higher than on the top of this pallet (P2_A_T) and on the side of pallet 1 (P1_A_MC) where the temperature was the lowest (Fig. 2a). This might be because pallet 2 was placed closer to the door of the cold store and with the mentioned side facing the door which was opened for the loading/unloading processes.

It can be seen from Fig. 2b that the temperature inside boxes was relatively high (up to about 5C) when the pallets were transferred into the cold storage after packing (step 1). This shows the possibility for the producer to improve the production, e.g., by adding slurry ice chilling (or another chilling method) to the processing line in order to lower the product temperature before packaging. The time required to get the average temperature below 2C in the

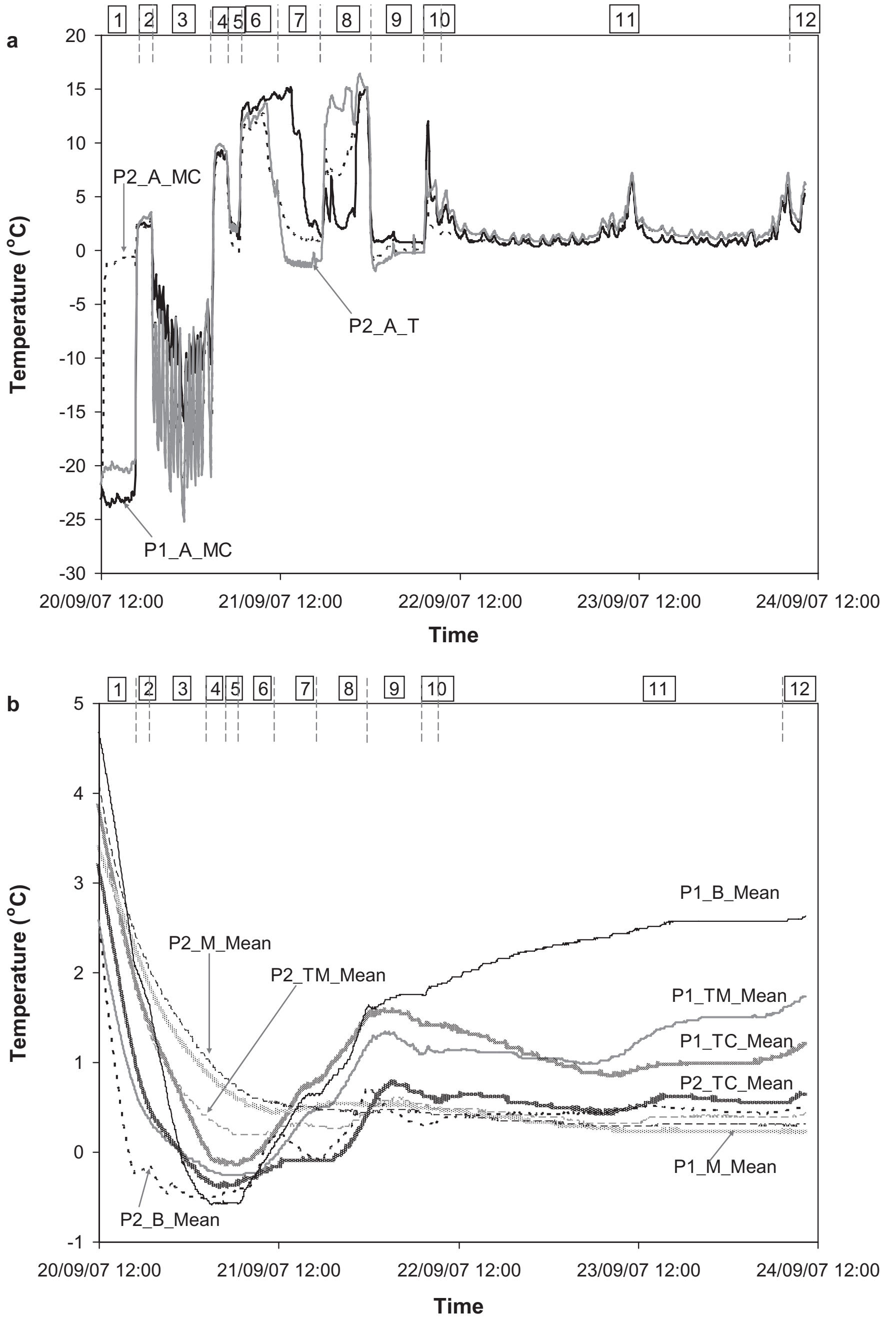


FIG. 2. AMBIENT TEMPERATURE ON THE BOXES (a), AVERAGE PRODUCT TEMPERATURE INSIDE THE BOXES (b) AND PRODUCT TEMPERATURE AT DIFFERENT LOCATIONS INSIDE EACH BOX (c) DURING THE AIR CARGO STUDY IN SEPTEMBER 2007

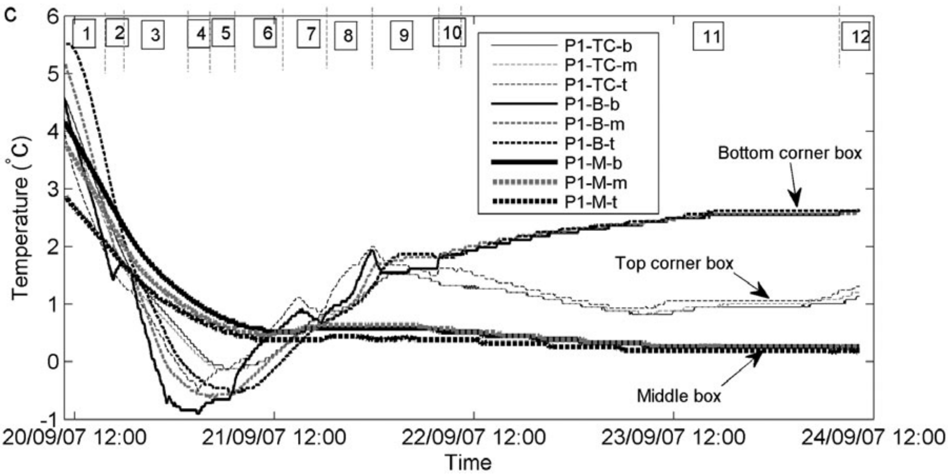


FIG. 2. *CONTINUED*

boxes was up to above 8 h, despite the fact that the pallets were mostly facing ambient temperature around −20C. This is because the product was well insulated by the EPS boxes, and the palletization of the boxes.

Some relations can be noted between the placement of the boxes on the pallet(s) and the temperature evolution inside the packaging. The middle boxes (P1_M_ and P2_M_) with no free side required considerably longer time to be cooled down than the boxes with more free sides (Fig. 2b). Temperature in the boxes with more exposed surfaces, e.g., the top and bottom corner boxes of the two pallets (P1_TC_, P2_TC, P1_B and P2_B), has experienced more fluctuation. It is in good agreement with other research results (Moureh and Derens 2000; Moureh *et al*. 2002). The bottom corner of pallet 1 has faced a continuous increase in product temperature from step 4 onward, i.e., from the time when ambient temperature abuse started, and ending up with the highest temperature (2.6C) compared with other boxes (0.2 to 1.7C).

Interestingly, the patterns of temperature evolution of the same positions top corner (TC) and middle (M) on the two pallets are very similar (almost parallel curves: P1_TC_Mean and P2_TC_Mean; P1_M_Mean and P2_M_Mean) (Fig. 2b). For example, the temperatures of both the top corner boxes decreased sharply during steps 1–4, reaching the lowest points at about the end of step 4, increasing again in steps 5–8 and peaked in early time of step 9. After that, there was a slight decrease until the end of step 9 and some up and down changes afterward.

There is some noticeable difference between the two pallets. First of all, the temperatures on the top of product after packaging were not even for the two pallets, much lower for pallet 2 when comparing boxes at the same

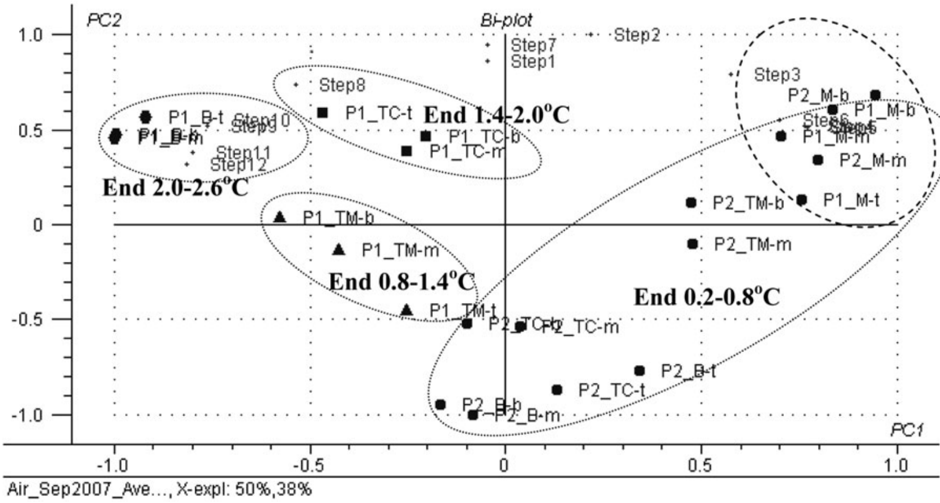


FIG. 3. PRINCIPAL COMPONENT ANALYSIS BI-PLOT BASED ON AVERAGE-WITHIN-STEP TEMPERATURE FROM THE AIR TRANSPORTATION STUDY IN SEPTEMBER 2007

Samples are labeled with the pallet number (P1, P2), box position on the pallets (TC, TM, M and B), and the location inside a box (T, M and B). Dotted ellipses group the samples with similar product temperature at the end of the logistics (end of step 12). The dash ellipse shows subgroup of those positions where the product temperature was the most stable.

positions (i.e., B and TC) (see Fig. 9). It might be because boxes of pallet 2 were packed earlier (with the ice mats on top) than those of pallet 1 before the loggers were activated to record the temperature. The product temperature of pallet 2 was far lower than that of pallet 1 (except for the middle box of P1) for the whole period from step 8 onward (Fig. 2b). It is mainly because pallet 2 has been exposed to lower temperature environment during a quite long refrigerated truck transportation to Reykjavik (for more than 8 h in step 3), and also during the storage at Keflavik airport (for more than 11 h in steps 6 and 7) (Fig. 2a). It is very likely that pallet 2 was placed close to the cooling equipment during chilled transportation (step 3) and storage (step 7).

It can be seen from Fig. 2c that the product temperature at different locations inside a box was not the same, with larger range at the beginning (steps 1–10), but becoming more even at the later stages of the logistics (steps 11 and 12).

When the results were analyzed with PCA (Fig. 3), a clear grouping was found between the samples with different degrees of temperature abuse exposure. Principal component 1 (PC1) explains 50% of the variance, whereas principal component 2 (PC2) explains 38%. Product at different locations in the bottom corner box on pallet 1 (P1_B_t, _m and _b), which was the most influenced, forms one group of samples. Similarly, products in the top corner box (P1_TC_) and in the top middle box (P1_TM_) of this pallet make two other distinct groups. Those three boxes had higher temperature at the later stages of the chain (steps 8–12, Fig. 2b), of which the top product temperature inside the top corner box was the highest in step 8 (curve P1_TC_t, Fig. 2c); thus, the sample score is located very close to the loadings of step 8. Product temperature of pallet 2 (P2) and in the middle box of pallet 1 (P1_M_) was more stable during the chain, grouping together in the PCA plot. Temperature in the middle boxes of the two pallets was the most resistant to change because these boxes are insulated by others; the change was mostly observed during steps 3–6 (Fig. 2b), making those scores and loadings group together (dash ellipse). This resistance is in a good agreement with the results of other studies (Moureh and Derens 2000; Moureh *et al*. 2002). Despite the fact that the temperature behavior at different positions inside each box was somewhat different, their PCA scores are located relatively close to each other, which in turn contribute to the discrimination of the product temperature between boxes. It would be possible to group the boxes with similar temperature evolution so as to have a better management for the quality, safety and shelf life of the product. For example, it might support the sale managers in further utilization of the resources: highest end temperature in – first out.

Air Freight in June 2008. Figure 4a reveals some hazardous parts of the chain considering the temperature abuse that the pallets have experienced. The two most noticeable steps were the storage over night in Reykjavik (step 3) and the loading at Keflavik airport followed by the flight to the U.K. (step 6). During the loading period of the airplane (beginning of step 6), the top of pallet 2 experienced a rise of air temperature from 10 to 20C (see curve P2_A_T in Fig. 4a). The warming and cooling periods took about 1 hour. The explanation may be that the sunlight might have reached a part of the pallet while loading the airplane (increasing the ambient air temperature for a short period). Total abusing time was about 14.5 h (ambient temperature >5C), which was 36.1% of the total logistics time from producer to final destination. This shows that a considerable time in air transportation is under nonrefrigerated conditions as stated elsewhere (James *et al*. 2006).

The ambient air temperature was much lower for pallet 1 than pallet 2 in the cold storage after packaging (step 1), and the same but to a lesser extent in the following step (Fig. 4a). Therefore, the temperature inside the boxes on pallet 1 has decreased faster than that of pallet 2 during the first 12 h from the processor at Dalvik until the arrival in Reykjavik (steps 1 and 2) (Fig. 4b). Exposure of the pallets to unchilled conditions for over 10 h (step 3) caused a sharp increase of product temperature in the top and bottom corner boxes of

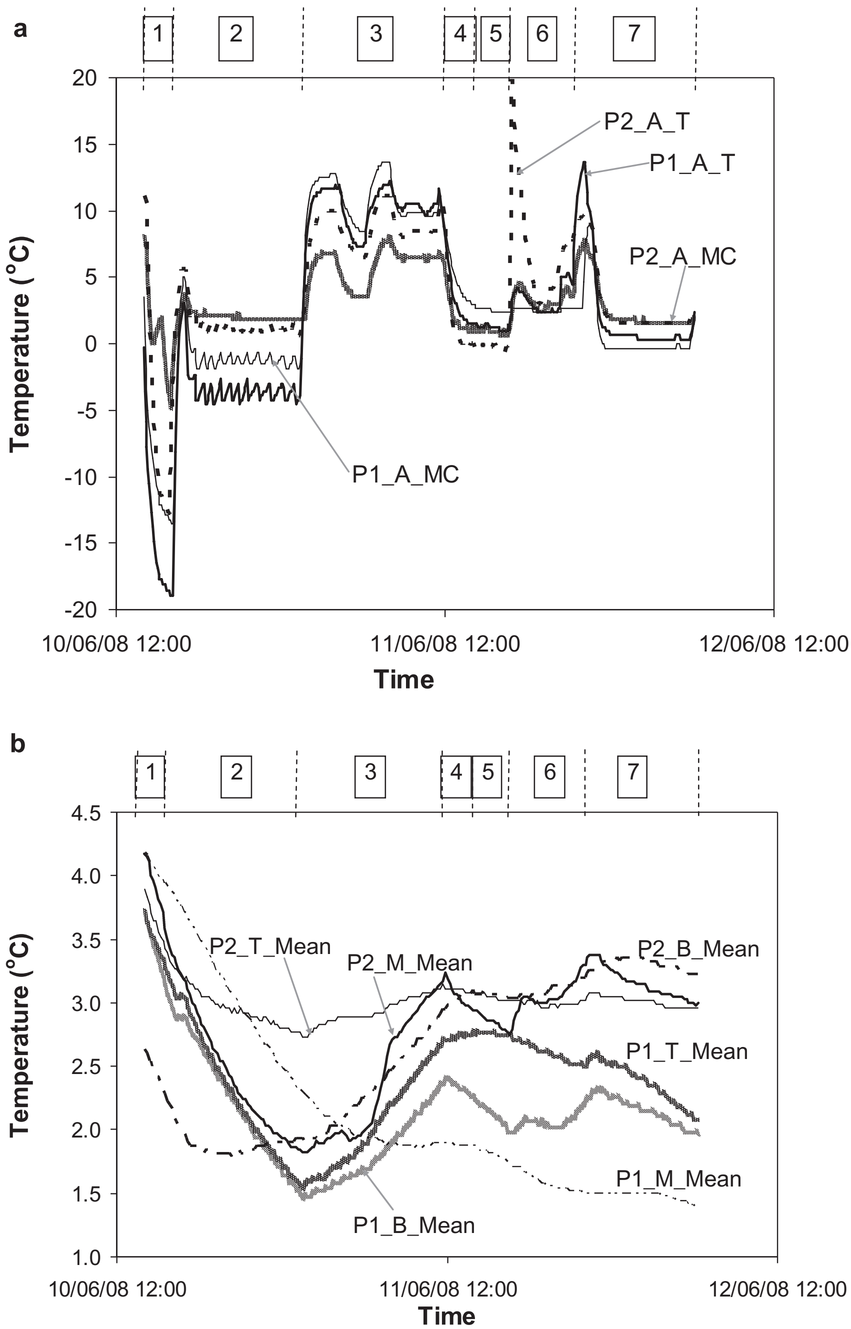


FIG. 4. AMBIENT TEMPERATURE ON THE BOXES ON THE TOP (T) AND SIDE (MC) OF THE PALLETS (a), AVERAGE PRODUCT TEMPERATURE INSIDE THE BOXES (b) AND PRODUCT TEMPERATURE RANGE OF DIFFERENT POSITIONS INSIDE EACH BOX (c) DURING AIR CARGO STUDY IN JUNE 2008

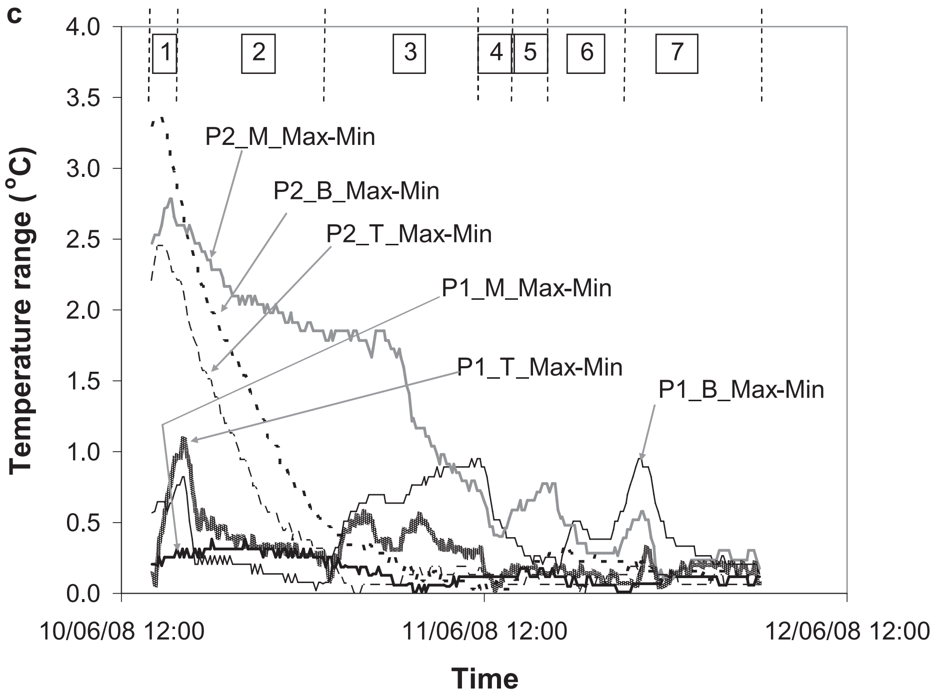


FIG. 4. *CONTINUED*

pallet 1 and in the bottom corner box of pallet 2 (Fig. 4b). It is clear from Fig. 4b that the top corner box of pallet 1 (P1_T_) was more affected than the bottom one (P1_B_), especially from step 3 onward. The temperature in the middle box of pallet 1 (P1_M_Mean) was more resistant to change compared with those in the top and bottom boxes. This result is comparable with the one found during the mapping in September 2007, and with the results reported elsewhere (Moureh *et al*. 2002). Since the central boxes are better insulated to the ambient air, ambient temperature change affects them to a smaller degree than the other boxes.

Figure 4c shows the evolution of temperature range between different heights (top, middle and bottom) of product inside each box. The ranges in the first two steps of the boxes on pallet 2 were much higher than on pallet 1. It can be explained by two reasons. First, it is because the top of boxes on pallet 2 had lower initial temperature (1.0 to 2.9C) than on pallet 1 (3.3 to 4.2C) (see Fig. 9). Meanwhile, the deeper layers of product inside boxes on pallet 2 had higher initial temperature (4.3 to 5.3C) than on pallet 1 (3.7 to 4.3C) (see Fig. 9). It is very likely that the boxes of pallet 2 were packed earlier (with the ice mats on top) than those of pallet 1. Second, higher ambient temperature of pallet 2 during steps 1 and 2 (Fig. 4a) caused slower cooling process for the

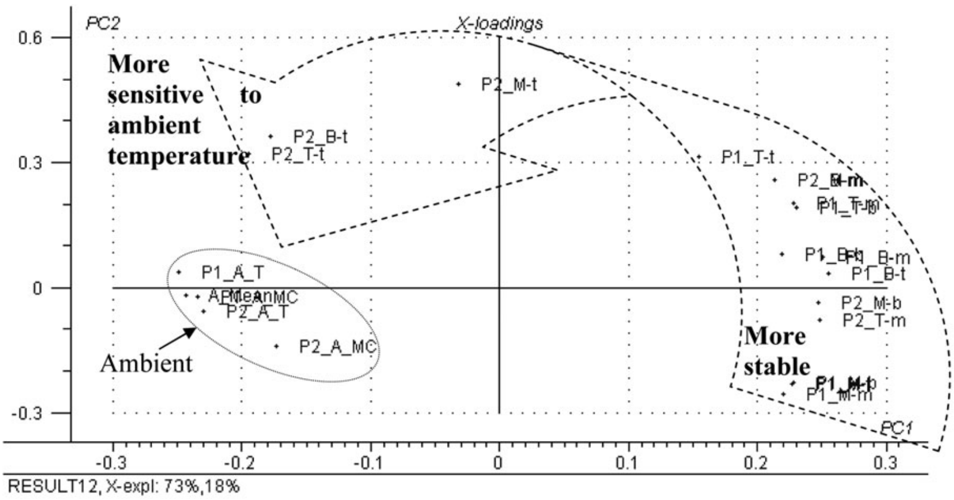


FIG. 5. PRINCIPAL COMPONENT ANALYSIS LOADING PLOT BASED ON THE AVERAGE WITHIN-STEP TEMPERATURE OF PRODUCT AND BOX SURFACE DURING AIR CARGO STUDY IN JUNE 2008
The dash curved arrow shows the affecting trend of product positions to its temperature. The dotted ellipse groups the loadings of ambient temperatures on the box surfaces.

product on pallet 2. The temperature behavior of the top corner box of pallet 2 (P2_T_Mean, Fig. 4b) showed that the top corner box was very sensitive to environmental changes, e.g., when the product was moved from a cold store (step 1) to a chilled store (step 2) and then to unchilled conditions (step 3). Similar results were found in September 2007 and in other studies (Moureh and Derens 2000; Moureh *et al*. 2002). Colder environment temperature for pallet 1 during the first two steps led to a faster product cooling (Fig. 4b) and depletion of the temperature range (Fig. 4c) over this time.

Large increase in ambient temperature of pallet 1 from step 1 to 3 and high fluctuation during steps 3 (Fig. 4a) led to an increase in variability of product temperature (temperature range) of the outer (B and T) boxes on this pallet in step 3 (Fig. 4c). It is understandable because the top product in a box is more sensitive to the environment change than the one in the middle or at the bottom due to higher thermal diffusivity of air relative to fish, causing the range of inside temperature to become larger with higher degree of the ambient fluctuation.

The temperature inside the boxes at the beginning of the transportation was considerably high (up to 4.2C, Fig. 4b). A possible way to decrease the product temperature at this stage is to utilize some kind of precooling methods, e.g., a CBC system or precooling in liquid ice.

PCA loadings (Fig. 5) illustrate the correlation between the product temperature and the ambient temperature. PC1 explains 73% and PC2 explains

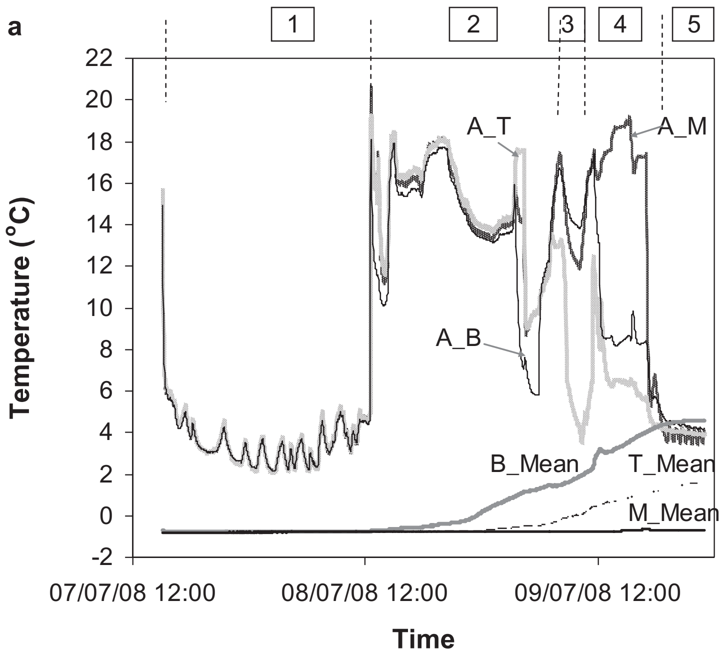
18% of the variance. The loadings of inside temperatures of the pallet 1 middle box, which was the most stable (see Fig. 4b), are located on the positive direction of PC1, oppositely to the loadings of ambient temperatures on the other side of this PC. The arrow shows the sensitivity trend of inside temperature, depending on the locations inside a box and box positions on a pallet, toward ambient changes. The loadings of temperature on top of product in boxes on pallet 2 (P2_T_t, P2_B_t, and P2_M_t), which were more sensitive to change compared with other locations, are located closer to variables "ambient." It is because the top loggers were placed on the top of the fish in the boxes, and were influenced not only by the product surface temperature, but also by the air headspace condition, which was very sensitive to the outside temperature.

It could be seen that the results were comparable to the measurements in September 2007. The overall temperature of the product was noticeably higher in this measurement than in 2007, although the ambient air temperature was very similar. A probable explanation is that the precooling period, which the product went through in the frozen storage room at the processor in Dalvik, was longer during the measurements in 2007 than in the 2008 trials. The set point temperature in the truck during transportation from Dalvik to Reykjavik was −20C in the measurements of 2007 but 0C in 2008. This resulted in better precooling of the product, which was greatly needed, since the product temperature before packing was approximately 5C.

These measurements confirm that there are certain critical points which can be improved regarding the temperature control in the supply chain from Iceland to the U.K.. Cooling the product below 0C without freezing it is important to ensure the highest quality of the fresh product and to make the product less sensitive to temperature fluctuations during transportation and storage.

Air Transportation (Passenger Flight) in July 2008. The mapping results for the ambient temperature in July 2008 (Fig. 6a) show that the boxes have undergone long temperature abuse from leaving the processor store to the storage at the destination airport (step 2 to 4), which lasted for 29.5 h. This made 46.6% of the total logistics time, which was much longer than in the air cargoes in September 2007 and June 2008. The results agree with the fact that air transportation of perishable food faces such unrefrigerated temperature problem for much of its voyage (James *et al.* 2006).

From Fig. 6a,b, it can be seen that small fluctuation of outside temperature in step 1 led to small variability (small range) of temperature inside the boxes. In contrast, high fluctuation of ambient temperature in other steps (steps 2 to 4) caused a very large variability of inside temperature, especially for



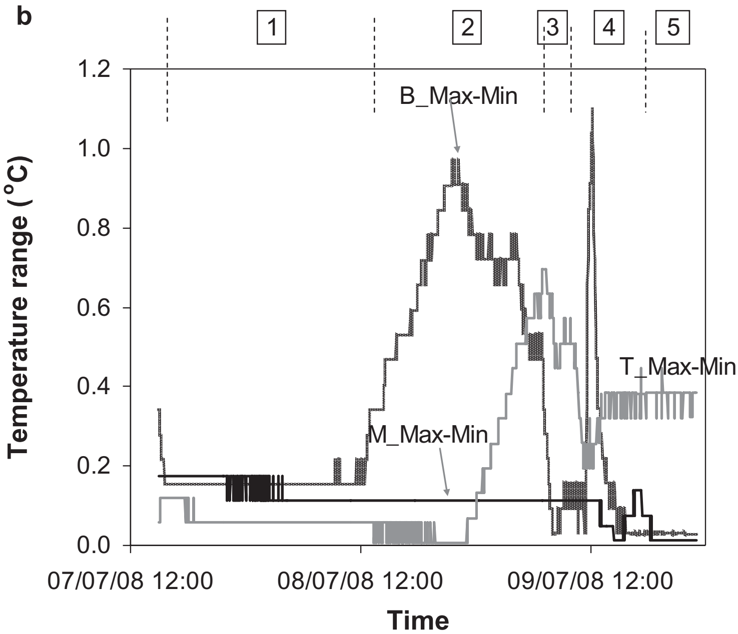


FIG. 6. AMBIENT AND AVERAGE PRODUCT TEMPERATURE (a), TEMPERATURE RANGE INSIDE THE BOXES (b) AND TEMPERATURE IN THE MIDDLE BOX (c) DURING PASSENGER AIR FREIGHT STUDY IN JULY 2008

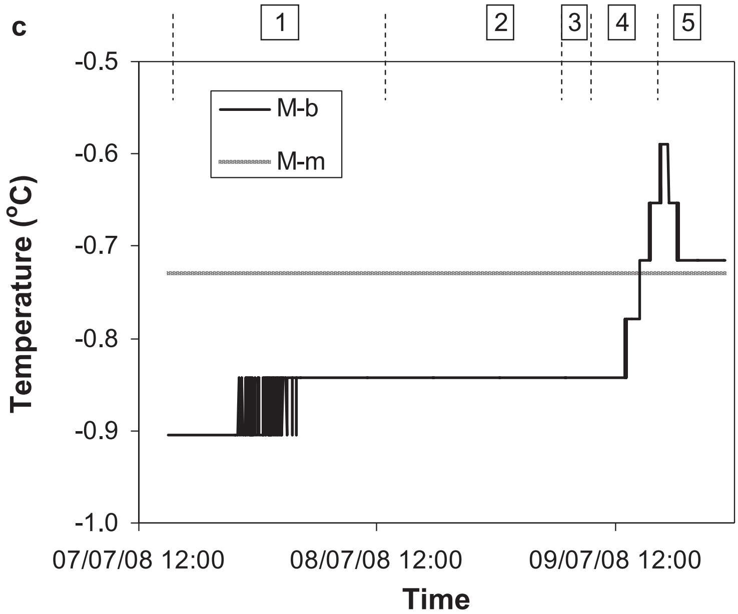


FIG. 6. *CONTINUED*

boxes with many free sides such as bottom and top corner boxes. This result is comparable with the results found for the air freight in June 2008.

The temperature mapping results showed that the product in the bottom corner box of the pallet was the one most influenced by the ambient, especially by high temperature fluctuation during steps 2 (transportation to the airport and storage at the airport before taking off) and 4 (storage at the airport after landing). This was well indicated by the fact that the temperature range between the center and the bottom of the product was large (up to 1.1C) during these steps, and the product temperature at end of the studied links was extremely high (4.6C at the secondary processor). The product in the top corner box was the second most affected by the environment, particularly with long temperature abuse from step 2 to step 4, causing large temperature range (0.7C) during this time and high end temperature (1.6C at the secondary processor). These facts point out that steps 2, 3 and 4 (i.e., transportation and storage before taking off, during the flight and storage at the destination airport, respectively), where the temperature was not well controlled, are the hazardous ones in the chain. It should be noticed that in this case study, the plane was a passenger aircraft and not a dedicated freight transport plane, resulting in a need to break the pallet up for loading the individual boxes in the plane hold before taking off. As apparent from Fig. 6a, the ambient temperatures between boxes became clearly distinguished some hours before the taking off.

The product temperature in the middle box was stable throughout the chain with relatively small temperature range between the product locations (<0.2C, Fig. 6b) and with low final temperature (–0.7C, Fig. 6c). Interestingly, the temperature in the center of the product in this box remained constant (at –0.70C) in all the steps (Fig. 6c). Therefore, despite the lack of information on how the pallet was split and where the boxes have been placed afterward, it is reasonable to speculate that the middle box has been kept surrounded by other boxes all the time. This is based on the other two air cargo studies in September 2007 and June 2008, and on the results of other researchers (Moureh and Derens 2000; Moureh *et al.* 2002) that the temperature inside middle boxes is least voluntary to change. Because of high fluctuation in the ambient temperature of the middle box after the pallet breakup (see line A_M in Fig. 6a), it is also speculated that the side with ambient logger of this box has been exposed to the environment during this time.

The temperature in the center of product in the middle box was much more stable (actually kept constant) compared with that of the two previous air freights. This may be explained by the fact that the EPS boxes in this case were of 12 kg product, much larger compared with the other freight boxes (of 3 kg product). The center product of the middle box in this flight was therefore very well insulated by the surrounding fillets. It is also because the initial temperature in this case was –0.7C (fillets partially frozen, thanks to the CBC precooling), much lower than in the two freighter aircraft flights (3.8 to 4.6C, with no precooling) (Fig. 9).

The difference in the end temperatures of products from different locations on a pallet again supports the statement above that the products should be grouped by the positions and handled in an appropriate way. The more abused products should be used earlier.

Sea Transportation September 18–23, 2008. The results of the temperature mapping showed that the box was kept at low and stable temperature (–0.2 ± 0.5) for the whole trip of 4.8 days (Table 1). Starting with relatively high ambient temperature (around 9.3C), the surface of the middle box was cooled down below 0C after about 3 h of containerization (results not shown).

Sea Transportation September 23–29, 2008. Figure 7 shows that the surface temperature on the middle box (A_M) has decreased very fast, reaching a minimum temperature of −18.1C after about 3.3 h of the cold storage at the producer (step 1). Meanwhile, the top corner (A_T) and the bottom corner (A_B) boxes of the pallet gained their coolest points at −13.5 and −10.3C, respectively, at later time of this step. This indicates that the middle height box was located closer to the air blast refrigeration unit than the other two boxes during step 1. During step 3 (partly chilled hold in Reykjavik), the surface

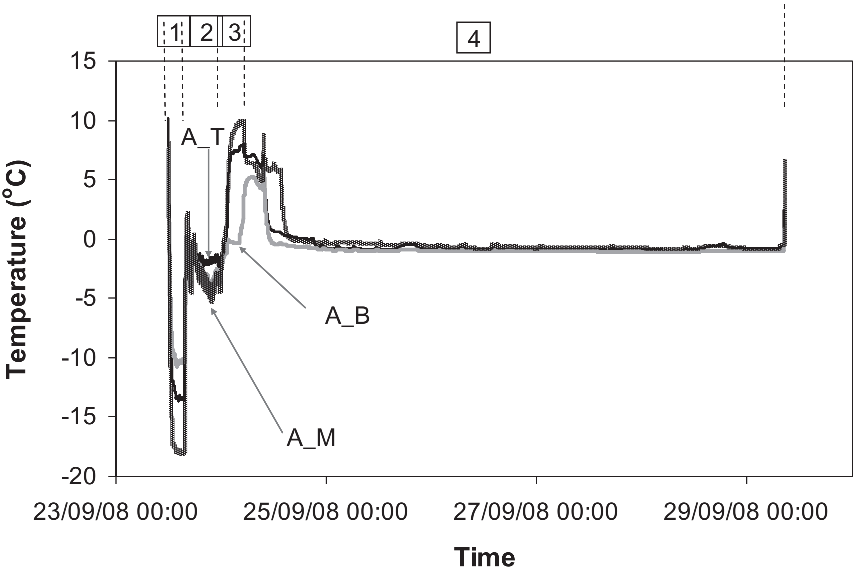


FIG. 7. SURFACE TEMPERATURE OF THE TOP CORNER (A_T), MIDDLE (A_M) AND BOTTOM CORNER (A_B) BOXES ON THE PALLET DURING THE SEA TRANSPORTATION STUDY ON SEPTEMBER 23–29, 2008

temperature of the boxes sharply increased due to the turning off of the cooling equipment. In step 4, when the cooling equipment inside the container was functioning, the temperatures of all boxes became stable, maintaining below 0C most of the time until the destination.

Sea Transportation September 24–October 1, 2008. Figure 8a indicates that the temperature of product inside the boxes were very stable compared with the air transportation. It is because in the sea freight chain, the boxes were kept in a refrigerated container for the whole trip from processor to the final destination. The temperature difference between the locations inside a box was also small (≤0.2C most of the time) (Fig. 8b) because the fish was cooled during processing (by liquid and CBC cooling before skinning) and then put with ice on top of the fillets when packed into the EPS boxes. Despite the initial temperature difference of product between inside positions and between box locations on the pallet (see Fig. 9), all the inside temperatures dropped below 0C very soon after 2 h of containerization (Fig. 8a). The temperature was then maintained stable between –0.9 and 0C for the remaining logistics process. This makes a clear distinction between sea and air transportations: in the latter case, there are several critical steps where the product is subjected to temperature abuse.

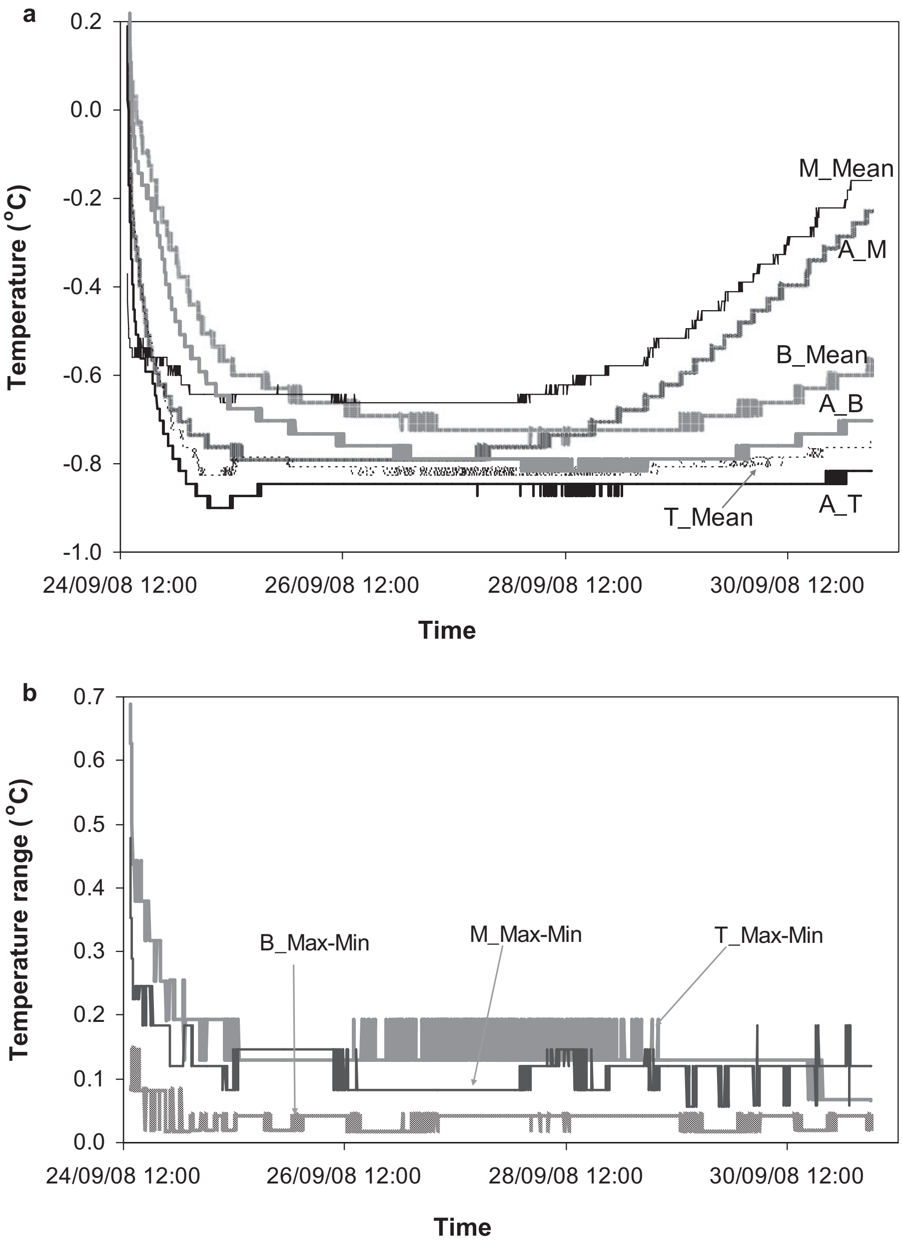


FIG. 8. TEMPERATURE INSIDE AND OUTSIDE (a) AND TEMPERATURE RANGE INSIDE (b) THE BOXES DURING SEA TRANSPORTATION SEPTEMBER 24–OCTOBER 1, 2008

The inside and outside temperatures of each box behave similarly. This can be seen from Fig. 8a where the temperature curves of each box are closer to each other than to the curves of other boxes. For a long period (more than 2 days), the temperatures inside and outside the bottom corner box were higher than those at the top corner and in the middle of the pallet. The surface temperature of the bottom box reached 0C just after 1 h of operation, whereas it took only about 20 min for the top corner box to be cooled down to this temperature. The temperature inside the top corner box of the pallet was the fastest to change. This is comparable with the results from the air chains above and from other studies (Moureh and Derens 2000; Moureh *et al*. 2002) that the top corner box is very sensitive to the environment conditions.

Comparison between the Freights

Initial Temperature Inside and Outside the Boxes. Figure 9 shows that, normally, the initial temperature of product in a box, or on a pallet, is not even. Due to the insulation of the package and surrounding boxes, the product is very difficult to be cooled down after being packed. A good solution would be to use some superchilling technique, e.g., a CBC system or slurry ice, to chill the product before packing. In the experiments in July 2008 (passenger flight) and September 2008 (shipping), the product was prechilled by CBC

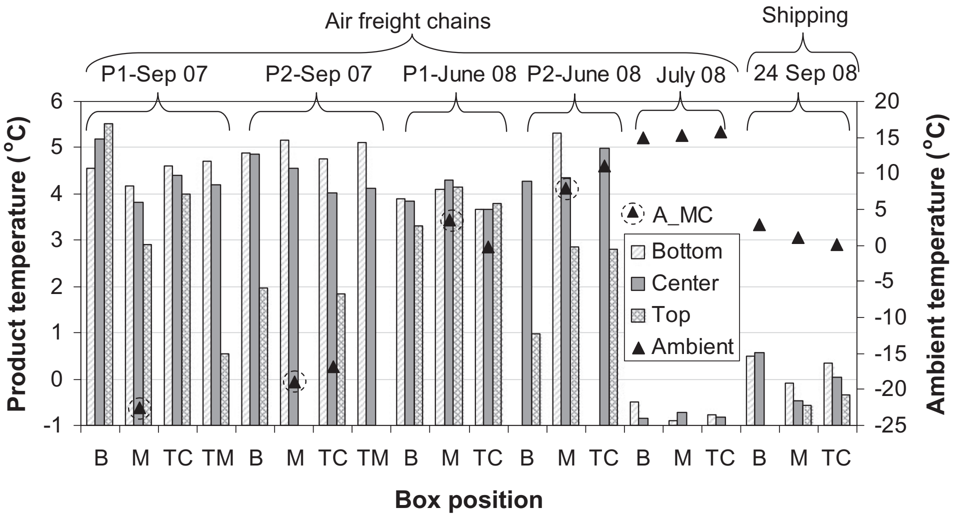


FIG. 9. INITIAL TEMPERATURE AT DIFFERENT POSITIONS INSIDE AND ON THE SURFACE OF BOXES PLACED AT THE BOTTOM CORNER (B), MIDDLE (M), TOP CORNER (TC) AND TOP CENTER (TM) OF EACH PALLET (P1, PALLET 1; P2, PALLET 2); AMBIENT TEMPERATURE ON THE SIDE OF PALLETS IS SHOWN AS A_MC

cooling; therefore, its initial temperature (–0.6 to 0.6C) was much lower than in the other two air freights where the initial temperature was as high as 5.5C.

In most cases, the initial temperature on top of product is the lowest, and the one at the bottom is the highest. It is understandable because either ice mats (in September 2007 and June 2008) or ice (in September 2008) were placed on top of the product when packaged into boxes. There are some exceptional cases, such as the bottom corner box (B) of pallet 1 in September 2007 and top corner (TC) box of pallet 1 in June 2008, where the highest temperature was on the top of product. It may be because these products have been exposed to unchilled conditions for rather long time before the ice mats were put on top and the temperature recording started.

Ambient Temperature of the Freights. The mean and standard deviation of box surface temperature in each step of the trips and in each trip are shown in Table 1.

A clear distinction between the surface temperature of sea and air freights was observed. The temperature in sea transportation was well below 0C and with smaller deviation, whereas in the air trips, it was much higher and with larger variation. The passenger flight yielded the highest average temperature on the boxes; this is because they became more exposed to the surroundings after the pallet splitting. Furthermore, the difference in surface temperature between pallets 1 and 2 as previously mentioned can also be clearly observed in this table.

Statistical Test Results Regarding the Effect of Different Factors on the Temperature. The statistical test results shown in Table 2 indicate that the null hypothesis, i.e., that product locations, box positions and chain steps have no influence on the temperature of product and box surface, is rejected. The average product temperatures over the whole logistics period at different locations inside each of the boxes, except for the top corner box of pallet 1 (P1_T) in June 2008, are significantly different ($P < 0.001$). For box P1_T in June 2008, only top temperature is different ($P < 0.001$) from the other parts in the box (see rows "Location"). The difference in product temperatures between the inside box positions is not the same for all the steps in the three air freights ($P < 0.001$ for all the studied boxes of the air freights, see rows "Location*Step"). The average product temperature inside each box is significantly different between the steps in the three air freights ($P < 0.001$ for all the studies boxes of the air freights, see rows "Step").

The inside-box product mean temperatures (named as inside mean) over the whole logistics are significantly different between the boxes of a trip ($P < 0.001$ for all the boxes, see rows "Location" – column "Inside Mean"), meaning that the product temperature depends on the locations of boxes during the logistics. The difference in inside mean temperature between the box

TABLE 2.
STATISTICAL TEST RESULTS FOR THE EFFECT OF PRODUCT LOCATIONS INSIDE A BOX, BOX POSITIONS ON A PALLET AND LOGISTICS STEPS ON THE PRODUCT AND BOX SURFACE TEMPERATURES

Freight			P1_TM	P1_TC	P1_B	P1_M	P2_TM	P2_TC	P2_B	P2_M	Inside Mean	A
Air_Sep 2007	Location	*F*	617.3	87.4	1,222.6	13,506.3	4,067.8	1,921.9	52.4	25,021.8	4,796.7	12.5
		df	1.0	1.1	1.2	1.3	1.0	1.1	1.1	1.0	3.1	1.8
			1,476.1	1,567.7	1,690.9	1,870.2	1,422.0	1,508.1	1,538.5	1,422.0	4,408.0	2,517.8
		P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		Difference*	t, m, b	t, m, b	t, m, b	t, m, b	m, b	t, m, b	t, m, b	m, b	All 8 boxes	P2_A_T
	Location * Step	*F*	516.5	1,096.1	1,434.6	1,963.7	1,184.3	580.3	176.9	3,102.7	1,759.7	332.8
		df	11.4	12.1	13.1	14.5	11.0	11.7	11.9	11.0	34.1	19.5
		P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Step	*F*	698.1	858.8	1,290.9	3,044.4	1,178.1	879.5	221.3	2,134.4	829.0	1,275.5
		df	11	11	11	11	11	11	11	11	11	11
		P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Air_June 2008	Location	*F*		140.9	462.5	334.0		370.5	598.2	875.4	839.8	103.5
		df		1.1	1.3	1.9		1.0	1.0	1.1	2.2	2.6
				248.8	304.0	451.8		235.0	235.0	262.0	520.6	607.1
		P		<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001
		Difference*		t	b, m, t	b, m, t		m, t	m, t	b, m, t	All 6 boxes	P1_A_T, P1_A_MC
	Location * Step	*F*		148.7	79.8	108.4		236.1	317.7	181.1	283.6	159.4
		df		6.4	7.8	11.5		6.0	6.0	6.7	13.3	15.5
		P		<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001
	Step	*F*		47.1	56.3	368.2		79.4	414.6	58.6	59.8	148.2
		df		6	6	6		6	6	6	6	6
		P		<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001

TABLE 2. *CONTINUED*

Freight			P1_TM	P1_TC	P1_B	P1_M	P2_TM	P2_TC	P2_B	P2_M	Inside Mean	A
Air_July 2008	Location	*F*		3,277.4	1,417.2	3,558.4					25,286.0	1,928.0
		df		1.0	1.0	1.0					1.0	1.9
				1,676.0	1,676.0	1,676.0					1,738.3	3,179.7
		P		<0.001	<0.001	<0.001					<0.001	<0.001
		Difference*		b, m	b, m	b, m					All 3 boxes	A_B, A_M, A_T
	Location * Step	*F*		688.3	1,162.0	879.5					5,118.6	1,150.4
		df		4.0	4.0	4.0					4.1	7.6
		P		<0.001	<0.001	<0.001					<0.001	<0.001
	Step	*F*		13,997.1	5,726.1	879.5					7,494.5	2,652.8
		df		4	4	4					4	4
		P		<0.001	<0.001	<0.001					<0.001	<0.001
Sea_Sep 24 2008	Location	*F*		6,878.3	350.6	3,592.2					2,153.1	6,592.3
		df		1.5	1.0	1.3					1.2	1.5
				2,939.5	1,927.0	2,431.9					2,353.7	14,068.0
		P		<0.001	<0.001	<0.001					<0.001	<0.001
		Difference*		b, m, t	b, m	b, m, t					All 3 boxes	A_B, A_M, A_T

*Location(s) where the mean temperatures is/are significantly different.

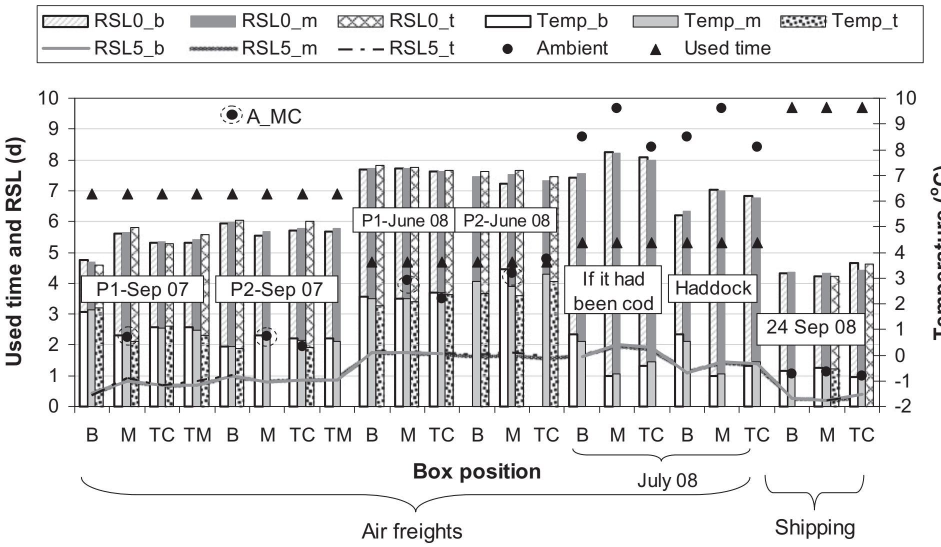


FIG. 10. TOTAL USED TIME FROM CATCH AND PREDICTED REMAINING SHELF LIFE (RSL) OF PRODUCT AT 0C (RSL0) AND 5C (RSL5)

The average ambient and product temperatures over the whole logistics from different pallets (P1, P2), box positions on a pallet (B, M, TC, and TM), and locations inside a box (b, m, and t) are also shown. A_MC means the temperature on the side of a pallet. The three lines of predicted RSL at 5C (RSL5_b, _m, and_t) are almost identical on the graph.

locations is not the same for all the steps in the three air freights ($P < 0.001$ for all the boxes of the air freights, see rows "Location*Step" – column "Inside Mean"). The average of inside mean temperatures of all the boxes in a trip is significantly different between the steps ($P < 0.001$ for all the three air freights, see rows "Step" – column "Inside Mean").

The average ambient temperatures (measured on the box surfaces) are different between the box locations on a pallet ($P < 0.001$ for all the four above freights, see rows "Location" – column "A"). For example, for the air trip in September 2007, the temperature on top of pallet 2 (P2_A_T) differs significantly from the temperatures measured on the sides of pallets 1 ($P < 0.001$, not shown in Table 2) and 2 ($P < 0.001$, not shown in Table 2). The difference in ambient temperatures between the box locations is not the same for all the steps ($P < 0.001$ for all the three air freights, see rows "Location*Step" – column "A"). The average ambient temperature from all the surface loggers of each trip is significantly different between the steps ($P < 0.001$ for all the three air freights, see rows "Step" – column "A").

Predicted RSL of the Product from Different Freights. Figure 10 gives an overview on all the three air and one sea trips regarding total used time, predicted RSL and (average) temperatures of product and box surface. Of the three air freights, the September 2007 batch had the longest logistics. The product in June 2008 had the highest average temperature, but the shortest used time (less than 5 days). The July 2008 trip has undergone the most severe abuse by outside temperature, but with relatively low average product temperature. The sea trip during September 24–October 1, 2008 took the longest time, but was the best regarding temperature control. The temperatures of both environment and product therein were the lowest (below 0C).

Although the product in the sea trip was kept at a very low and stable temperature, it has traveled for a long time, taking almost 7 days (or 10 total used days from catch). That explains why it has the shortest predicted RSL of less than 5 days. The short RSL of the sea freight verifies the fact that the quality of perishable product decreases apparently with time even under optimal conditions (Pawsey 1995).

The air September 2007 samples have the second shortest predicted RSL. It is because the trip was quite long (almost 4 days, total used time around 7 days) and the initial product temperature was high (up to 5.5C, see Fig. 9). This reveals the importance of precooling the product before packing. It has also been reported by others (James *et al.* 2006) that precooling products before transportation is essential. The air June 2008 samples have relatively long RSL due to short logistics (1.7 days).

The air July 2008 product also has long RSL because its temperature was relatively low. This once again indicates how important the precooling is. The product of this set was cooled in a CBC cooler before packing into EPS boxes.

Difference in the predicted RSL between product and box locations and between pallets of the same trips indicates that the samples have different temperature evolutions.

It should be mentioned that the end product temperature of many measurements was considerably high, 2.2–3.3C and some up to 4.6C (i.e., higher than rejection limit upon reception at most retailers which is 4C). The product was then kept in retailer and home refrigerators where it could hardly be chilled down to 0C. This is because the temperature in retail cabinets and household refrigerators is usually high (Laguerre *et al.* 2002; Kennedy *et al.* 2005), e.g., average 6.6C in home refrigerators in France (Laguerre *et al.* 2002). These may dramatically reduce the shelf life of the fish. This can clearly be seen from Fig. 10 when comparing the predicted RSL of the same product location at temperatures 0 and 5C. For example, for the product in the top corner box (TC) of pallet 2 in the June 2008 study, the RSL is more likely below 2 days at 5C, instead of around 7.5 days at 0C, because the product temperature in this box at the logistics end was considerably high (about 3C, see Fig. 4b). Another example is the product in the bottom corner box (B) in July 2008; the RSL of haddock is very likely below 1.5 days at 5C, rather than

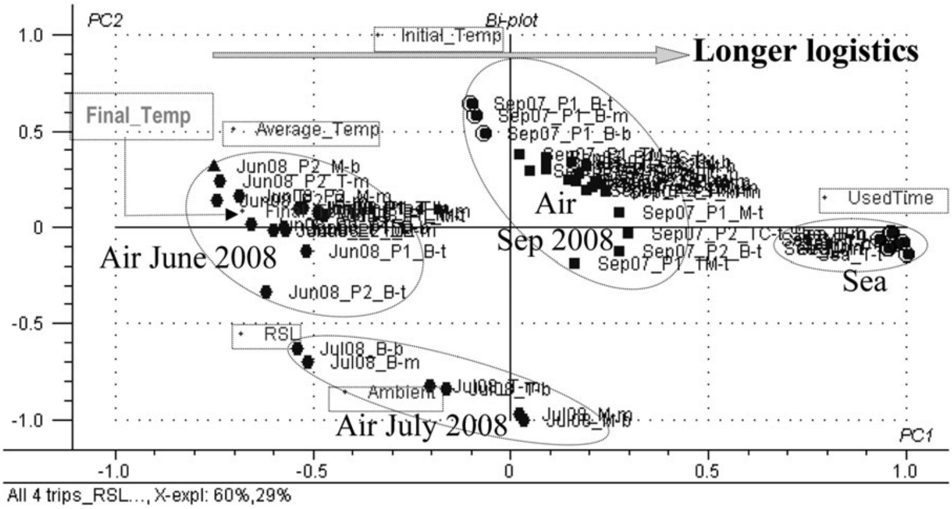


FIG. 11. PRINCIPAL COMPONENT ANALYSIS BI-PLOT BASED ON ALL THE TEMPERATURE MEASUREMENTS AND PREDICTED REMAINING SHELF LIFE (RSL) FROM THREE AIR AND ONE SEA SHIPMENTS FOR COD LOINS

Sample scores are labeled with time or transport mode of the trip_(pallet number)_box position_product location. Loadings of variables RSL; total used time (UsedTime); average ambient temperature (Ambient); initial (Initital_Temp), final (Final_Temp), and average within product location (Average_Temp) temperatures are shown in rectangular. Dotted ellipses group the samples of the same trips. The same symbol of the samples shows similarity in RSL: the circles indicate a group of samples with the RSL of 4.2–4.7 days; the squares for group with RSL of 5.2–6.0 days; the triangle with RSL of 7.2 days; and the hexagons for the RSL of 7.3–8.3 days at 0C.

above 6 days at 0C since the final temperature was very high (4.6C, see Fig. 6a).

The PCA bi-plot (Fig. 11) shows the ability to discriminate between the products of different trips based on the time–temperature history. A total of 89% of the variance is explained by the first two PC, 60% by PC1 and 29% by PC2. The right-hand side of PC1 represents the total used time of the logistics. Samples located more to the positive part of PC1 and closer to the variable “UsedTime,” e.g., the product from the sea trip in September–October 2008, have undergone longer logistics time. The lower left quarter of the plot represents the RSL, samples placed to the left of PC1 and closer to variable “RSL,” e.g., the product from the air trip in July 2008, have longer RSL.

For the air trip in September 2007, the product in the bottom corner box (Sep07_P1_B_) had high initial temperature (4.5 to 5.5C, Fig. 9), located close to the variable “Initial_Temp” on the positive direction of PC2 (Fig. 11). The product of this box has been more exposed to high ambient temperature, the samples Sep07_P1_B_t; Sep07_P1_B_m; and Sep07_P1_B_b located more toward the variables “Final_Temp” and “Average_Temp” compared with other samples in the cluster "September 2008" (Fig. 11). This statement can be verified by the product temperature of this box against others: the average temperature was 1.7 to 1.8C against 0.3 to 1.1C of other boxes in this trip (Fig. 10), and the final temperature was 2.6C in contrast to 0.2 to 1.8C in other boxes (Fig. 2b). Thus, the product of this bottom corner box has shorter RSL than of others (4.6 to 4.7 days versus 5.2 to 6.0 days, Fig. 10).

The July 2008 trip samples have undergone most ambient temperature fluctuations, located very close to the variable "Ambient." Furthermore, samples of different box positions are differed on the bi-plot relatively to this variable, meaning that they were exposed to very different ambient conditions during the whole trip (see also Fig. 6a). This interesting point has already been discussed above, considering the fact that the pallet was broken up in this passenger flight.

Overall, the predicted RSL and PCA results (Figs. 10 and 11) support the need to continuously monitor time and temperature history of product (Giannakourou *et al*. 2005). Long exposure to high temperature also facilitates the pathogens to growth (Raab *et al*. 2008) which causes food safety problems. To better manage the fish quality and safety, it is useful to apply some technique such as temperature loggers, time temperature indicator labels, radio frequency identification tags with the temperature sensor and time recorder and so forth on or inside the packaged product. Heat transfer modeling of individual and palletized EPS boxes containing fresh fish, similar to the modeling of frozen fish pallets by Moureh and Derens (2000) and Moureh *et al*. (2002), would be useful to predict product temperatures under dynamic ambient conditions as described in the current study. The models could even be used for improving packaging design in order to decrease the negative effect of ambient temperature fluctuations on product temperature.

Furthermore, trade-off between modes of transportation should be made based on: the quality and safety perspective regarding time–temperature history, customer requirement on delivery time, economic efficiency related to cost of transport, cost of more efficient packaging and weight against the resulting overall environmental impacts.

Air transportation is quick, but with several hazardous steps during ground and flight operations regarding temperature abuse. Precooling the product before packing shows to be necessary to minimize the negative effect of abusive temperature, especially during passenger flights where boxes are more exposed to the environment due to the splitting up of pallets. Freighter aircraft flights are more fuel efficient than passenger flight but are affected more by fuel prices than passenger aircraft operators since their fuel cost is a much larger part of total expenses (Morrell 2008).

Sea transportation is considered as a cheaper but slower means of transport. The product temperature is well controlled during the whole logistics inside refrigerated containers. While air transport has several strong, but short lasting, effects on the global temperature, shipping emissions have a cooling effect on climate that lasts 30–70 years due to very high emissions of SO_2 and NO_x, but with dominating warming effect in the long term because of significant amounts of CO_2 emitted (CICERO 2008).

CONCLUSION

Abusive temperature during air freighting causes fluctuation and/or rise of product temperature inside boxes, especially in those with more free sides such as at top corner of the pallets. The more temperature around the boxes fluctuates, the larger the temperature range inside the packaged product becomes. Temperature on top of product inside the EPS boxes is more sensitive to environment changes than those deeper in the box. Thus, grouping products according to their positions during transportation is useful for further management of the resource.

There are several critical steps found in air freighting, especially in passenger flight, including the flight itself, loading/unloading operations and holding storage at unchilled conditions. This reveals the importance of precooling the product before packing. Temperature during sea transportation in refrigerated containers is well maintained at low temperature. However, long shipment time causes a relatively short RSL of product in sea freight. This indicates that the trade-off between transportation modes would need to be based on several aspects such as quality and safety, available time to reach market as well as differential costing of transport (air versus ship) and the resulting environmental impact for the different options.

NOMENCLATURE

P	pallet
A	ambient (box surface)
T or TC	top corner box of a pallet
TM	top center (top middle) box of a pallet
MC	middle side box: box at the middle of a pallet side
M	middle box: box in the middle of a pallet
B	bottom corner box of a pallet
t	top of product inside a box
m	middle of product inside a box
b	bottom of product inside a box
Mean	average, e.g., temperature average

Max	maximum
Min	minimum
Max–Min	range, e.g., temperature range
RSL	remaining shelf life
PCA	principal component analysis
EPS	expanded polystyrene

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Experimental and numerical modelling comparison of thermal performance of expanded polystyrene and corrugated plastic packaging for fresh fish

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ABSTRACT

Experiments were carried out to compare the thermal performance of wholesale fresh fish boxes made of corrugated plastic (CP) and expanded polystyrene (EPS). Free standing boxes containing whole, fresh fillets were exposed to dynamic thermal loads. The chilling effect of frozen ice packs was studied by including them in some of the boxes. The frozen ice packs proved efficient for protecting fresh fish fillets against temperature abuse. Furthermore, the results show that the insulating performance of EPS is significantly better than the insulating capacity of CP. Maximum fish temperature of 16.1 °C (CP) and 11.0 °C (EPS) were recorded inside the thermally abused boxes without ice packs, initially at 1.9 to 2.1 °C and stored for 6.1 h at a mean ambient temperature of 19.4 °C. The fish temperature distributions during thermal abuse were studied with a numerical model for both packaging types, applying effective thermal properties of the sandwich-structured CP box. The purpose of the model was to cost effectively improve the packaging design. A satisfactory agreement between numerical results and experimental results was obtained.

Comparaison expérimentale et numérique de la modélisation de la performance thermique du polystyrène expansé et de la matière plastique ondulée utilisés comme emballage du poisson frais

Mots clés : Produit alimentaire réfrigéré ; Variation de température ; Isolation ; Emballage ; Modèle-transfert de chaleur

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Nomenclature

A	internal area of packaging, m^2
c_p	specific heat capacity, kJ kg^{-1} K^{-1}
CP	corrugated plastic
d	thickness of box wall, m, mm
EPS	expanded polystyrene
g	gravitational acceleration, ms^{-2}
h_{conv}	convective heat transfer coefficient, W m^{-2} K^{-1}
h	surface heat transfer coefficient ($h_{conv} + h_{rad}$), W m^{-2} K^{-1}
h_{rad}	radiative heat transfer coefficient, W m^{-2} K^{-1}
H	box height, m
k	thermal conductivity, W m^{-1} K^{-1}
L	box length, m
m	mass, kg
Ra	Rayleigh number, dimensionless
R	thermal contact resistance, m^2 K W^{-1}
S	surface area, m^2
t	warm up time, hours
T	temperature, °C, K
V	volume, m^3
w	width, m
W	box width, m
x	characteristic length, m

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume coefficient of expansion, K^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
σ	Stefan-Boltzmann's constant, ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-4})

Subscripts

amb	ambient
b	box
bot	bottom of box
f	fish fillet
in	inside
init	initial
ls	long side of box
mid-h	mid height of fillets
o	outside
ss	short side of box
top	top of box
w	wall

1. Introduction

The quality of perishable foodstuffs such as fresh fish can be seriously affected by the temperature control during storage and transportation from processing to consumers. This can be explained by the large impact that temperature and time can have on both microbial and chemical properties of the perishable products. Because of the importance of storage and transport temperature almost all countries in Europe, USA and many other countries have signed the ATP–Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (United Nations Economic Commission for Europe, 1970). Some studies (Margeirsson et al., 2008; Giannakourou et al., 2005) have revealed that temperature control in real fish cold chains is quite often far from what is described in the ATP (fish temperature should be as close to 0 °C as possible without freezing the products), thereby decreasing product quality, shortening shelf life and decreasing product value. According to Mai et al. (in press), the temperature regulation in fresh fish distribution chains is actually only a problem for air freight, but not sea freight. This is caused by the fact that more interfaces, where ambient conditions are not well controlled, are found in air logistic chains. Temperature control can in fact be improved in chilled distribution chains for other perishable products such as beef (Gill et al., 1996), poultry (Raab et al., 2008) and vegetables (Rediers et al., 2009).

The negative impact of unsatisfactory ambient temperature fluctuations during distribution of perishable products can still be dampened by thermal insulation of the packaging. Other characteristics of packaging, which can influence the quality of the products, include cost (including cost related to material disposal, i.e. if the material can be recycled), strength and space. Here, space includes both internal space for cooling mats or ice in order to maintain low product temperature and space required for storage.

The annual export of fresh fish products (whole fillets and loins) from Iceland was about 15–23 thousand tons from 2004 to 2009 (Statistics Iceland, 2010). The British market for fresh fish products is very important for Icelandic fresh fish processors, who must strive to preserve their products as well as possible through the sometimes inadequately temperature controlled transportation phase. Thus, rather well insulated expanded polystyrene (EPS) boxes have traditionally been utilized for export of Icelandic fresh fish products up to this date. EPS boxes are usually white, manufactured from moulded polystyrene beads and up to 98% of the boxes consists of air pores. The air decreases the density and increases the insulation performance but decreases strength and of course increases the required storage volume for the boxes. Another type of wholesale fresh fish packaging has been receiving increased international attention because of environmental and economic reasons, i.e. corrugated plastic (CP) boxes. These boxes are produced from extruded corrugated plastic (polypropylene) sheets which are 2.0–3.3 mm in thickness. The CP boxes can be flat packaged, which can save valuable storage space but they have poor strength and former studies have indicated that the insulation is worse than for EPS boxes (Anyadiegwu and Archer, 2002). In the United Kingdom, usage of EPS and CP boxes as wholesale fresh fish boxes has been estimated at 14 and 0.6 million boxes, respectively (Seafish Industry Authority, 2009) but the ratio between these two box types may change in the future, bearing the aforementioned environmental and economic reasons in mind.

Since the CP packaging is relatively new, more emphasis has been put on investigating thermal insulation of EPS. Froese

(1998) examined insulating properties of EPS boxes containing live fish immersed in water being chilled by low ambient temperature. Burgess (1999) calculated and compared thermal resistance (R-value) of different insulating packaging by letting regular ice inside the packaging melt when stored in a constant temperature environment. Further comparison between different packaging solutions was performed by Singh et al. (2008), also using ice-melt tests. The authors not only calculated R-values for different packaging solutions but also melting point and latent heat (thereby cooling capacity) of 12 different gel packs and PCMs (phase change materials), whose purpose is to maintain required product temperature. The authors state that the thermal resistance is a property of the whole package including the product, i.e. not just a property of the insulating material. This suggests that the most reliable way to compare thermal performance of different wholesale fresh fish packaging is to actually test the packaging while containing fish under challenging, dynamic temperature conditions. Cooling capacity of gel packs and phase change materials was studied experimentally by Labranque and Kacimi (2007) and Elliott and Halbert (2005) and Zalba et al. (2003) reviewed a number of studies on application of phase change materials in conservation and transport of temperature sensitive materials. Choi and Burgess (2007), East and Smale (2008), Laguerre et al. (2008) and East et al. (2009) have all reported on applicability and reliability of heat transfer models of different complexity for insulated containers and PCMs.

The objective of the present study was to investigate the thermal performance of two types of wholesale fresh fish boxes, one made of expanded polystyrene and the other made of corrugated plastic (polypropylene). The packages contained fresh haddock fillets, while challenged by ambient temperature conditions similar to or even more exaggerated than Mai et al. (in press) and Margeirsson et al. (2008) reported (up to 20 h at mean ambient temperature of 10–15 °C). The ability of ice packs to maintain desired temperatures during temperature abuse was also studied. Furthermore, the objective was to develop numerical models for fresh fish being thermally abused while packaged in both CP and EPS boxes without ice pack. The purpose of the model development was to cost effectively improve the packaging design with regard to thermal insulation since using numerical modelling can be cheaper than conducting a number of experiments. This implies that thermal insulation, which all the focus is on in the present study, is the main characteristic of the packaging. The models include thermal conduction in the food product, air and packaging materials and radiation outside and inside the boxes. Calculation of the effective thermal properties of the sandwich-structured CP box is one of the novelties of the paper. The numerical heat transfer models can be utilized to predict temperature evolution in fresh fillets packaged in boxes under dynamic temperature conditions.

2. Materials and methods

2.1. Wholesale fresh fish boxes, fish fillets and ice packs

Figs. 1 and 2 show whole fillets in a corrugated plastic and an expanded polystyrene box, respectively. The dimensions and thermal properties of the investigated boxes are shown in Table 1. Each fish box contained 2955 ± 12 g of chilled, fresh haddock fillets, which were distributed evenly throughout the area of the box when temperature abused. Mean thermal properties of fresh haddock fillets over the temperature range in the current study are the following: $\rho = 1054$ kg m^{-3}(Zueco et al., 2004), $c_p = 3.73$ kJ kg^{-1} K^{-1}(mean value between 4 and 32 °C, see Rao and Rizvi (1995)) and $k = 0.43$ W m^{-1} K^{-1} (applies both at 0 and 10 °C according to Zueco et al. (2004)). The ice packs from Promens Tempra (Hafnarfjordur, Iceland), which contained frozen water when put on top of the fillets in one EPS box and one CP box in the beginning of the warm up periods, weighed 252 ± 1 g and had the dimensions 310 × 175 × 13 mm.

Fig. 1 – Whole haddock fillets in a CP box. Also shown is one of the temperature loggers used for monitoring temperature in between fillets.

2.2. Measurement devices

Ibutton temperature loggers (DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) distributed by NexSens Technology (Dayton, OH, USA) were used to monitor the temperature inside the insulated boxes under testing. The Ibutton temperature loggers had a resolution of 0.0625 °C, measurement range of −40 to 85 °C and an accuracy of ±0.5 °C between −15 and 65 °C. Tidbit v2 temperature loggers from Onset Computer Corporation (Bourne, MA, USA) were used to monitor the temperature at the outside surface and of the

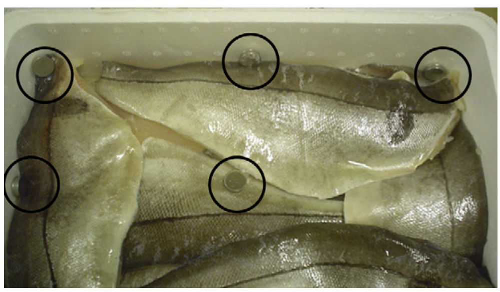

Fig. 2 – Whole haddock fillets in an EPS box. Also shown are temperature loggers used for monitoring temperature on top of fillets.

Table 1 – Dimensions and thermal properties of fish boxes.

Box type	Inner dim. $L \times W \times H$ (mm)	Outer dim. $L \times W \times H$ (mm)	m (g)	ρ (kg m^{-3})	c_p (kJ kg^{-1} K^{-1})	k (W m^{-1} K^{-1})
EPS	355.5 × 220 × 85	400 × 264.5 × 135	181	23[a]	1.28 ± 0.05[b]	0.031–0.036[c]
CP	370 × 230 × 80	395 × 247 × 85	178	116-164[d]	1.894 ± 0.002[d]	0.0184–0.0350[d]

a See Gudmundsson (2009).
b See Al-Ajlan (2006).
c See Al-Ajlan (2006); Holman (2002); BASF (2001).
d See Table 3.

ambient air. The Tidbit temperature loggers had a resolution of 0.02 °C, measuring range of −20 to 70 °C and an accuracy of ±0.2 °C between 0 and 50 °C. All temperature loggers were factory calibrated and re-calibrated by the authors in thick mixture of fresh crushed ice and water.

Relative humidity was monitored with HoBo U12 temperature and relative humidity loggers from Onset Computer Corporation (Bourne, MA, USA). The accuracy of the humidity measurements of the HoBo U12 logger is ±2.5%, the resolution is 0.03% and the operating range is 5–95%. The accuracy of the temperature measurements is ±0.4 °C, the resolution is ±0.03 °C and the operating range is −20 to 70 °C.

Air velocity was measured with Thermo-Anemometer Data logger (model 451126) from Extech Instruments (Waltham, MA, USA). The anemometer had a resolution of 0.01 ms^{-1}, measuring range of 0.3–45 ms^{-1} with an accuracy of ±(3% + 0.1) ms^{-1}.

2.3. Control of ambient environment and configuration of monitoring devices

The packaged fillets were temperature abused standing on the floor of a controllable air climate chamber (Celsius, Reykjavík, Iceland) four times for 5.2–6.1 h, then chilled with (Trials 2 and 4) or without (Trials 1 and 3) air blast for 6–9 h. The chamber's floor was made of plywood with surface roughness of approximately 0.5–1 mm. The mean air velocity in Trial 2 (measured uninterrupted with 5 s intervals for 5 min at each position) is shown in Fig. 3, which also shows the configuration of humidity and temperature loggers at box surfaces, floor and air. Surface, air and floor temperature loggers are indicated by circular units and the small box on top of EPS2 (EPS box without an ice pack) represents a relative humidity and temperature logger (all dimensions are in mm).

The product temperature was measured at twelve different positions inside each box; four at the bottom, four at mid-height and four at top of the fillets. The positions in each of the three horizontal planes are shown in Fig. 4 a and in a vertical cut in Fig. 4b. The mean product temperature was calculated as a volume weighted mean temperature according to:

$$\int_V C_p \cdot \rho \cdot T \cdot dV = C_p \cdot \rho \cdot T_{mean} \cdot V \tag{1}$$

$$\Rightarrow T_{mean} = \frac{1}{V} \int_V T \cdot dV \tag{2}$$

$$T_{mean} = \frac{1}{V} \sum_{wholedomain} T_i \cdot \Delta V_i = \sum_{wholedomain} T_i \cdot \frac{\Delta V_i}{V} \tag{3}$$

where V and ΔV_i represent the volume of the whole domain and partial volume, respectively. It has been assumed that the product temperature distribution is symmetric in each horizontal plane and symmetric images of corresponding loggers are used (black circles in Fig. 4a) in calculation of the mean product temperature (Eq. (4)). Thus, in the current case of twelve product temperature loggers, the mean temperature becomes:

$$T_{mean} = \frac{1}{16}(T_{L1} + T_{L2} + T_{L3} + T_{L4})_{bottom} + \frac{1}{8}(T_{L1} + T_{L2} + T_{L3} + T_{L4})_{mid-height} + \frac{1}{16}(T_{L1} + T_{L2} + T_{L3} + T_{L4})_{top} \tag{4}$$

where T_{L1} is the temperature recorded by data logger L1 in volume 7 in Fig. 4 etc.

The mean ambient air and floor temperatures over the whole warm up periods are given in Table 2 and the temperature evolution throughout the warm up and cooling periods is displayed in Section 3.

2.4. Numerical model for warm up of packaged products

A three dimensional finite volume heat transfer model was developed using the Computational Fluid Dynamics (CFD) software FLUENT for each package without an ice pack (CP2 and EPS2) in Trial 1. The main advantage of the numerical models compared to lumped heat capacity models is that not only the mean product temperature during thermal load can be predicted but also the temperature distribution inside the whole package.

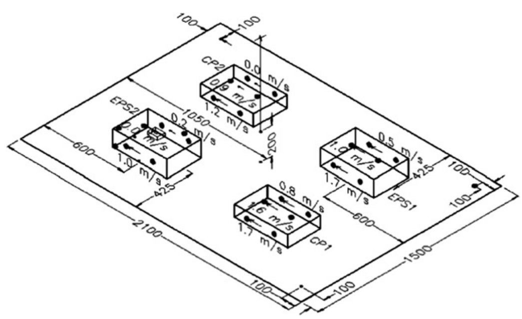

Fig. 3 – Wind speed around free standing wholesale fish boxes positioned on the air climate chamber floor during air blast chilling in Trial 2. Also shown are relative humidity logger on box EPS2, surface temperature loggers on each box and positions of three ambient temperature loggers at the floor and one 20 cm above the centre of the chamber floor. All dimensions are in mm.

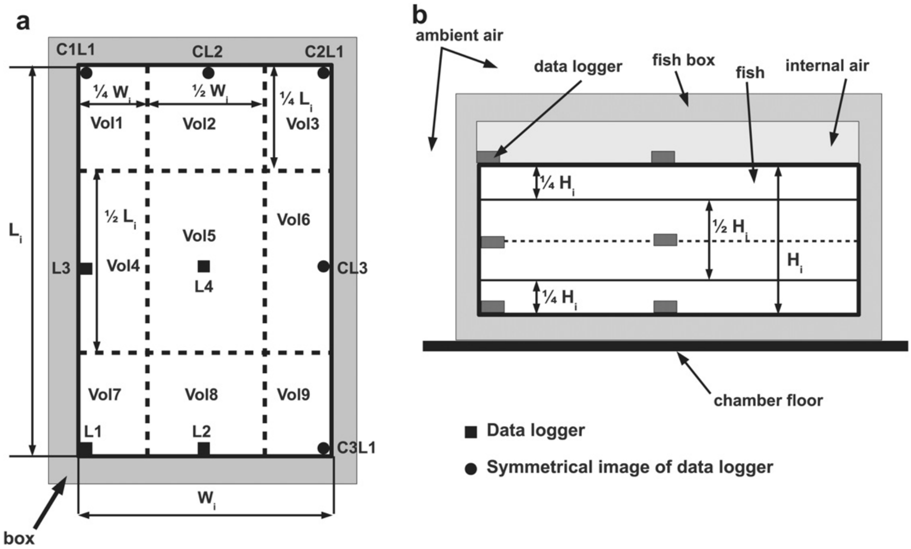

Fig. 4 – Positions of product temperature loggers inside fish boxes along with corresponding copies of the product temperature loggers: a) in horizontal plane, b) in vertical plane.

2.4.1. *Computational domain and mesh*

The computational domain was limited to a whole CP/EPS box containing fish fillets distributed evenly at the bottom of the box and air above the fillets, thereby not resolving air flow outside the box. A fully structured computational mesh was used for both box types in the simulation. The number of cells was 61864 and 54873 for CP and EPS, respectively. The geometries of the two models are presented in Fig. 5 (CP) and Fig. 6 (EPS).

2.4.2. *Modelling approach*

Inside the fish fillets heat is transferred only by conduction and is modelled using the following equation

$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} = k_f \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} + \frac{\partial^2 T_f}{\partial z^2} \right) \quad (5)$$

The air layer above the fish fillets in each box is assumed to be static, meaning that heat transfer in the air is assumed to be conductive, modelled as in Eq. (5), and radiative, modelled with the Surface-to-Surface (S2S) radiation model, see Siegel and Howell (1992). The assumption of no convection inside above the fish fillets can be explained by the fact that the fish fillets are maintained at lower temperature than the inside of the box lid. This causes higher-density air to be trapped below lower-density air in the enclosed space above the fish fillets and no convection currents to be experienced according to Holman (2002), page 336.

The initial conditions throughout the whole computational domain (fish + box + air) were defined as the mean fish temperature in each package without an ice pack in Trial 1:

$$T_{CP,init} = 1.90\,^{\circ}C \quad (6)$$

$$T_{EPS,init} = 2.08\,^{\circ}C \quad (7)$$

Mixed convection and external radiation boundary conditions were applied for both top and sides of the two boxes. The convective heat transfer coefficient outside each box (h_{conv}) can be estimated by well known correlations, see Holman (2002) for laminar natural convection in air ($Ra < 10^9$), as follows:

- Box top (horizontal plane):

$$h_{conv} = 1.32 \left(\frac{\Delta T}{x} \right)^{1/4} \quad (8)$$

Table 2 – Mean ambient air and floor temperatures during warm up periods in the four trials completed. The mean temperatures are shown with ±1 standard deviation.

Trial no.	amb. air temp.(°C)	Floor temp. (°C)	Warm up time (hours)	With/without air blast during cooling period
1	19.4 ± 0.3	19.6 ± 0.3	6.1	Without air blast
2	20.4 ± 0.3	20.6 ± 0.4	5.9	With air blast
3	21.1 ± 0.5	21.4 ± 0.4	5.2	Without air blast
4	21.3 ± 0.6	21.6 ± 0.6	5.5	With air blast

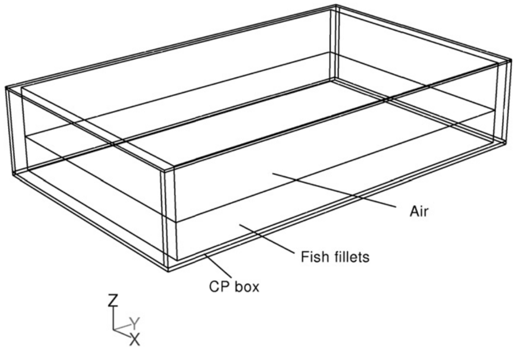

Fig. 5 – Geometry of the numerical FLUENT model consisting of a CP box, fish fillets and an air layer above the fish fillets.

- Box sides (vertical planes):

$$h_{conv} = 1.42\left(\frac{\Delta T}{x}\right)^{1/4} \quad (9)$$

where $\Delta T = T_{amb} - T_w$ (T_w: outside wall temperature) and x is the characteristic length (taken as $\frac{L_o+W_o}{2} = 0.33225$ m in Eq. (8) and as $H = 0.135$ m in Eq. (9)).

The results from the outside surface loggers shown in Fig. 3 were used for representing T_w in Eq. (5) and for the CP box resulting in $h_{top,CP} = 2.3$ W m^{-2} K^{-1} for the top plane and $h_{side,CP} = 3.5$ W m^{-2} K^{-1} for the sides. The corresponding values for the EPS box were $h_{top,EPS} = 2.1$ W m^{-2} K^{-1} and $h_{side,EPS} = 3.0$ W m^{-2} K^{-1}. The time dependent ambient temperature measured 20 cm above the chamber floor centre was adopted as the free flow (external) temperature for the convective and radiative boundary conditions at top and sides.

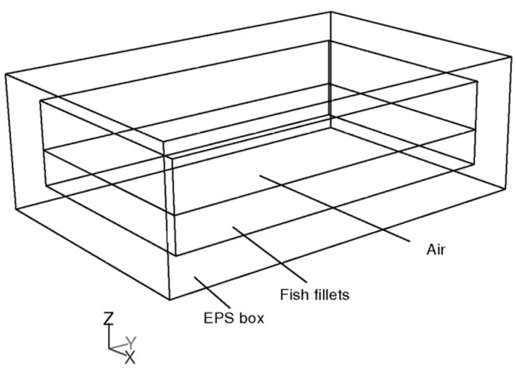

Fig. 6 – Geometry of the numerical FLUENT model consisting of an EPS box, fish fillets and an air layer above the fish fillets.

Table 3 – Calculated equivalent thermal properties of CP walls.

Wall type	d mm	ρ (kg m^{-3})	c_p (kJ kg^{-1} K^{-1})	k (W m^{-1} K^{-1})
Top	2.0	164.4	1.895	0.0350
Bottom	3.3	116.4	1.896	0.0316
Long side	5.3	134.5	1.893	0.0216
Short side	13.9	130.2	1.893	0.0184

The radiative heat transfer coefficient outside the box (h_{rad}) can be expressed according to the following relation (Moureh and Derens, 2000):

$$h_{rad} = \frac{\sigma}{\frac{1}{\epsilon_{amb}} + \frac{1}{\epsilon_{b,o}} - 1}\left(T_{b,o}^2 + T_{amb}^2\right)\left(T_{b,o} + T_{amb}\right) \quad (10)$$

The emissivity adopted for both EPS and the chamber walls was 0.9 according to The Engineering Toolbox (2010) and Holman (2002).

Non-ideal surface contact was assumed between the bottom of each box and the plywood floor, meaning that a certain thermal contact resistance between the two surfaces, $R_{b,floor}$, was estimated and the time dependent temperature measured at the chamber floor was used as the floor (external) temperature. In plate freezing applications with poor contact, the thermal contact resistance may be as high as 0.01–0.02 m^2 K W^{-1} according to Cleland and Valentas (1997), partly relying on the existence of air at the interface (Cowell and Namor, 1974). In general, lower contact pressure implies higher contact resistance (Novikov, 1970; Shojaefard and Goudarzi, 2008). Thus, the relatively high contact pressure and low roughness in plate freezers compared to the subject (fish box standing on rough plywood floor) makes a significantly higher value of $R_{b,floor} = 0.1$ m^2 K W^{-1}

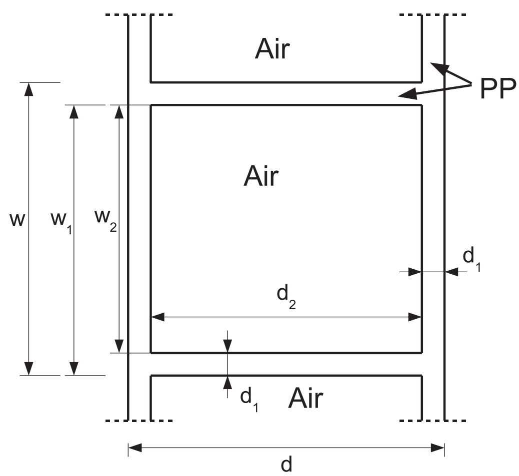

Fig. 7 – Schematic cut through a corrugated plastic (CP) box wall consisting of polypropylene (PP) and air displaying necessary dimensions for calculating equivalent thermal properties of the corrugated box walls. The equivalent thermal properties for different walls (top, bottom, short side, long side) are given in Table 3.

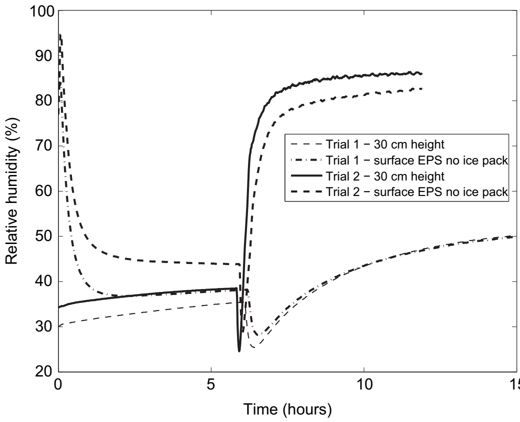

Fig. 8 – Evolution of relative humidity during two temperature abuse trials with fresh haddock fillets in wholesale fish boxes.

appropriate for the two fish boxes. BASF (2001) recommends as high as 0.2 m^2 K W^{-1} for thermal contact resistance between solid food and food package, which further strengthens the choice of a high $R_{b,floor}$. Since the water content of fresh haddock is as high as 80–82%, a lower thermal contact resistance is expected between the fish fillets and the box ($R_{f,b}$) than between the box and the floor. According to BASF (2001) it should even be taken as zero but taking the aforementioned results for freezing applications into account (Cleland and Valentas, 1997; Cowell and Namor, 1974), a value of $R_{f,b} = 0.05$ m^2 K W^{-1} was adopted.

2.4.3. *Equivalent thermal properties for multi-layered CP walls*

The model for the CP box takes into account conductive heat transfer through the CP box walls, which are multi-layered, by estimating equivalent thermal parameters for each wall (top, bottom, long side, short side). As Choi and Burgess (2007) noted, this estimation is a difficult task because of the complexity of the heat transfer process through the air spaces in such structures. The estimated wall thickness and equivalent thermal properties for the CP walls are shown in Table 3.

The equivalent thermal properties for the CP box walls were calculated according to the following equations (see Fig. 7)

$$\rho_{CP} = \frac{\rho_{PP} \cdot S_1 + \rho_{Air} \cdot S_2}{S_1 + S_2} \tag{11}$$

$$c_{p,CP} = \frac{\rho_{PP} \cdot c_{p,PP} \cdot S_1 + \rho_{air} \cdot c_{p,air} \cdot S_2}{\rho_{PP} \cdot S_1 + \rho_{air} \cdot S_2} \tag{12}$$

$$k_{CP} = \frac{d}{\frac{2d_1}{k_{PP}} + \frac{d_2}{k_{PP} \cdot \frac{d_1}{w_1} + k_{air} \cdot \frac{w_2}{w_1}}} \tag{13}$$

where the different areas are calculated according to the following equations:

$$S_2 = d_2 \cdot w_2; S = d \cdot w_1; S_1 = S - S_2 \tag{14}$$

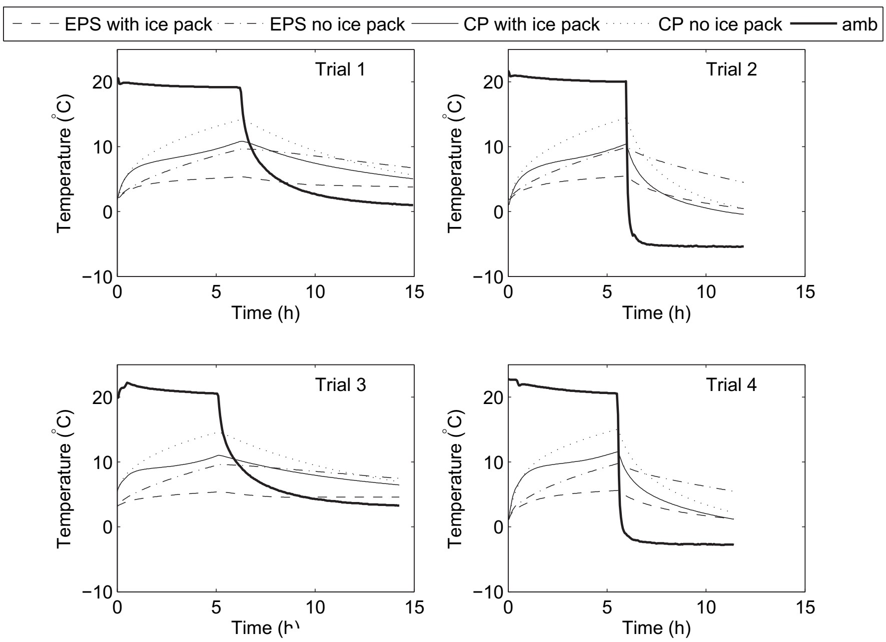

Fig. 9 – Evolution of ambient temperature (a: luct temperature during four temperature abuse trials with haddock fillets in free standing wholesale fr

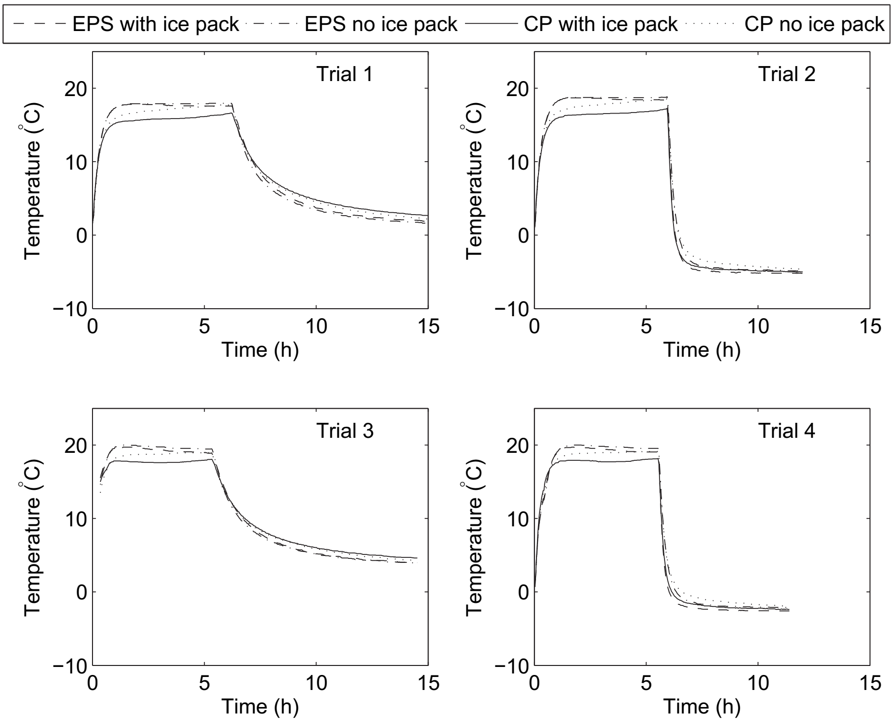

Fig. 10 – Surface temperature (mean from six positions) evolution during four temperature abuse trials with haddock fillets in free standing wholesale fresh fish boxes.

The following thermal properties for PP and air were adopted: $c_{p,PP} = 1.900$ kJ kg^{-1} K^{-1}, $\rho_{PP} = 855$ kg m^{-3}, $k_{PP} = 0.16$ W m^{-1} K^{-1}, $c_{p,air} = 1.005$ kJ kg^{-1} K^{-1}, $\rho_{air} = 1.205$ kg m^{-3}, $k_{air} = 0.0242$ W m^{-1} K^{-1}.

The thickness of the polypropylene walls (d_1) was measured as 0.15 mm and the width (w) as 3.25 mm. As noted in Table 3, the CP box walls (top, bottom, long sides and short sides) all have different thicknesses relying on the fact that the top and bottom are made of single sheets but the sides are made of multiple sheets. The lid (top) is made of a single 2.0 mm thick sheet while the bottom is made of a single 3.3 mm thick sheet. The short side consists of two 2.0 mm sheets and three 3.3 mm sheets and the long side of one 2.0 mm sheet and one 3.3 mm sheet. The results for the equivalent thermal properties of the top and bottom (presented in Table 3) were used for calculating the equivalent thermal properties for the side walls in the following way: c_p and ρ were calculated as mass-weighted averages and the equivalent thermal conductivity as:

$$k_{CP,side} = \frac{d_{CP,side}}{n_{2.0} \cdot \frac{d_{2mm}}{k_{2mm}} + n_{3.3} \cdot \frac{d_{3.3mm}}{k_{3.3mm}} + (n_{total} - 1) \cdot R_{CP,CP}} \tag{15}$$

where $n_{2.0}$, $n_{3.3}$ and n_{total} refer to the number of 2.0 mm sheets, number of 3.3 mm sheets and the total number of sheets, respectively. $R_{CP,CP}$ is the thermal contact resistance between two adjoining sheets, which was estimated as 0.08 m^2 K W^{-1},

Table 4 – Product temperature changes in Trial 1, with mean ambient temperature 19.4 °C and warm up time 6.1 h.

Packaging solution	Temp.before warm up (°C)	Temp. after warm up (°C)	Temp. increase during warm up (°C)	Mean rate. of temp. increase (°C/hour)
EPS1 = EPS with ice pack	2.2	5.4	3.2	0.51
EPS2 = EPS no ice pack	2.1	9.6	7.5	1.21
CP1 = CP with ice pack	2.1	10.8	8.7	1.41
CP2 = CP no ice pack	1.9	14.1	12.2	1.97

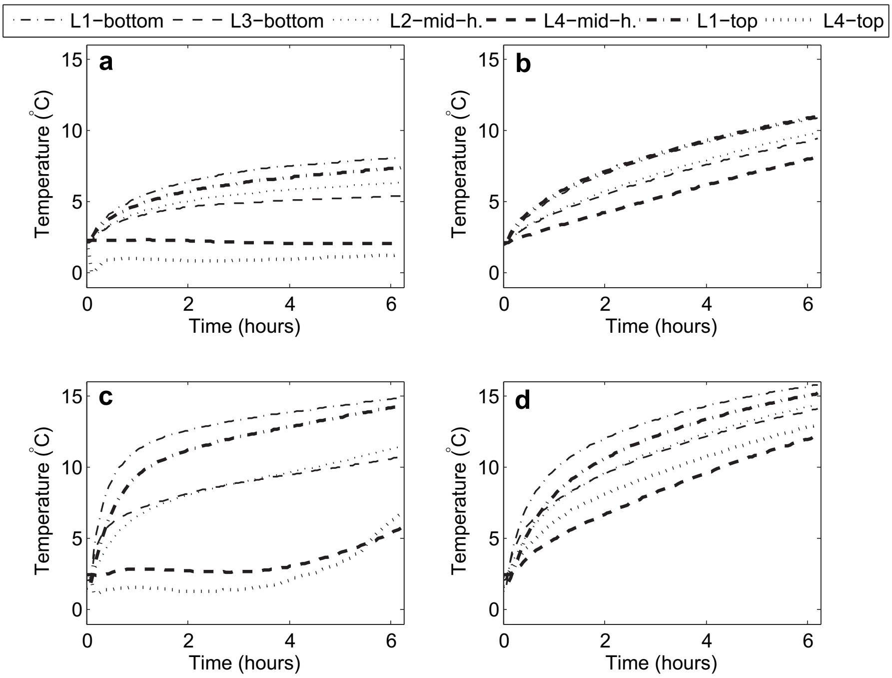

Fig. 11 – Temperature evolution at different positions inside wholesale boxes containing haddock fillets during 6.1 h temperature abuse with mean ambient temperature 19.4 °C in Trial 1: a) EPS with ice pack, b) EPS without ice pack, c) CP with ice pack, d) CP without ice pack.

i.e. slightly lower than the thermal contact resistance between the box outside bottom and the plywood chamber floor.

3. Results and discussion

3.1. *Relative humidity*

In general, relative humidity increases convective heat transfer, which is the reason why it was monitored during the trials. Relative humidity both in the ambience of the fish boxes and at the surface of the EPS box without ice pack in two of the four trials, is presented in Fig. 8. The results shown are for humidity at 30 cm height and on top of the EPS box without an ice pack–see position of the surface humidity logger in Fig. 3. The effect of the air blast and decreasing air temperature during the chilling period is evident by comparing the humidity in Trial 2 (with blast) with the humidity in Trial 1 (without blast). The relative humidity in Trials 3 and 4 are not presented here but similar tendencies were experienced in these trials as in the corresponding Trials 1 and 2, respectively.

3.2. *Influence of packaging solution*

The temperature evolution in the four trials is shown in Figs. 9 and 10. The mean product temperature is calculated from temperature in twelve different locations at three levels of each box according to Eq. (4) and Fig. 4. The ambient temperature shown in Fig. 9 was measured at 20 cm height at the chamber centre. In Trials 2 and 4, the fan of the cooling unit, which was situated around 1.8 m above the four boxes, induced a horizontal air velocity of around 9–10 ms^{-1} directly in front of the cooling unit. The forced convection caused more even temperature distribution inside the chamber (temperature at the bottom of chamber closer to the temperature of the cooling unit, i.e. lower) than in Trials 1 and 3. Thus, the faster product cooling in Trials 2 and 4 (see Fig. 9) can both be explained by lower air temperature surrounding the boxes and the air flow over the boxes (see mean velocity in Fig. 3). It could even be related to the high relative humidity shown in Fig. 8 during the chilling periods in Trials 2 and 4.

The differences between the fillet temperature fluctuations using the four packaging solutions studied were similar in all four trials (see Fig. 9). As an example, fillet temperature fluctuations in Trial 1 are analyzed and presented in Table 4. The table clearly shows that the best solution for protecting fresh fillets against severe temperature abuse is using ice packs in an EPS box and that the worst of the four solutions is using a CP box without any ice pack. In other words: the fish fillets in the CP boxes are obviously less protected against temperature abuse than the fillets in the EPS boxes and using ice packs delays the temperature increase in the fillet pile. Furthermore, EPS boxes without ice packs seem to maintain similar product

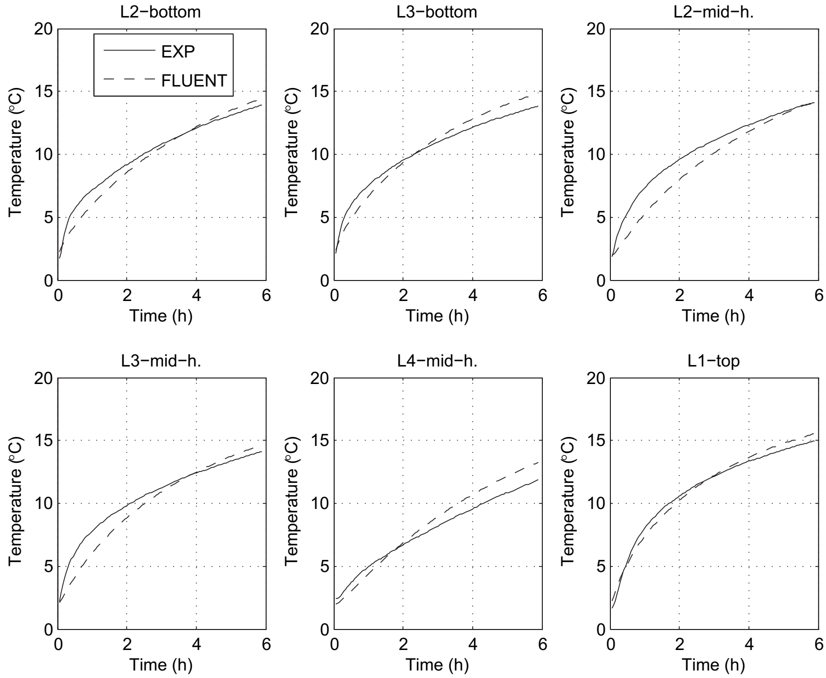

Fig. 12 – Comparison between numerical results obtained with FLUENT and experimental results for 6 selected positions (see positions in Fig. 4) inside the CP box without an ice pack during the first 6 h in Trial 1.

temperature during temperature abuse as CP boxes with ice packs.

As can be seen in Fig. 9, the ambient temperature was stable during the warm up part of each trial, still decreasing very slowly with time because of the insertion of the four cold fish boxes inside the insulated air climate chamber. As already mentioned for results in Table 4, Fig. 9 reveals that the fillet temperature increase is considerably faster in the CP boxes than in the EPS boxes, independent of usage of ice packs. The figure also shows that the fillet temperature decrease during the cooling periods is obviously faster for CP than EPS, again as a result of less insulation of the CP box. This illustrates that less insulation can actually be preferable at some stages of broken chill chains, i.e. in case of lower ambient temperature than product temperature. The influence of air blast during the cooling period in the climate chamber (see wind speed in Fig. 3) is evident by comparing the cooling of fillets in Trials 1 and 3 (no air blast) to Trials 2 and 4 (with air blast) in Fig. 9.

3.3. *Product temperature distribution*

Variable temperature distributions were measured inside the boxes during the warm up periods as is shown for Trial 1 in Fig. 11. The effect of the ice pack can be seen in Fig. 11a and c (ice packs included) showing much larger temperature differences between the centre and corners in comparison with Fig. 11b and d (ice packs excluded). The cooling effect of the ice pack is most obvious at the top centre in both the CP and EPS boxes, i.e. directly below the ice pack and even at the mid-height centre. Even though the frozen ice pack caused localized temperature decrease in the beginning of the warm up period, the minimum top centre temperature of 0.0 °C was well above the initial freezing point, which is around −1 °C for most fresh food (Pham, 1996). This shows that no freezing of the fish fillets in direct contact with the ice packs was experienced. These results therefore imply that the danger of localized freezing of fresh fish fillets as a result of using ice packs is not substantial, at least when the ice pack size is moderate (252 ± 1 g with 3 kg of fish in the present study). The relatively high heat, which needs to be extracted from the fish to the ice pack during the phase change of the water in the fish muscle (described by e.g. Heldman and Lund (1992) and Rao and Rizvi (1995)), is an important reason for this.

Unsurprisingly, the temperature at the centre of the EPS box without an ice pack (see Fig. 11b) is lowest (8.1 °C) at the end of the warm up period, compared to 10.9–11.0 °C at the corners (both at the bottom and top). The same trend is clearly seen in case of the CP box without an ice pack, see Fig. 11d. After the warm up, the minimum temperature inside the CP box without ice pack, 12.2 °C, is found at the mid-height centre compared to the maximum temperature of 16.1 °C found at the mid-height corner of the CP box (not shown in the figure) and 15.7 °C at the bottom corner. The higher temperature difference experienced inside the CP box (3.9 °C) compared to the EPS box (2.9 °C) can be explained by low thermal diffusivity of the fish fillets and poorer insulation of the CP relative to EPS.

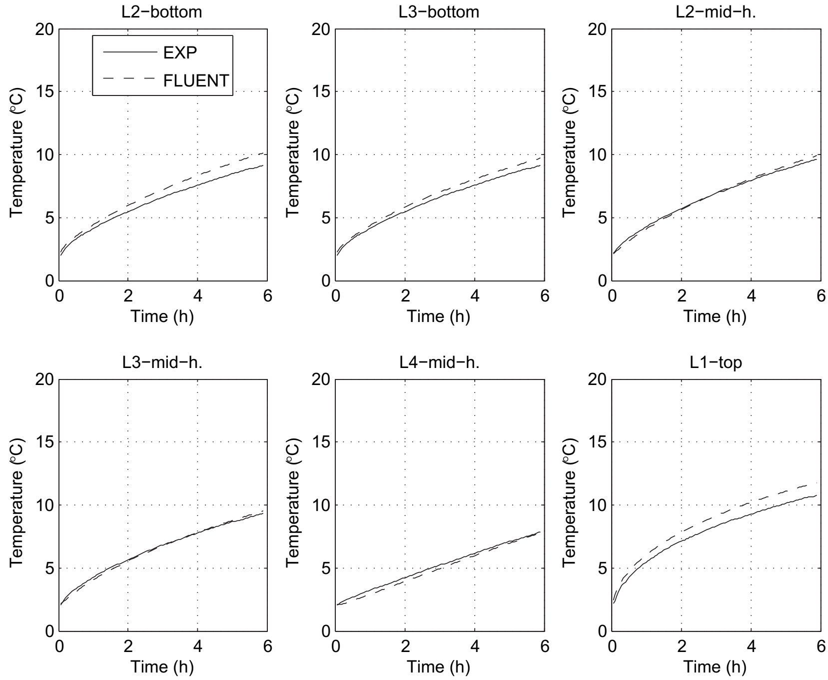

Fig. 13 – Comparison between numerical results obtained with FLUENT and experimental results for 6 positions (see positions in Fig. 4) inside the EPS box without an ice pack during the first 6 h in Trial 1.

3.4. *Numerical heat transfer model*

Results from the FLUENT simulation and the experimental results in Trial 1 for six different positions inside the CP and EPS boxes are compared in Figs. 12 and 13, respectively. As can be seen by comparing the two figures, a better agreement is obtained for the EPS box than for the CP box. The mean values of the absolute errors during the first 6 h of warm up in Trial 1 of results obtained by the FLUENT software for the six data loggers are presented in Table 5. The mean absolute errors and overall mean absolute errors in the table are calculated using the following relations:

Table 5 – Mean absolute error (°C) during the first 6 h of warm up in Trial 1 of results obtained by the FLUENT software for 6 data loggers for both packaging types without ice packs (CP and EPS).

Position	CP	EPS
L2-bottom	0.5	0.6
L3-bottom	0.6	0.4
L2-mid-height	1.0	0.1
L3-mid-height	0.7	0.1
L4-mid-height	0.8	0.2
L1-top	0.4	0.8
Overall	0.7	0.4

$$\text{Mean abs. error} = \sum_{\text{timesamples}} \frac{|T_{\text{exp}}[^\circ\text{C}] - T_{\text{numerical}}[^\circ\text{C}]|}{120} \quad (16)$$

$$\text{Overall mean abs. error} = \sum_{\text{data loggers}} \times \sum_{\text{time samples}} \frac{|T_{\text{exp}}[^\circ\text{C}] - T_{\text{numerical}}[^\circ\text{C}]|}{6 \cdot 120} \quad (17)$$

since the number of time steps was 120 (3 min intervals between measurements) and the number of positions (data loggers) was six.

From Table 5 it can be concluded that the mean absolute errors for the numerical results obtained with FLUENT are below 1 °C for most positions inside the two boxes and that the overall mean absolute error was 0.7 °C for the CP box and 0.4 °C in case of the EPS box. The largest mean absolute errors are found for positions L2 (side), 1.0 °C, and L4 (centre), 0.8 °C, at mid height for the CP box and for the L1 (corner) top position, 0.8 °C, for the EPS box. The minimum mean absolute error obtained was as low as 0.1 °C at the positions L2 and L3 at mid height in the EPS box.

Part of the errors of the heat transfer models could possibly be attributed to inaccurate placement of the data loggers. Another source of error is the simplification of adopting a steady, uniform convective heat transfer coefficient (h_{conv}) for each outside surface of the two boxes. In reality, h_{conv} is non-uniform for each side and is highest at the beginning of the warm up period when the temperature difference between the ambience and the outside surface is greatest. The effect of decreasing h_{conv} during prolonged warm up is more evident for the CP box (see the experimental results in Fig. 12) even though it can also be detected for the EPS box in Fig. 13. The figures show that the FLUENT models under-estimate the warm up in the beginning of the warm up period (h_{conv} under-estimated) and they over-estimate the product temperature increase at the end of the warm up period (h_{conv} over-estimated).

The inaccuracy following the estimation of the equivalent thermal parameters of the multi-layered walls (Choi and Burgess, 2007) of the CP box should also be mentioned as a possible contributor to the overall error. This source of error does not exist for a homogeneous material like EPS. As a conclusion, it is shown that the numerical model is capable of predicting the temperature rise at different positions inside thermally abused corrugated plastic and expanded polystyrene fish boxes with sufficient accuracy.

4. Conclusions

The following conclusions can be drawn based on the results from this study:

- Applying frozen ice packs in fish boxes reduces the impact of temperature abuse on fresh fish fillets.
- Insulating performance of expanded polystyrene is significantly better than of corrugated plastic. The difference in insulating performance between the two packaging types is exaggerated when ice packs are used.
- Insulating properties of the expanded polystyrene boxes makes this type of packaging more suitable for the case of chilled chains with insufficient control. However, since the corrugated plastic boxes are less insulating, they offer more rapid cooling of the product inside the box.
- Good agreement was obtained between numerical results and experimental results both for the heat transfer model for the EPS box and the CP box without ice pack. This implies that the models can give valuable information on the temperature distribution inside a thermally loaded free standing package. The overall absolute error of the numerical model for the EPS box (homogeneous material) was lower (0.4 °C than the corresponding error of the numerical model for the non-homogeneous CP box (0.7 °C).
- The current study indicates that numerical modelling can be valuable for redesigning thermally insulated packaging in order to minimize temperature differences inside each thermally abused package and thereby further secure even quality of products in each package. To maximize the usefulness of the numerical modelling, packaging with ice packs or other phase change materials should be considered in future work.

Another paper will cover a numerical model, which takes ice packs into consideration. Such model should be able to grasp the localized temperature decrease at the beginning and slow temperature rise during the rest of the warm up period presented in Fig. 11a and c. Further studies should also include similar comparison between wholesale fish boxes with whole pallets, i.e. many boxes palletized. In large parts of real fresh fish distribution chains, the inside boxes of a whole pallet are protected against thermal load from the ambient air by the neighbouring boxes and therefore it is important to better understand the temperature distribution inside pallets. This is, however, not always the case because frequently, pallets are broken up before being loaded onboard airplanes in order to maximize volume exploitation of the cargo hold.

Acknowledgements

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Paper III

Mathematical model for estimation of the three-dimensional unsteady temperature variation in chilled packaging units

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Abstract
A mathematical model for heat transfer from surrounding environment to a single food package is developed. A simplified analytical solution for three dimensional (3D) unsteady temperature distribution in the food package with rectangular geometry taking into account the ambient temperature is obtained. The model is developed to be used as an efficient tool for estimating the effects of temperature abuse on the food product inside a single packaging unit. The food product is considered to be a homogenous solid body. The packaging material and air inside the package are modeled using an effective heat transfer coefficient. The developed model is validated by a comparison with experimental results obtained for fresh haddock fillets in expanded polystyrene (EPS) boxes exposed to temperature abuse and by comparison with numerical results obtained by the commercial software FLUENT. A satisfactory agreement was obtained between the experimental and numerical results.

Keywords: Heat transfer, Temperature variation, Modelling, Unsteady state, Fish, Packaging

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Nomenclature:

k	thermal conductivity [W m^{-1} K^{-1}]
c	specific heat [J Kg^{-1} K^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
T	temperature [K or °C]
$\bar{T}$	mean temperature [K or °C]
t	time [s]
L	length [m]
d	thickness [m]
q	heat flux [W m^{-2}]
A	surface [m^2]
R	thermal insulance [K m^2 W^{-1}]
Q	heat transfer rate [W]
Nu_{ver}	mean Nusselt number for vertical plate ($Nu_{ver} = h_{ver}$ L/k)
Nu_{hor}	mean Nusselt number for horizontal plate ($Nu_{hor} = h_{hor}$ L/k)
Ra	mean Rayleigh number (Ra=Pr·Gr)
Pr	Prandtl number ($Pr = \nu/\chi$)
Gr	mean Grashof number ($Gr=g\cdot\beta\cdot\Delta T\cdot L^3/\nu^2$)
g	acceleration due to gravity [m s^{-2}]
E(x)	complete elliptic integral
$B_{in}^{l}(j+1)$	The third order tensors used for transformation between orthogonal bases at j+1 time step in x, y and z directions
SDL	The Surface Data Loggers
e	The basis of the natural logarithm
	Greek letters
ρ	density [kg m^{-3}]
δ	$\delta = A_{la}/A_{fa}$
μ	dynamic viscosity [Pa·s]
ν	kinematic viscosity ($\nu = \mu/\rho$) [m^2 s^{-1}]
χ	thermal diffusivity($\chi = k/\rho\cdot c$) [m^2 s^{-1}]
β	coefficient of thermal expansion (1/T) [K^{-1}]
ε	emissivity
σ	Stefan-Boltzmann's constant (5.67×10^{-8} W m^{-2} K^{-4})
τ	time constant or characteristic time [s]
	Superscript
j	The j+1 time step
	Subscript
a	air
amb	ambient
av	average
f	food product
p	packaging material
fa	interface between the food product and air layer
fp	interface between food product and packaging material
la	lateral interface between air layer and packaging material
pa	top interface between packaging material and air layer
lf	lateral interface between food and packaging material
pout	outside surface of the package
x, y, z	x, y and z directions or components
ztop, zbott	z direction on the top and bottom of the package
ver, hor	vertical and horizontal
radout, radin	outside and inside radiation
left, right	left and right side of the packaging

1. Introduction

The quality and safety of the perishable food products is seriously affected by temperature abuse, which may occur during various steps in the supply chain. The temperature variation has a big impact on the microbial growth and chemical properties of the food products and it should be included in the estimation of the main food parameters such as shelf life and risk of illness (Giannakourou et al., 2005; Zwietering et al., 1991; Olafsdottir et al., 2006; Van Impe et al., 1992).

The temperature is not necessarily equal in all packaging units and at different locations inside a packaging unit (Hoang et al., 2003). Due to this heterogeneity in temperature distribution the relevant food parameters related to the quality and safety of the food product will be different at different locations inside the same packaging unit.

In a general case the temperature distribution inside a packaging unit will be complex, non-homogenous and time dependent and will be affected by the ambient conditions, type of storage, dimensions and geometry of the packaging, cooling techniques used, the temperature history of the product and thermal properties of the packaging material and the food product (Moureh and Derens, 2000; Margeirsson et al., 2011; Londahl, G., 1983). Computational Fluid Dynamics (CFD) models have been used to analyze the air flow and temperature distribution in cooling stores without taking into account the geometry and the properties of the packaging material and temperature distribution inside the food product (Hoang et al., 2000; Nahor et al., 2005; Jing Xie et al., 2006; Pierre-Sylvain and Laurent, 2006; Mitoubkieta et al., 2006). Several investigations have attempted inclusion of environmental conditions, e.g., solar radiation (Dolan et al., 1987), geometry of the packaging, structure and properties of the packaging material and food product (Moureh and Derens, 2000; Hoang et al., 2003, Oskam, 1998) in order to characterize the temperature changes inside the product. A CFD model has been used to analyze heat transfer phenomena in the case of the forced-air cooling process within individual packages of food products (Ferrua and Singh, 2009).

Zuritz and Sastry (1986) have developed an analytical solution for one dimensional temperature distribution in food packaging without taking into account the 3D structure of the packaging. Kuitche and Daudin (1996) developed an analytical solution for transient heat transfer for the case of an infinite cylinder for modeling of the temperature and weight loss kinetics during meat chilling process. A numerical scheme based on the finite element method (FEM) has been used for modelling of thermal food-process operations (Puri and Anantheswaranb, 1993). Chen and Ramaswamy (2006) developed a simulation package for modelling thermal processes in food based on a scheme combining numerical and some simple analytical approaches. Seonggyun and Santi (1990) developed a numerical scheme based on the Douglas algorithm for simulation of the thermal processes in cylindrical plastic cans containing heated food products.

Sergio and Antonio (1993) combined a numerical 3D heat transfer and a microbial model to estimate shelf life of the product taking into account packaging size and materials' heat transfer properties. Wang and Sun (2002) have modeled the cooling process in food products using 3D transient heat conduction in heterogeneous isotropic body. The generalized methodology for mathematical modeling of heat transfer and testing has been presented by Tanner et al. (2002).

The objective of this work is to obtain and validate a mathematical model and analytical solution for non-stationary 3D temperature distribution inside a solid homogeneous food product, for a single food package with rectangular geometry. The purpose of the model is to develop a valuable tool for rapid and effective temperature distribution estimation inside the food product which can be used in the risk assessment (RA) and shelf life (SL) prediction in real supply chains for improvement of the safety and quality of food products (Janevska et al., 2010). As fresh fish is perishable food product whose quality and safety could be affected by the temperature variation during transport and storage (Giannakourou, at al. 2005; Margeirsson et al. 2011) experimental results obtained using fresh haddock fillets were used for development and validation of the model. Haddock fillets came as a natural choice for this study, as the main support for this study was provided through the CHILL-ON FP6 European Commission project, in which Icelandic haddock was selected as one of the products to analyze. The model results are compared to the experimental results for fresh haddock fillets packaged into EPS boxes and exposed to a variable temperature profile, and to the numerical results obtained using the commercial software FLUENT (Margeirsson et al., 2011). The ambient air temperature used in the experiment represents a good approximation of the actual air temperature abuse in a real fresh fish supply chain (Mai et al., 2011).

2. Material and methods

2.1 Experimental design

Fresh haddock fillets weighing 2944 ± 5 g were packaged evenly throughout the area of an expanded polystyrene (EPS) box and twelve temperature loggers were inserted (see Fig. 1). The package was subjected to temperature abuse in a controllable air climate chamber (Celsius, Reykjavík, Iceland). The product temperature was 2.0 to 2.2 °C at the start of the thermal load, which lasted for 6 hours. During the thermal load the ambient air temperature decreased from 20.5 °C at the beginning to 19.2 °C, at the end of the temperature abuse. The mean ambient temperature measured at 20 cm height in the chamber was 19.4 °C. The thermal properties of the haddock fillets, EPS material and air (Zueco et al., 2004; Rao and Rizvi, 1995; Gudmundsson, 2009; Moureh and Derens, 2000) are given in Table 1.

Table 1. Thermal parameters of the fish, EPS and air used in the mathematical model

	fish	EPS	air
k [W m^{-2} K^{-1}]	0.43	0.0345	0.0242
ρ [kg m^{-3}]	1054	23	1.225
c [J kg^{-1} K^{-1}]	3.73×10^{3}	1.280×10^{3}	1.006×10^{3}
ε	ε_{fa}= 0.9	ε_{pout}=ε_{pa}= 0.9	-
ν [m^{2} s^{-1}]	-	-	1.4833×10^{-5}

Table 2. Dimensions of the EPS package and food product (fresh haddock fillets) used in the experiment

Geometrical feature	Dimension [m]
L_x	0.22
L_y	0.3555
L_z	0.03571
d_a	0.0486
d_{ztop}	0.025
d_{zbott}	0.025
d_x	0.02225
d_y	0.02225

Table 2 provides the dimensions of the EPS boxes used in the experiment, see Fig. 2, and the food product inside the box. Ibutton temperature loggers (DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) distributed by NexSens Technology (Dayton, OH, USA) were used to monitor the temperature inside the insulated boxes under testing. Ibutton temperature loggers had a resolution of 0.0625 °C, measurement range of -40 to 85 °C and an accuracy of ±0.5 °C between -15 and 65 °C.

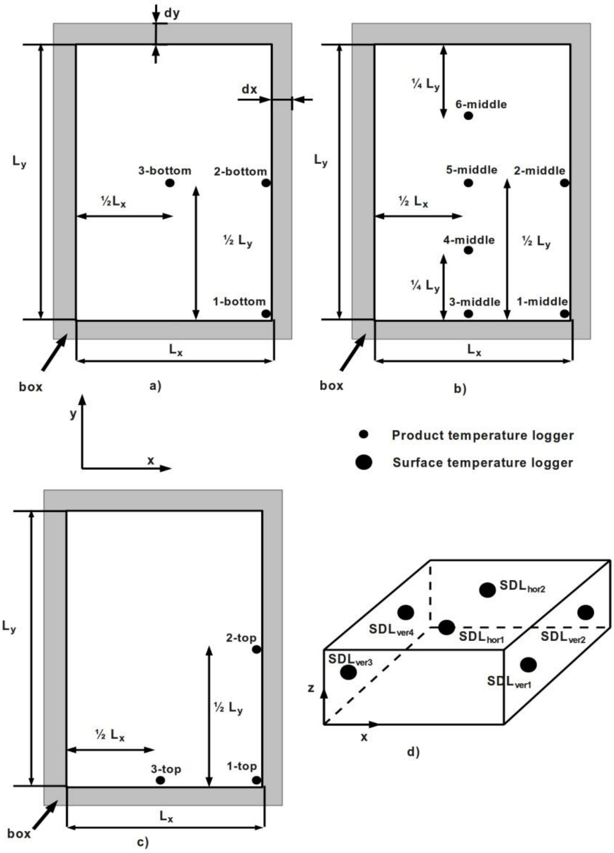

Figure 1. Position of the data loggers at three different levels inside the EPS box (a-bottom, b-middle and c-top) and the position of the surface data loggers (SDL) on the outside surface of the EPS box (c)

Tidbit v2 temperature loggers from Onset Computer Corporation (Bourne, MA, USA) were used to monitor the temperature at the outside surface and of the ambient air. The Tidbit temperature loggers had a resolution of 0.02 °C, measuring range of -20 to 70 °C and an accuracy of ±0.2 °C between 0 and 50 °C. All temperature loggers were factory calibrated and re-calibrated by the authors in a thick mixture of fresh crushed ice and water. The product temperature was measured at twelve different positions inside each box; three at the bottom, six at mid-height and three at top of the fillets. The positions in each of the three horizontal planes (bottom, mid-height and top) are shown in Figs. 1a, b, and c, respectively. The position of the surface loggers is shown in Fig. 1d.

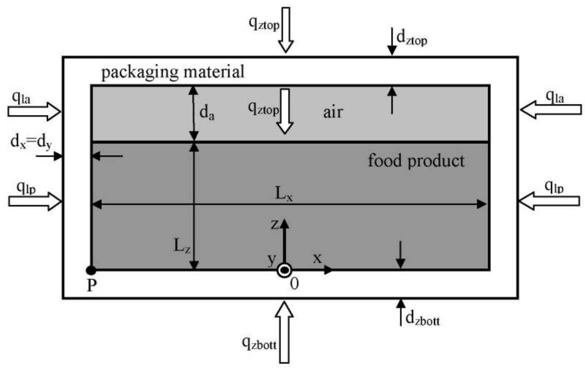

Figure 2. Geometry, dimensions and orientation of coordinate system for the food packaging with the heat flux from surrounding environment shown in x-z plane

2.2 Mathematical model for heat transfer inside the food package

A heat transfer model for a single box containing the food product was developed. The analytical solution for a non-stationary 3D temperature distribution inside the food product contained in the packaging of rectangular geometry was obtained. The food product was considered to be a homogenous solid body and only heat conduction inside the food product was analyzed. The dimensions and physical properties of the packaging material and food product are taken into account. The heat transfer through the air inside the packaging unit was modeled by conduction and internal radiative heat transfer. As the food product was maintained at a lower temperature then the outside air temperature above the box lid this will cause the colder and higher-density air layer near the product surface to become trapped below the warmer and lower-density air (Holman, 2002). According to this convective heat transfer due to air flow inside the box could be neglected. The environmental conditions outside the package are included in the model through the heat exchange between the package and the surrounding air due to free convection and external radiation. The model was extended to include the ambient temperature variation in the form of step functions. This extended model is valid under the condition that changes of the ambient temperature are sufficiently slow to be considered as constant during each time interval and that free convection outside the box is achieved almost instantaneously at the beginning of each time interval.

The packaging walls and internal air layer were modeled using effective heat transfer coefficients. The developed model could be used for different rectangular geometries and for symmetrical and non-symmetrical temperature distributions.

For the food product (considered a solid body), the heat transfer is predominantly due to conduction and was modeled using the heat conduction equation:

$$k_f \cdot \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} + \frac{\partial^2 T_f}{\partial z^2} \right) = \rho_f \cdot c_f \frac{\partial T_f}{\partial t}. \tag{1}$$

The considered package with the food product inside is rectangular in shape and the geometry, dimensions and orientation of the coordinate system are shown in Fig. 2. The coordinate origin is placed at the center of the packaging at the lower side, see Fig. 2. It was assumed that there was an air layer at the top of the food product inside the package.

The main assumption used for the boundary conditions in Eq. (2) was that there is no energy absorption in the walls of the packaging and in the air layer inside the box. This means that the energy from the ambient is continuously transferred through the packaging walls and the air layer inside the box to the food product. Under this assumption the temperature profile inside the walls and the air layer could be considered as linear. This assumption allows the use of the effective heat transfer approach for the packaging walls and air layer inside the box which simplified the boundary conditions.

The above simplification is valid if the materials used in the packaging have much lower thermal capacity compared to the thermal capacity of the food product, which is satisfied when the thicknesses of the packaging walls are much smaller than the dimensions of the food product and/or if the density and the specific heat of the packaging material are much smaller than those of the food stuff. These conditions are satisfied for the majority of the food packaging materials and food products nowadays. The density and specific heat of the packaging material, air and food product used in this study are presented in the Table 1. The dimensions of the food product and thickness of packaging wall and air layer used in this study are presented in the Table 2.

It was assumed that the initial product temperature had uniform distribution and that the ambient temperature was constant. Under these assumptions the initial and boundary conditions on the interface between food product and packaging material and air layer are given by the following equations:

$$
\begin{aligned}
&T_f = T_0 \text{ at } t = 0; \\
&-k_f \frac{\partial T_f}{\partial x}\Big|_{x=L_x/2} = h_x\left(T_f - T_{amb}\right)\Big|_{x=L_x/2}; \quad -k_f \frac{\partial T_f}{\partial y}\Big|_{y=L_y/2} = h_y\left(T_f - T_{amb}\right)\Big|_{y=L_y/2} \qquad (2)\\
&k_f \frac{\partial T_f}{\partial z}\Big|_{z=0} = h_{zbott}\left(T_f - T_{amb}\right)\Big|_{z=0}; \quad -k_f \frac{\partial T_f}{\partial z}\Big|_{z=L_z} = h_{ztop}\left(T_f - T_{amb}\right)\Big|_{z=L_z}.
\end{aligned}
$$

If the food package is symmetric in x and y direction the temperature distribution will be symmetric in these directions and only one quarter of the package needs to be considered.
Under this assumption the boundary conditions in the middle of the package for the symmetric temperature distribution are expressed by the following equations:

$$
\frac{\partial T_f}{\partial x}\Big|_{x=0} = 0; \quad \frac{\partial T_f}{\partial y}\Big|_{y=0} = 0. \qquad (3)
$$

The temperature distribution in the z direction was not symmetric due to non-symmetric material distribution in this direction.

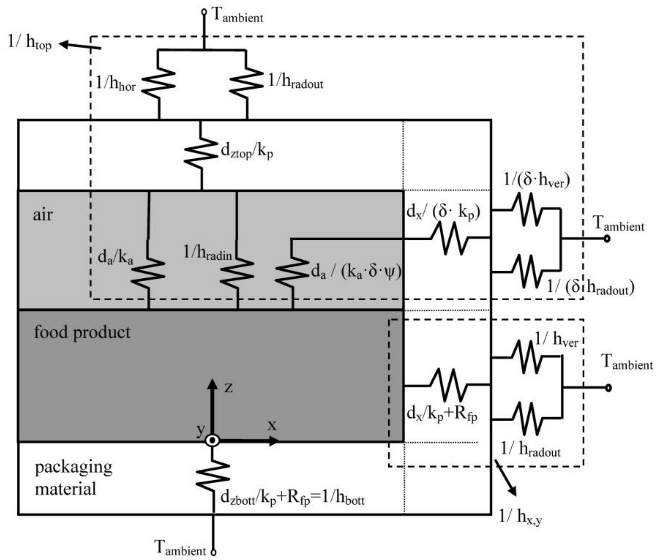

Figure 3a. Equivalent heat transfer diagram for heat transfer coefficients h_x, h_y, h_{zbott}, h_{ztop}

An electrical analogy was used in the heat transfer model and corresponding heat transfer diagram for heat transfer coefficients h_x, h_y, h_{zbott}, h_{ztop} is shown in Fig. 3a. The heat transfer coefficients in x and y direction (h_x and h_y, respectively) and in z direction at the bottom of the box (h_{zbott}) can be expressed using electrical analogy of electrical resistance and resistance to heat transfer and equivalent diagram in Fig. 3a:

$$h_x = \frac{1}{\frac{d_x}{k_p} + R_{fp} + \frac{1}{h_{ver} + h_{radout}}}; \quad h_y = \frac{1}{\frac{d_y}{k_p} + R_{fp} + \frac{1}{h_{ver} + h_{radout}}}; \quad h_{bott} = \frac{1}{\frac{d_{zbott}}{k_p} + R_{fp}}. \qquad (4)$$

The value for the thermal resistance between the solid food product and packaging material R_{fp} has been found from the open literature to be in the region of 0.05 to 0.2 m^2 K W^{-1} and in this study R_{fp}=0.1 m^2 K W^{-1} was adopted (Cleland and Valentas, 1997; Cowell and Namor,1974; BASF, 2001). The heat transfer coefficient for outside radiation could be expressed using the following relation (Moureh and Derens, 2000):

$$h_{radout} = \frac{\sigma}{\frac{1}{\varepsilon_{amb}} + \frac{1}{\varepsilon_{pout}} - 1} \left(\overline{T}_{amb}^2 + \overline{T}_{pout}^2\right) \cdot \left(\overline{T}_{amb}^2 - \overline{T}_{pout}^2\right) \qquad (5)$$

Where $\overline{T}_{pout}$ is average temperature of the outside surface and it is explained in section 3.1. For the heat transfer coefficient at the bottom of the box it is assumed that thermal contact between the bottom of the package and floor is ideal. The heat transfer from the surrounding air to the box is modeled by free convection. The temperature of the floor was assumed to be equal to the ambient temperature.

The heat transfer coefficient for laminar free convection for the vertical outer surface of the packaging h_{ver} could be obtained using the mean Nusselt number for vertical plate (Churchill et al., 1975; Churchill 1983) by the following equation:

$$Nu_{ver} = 0.670 \cdot Ra_{ver}^{1/4} \cdot \left(1 + \left(\frac{0.492}{\Pr}\right)^{9/16}\right)^{-4/9} + 0.68. \quad (6)$$

The Rayleigh number for the outside vertical surface of the package could be expressed by the following equation:

$$Ra_{ver}^{1/4} = P_r \cdot Gr_{ver}; \quad Gr_{ver} = \frac{g \cdot \beta \cdot \left(\overline{T}_{amb} - \overline{T}_{poutver}\right) \cdot L_{ver}^3}{\nu^2};$$
$$L_{ver} = L_z + d_{air} + d_{ztop} + d_{zbott}; \quad \beta = 1/\overline{T}_{amb}. \quad (7)$$

The coefficient of thermal expansion in the above relation is valid if the air is considered as ideal gas.

The heat transfer from the environment to the top of the food product could be expressed as a sum of the heat transfer rate on the top of the packaging (Q_{ztop}) and the heat transfer rate through air layer from lateral sides of the packaging (Q_{la}), as shown in Fig. 3b. The heat transfer coefficient on the top of the food product was approximated taking into account contribution of this lateral heat fluxes to the total flux for the packaging.
It has been assumed that thermal resistances which correspond to the Q_{ztop} and Q_{la} are parallel as showed in Fig. 3b.

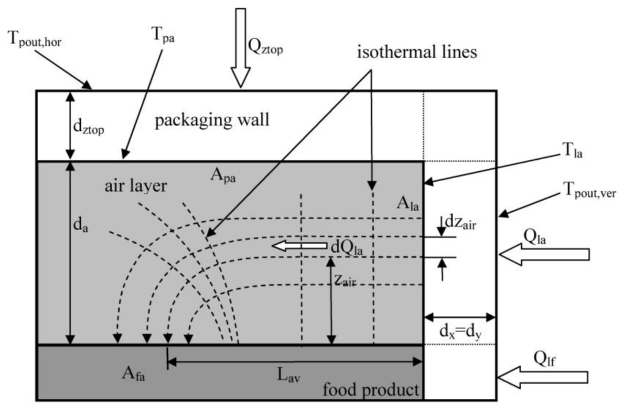

Figure 3b. Details of the geometry at the corner of the package with heat transfer from surrounding environment to food product, isothermal lines in the air layer and positions of the surface temperatures

As is presented in Fig. 3a, the lateral heat flux is transferred along curved lines which are normal to the isothermal lines which were assumed to have an elliptical shape. The average semi major axis (horizontal axes) along all of these curves (ellipses) in Fig. 3b is denoted with L_{av} and it was approximated as $L_{av}=(L_x+L_y)/4$ representing the mean value of the half-length and half-width of the food volume. The minor semi axis (vertical axis) of these elliptical curves denoted by z_{air} varies in the range from 0 to d_a. The effective length of the air layers or the paths along which the lateral heat flux is transferred could be approximated as one quarter of circumference of an ellipse denoted as L_{la}. To simplify further the analysis the semi major axes (horizontal axes) of these ellipses was fixed and approximated with the average value for the semi major axes L_{av}. The infinitesimal lateral heat transfer rate dQ_{la} through curved air layer with thickness dz_{air} (Fig. 3b) is assumed to be constant along this layer (there is no energy absorption inside the air layer). It is further assumed that dQ_{la} is proportional to the difference between the temperatures at the ends of this curve. The overall heat transfer rate could be obtained by the integration of dQ_{la} along z direction from the top of the food product ($z_{air} = 0$) to the top of air layer ($z_{air} = d_a$). Under this assumption dQ_{la}, Q_{la} and overall lateral heat flux q_{la} through the lateral surface A_{la} could be expressed by the following equations:

$$dQ_{la} \approx \frac{k_a}{L_{la}} \cdot \left(\overline{T}_{la} - \overline{T}_{fa}\right) \cdot dA_{la} = \frac{k_a \cdot \left(\overline{T}_{la} - \overline{T}_{fa}\right) \cdot 2 \cdot \left(L_x + L_y\right)}{L_{av} \cdot E\left(\sqrt{1 - \left(z_{air} / L_{av}\right)^2}\right)} \cdot dz_{air}$$

$$\Rightarrow Q_{la} = \int_0^{d_a} dQ_{la} = k_{air} \cdot \left(\overline{T}_{la} - \overline{T}_{fa}\right) \cdot 2 \cdot \left(L_x + L_y\right) \cdot \psi \qquad (8)$$

$$\Rightarrow \frac{Q_{la}}{A_{la}} = q_{la} \approx \frac{k_a}{d_a} \cdot \psi \cdot \left(\overline{T}_{la} - \overline{T}_{fa}\right) = q_{ztop} \cdot \psi; \qquad L_{la} = L_{av} \cdot E\left(\sqrt{1 - \left(z_{air} / L_{av}\right)^2}\right).$$

From the above equation follows that the ratio between lateral and top heat flux is equal to correction factor ψ. The correction factor ψ for the lateral heat flux and area A_{la} in the above relations are given by the following equations:

$$\psi = \int_0^{d_a} \frac{dz_{air}}{L_{av} \cdot E\left(\sqrt{1 - \left(z_{air} / L_{av}\right)^2}\right)}; \quad A_{la} = 2 \cdot (L_x + L_y) \cdot d_a. \qquad (9)$$

The complete Elliptic integral E(x) is used in Eq. (8) and (9) to express the circumference of the ellipse and to calculate the correction factor ψ (Richard and George 1977). In a general case the air layer in the above consideration of the lateral flux could be approximated by some other curve than an ellipse. In this case the effective length - L_{la} could be expressed as a function of the z_{air}. The correction factor ψ for the lateral heat flux in this general case could be calculated by the following equation:

$$\psi = \int_0^{d_a} \frac{dz_{air}}{L_{la}\left(z_{air}\right)}. \qquad (10)$$

As mentioned previously, in the above considerations it has been assumed that there are no thermal losses in the packaging walls and inside the air layer.

From the experimental data follows that the average temperature at the vertical outside surface ($\overline{T}_{poutvert}$=16.75 ºC) and the average temperature at the horizontal outside surfaces ($\overline{T}_{pouthor}$=17.13 ºC) of the package are similar. In this study we assumed that these temperatures are the same and equal to the arithmetic mean of $\overline{T}_{poutvert}$ and $\overline{T}_{pouthor}$. The same assumption was used for the temperatures on lateral and top interface between air layer and packaging material, T_{la} and T_{pa} respectively. The position of the above surface temperatures on the package are presented in Fig. 3a.

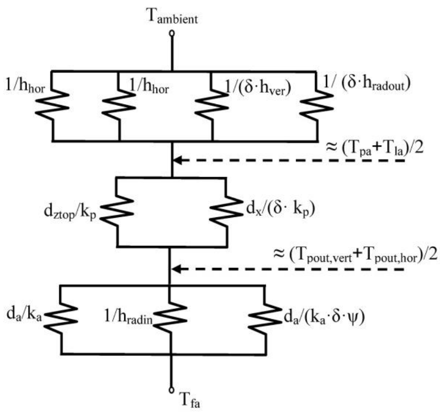

Figure 4. The equivalent heat transfer diagram for the heat transfer coefficient in the z direction at the top of the food package

By using the above assumptions and results obtained in Eq. (8) the equivalent heat transfer diagram for heat transfer coefficient i the z direction at the top of the food package (h_{top}) is obtained and presented in Fig. 4. From this heat transfer diagram the following relation for h_{ztop} is obtained:

$$h_{ztop} = \frac{1}{\dfrac{1}{h_{amb}} + \dfrac{1}{h_p} + \dfrac{1}{h_a}}; \quad h_{amb} = h_{hor} + \delta \cdot h_{ver} + h_{radout}(1+\delta);$$
$$h_p = k_p\left(\frac{1}{d_{ztop}} + \frac{\delta}{d_x}\right); \quad h_a = \frac{k_a}{d_a}(1+\delta \cdot \psi) + h_{radin}; \; d_x = d_y. \tag{11}$$

The heat transfer coefficient for radiation inside the package h_{radin} could be expressed using the following equation (Moureh and Derens, 2000):

$$h_{radin} = \frac{\sigma}{\dfrac{1}{\varepsilon_{fa}} + \dfrac{1}{\varepsilon_{pa}} - 1}\left(\overline{T}_{pa}^2 + \overline{T}_{fa}^2\right) \cdot \left(\overline{T}_{pa}^2 - \overline{T}_{fa}^2\right). \tag{12}$$

The heat transfer coefficient for laminar free convection on the horizontal outside surface of the packaging h_{hor} could be expressed using a mean Nusselt number for a horizontal plate (Goldstein et al., 1972; Rotem and Claassen, 1969; Churchill, 1982; Churchill, 1983) by the following equation:

$$Nu_{hor} = \frac{0.766 \cdot Ra_{hor}^{1/5}}{\left(1 + (0.322/\mathrm{Pr})^{11/20}\right)^{4/11}}. \tag{13}$$

The Rayleigh and Grashof numbers for the horizontal outside surface of the package could be expressed in the same way as in Eq. (7).

The characteristic length for the top surface of the packaging (L_{hor}) could be estimated using the following relation (Goldstein et al., 1972; Churchill, 1982): $L_{hor}=(L_x \times L_y)/(L_x^2 + L_y^2)^{1/2}$.

Eqs. 6 and 13 are valid only for steady-state laminar free convection and can not be used for arbitrary time dependent temperature abuse (Churchill et al., 1975; Goldstein et al., 1972; Rotem and Claassen, 1969; Churchill 1982;). If the temperature variation resembles the step function in respect to time, (6) and (13) for the heat transfer coefficients could be used for each time period where the temperature is constant and the steady-state laminar free convection is developed.

The outside air flow could be included in the developed model through the heat exchange between packaging and outside air when forced convection exists. If the surface A_{la} is much smaller than the surface on the top of the food packaging $A_{fa}=L_x \times L_y$ the ratio $\delta=A_{la}/A_{fa}$ is much less than one (i.e. the thickness of the air layer is much less then dimensions of the packaging in x and y directions) and the lateral fluxes could be neglected ($\delta \sim 0$ in (11)).

2.3 Analytical solution for 3D non stationary temperature distribution inside the food package

The analytical solution for (1) under initial and boundary conditions given in (2) and (3) are evaluated in the appendix A (A1-A8) and could be expressed in the following form:

$$T_f = T_{amb} + \left(T_0 - T_{amb}\right) \sum_{n,m,k=1}^{M} a_{xn} a_{ym} a_{zk} \cos\left(\lambda_{xn} x\right) \cos\left(\lambda_{ym} y\right) \left(\sin\left(\lambda_{zk} z\right) + \frac{k_f \lambda_{zk}}{h_{zbott}} \cos\left(\lambda_{zk} z\right) \right) \exp\left(-t/\tau_{nmk}\right). \quad (14)$$

Only the first M terms in the above equation are used instead of the infinite series in (A6).

In the general case if the geometry of the packaging is not symmetric in x and y directions the heat transfer coefficients in x and y directions from left and right side $h_{xleft,yleft}$ and $h_{xright,yright}$ respectively are not the same and the boundary conditions in (3) are not valid any more. In this case the functions f_{xn} , f_{ym} , f_{zk} from general solution in (A6) are given by the following expressions:

$$f_{xn}(x) = \sin\left(\lambda_{xn} \cdot x\right) + \frac{k_f \cdot \lambda_{xn}}{h_{xleft}} \cos\left(\lambda_{xn} \cdot x\right); \quad f_{ym}(y) = \sin\left(\lambda_{ym} \cdot y\right) + \frac{k_f \cdot \lambda_{ym}}{h_{yleft}} \cos\left(\lambda_{ym} \cdot y\right)$$
$$f_{zk}(z) = \sin\left(\lambda_{zk} \cdot z\right) + \frac{k_f \cdot \lambda_{zk}}{h_{zbott}} \cos\left(\lambda_{zk} \cdot z\right). \quad (15)$$

Where the dimensions of the food packaging are the same and the coordinate origin is in the point P, as showed in Fig. 2. The constants λ_{zk} and a_{zk} are the same as ones used in (A6). The constants λ_{xn} and λ_{ym} are roots of the analogues transcendental equations given as the second equation in (A3) where h_{ztop} and h_{zbott} must be replaced with h_{xright} and h_{xleft} for constants λ_{xn} and with h_{yright} and h_{yleft} for constants λ_{yn}. The constants a_{nx} and a_{ym} are given by the similar relation as second equation in (A7) where same replacement must be done and normalization constants C_{xn} and C_{ym} are given by similar expression as in (A8).

If the ambient temperature is given in the form of a step function the distribution of the temperature field inside the product could be obtained using the recurrent relations given in (B1) and (B2) from appendix B.

3. Results and discussion

3.1. Validation of the developed mathematical model

To validate the developed mathematical model, the experimental results for fresh haddock fillets packaged in an EPS box exposed to temperature abuse for six hours are used for comparison with the model prediction. The developed model is also validated through comparison with numerical results obtained with the commercial software FLUENT. In the numerical model used in FLUENT the geometry of the packaging material and air layer was included taking into account the heat losses in the package and in the air layer.

In Tables 1 and 2 the thermal parameters and the dimensions of the food product, air and EPS boxes are presented. The ratio δ in this case is 1.378 which means that the lateral fluxes in (10) cannot be neglected. In Table 3 the numerical values for the heat transfer coefficients h_x, h_y, h_{ztop}, $h_{zbotton}$ used in this study are presented respectively.

Table 3. The numerical values for the heat transfer coefficients

Heat transfer coefficient	Num. value [W/ $m^2 \cdot K$]
h_x	1.125
h_y	1.125
h_{ztop}	1.536
$h_{zbottom}$	1.212

The mean initial temperature of the fresh haddock fillets was T_0 = 2.1 °C. The average temperature on the interface between food product and air layer $\overline{T}_{fa}$ = 7.02 °C in (5) is calculated as average value from data loggers 1-3-top, which are shown in Fig. 1c. The average temperature of the outside surface of the package $\overline{T}_{pout} = \dfrac{\overline{T}_{poutvert} + \overline{T}_{pouthor}}{2}$ =16.94 °C in (10) is estimated as arithmetic mean of the average temperatures on the vertical and horizontal outward surfaces of the package, $\overline{T}_{poutvert}$ and $\overline{T}_{pouthor}$ respectively. The $\overline{T}_{pouthor}$ and $\overline{T}_{poutvert}$ are calculated as average values from the surface data loggers $SDL_{hor1,2}$ and $SDL_{ver1\text{-}4}$ respectively. The position of the surface data loggers is shown in Fig. 1d. The average temperature on the interface between the EPS material and air layer inside the packaging $\overline{T}_{pa}$ in (5) is estimated using the fact that if the thermal losses inside the packaging material are neglected, the thermal flux from ambient to the top of the package is the same as the thermal flux through the top wall of the package. From this condition the following equation for $\overline{T}_{pa}$ is obtained:

$$\begin{aligned} &\frac{k_p}{d_{ztop}} \cdot \left(\overline{T}_{pouthor} - \overline{T}_{pa}\right) = h_{hor}\left(\overline{T}_{amb} - \overline{T}_{pouthor}\right) \Rightarrow \\ &\overline{T}_{pa} = \overline{T}_{pouthor} - h_{hor}\frac{d_{ztop}}{k_p}\left(\overline{T}_{amb} - \overline{T}_{pouthor}\right) \end{aligned} \quad (16)$$

Using the above equation: $\overline{T}_{pa}$ =14.86 °C, is obtained.

The emissivity of the outside environment was ε_{amb}=0.8 (Moureh and Derens, 2000).

The criterion used for selection of the number of terms M in the summation in Eq. (14) was that the relative difference between temperatures obtained with M and M+1 terms is negligible (several orders of magnitude less than 1). In this study M=30 was adopted.

In Figs. 5-9 the comparison between analytical solutions given by Eq. (14), numerical results obtained by using the commercial software FLUENT and experimental results for different positions of the data loggers are shown. A hexagonal mesh with 54 873 cells and 67 566 nodes is used in the FLUENT simulation. The surface-to-surface (S2S) radiation model has been included in the simulation (Siegel and Howell, 1992). The time constant τ_{111} which corresponds to the leading term in the sum given by Eq. (14) for this case is 11.344 hours. After this time the leading term in Eq. (14) drops to 1/e of its initial value. The nine data loggers with the characteristic positions inside the packaging presented in Fig. 1a-b are used in the validation process of the mathematical and the FLUENT model.

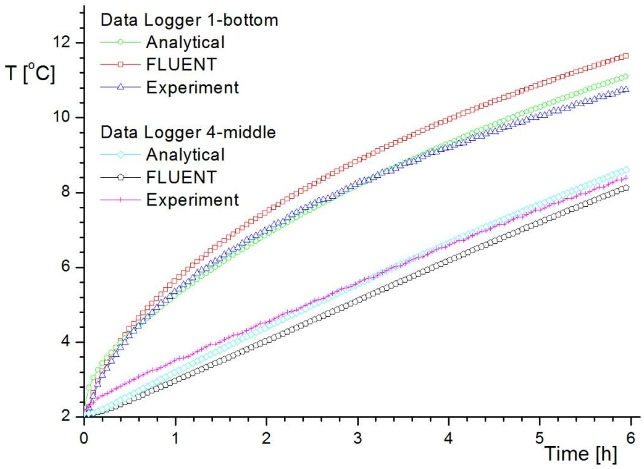

Figure 5. Comparison between analytical results, numerical results obtained with FLUENT and experimental results for data loggers 1-bottom and 4-middle

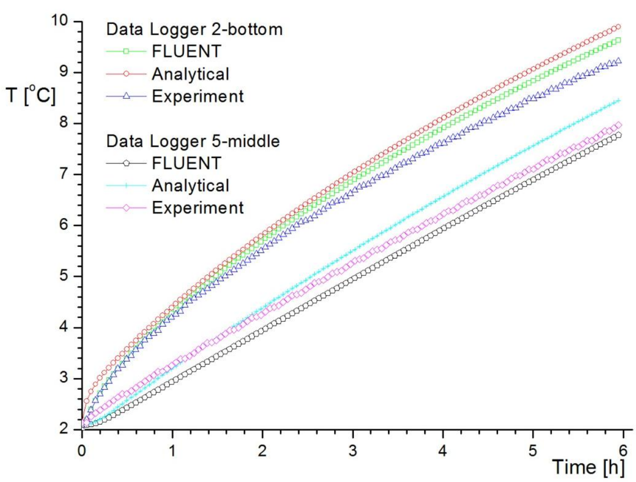

Figure 6. Comparison between analytical results, numerical results obtained with FLUENT and experimental results for data loggers 2-bottom and 5-middle

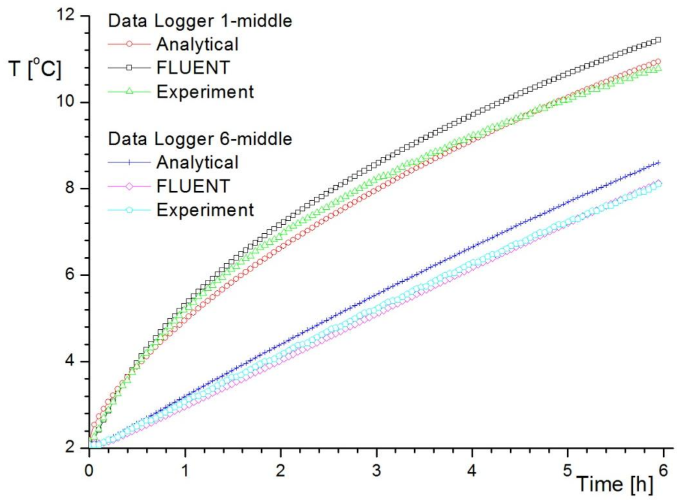

Figure 7. Comparison between analytical results, numerical results obtained with FLUENT and experimental results for data loggers 1-middle and 6-middle

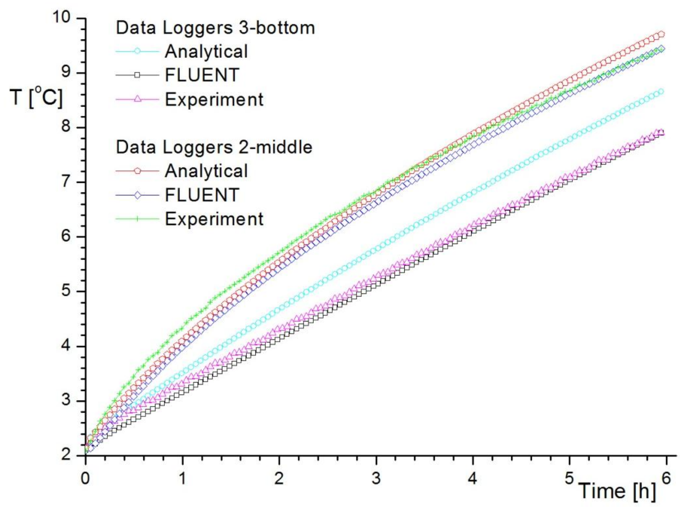

Figure 8. Comparison between analytical results, numerical results obtained with FLUENT and experimental results for data loggers 3-bottom and 2-middle

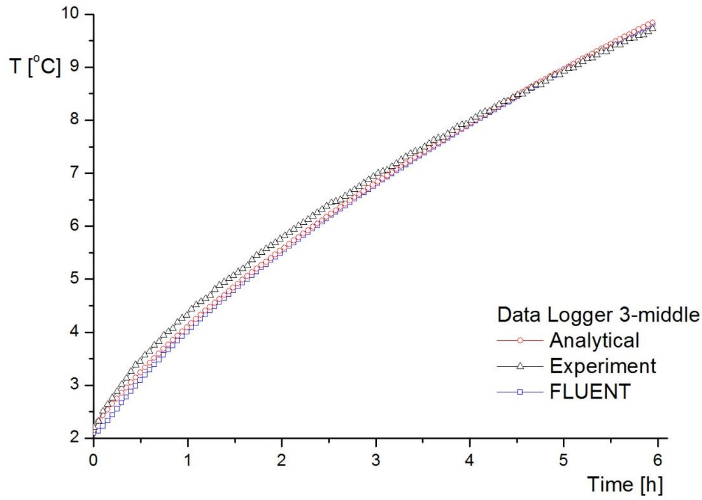

Figure 9. Comparison between analytical results, numerical results obtained with FLUENT and experimental results for data logger 3-middle

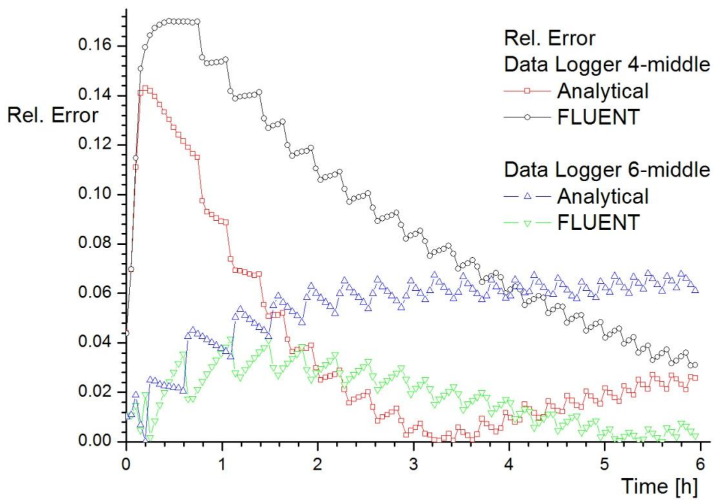

Figure 10. Relative error at different time instants for analytical results and results obtained with FLUENT at position of data loggers 4-middle and 6-middle

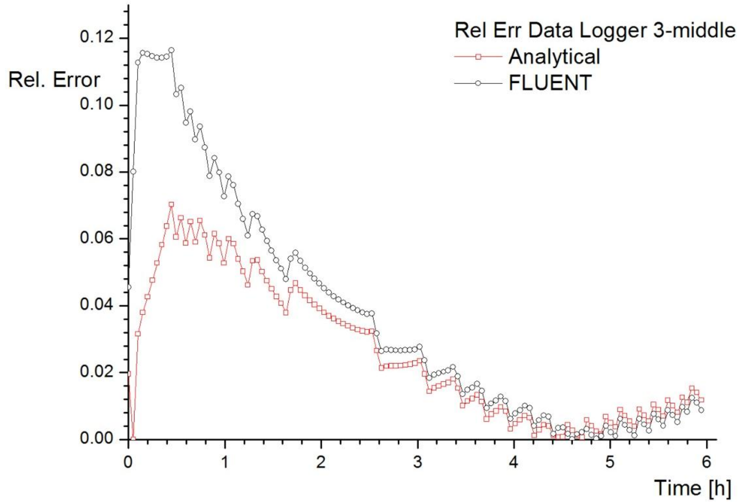

Figure 11. Relative error at different time instants for analytical results and results obtained with FLUENT at position of data logger 3-middle

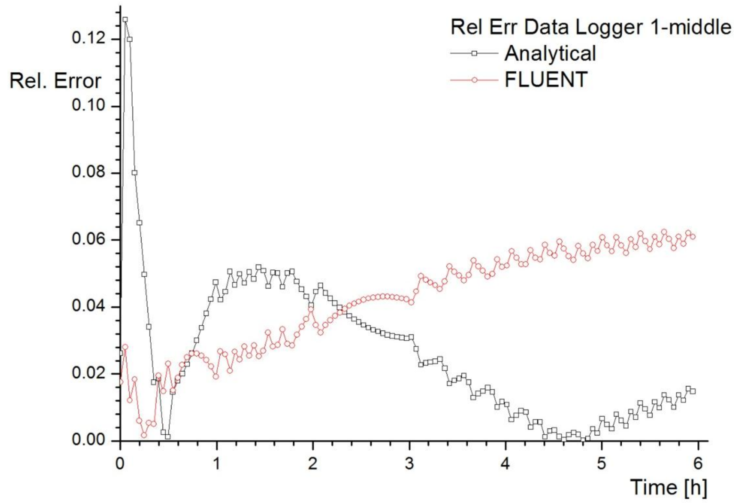

Figure 12. Relative error at different time instants for analytical results and results obtained with FLUENT at position of data logger 1-middle

From these figures it could be noticed that the relative error at the beginning of the simulation is higher due to low product temperature and after this period the relative error is decreasing. The mean values of the relative errors during the entire period of time for the analytical solution given by Eq. (14) and results obtained using the FLUENT software for different temperature loggers are given in Table 4.

Table 4. Mean values of the relative error during the entire period of time for the analytical solution and results from FLUENT software at different locations within the package

Location	Analytical [%]	FLUENT [%]
2-bottom	6.2	3.0
3-bottom	8.1	2.9
1-bottom	2.4	7
2-middle	2.7	4.1
5-middle	4.5	6.1
1-middle	2.6	4.2
3-middle	2.6	2.7
6-middle	5.4	1.7
4-middle	3.8	9.0
Overall Mean	4.3	4.7

The overall mean relative error is calculated as a mean value over all temperature loggers.
The mean relative errors and overall mean relative errors presented in Table 4 are calculated using the following relations:

$$Mean\ \mathrm{Rel.}\ Err = \sum_{\text{time samples}} \frac{\left|T_{\exp} - T_{numerical}\right|}{T_{\exp}};$$
$$Overall\ Mean\ \mathrm{Rel.}\ Err = \sum_{\text{data loggers}} \sum_{\text{time samples}} \frac{\left|T_{\exp} - T_{numerical}\right|}{T_{\exp}}; \qquad (17)$$

From the above table it could be concluded that the mean relative errors for the analytical solution are between 2.4% (data logger 1-bottom) and 8.1% (data logger 3-bottom) and for the numerical results obtained by the FLUENT between 1.9% (data logger 6-middle) and 9% (data logger 4-middle). In the above considerations the ambient temperature is approximated by its mean value.

In Fig. 13 the real ambient temperature profile obtained by measurements during the experiment is shown.

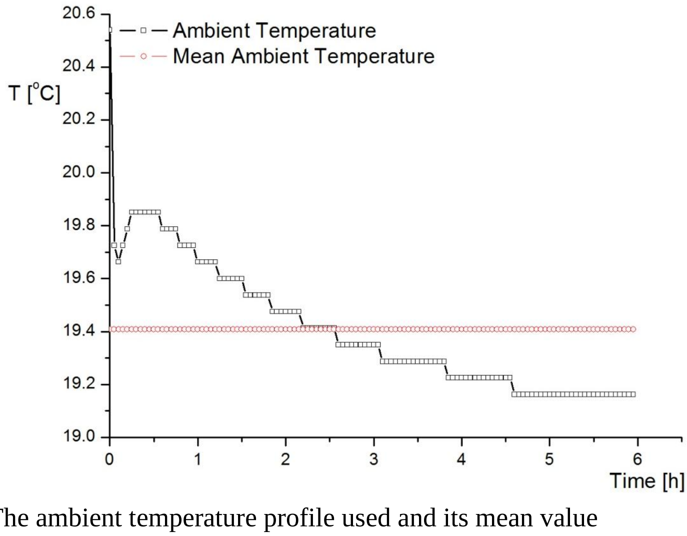

Figure 13. The ambient temperature profile used and its mean value

3.2. The periodic changes of the ambient temperatures

As an example of practical use of (B1) and (B2), periodic temperature variation, as shown in Fig. 14, is considered. The ambient temperature variation is approximated with periodic changes between two constant temperatures 20 ºC and 1 ºC. It was assumed that the duration of each period is 2 hours. The geometry and properties of the food package were the same as in the previous section. For the sake of simplicity it was assumed that h_{ver} and h_{hor} do not change considerably during the temperature variation and the same values for h_{ver} and h_{hor} were used as in the previous example. Under this assumption the relation (B2) is simplified as the tensors $Bx_n^l(j+1)$, $By_m^s(j+1)$ and $Bz_k^p(j+1)$ from (3) become unity tensors. In Fig. 14 the variation of the ambient temperature and the comparison between results obtained using the analytical solution given by Eq. (B1) and numerical results obtained by software FLUENT at the position of the data loggers 1-bottom and 4-middle are presented. The same geometry and mesh as in the previous example are used in the numerical simulation using FLUENT.

In Fig. 15 the comparison between results obtained using the analytical solution given by Eq. (B1) and numerical results obtained by FLUENT at the position of the data loggers 1-middle and 5-middle are shown. The largest differences between the analytical solution and numerical results obtained by FLUENT are at the corners of the food package (data loggers 1-bottom and 1-middle). For the points inside the food product (data loggers 4-middle and 5-middle) good agreement between the analytical and numerical results is obtained.

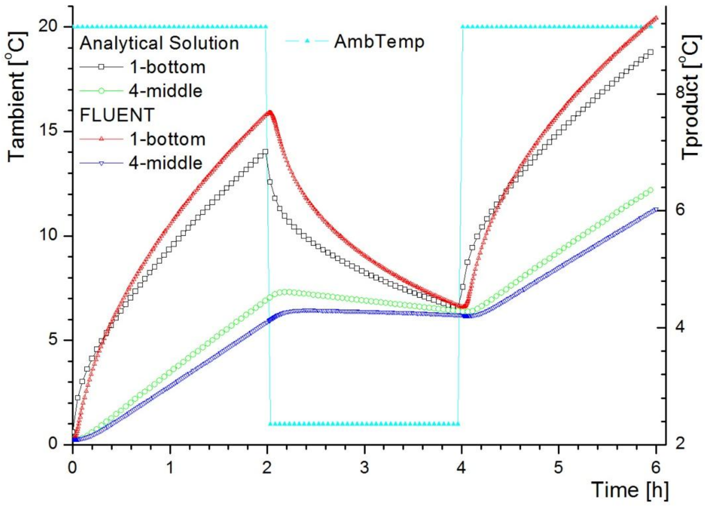

Figure 14. Periodic ambient temperature variation and comparison between product temperatures obtained using Eq. (B1) (analytical solution) and FLUENT for data loggers 1-bottom and 4-middle

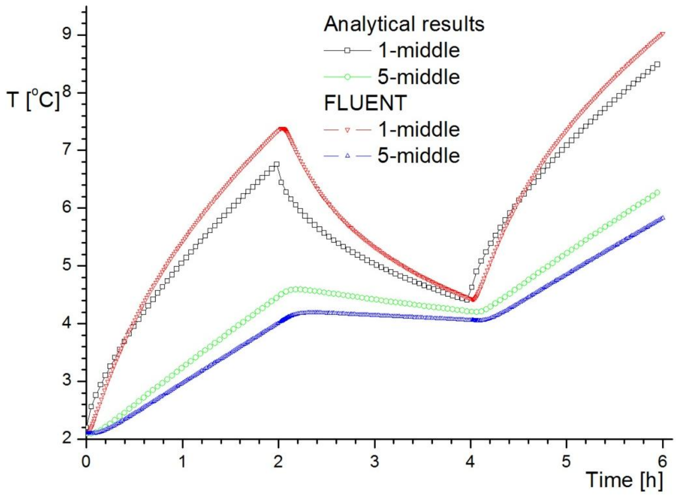

Figure 15. Comparison between product temperatures obtained using Eq. (B1) (analytical solution) and FLUENT for data loggers 1-middle and 5-middle

4. Conclusions

Mathematical model for heat transfer from the surrounding environment to a single food package with rectangular geometry was developed. The internal heat transfer in the food package was considered taking into account the geometry and properties of the packaging. The lateral thermal fluxes through the air layer are included in the model. The analytical solutions for the three-dimensional non stationary temperature distribution for the symmetric and for the general non-symmetric cases were obtained. The model was extended for the variable ambient temperature given in the form of a step function under the condition that free convection is developed during each time period with constant ambient temperature.

The obtained numerical results for static ambient temperature were validated through comparison with temperature measurements for fresh haddock fillets packed in EPS boxes exposed to temperature variation and with results obtained using the commercial software FLUENT. The comparison was performed at nine points inside the food product, where temperature loggers were positioned. The results obtained using the analytical solution and numerical simulation using the FLUENT software showed good agreement with the experimental results. The mean relative errors for the analytical solution compared with the experimental results were in the range between 2.4% and 8.1%. The mean relative errors, obtained by comparing the results obtained using the commercial software FLUENT and the experimental results, were between 1.9% and 9%.
From these results it could be concluded that there is no significant difference between the mean relative errors obtained by analytical solution and by the FLUENT software.
The analytical solution for the temperature distribution inside the fresh haddock fillets packaging units under periodic ambient temperature variation were compared with the numerical results obtained with the commercial software FLUENT. The largest differences between analytical and numerical results were obtained at the corners of the food package. For the points inside the food package a good agreement between analytical and numerical results was obtained.

The developed model is of practical relevance for fast estimation of influence of ambient temperature abuse on a single food package. The presented analytical model could be used both for stationary or non-stationary heat transfer analysis and for symmetric or non-symmetric geometry of the food package.

The developed analytical solution for the temperature distribution inside the food package has an advantage compared to the numerical approach since the temperature distribution was evaluated in a closed form without a need for meshing procedures. The product temperature could be obtained at an arbitrary location inside the food product at any time, while the numerical solution is usually obtained at a set of discrete points. Also, the numerical solution based on time marching schemes includes the solutions at all previous time steps. The presented results in the current study imply that the developed mathematical model could be used as a valuable tool for quick and reliable estimation of the temperature variation inside single packaging units when exposed to temperature abuse.

Acknowledgments
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Appendix A:
To obtain the analytical solution of Eq. (1) with corresponding initial and boundary conditions given in Eq. (2), the method of variable separation is used. One particular solution of Eq. (1) could be expressed using the following substitution and separation of variables:

$$T(x,y,z,t) = T_f(x,y,z,t) - T_{amb} = f_x(x)\cdot f_y(y)\cdot f_z(z)\cdot f_t(t). \qquad \text{(A1)}$$

Using the above transformation the following system of ordinary differential equations (ODE) is obtained:

$$\begin{aligned} & f_x'' + \lambda_x^2 \cdot f_x = 0; \quad f_y'' + \lambda_y^2 \cdot f_y = 0; \quad f_z'' + \lambda_z^2 \cdot f_z = 0 \\ & \frac{1}{\chi} f_t' = -\lambda_t \cdot f_t; \quad \lambda_t = \lambda_x^2 + \lambda_y^2 + \lambda_z^2. \end{aligned} \qquad \text{(A2)}$$

The constants $\lambda_{x,y,z}$ are determined by the boundary conditions given in Eqs. (2) and (3) as roots of the following transcendental equations (Gospavic et al., 2005):

$$\lambda_{x,y} \cdot \tan\left(\lambda_{x,y} \cdot \frac{L_{x,y}}{2}\right) = \frac{h_{x,y}}{k_f}; \quad \tan(\lambda_z \cdot L_z) = \frac{\lambda_z \cdot (h_{ztop} + h_{zbott})/k_f}{\lambda_z^2 - h_{ztop} \cdot h_{zbott}/k_f^2}. \qquad \text{(A3)}$$

All roots of the above equation are real and all roots of the first two equations are even which means that for any positive root, $\lambda_{x,y}$ and - $\lambda_{x,y}$ represents root of the same equation. As the particular solutions are even functions, solutions which correspond to negative roots are linearly dependent on the solutions with positive roots and will not be included in the general solution.

The particular solution of the governing equation given in Eq. (1) which corresponds to constants λ_{xn} , λ_{ym} , λ_{zk} and the system of ODE's given by Eq. (A2) can be expressed as:

$$T_{nmk}(x,y,z,t) = f_{xn}(x)\cdot f_{ym}(y)\cdot f_{yk}(z)\cdot \exp(-t/\tau_{nmk})$$
$$\tau_{nmk} = \frac{1}{\chi_f \cdot (\lambda_{xn}^2 + \lambda_{ym}^2 + \lambda_{zk}^2)} = \frac{1}{\chi_f \cdot \lambda_t}. \quad \text{(A4)}$$

Taking into account boundary conditions given in Eq. (3) functions f_{xn} , f_{ym} , f_{zk} have the following form:

$$f_{xn}(x) = \cos(\lambda_{x1n}\cdot x); \quad f_{ym}(y) = \cos(\lambda_{ym}\cdot y); \quad f_{zk}(z) = \sin(\lambda_{zk}\cdot z) + \frac{k_f \cdot \lambda_{zk}}{h_{zbott}}\cos(\lambda_{zk}\cdot z). \quad \text{(A5)}$$

As all the functions f_{xn} , f_{ym} , f_{zk}, which correspond to roots of Eq. (A3), form an orthogonal bases (Nicolas, 2004) the general solution which satisfies the initial condition could be expressed by the following expression:

$$T(x,y,z,t) = (T_0 - T_{amb})\cdot \sum_{n,m,k=1}^{\infty} a_{xn}\cdot a_{ym}\cdot a_{zk}\cdot f_{xn}(x)\cdot f_{ym}(x)\cdot f_{zk}(x)\cdot \exp(-t/\tau_{nmk}). \quad \text{(A6)}$$

For practical calculation, instead of the infinite series in Eq. (A6), only the first M terms until convergence is reached could be used.
Constants $a_{xn,ym,zk}$ are determined from the initial conditions in Eq. (2) in the following form:

$$a_{xn,ym} = \frac{4\cdot \sin\left(\frac{L_{x,y}\cdot \lambda_{xn,ym}}{2}\right)}{L_{x,y}\cdot \lambda_{xn,ym} + \sin(L_{x,y}\cdot \lambda_{xn,ym})};$$
$$a_{zk} = Cz_k \cdot \frac{h_{zbott}\cdot L_z \cdot (1-\cos(\lambda_{zk}\cdot L_z)) + k_f \cdot \lambda_{zk}\cdot L_z \cdot \sin(\lambda_{zk}\cdot L_z)}{L_z \cdot \lambda_{zk}\cdot h_{zbott}}. \quad \text{(A7)}$$

The normalization constant C_{zk} is given by the following equation:

$$C_{zk} = \frac{1}{\int_0^{L_z} f_{zk}(z)^2 \cdot dz} = \frac{2h_{zbott}^2 \lambda_{zk}}{h_{zbott}k_f + (h_{zbott}^2 + k_f^2)L_z\lambda_{zk} - h_{zbott}k_f\cos(2L_z\lambda_{zk}) + \frac{(k_f^2 - h_{zbott}^2)}{2}\sin(2L_z\lambda_{zk})}. \quad \text{(A8)}$$

Appendix B:
If the ambient temperature is approximated as a step function over the time and if the steady-state free convection is developed during each time interval Eqs. (6) and (12) for heat transfer coefficients for constant temperature could be used during each time interval.
For this type of temperature variation the whole time period could be divided into N time instants namely: $t_1, t_2, \ldots, t_N$. During any time interval Δt_j between two adjacent time instants t_j and t_{j+1} the ambient temperature is constant and equal to T_j. The initial condition for the temperature distribution inside the food package during this time interval is the temperature distribution from the end of the previous interval at moment t_j.

In the general case the heat transfer coefficients on the vertical and horizontal exterior surfaces h_{ver} and h_{hor}, respectively, are not the same for different time intervals which means that also constants λ_{xn} , λ_{ym} , λ_{zk} from Eq. (A3) will not be the same for different time intervals. According to these considerations the temperature distribution inside the food package for j+1-th time interval could be expressed by the following equation:

$$T_f^{j+1}(x,y,z,t) = T_{amb}^{j+1} + \sum_{n,m,k=1}^{M} a_{nmk}(j+1)\cdot f_{xn}^{j+1}(x)\cdot f_{ym}^{j+1}(y)\cdot f_{zk}^{j+1}(z)\cdot \exp\left(-t/\tau_{nmk}^{j+1}\right) \quad \text{(B1)}$$

The constants λ_{xn}^{j+1} , λ_{ym}^{j+1} and λ_{zn}^{j+1} for j+1 time interval are given by the relations analogous to the Eq. (A3).

The constants $a_{nmk}(j+1)$ used in the above series are given by the following recurrent relations for the each time step:

$$\begin{aligned} a(1)_{nmk} &= (T_0 - T_{amb})\cdot a_{xn}^1 \cdot a_{ym}^1 \cdot a_{zk}^1 \\ a(j+1)_{nmk} &= B_{nmk}^{lsp}(j+1)\cdot\left(a_{lsp}(j)\cdot \exp\left(-\left(t_{j+1}-t_j\right)/\tau_{lsp}(j)\right) + \left(T_{amb}^{j} - T_{amb}^{j+1}\right)\cdot a_{xl}^j \cdot a_{ys}^j \cdot a_{zp}^j\right) \quad \text{(B2)} \\ B_{nmk}^{lsp}(j+1) &= B_{1n}^{l}(j+1)\cdot B_{2\mathrm{m}}^{s}(j+1)\cdot B_{3\mathrm{k}}^{p}(j+1),\ j = 1,2,\cdots,N-1 \end{aligned}$$

In the above relation the Einstein notation is used for summation.

The constants a_{xn}^j , a_{ym}^j and a_{zk}^j for j+1 time interval are given by the relations analogous to the Eq. (A7). The third order tensor $B_{in}^{l}(j+1)$ (i=1,2,3) is obtained using the transformation relations between two orthogonal bases for j and j+1 time intervals in the following way:

$$\begin{aligned} &B_{1\mathrm{n}}^{l}(j+1) = C_{xn}^{j+1}\cdot\int_0^{Lx} f_{xl}^{j}(x)\cdot f_{xn}^{j+1}(x)\cdot dx\ ;\ B_{2\mathrm{m}}^{s}(j+1) = C_{ym}^{j+1}\cdot\int_0^{Ly} f_{ys}^{j}(y)\cdot f_{ym}^{j+1}(y)\cdot dy\ ; \\ &B_{3\mathrm{k}}^{p}(j+1) = C_{zk}^{j+1}\int_0^{Lz} f_{zp}^{j}(y)\cdot f_{zk}^{j+1}(y)\cdot dy \end{aligned} \quad \text{(B3)}$$

The normalization constants, C_{xn}^{j+1} ,C_{ym}^{j+1} and C_{zk}^{j+1} for j+1 time interval are obtained in a similar way to Eq. (A8).

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Paper IV

Numerical modelling of temperature fluctuations in superchilled fish loins packaged in expanded polystyrene and stored at dynamic temperature conditions

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Abstract

An appropriate thermal insulation of fresh fish packaging can substantially reduce negative effects of poor temperature management in chill chains. The aim of the current study is to experimentally and numerically investigate the performance of two types of EPS (expanded polystyrene) boxes in protecting superchilled fresh fish products subjected to temperature fluctuations, simulating conditions during transport. One EPS box type is a new improved version designed by utilising numerical heat transfer modelling for minimising the maximum product temperature during thermal load. This box weighed 11% less than the older box type. The performance of the boxes was evaluated by means of temperature monitoring and sensory evaluation. The thermal insulation of the new boxes was significantly better compared to the old boxes. According to sensory evaluation, storage in the new boxes resulted in approximately 2 days longer storage life. A satisfactory agreement between numerical results and experimental results was obtained.

Keywords: Fish, Temperature variation, Heat transfer model, Packaging, Superchilling, Storage life

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Nomenclature

B	bound water as kg per kg dry solids
c_p	specific heat capacity, $\mathrm{kJ\,kg^{-1}\,K^{-1}}$
Co	corner
EPS	expanded polystyrene
h_{conv}	convective heat transfer coefficient,$\mathrm{W\,m^{-2}\,K^{-1}}$
h_{rad}	radiative heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
H	height, m, mm
k	thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
L	length, m, mm
Mi	middle
m	mass, kg
N	new box
O	old box
P	temperature data logger position
R	thermal contact resistance, $\mathrm{m^2\,K\,W^{-1}}$
t	time, h, s
T	temperature, °C, K
T_{amb}	ambient temperature, °C, K
$T_{\mathrm{f,init}}$	initial freezing point of fish, °C
W	width, m, mm
X_{I}	ice content
X_{w}	unfreezable water content
$X_{\mathrm{w,o}}$	total water content
$X_{\mathrm{w,u}}$	unfrozen water content

Greek symbols

ϵ	emissivity
ρ	density, $\mathrm{kgm^{-3}}$
σ	Stefan–Boltzmann's constant, ($5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$)

Subscripts

amb	ambient
b	box
EXP	experimental
f	fish fillet
I	ice
init	initial
in	inside
out	outside
pack	gel pack
side	box side
top	box top

1. Introduction

Superchilling of fresh food products is a process where the food temperature is lowered to no more than 1–3 °C below the initial freezing point of the food, $T_{\mathrm{f,init}}$ (Aune, 2003; Magnussen, 2008; Kaale et al., 2011). The initial freezing point of most fresh food is around −1 °C (Pham, 1996) and the initial freezing point of cod is specified by Rahman (2009b) as −0.91 °C. The term superchilling has also been used when chilling a produce to a temperature between the initial freezing point of the product and 0 °C (Aune, 2003; Ando et al., 2004). Superchilling cod with water content of 80–82% down to −2 °C implies that around 50–55% of the product's water content is frozen (Rha, 1975). In order to avoid excessive surface freezing and ice crystal growth, which can cause structural damage and negative texture changes to the fish flesh and increase drip loss (Bahuaud et al., 2008; Magnussen, 2008; Kaale et al., 2011), cod is normally superchilled to around −1 °C in modern industrial applications (Valtýsdóttir et al., 2010; Stevik and Claussen, 2011).

The "SuperChiller" cooling technique by Marel Ltd., Garðabær, Iceland (formerly referred to as combined blast and contact (CBC) cooling technique by Skaginn Ltd., Akranes, Iceland) is an efficient method for superchilling fresh fish loins/fillets before packaging and prolonging shelf life due to inhibited microbial activity (Martinsdóttir et al., 2005; Olafsdottir et al., 2006; Gao, 2007; Magnússon et al., 2009). One of the main advantages of the SuperChiller technique is a quick reduction of the product temperature to around −1 °C before packaging, causing around 10–15% of the water of the fish muscle to be frozen (Rha, 1975) when packaged. This means that extra energy is needed for melting the partly frozen water so that the superchilled, packaged fish products can withstand more severe thermal load than non-superchilled products in similar packaging. This could be related to the fact that by comparing the results of Magnússon et al. (2009) and Gao (2007), the superchilled processing is probably more important for products subjected to thermal loads during transport and storage than for products kept at steady temperature conditions. Such dynamic temperature conditions are much more likely to be experienced during air freight than during sea freight according to Mai et al. (2011). Because of this, the dynamic temperature storage applied in the current study is only meant to simulate the temperature conditions during air transport. The temperature conditions used here are similar or even less hazardous than Mai et al. (2011) reported. The main advantage of the air transport, on the other hand is shorter transport time, e.g. around three to six days shorter for fresh fish export from Iceland to UK or France.

Other possible methods for protecting the perishable fish products against thermal loads during transport and storage are insulated packaging and phase change materials such as cooling packs (containing ice or gel). By performing experiments and using numerical heat transfer modelling, Margeirsson et al. (2009, 2011) showed that expanded polystyrene (EPS) wholesale boxes are better insulated than corrugated plastic (CP) wholesale boxes but the need for thermal insulation is lower for multiple boxes arranged on a pallet, compared to free standing boxes. Furthermore, they found that placing a 250 g ice pack on top of 3 kg of fillets inside wholesale fish boxes significantly reduced the product temperature increase during thermal load. Margeirsson et al. (2009) studied only one type of EPS box and the fish fillets were not superchilled before being thermally loaded. The importance of good temperature control during distribution was underlined by the results of Margeirsson et al. (2012) which suggest that the storage life difference between the most and the least sensitive boxes on a full size fish pallet in a real air transport chain can exceed 1 to 1.5 days, depending on the level of ambient thermal load.

Experimental comparison between thermal resistance of different packaging solutions was performed by Burgess (1999) and Singh et al. (2008), using ice-melt tests in both cases. Choi and Burgess (2007), Laguerre et al. (2008) and East et al. (2009) have all discussed the applicability and reliability of heat transfer models for insulated packages and phase change materials.

Many mathematical models have been developed in order to predict thermal properties of foodstuffs. Jowitt et al (1983), Choi and Okos (1986), Harðarson (1996), Pham (1996), Fikiin (1998) and Rahman (2009a) are among the authors that have reported different models, the first and the latest providing a broad overview of available models and tabulated data. Difficulties in estimating the ratio of frozen water (ice content) in the food and the importance of the initial freezing temperature of the food substance for the phase change, are among the problems encountered by the models. Phase change in products with no sharply defined phase change region, such as fish, can in general cause complications in numerical heat transfer modelling according to Pham (1995) and Harðarson (1996). For problems solved with fixed grid methods, such as apparent heat capacity methods, the complications can be related to the sharp peak in the apparent heat capacity of the food, which is due to the latent heat component of the apparent heat capacity.

In the current study the performance of two different types of wholesale EPS fish boxes in protecting superchilled, fresh fish products are investigated, subject to temperature conditions, which are likely to occur during air- and land based transport from Iceland to Europe. The performance of the boxes was evaluated by means of temperature monitoring, numerical heat transfer modelling and sensory evaluation. Furthermore, the effect of the loin's position inside the wholesale fish package (corner vs. middle) was investigated by means of the aforementioned methods.

2. Materials and methods

2.1. Materials

The two investigated box types were: (i) a new improved EPS box type manufactured by Promens Tempra (Hafnarfjörður, Iceland), and (ii) an older EPS type manufactured by Plasteyri (Akureyri, Iceland). The dimensions and thermal properties of the boxes and gel packs, which were adopted in the numerical heat transfer models (see Section 2.4), are shown in Table 1. As can be seen in the table, the dimensions of the two box types were similar except the height. The thicker air layer in the old box (around 35–80 mm) should increase thermal performance of the old box because of thermal resistance of the extra air as compared to the new box with air layer thickness of around 15–60 mm. The gel packs (see Figure 1) were manufactured by Ísgel (Blönduós, Iceland).

Ibutton temperature loggers (type DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) were used to monitor the temperature inside the insulated boxes under testing. The Ibutton temperature loggers had a resolution of 0.0625 °C, measurement range of −40–85 °C with an accuracy of ±0.5 °C between −15 and 65 °C. All temperature loggers were factory calibrated and re-calibrated by the authors in a thick mixture of fresh, crushed ice and water. According to Rahman (2009b), the different types of water

Table 1: Dimensions and thermal properties of fish boxes and gel pack.

Material	Inside dim. $L_{\text{in}} \times W_{\text{in}} \times H_{\text{in}}$ (mm)	Outside dim. $L_{\text{out}} \times W_{\text{out}} \times H_{\text{out}}$ (mm)	m (g)	ρ (kg m^{-3})	c_p (kJ kg^{-1} K^{-1})	k (W m^{-1} K^{-1})
Old	355.5 x 220 x 109	400 x 265 x 159	205 ± 4	25[a]	1.28± 0.05[b]	0.0345
New	355.5 x 220 x 90	400 x 264.5 x 135	183 ± 1	23[c]	1.28± 0.05	0.0345[c]
Gel pack		160 x 125 x 6	125 ± 2	999[d]	4.2[d]	0.57[d]

[a] Baldursson (2008); [b] Al-Ajlan (2006); [c] Gudmundsson (2009); [d] for $T \geq 0\,°\text{C}$

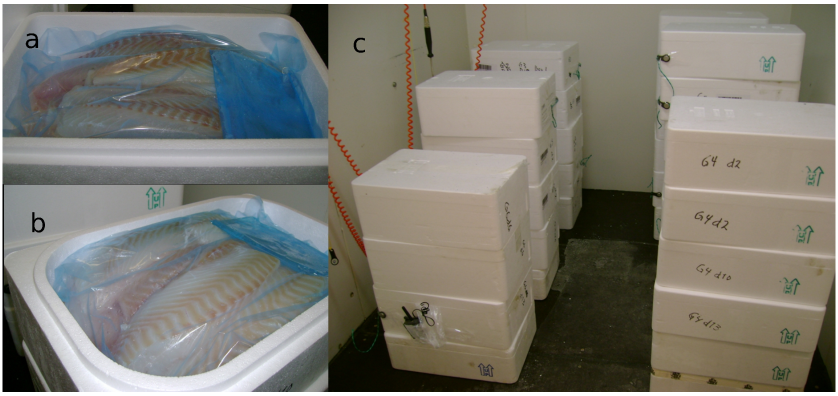

Figure 1: Superchilled cod loins in an old EPS box (a) and a new EPS box with rounded corners (b) with boxes piled up (c) during dynamic temperature storage.

found in frozen foods are usually defined as total water ($X_{\text{w,o}}$), ice (X_{I}), unfreezable water (X'_{w}) and unfrozen water ($X_{\text{w,u}}$). The following relationship from Rahman (2009b) was adopted for calculating the ice content of the fish as a function of temperature (T):

$$X_{\text{I}} = (X_{\text{w,o}} - X'_{\text{w}})(1 - \frac{T_{\text{f,init}}}{T}) \tag{1}$$

The initial freezing point of cod ($T_{\text{f,init}}$) is listed by Rahman (2009b) as $-0.91\,°\text{C}$ but was taken as $-0.92\,°\text{C}$ in the FLUENT models because of better fit with the experimental data. The initial freezing point is lower than the freezing point of pure water because of dissolved substances in the moisture within the foodstuff. The unfreezable water content was estimated according to Rahman (2009b) as

$$X'_{\text{w}} = B(1 - X_{\text{w,o}}) = 0.278(1 - 0.803) = 5.3\% \tag{2}$$

The generic model by Choi and Okos (1986) was used for estimating linearly temperature dependent apparent specific heat capacity (c_p, both accounting for sensible and latent heat) of cod as shown in Table 2. Both a constant density of 1054 kg m^{-3} and values for thermal conductivity were adopted from Zueco et al. (2004) assuming a sharp change at $T_{\text{f,init}}$.

Table 2: Linearly temperature dependent thermal properties of cod fish.

T (°C)	−1.00	−0.92	−0.9	−0.85	0	5
c_p (kJ kg^{-1} K^{-1})	189.4	223.0	3.679	3.679	3.675	3.752
k (W m^{-1} K^{-1})	1.302	1.302	0.43	0.43	0.43	0.43

2.2. Experimental setup

After bleeding in cold seawater, gutting and washing on board the fishing trawler, the raw material (cod) was packed and stored with about 5 layers of ice (fish to ice ratio approximately 3:1) in 460 L tubs on board the vessel. The tubs were kept in a chilled hold on board the trawler. The product was landed in Dalvík in North-Iceland and transported in the tubs by a forklift directly after weighing tubs on harbour scale to the main processing cold storage in Dalvík (less than 250 meters from the vessel at quay). During processing between 11 and 12 AM on 9 March 2010, fillets were superchilled with a CBC cooler before skinning, portioning and packaging into the two different types of EPS boxes. One frozen gel pack (Section 2.1) at around −18 °C was put on top of the loins in each fish box during packaging. After inserting the temperature data loggers, the boxes were palletised and kept in chilled and frozen storage rooms before being land transported in a mechanically refrigerated truck from the processor's storage to Matís facilities in Reykjavík between 4 PM and midnight on 9 March 2010. There the boxes were stored under non-blast conditions in temperature controlled air climate chambers with each experimental group divided into free standing piles. The dynamic conditions were obtained by storing the fish boxes in a warm up air climate chamber at mean temperature around 9 °C for 9 h from arrival at Matís. After that, all the fish boxes were chilled at around 0–4 °C for 3 h in the same chamber before being subjected to thermal load at around 16 °C for 4 h. Finally, the boxes were transferred to an air climate chamber at around 2 °C and kept there for the rest of the experiment.

Environmental temperature (Figure 2) was measured at the outside surface of the boxes (see Figure 3) and in the air at the same level as the top boxes. Comparison to the results of Mai et al. (2011) reveals that the environmental thermal load during this experiment was not exaggerated compared to the thermal load that can occur in fish air transport chains in Europe during the summer time. The experimental setup in an air climate chamber is presented in Figure 1. Temperature was measured in boxes at three different levels for each box type but only results for the top box for each type are presented here. Each fish box contained 5.00±0.01 kg of superchilled, fresh cod loins, which were packaged such that the fish pile was thickest in the middle of the box and thinner at the box ends as shown in Figure 1. The product temperature was measured at four different positions inside each box as shown in Figure 3.

2.3. Sensory evaluation

The three experimental groups were the following: 1) O-Co, 2) N-Co and 3) N-Mi, where O stands for the old Plasteyri EPS box, N for the new Tempra EPS box, Co for loins taken from box corners and Mi represents loins taken from the middle of the box. The sampling took place on days 0, 2, 6 and 10 where day 0 represents the day of processing and packaging (one day post-catch). For groups O-Co and N-Co pieces of loins were aseptically cut from each corner of a box and transferred to a cutting board.

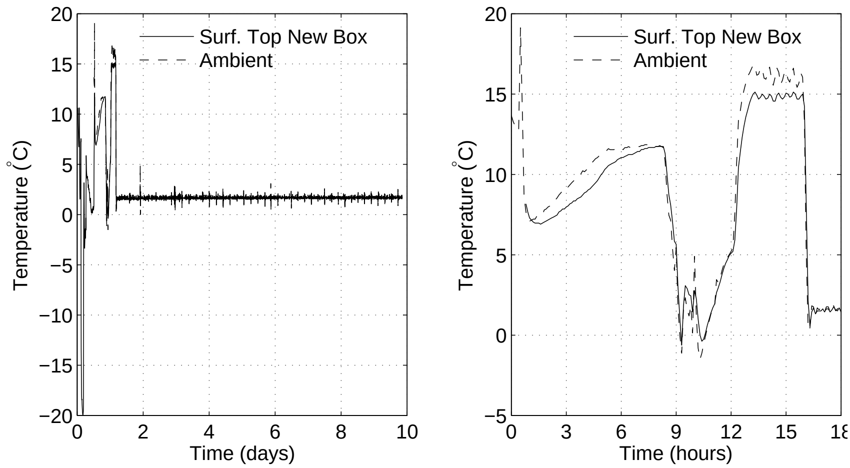

Figure 2: Environmental temperature. Left: during the first 10 days post-packaging, right: zoom-up of the dynamic temperature period in air climate chambers starting around 12 h post-packaging.

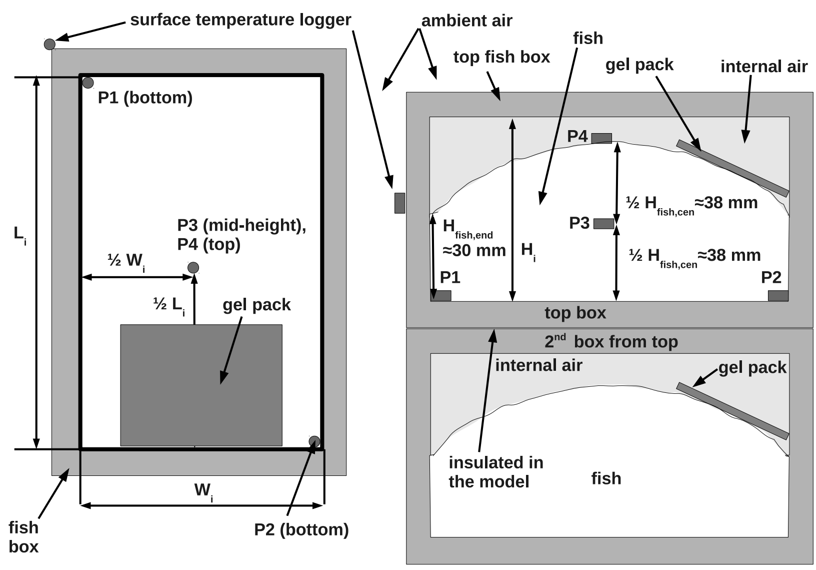

Figure 3: Positions of temperature loggers inside fish boxes: in horizontal plane (left), in vertical plane (right).

From each corner, three 40 g pieces from loins were then cut to use for sensory evaluation, totally 12 pieces from each box. For group N-Mi, three loins were taken from the centre of the box. From each loin, four 40 g pieces were cut to use for sensory evaluation. Two boxes were used for each group resulting in duplicate samples. Torry freshness score sheet (Martinsdóttir et al., 2001; Shewan et al., 1953) was used to assess cooked samples of cod. Nine trained panellists participated in the sensory evaluation. They were familiar with the Torry method and experienced in sensory analysis of cod. Samples (ca. 40 g each) were cooked in a pre-warmed oven to a core temperature of 67 °C (Convotherm Elektrogeräte GmbH, Eglfing, Germany) at 95–100 °C with air circulation and steam, and then served to the panel. Each panellist evaluated duplicates of each sample (coded with three digit random numbers) in a random order in 14 sessions (maximum four samples per session). A computerized system (FIZZ, Version 2.0, 1994–2000, Biosystèmes) was used for data recording.

2.4. Numerical heat transfer model

A three dimensional finite volume heat transfer model was developed using the Computational Fluid Dynamics (CFD) software ANSYS FLUENT for the two top boxes (the new box and the old box) studied experimentally. The main purpose of the numerical models was to predict the temperature distribution inside the packages during the dynamic temperature period shown to the right in Figure 2. The computational domain was limited to a whole new/old box at the top of each pile (see box piles in Figure 1) containing a gel pack and air above fish loins, thereby not resolving air flow outside the boxes. An unstructured computational mesh was used for both box types in the simulation, see Figure 4. Similar modelling approach was adopted as in Margeirsson et al. (2011). Inside the fish loins and gel packs heat is transferred only by conduction and is modelled using the following equation:

$$\rho_{\mathrm{f}} c_{p,\mathrm{f}} \frac{\partial T_{\mathrm{f}}}{\partial t} = \nabla \cdot (k_{\mathrm{f}} \nabla T_{\mathrm{f}}) \tag{3}$$

Convection was not considered in the air above the fish fillets in each box, implying that heat transfer in the air was only conductive, according to Eq. 3, and radiative, modelled with the Surface-to-Surface (S2S) radiation model, see Siegel and Howell (1992). The uniform initial conditions throughout the whole computational domain (fish + gel pack + air + box) were defined as the mean fish temperature in each package: $T_{\mathrm{New,i}} = -0.93\,°\mathrm{C}$ and $T_{\mathrm{Old,i}} = -0.94\,°\mathrm{C}$. It should be noted that using the mean fish temperature for defining uniform initial temperature throughout the computational domains is a simplification since the temperature in the corners of the boxes at the start of the warm up period in the air climate chamber was as high as -0.88 to $-0.75\,°\mathrm{C}$. Mixed convection and external radiation boundary conditions were applied for both the top and the sides of the two boxes. The convective heat transfer coefficients outside both boxes (h_{conv}) were estimated according to Margeirsson et al. (2011) as $h_{\mathrm{top}} = 2.1\,\mathrm{W\,m^{-2}\,K^{-1}}$ and $h_{\mathrm{side}} = 3.0\,\mathrm{W\,m^{-2}\,K^{-1}}$. The time dependent ambient temperature measured at the top boxes height and presented in Figure 2 was adopted as the free flow temperature for the convective and radiative boundary conditions at the top and sides. The radiative heat transfer coefficient outside the box (h_{rad}) can be expressed according to the following

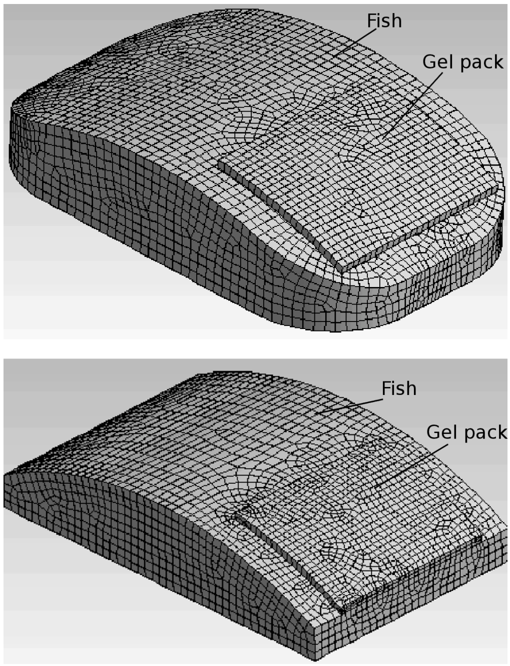

Figure 4: Computational mesh for the fish and gel pack inside the new box (above) and the old box (below).

relation (Moureh and Derens, 2000):

$$h_{\text{rad}} = \frac{\sigma}{\frac{1}{\epsilon_{\text{amb}}} + \frac{1}{\epsilon_{\text{box,out}}} - 1} \left(T_{\text{box,out}}^2 + T_{\text{amb}}^2\right)\left(T_{\text{box,out}} + T_{\text{amb}}\right) \tag{4}$$

An emissivity of 0.9 was adopted for both EPS and the chamber walls according to Margeirsson et al. (2011). The difference between the fish temperatures at the top-middle (P4) in the second box from the top and at the bottom-corners (P1 and P2) of the top box was found from experiments to be in the range of around 0–3 °C, i.e. negligible compared to the different temperature differences between the ambient conditions and the fish during the thermal load. Thus, it was assumed that the outside bottom wall of the boxes under consideration (the top boxes) was insulated. According to Margeirsson et al. (2011), non–ideal surface contact was assumed between adjoining surfaces. The following thermal contact resistances were estimated from the results by Cowell and Namor (1974); Cleland and Valentas (1997); BASF (2001) and Shojaefard and Goudarzi (2008), see explanations in Margeirsson et al. (2011): $R_{\text{fish,box}} = 0.05\,\text{m}^2\,\text{K}\,\text{W}^{-1}$, $R_{\text{fish,pack}} = 0.1\,\text{m}^2\,\text{K}\,\text{W}^{-1}$, $R_{\text{box,pack}} = 0.1\,\text{m}^2\,\text{K}\,\text{W}^{-1}$. The relatively high thermal resistances adopted between the gel pack and the other materials are due to the uneven surface of the pack and low contact pressure. The phase change of the gel pack was considered by using the melting/solidification model in ANSYS FLUENT (ANSYS, 2009). Temperature dependent thermal properties of water were adopted for the gel since the water content of the gel was very high. Latent heat of melting was defined as 333.55 kJ kg^{-1} (Heldman and Singh, 1981) and it was assumed that melting took place at the temperature range between –0.5 and 0.5 °C.

3. Results and discussion

3.1. Influence of packaging on product temperature - numerical heat transfer model

Results from the FLUENT simulation and the experimental results at four different positions inside the two box types are compared in Figure 5 during the dynamic temperature period in the experiment. Comparison of the experimental results (EXP) indicates that the rounded corners design of the new box offers better thermal protection with regard to maximum product temperature than the old box design. This despite the thicker, insulative air layer above the fish in the old box. Figure 5 shows that the ambient thermal load presented in Figure 2 obviously caused a very inhomogeneous temperature distribution inside each box which can be seen by the large temperature increase at bottom corners (P1 and P2) compared to the very stable temperature at the middle of the box (P3). This is in good agreement with the results of Margeirsson et al. (2011) for single packages and Margeirsson et al. (2012) for multiple packages, which did not include gel packs. The results show that more homogeneous product temperature distribution can be expected during dynamic temperature storage in the new box type compared to the older reference box type. This means, that more even product quality and safety inside each package can be ensured by using the new boxes' design in chill chains with a relatively high thermal load.

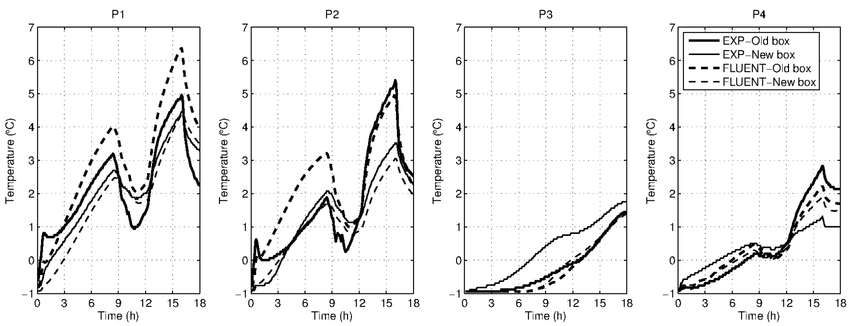

Figure 5: Comparison between numerical results obtained with FLUENT and experimental results (EXP) for four selected positions (see positions P1–P4 in Figure 3) inside the old and new boxes during the dynamic temperature period shown in Figure 2.

From Table 3 it can be seen that the mean absolute errors for the numerical results obtained with FLUENT were below 1 °C for all positions inside the two boxes. The overall mean absolute error was 0.5 °C for the old box and 0.4 °C in case of the new box.

These values should be compared to the accuracy of the temperature data loggers, which was ±0.5 °C, i.e. similar to the overall mean absolute errors. The positioning of the temperature loggers and the shape of the fish pile in each box should be mentioned as a possible source of error in the heat transfer models. As was already noted in Section 2.1, the initial freezing point of the cod, $T_{\mathrm{f,init}}$, was taken as −0.92 °C, i.e. 0.01 °C lower than the value proposed by Rahman (2009b). The reason for this was that adopting $T_{\mathrm{f,init}}$ as −0.91 °C yielded considerably larger overall mean absolute errors for both box types because then the FLUENT models over predicted the heat needed to warm up the product, thereby over predicting the warm up time during the thermal load. The fact that the cod fillets were immersed in lightly salted water (salinity around 2%) for around 12–15 min before they were superchilled with the CBC technique is likely to have increased the salt content of the fish muscle from 0.2–0.3% to 0.3–0.5% (Magnússon et al., 2009; Valtýsdóttir et al., 2010), which lowers the initial freezing point. The initial freezing point of the fish could have been measured independently, e.g. by slow melting, but due to the poor accuracy of the temperature sensors (±0.5 °C) with regard to the sensitivity of the initial freezing point, this may not have been of much use in the current study.

Table 3: Mean absolute error in °C of numerical results at four positions.

Position	Old Plasteyri box	New Tempra box
P1	0.9	0.3
P2	0.7	0.3
P3	0.1	0.6
P4	0.3	0.3

3.2. Influence of packaging on storage life

Figure 6 shows how the Torry freshness score changed with storage time. A Torry score around seven indicates that the fish has lost most of its freshness odour and flavour characteristics and has a rather neutral odour and flavour (Shewan et al., 1953). The time elapsed from processing until a Torry score of seven is reached is called the freshness period. This score was obtained after 2–3 days for O-Co and after 5–6 days for both N-Co and N-Mi. The Torry scores for N-Co and N-Mi were significantly higher than for O-Co both on day 6 ($p = 0.0012$) and on day 10 ($p = 0.0000$). When the mean Torry score is around 5.5, most of the sensory panellists detect spoilage attributes and this score has been used as the limit for consumption at Matís (Martinsdóttir et al., 2001). According to this, the storage life of the O-Co group was six days and around eight days for the N-Co and N-Mi groups. Thus it can be concluded that the storage in the boxes with the improved design as compared to the old boxes under dynamic temperature conditions resulted in approximately 2–3 days longer freshness period and about two days longer storage life. Furthermore, the sampling location within the new boxes did not affect the sensory quality significantly.

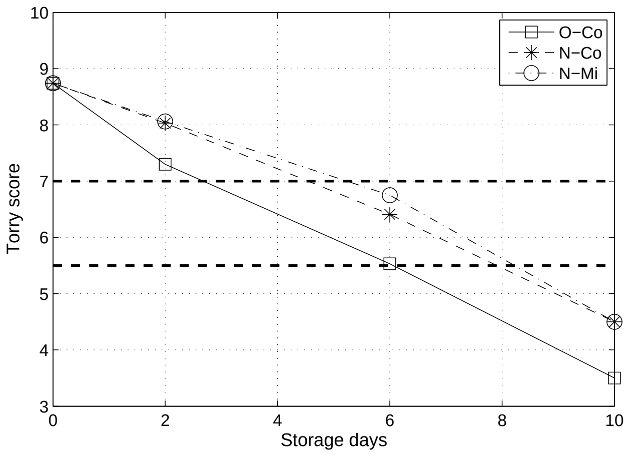

Figure 6: Mean Torry scores. O: Old box, N: New box, Co: Corner samples, Mi: Middle samples.

4. Conclusions

In this work, a combined experimental and numerical study has been performed on fresh fish fillets stored in two different EPS boxes. Of those two, the new round corner box design proved to be better than the older box design with respect to minimising the maximum product temperature during dynamic temperature storage. The other main conclusion for the packaging comparison is that the improved thermal protection of the new box design clearly results in prolonged storage life and freshness period, in particular during dynamic temperature storage. Furthermore, lower product temperature differences found in the new box results in more even product quality in each package. A satisfactory agreement was obtained between numerical results and experimental results, both for the heat transfer model for the old fish box and the new fish box (both models include a gel pack). The overall absolute error in the numerical model for the new box (0.4 °C) was similar to the corresponding error of the numerical model for the old box (0.5 °C). The numerical models were, however, sensitive to the initial freezing point of the fish. This implies that the models can give valuable information on the temperature distribution inside a thermally loaded fish package including both fish and gel pack and can thus be used for improving the packaging design in a cost effective way.

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Temperature fluctuations and quality deterioration of chilled cod (*Gadus morhua*) fillets packaged in different boxes stored on pallets under dynamic temperature conditions

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ABSTRACT

A study was carried out to evaluate temperature variation and quality deterioration of packaged cod fillets as influenced by the box type used and their position on pallets under dynamic temperature storage. Storage life of thermally abused fillets was compared to that of fillets stored at steady temperature. Thermal performance of fish boxes, made of corrugated plastic on one hand and expanded polystyrene on the other hand, was also compared. Fillet temperature at multiple positions on the pallets along with environmental temperature and humidity were monitored during storage. Differences in product temperature of up to 10.5 °C were recorded on the thermally abused pallets stored for 6.4 h at mean ambient temperature of 18.5 °C. A reduction in storage life of 1.5–3 days was observed depending on the box position on the abused pallets compared to steady temperature storage.

Fluctuations de température et altération de la qualité des filets de morue (*Gadus Morhua*) conditionnés dans différents types de caisse et entreposés sur des palettes sous différentes conditions de température dynamiques

Mots clés : Poisson ; Variation de température ; Packaging ; Palette ; Isolation ; Durée de conservation

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1. Introduction

Temperature control is a critical parameter to retard quality deterioration of perishable foodstuffs, such as fresh fish, during storage and transport from processing to consumers. Because of this, almost all countries in Europe, USA and many other countries have signed the ATP – Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (United Nations Economic Commission for Europe, 2010). According to the ATP, fish temperature should be as close to 0 °C as possible without freezing the products. However, the recommended transport temperature in the ATP could be decreased without any freezing because the initial freezing point of cod is around −0.9°C according to Rahman (2009). Prolonged ambient thermal load will eventually affect the product temperature. Thus the temperature inside the transport units must be strictly controlled. However, studies have shown that maintaining stable and homogeneous temperature distribution inside different transport units can be a difficult task (Giannakourou et al., 2005; Jedermann et al., 2009; Moureh and Flick, 2004; Punt and Huysamer, 2005; Rodríguez-Bermejo et al., 2007; Tanner and Amos, 2003a,b; Wild et al., 2005).

According to (Mai et al., 2011), who evaluated fish supply chains, ambient thermal load is much more likely to be experienced during air freight than sea freight. This is due to more numerous interfaces found in air logistic chains where ambient conditions are not well controlled. James et al. (2006) explained that during air freighting the product is unprotected for much of the relatively short journey and during flight the cargo hold is normally between 15 and 20 °C. Other publications have revealed that temperature control can in fact be improved in chilled distribution chains for other perishable products such as beef (Gill et al., 1996), poultry (Raab et al., 2008) and vegetables (Rediers et al., 2009).

Many experimental and numerical studies have been conducted in order to evaluate thermal load effects on refrigerated food (mainly frozen) and relate product temperature rise to abusive ambient conditions and thermal properties of the food and packaging solutions, such as insulating pallet covers (Zuritz and Sastry, 1986; Dolan et al., 1987; Almonacid-Merino and Torres, 1993; Moureh and Derens, 2000; Moureh et al., 2002; Stubbs et al., 2004).

The quality deteriorating impact of ambient temperature fluctuations during distribution of perishables can still be dampened by thermal insulation of the packaging. Expanded polystyrene (EPS) boxes are commonly used for fresh fish transport, but another type of wholesale fresh fish packaging is the more environmentally friendly corrugated plastic (CP) box. These boxes are produced from extruded corrugated polypropylene sheets which are 2–3 mm in thickness. The better insulating performance of EPS compared to the CP boxes, was reported by Anyadiegwu and Archer (2002) and confirmed by Margeirsson et al. (2009, 2011a). The insulation performance of the two box types used in the current study was compared in conjunction with the single packages studied by (Margeirsson et al., 2011a). Furthermore, the EPS box type used is the predecessor for the EPS box with rounded corners designed with numerical modelling and described by Valtýsdóttir et al. (2011). Other studies on insulating properties of EPS packaging have been carried out by Froese (1998), Burgess (1999) and (Singh et al., 2008), who stated that the most reliable way to compare thermal performance of different wholesale fresh fish packaging is to actually test them while containing fish under challenging, dynamic temperature conditions. In general, the product temperature distribution under dynamic temperature conditions will be inhomogeneous, time-dependent and influenced by different factors such as ambient conditions, temperature history of the product, dimensions and thermal properties of the food and packaging, surface contact resistance between food and packaging, location on pallet and convective conditions (Moureh and Derens, 2000; Moureh et al., 2002; Margeirsson et al., 2011b).

Indeed, proper logistics are required to maintain fish quality as delivery of high value products is of outmost importance. Freshness deterioration is the first step involved early post-catch due to the degradation of nucleotides by autolytic enzymes followed by microbial activity leading to spoilage. Enzymatic and microbiological processes are greatly influenced by temperature (Huss, 1995). Recent work has shown that superchilled storage of cod (*Gadus morhua)* fillets at −1.5 to −1.0 °C can extend the freshness period and storage life (Martinsdóttir et al., 2005; Olafsdottir et al., 2006; Wang et al., 2008; Lauzon et al., 2009). Freshness characteristics of newly caught, gutted and iced cod generally last for 7–9 days. On the other hand, temperature abuse may shorten the freshness period and storage life of fish products. An increase in mean product temperature by 0.5 °C may reduce the freshness period and/or the storage life of processed fish by one day (Lauzon et al., 2010). This emphasises the importance to protect fresh fish products from thermal abuses early post-packaging during transport and storage.

The objective of the present work was to study temperature variation and quality deterioration of packaged cod fillets and relate the deterioration to the storage temperature conditions, product temperature changes and the packaging type used. This is influenced by the box type used and their position on pallets under dynamic temperature storage. This was done for two types of wholesale fresh fish boxes (EPS and CP) assembled on separate pallets. The obtained experimental results can be utilised to estimate fish quality deterioration caused by temperature fluctuations as well as to calibrate and validate heat transfer models for fresh fillets packaged in boxes on pallets.

2. Materials and methods

The raw material (Atlantic cod) was caught north of Iceland on 3 December 2008. The fish was bled and washed onboard the fishing boat before being stored in insulated tubs filled with ice until landing in Siglufjörður, North Iceland. After landing it was transported to the processing plant Festi in Hafnarfjörður in Southwest Iceland and kept overnight in a cold storage. During processing the following day (one day post-catch), the fish was gutted, washed, beheaded, filleted, deskinned and trimmed before packaging into the two different types of fish boxes. Mean weight of fillets (±standard deviation) was 426 ± 37 g. The boxes were palletised and transported in a mechanically refrigerated truck to Matís facilities in Reykjavík with transport time of less than 1 h. After insertion of temperature data loggers (see Sections 2.2 and 2.3), the boxes were re-palletised and put in an air climate chamber at around 1 °C. Throughout the 11-day storage, dynamic conditions were obtained by transferring the two pallets between three temperature-controlled air climate chambers, see Section 2.3. In order to estimate the quality deterioration caused by the dynamic temperature storage simulating air transport, some boxes were kept at steady temperature of around −0.4 °C representing a well temperature-controlled sea transport and distribution for 12 days, see Section 2.4.

2.1. *Wholesale fresh fish boxes and cod fillets*

Thirty-two 3-kg EPS boxes from Promens Tempra (Hafnarfjörður, Iceland) were assembled into four layers on a Europallet (dimensions: 120 × 80 cm), see Fig. 1. Four box layers were expected to suffice to yield storage life and spatial temperature differences, which could be transferred to a full size pallet stack by using a calibrated numerical heat transfer model. A similar setup using 3-kg CP boxes from Coolseal (Grimsby, UK) was obtained on another Europallet (Fig. 2). The thickness of EPS and CP box walls was around 22 mm and 2–13 mm, respectively. The dimensions and thermophysical properties of the CP boxes have been described in more details by Margeirsson et al. (2011a). The dimensions and thermal properties of fresh cod fillets and boxes over the temperature range of the current study are listed in Table 2.

Each fish box contained 3.01 ± 0.16 kg of fresh cod fillets at 1–2 °C upon arrival at Matís, but did not contain any ice packs or other phase change materials as commonly used to protect fresh fish products against thermal load (Margeirsson et al., 2011a,b). A cooling medium was not used in this trial to focus on the thermal protection of the packaging. Ice inside fish boxes is not allowed on board air planes due to leakage. Instead, ice/gel packs are used if required by the buyer.

2.2. *Measurement devices*

The specification of the different measurement devices used is presented in Table 1. Ibutton temperature loggers (DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) were used to monitor the temperature inside the insulated boxes under testing. Its diameter is 17.35 mm and the thickness is 5.89 mm. Tidbit v2 temperature loggers from Onset Computer Corporation (Bourne, MA, USA) were used to monitor the external temperature. All temperature loggers were factory calibrated and re-calibrated in a thick mixture of fresh crushed ice and water to ensure uniformity of the collected data. Relative humidity was monitored with HoBo U12 temperature and relative humidity loggers from Onset Computer Corporation (Bourne, MA, USA). Finally, air velocity was measured with Thermo-Anemometer Datalogger (model 451126) from Extech Instruments (Waltham, MA, USA).

Fig. 1 – Thirty-two EPS boxes containing cod fillets on a Europallet.

Fig. 2 – Thirty-two CP boxes containing cod fillets on a Europallet.

2.3. *Control of ambient conditions and configuration of monitoring devices*

The dynamic conditions were obtained by storing the palletised fish boxes in three temperature-controlled air climate chambers from Celsius (Reykjavík, Iceland). Two chambers at around 20 °C were used to store each pallet during the dynamic temperature periods on days 3 and 6, which lasted for 6.3 to 6.4 h (see Section 3.1). Following the warm-up periods, the pallets were chilled in the same chambers without (first chilling period) or with (second chilling period) air blast for 5.0 to 5.4 h. During the rest of the storage time both pallets were stored in the third chamber at around 1 °C. The mean air velocity surrounding the EPS pallet during the air blast chilling on day 6 is shown in Figs. 3 and 4.

Table 1 – Specification of measurement devices.

Device	Resolution	Range	Accuracy
Ibutton	0.0625 °C	−40–85 °C	±0.5 °C[a] between −15 and 65 °C
Tidbit v2	0.02 °C	−20–70 °C	±0.2 °C between 0 and 50 °C
HoBo U12	0.03%	5–95%	±2.5%
Thermo-Anemometer Datalogger	0.01 m s^{-1}	0.3–45 m s^{-1}	±(3% + 0.1) m s^{-1}

a Equal to the allowed deviation from the set point by standards for food distribution (BS EN 12830, 1999).

Table 2 – Dimensions and thermal properties.

Material	Inner dim. L × W × H (mm)	Outer dim. L × W × H (mm)	m (g)	ρ (kg m s^{-1})	c_p (kJ $kg^{-1}K^{-1}$)	k ($Wm^{-1}K^{-1}$)
Cod				1054[a]	3.73[b]	0.43[c]
EPS	355.5 × 220 × 85	400 × 264.5 × 121	171	23[d]	1.28 ± 0.05[e]	0.0345[d]
CP	370 × 230 × 80	395 × 247 × 85	178	116–164[f]	1.894 ± 0.002[f]	0.0184–0.0350[f]

a See Zueco et al. (2004).
b Mean value between 4 and 32 °C; see Rao and Rizvi (1995).
c Applies both at 0 and 10 °C according to Zueco et al. (2004).
d See Gudmundsson (2009).
e See Al-Ajlan (2006).
f See Margeirsson et al. (2011a).

Fig. 3 presents the air velocity downstream (8.9–9.9 m s^{-1}) and upstream (3.3–3.6 m s^{-1}) the cooling unit above the EPS pallet. Very similar air velocity distribution was experienced in the chamber with the CP pallet: 8.5–9.9 m s^{-1} and 3.2–3.4 m s^{-1} downstream and upstream the cooling unit, respectively. Furthermore, the velocity at the CP pallet surface and at the walls and floor close to the pallet was 0.3–1.5 m s^{-1}, which is comparable to 0.2–1.4 m s^{-1} for the EPS pallet presented in Figs. 3 and 4. The evolution of ambient air temperature and relative humidity during the whole storage time is presented in Section 3.1.

The product temperatures were monitored at four different positions inside ten EPS boxes and four CP boxes. The locations of the EPS boxes on the Europallet are shown in Fig. 5 along with the locations of the monitored CP boxes (numbers in circles) on the other pallet. The aim of this configuration was to yield a fair comparison between the two different packaging types both at the most sensitive (corners) and least sensitive (centre) locations on each pallet. More emphasis was put on the EPS pallet because the EPS box is known to protect fish fillets better. The four different positions of temperature data loggers inside each box are shown in Fig. 6. Three loggers were located in the middle of the fish bulk in each box: at the top (L1), mid-height (L2) and bottom (L3). The fourth location was at the most temperature sensitive position, i.e. at the bottom corner (L4), as shown in the figure.

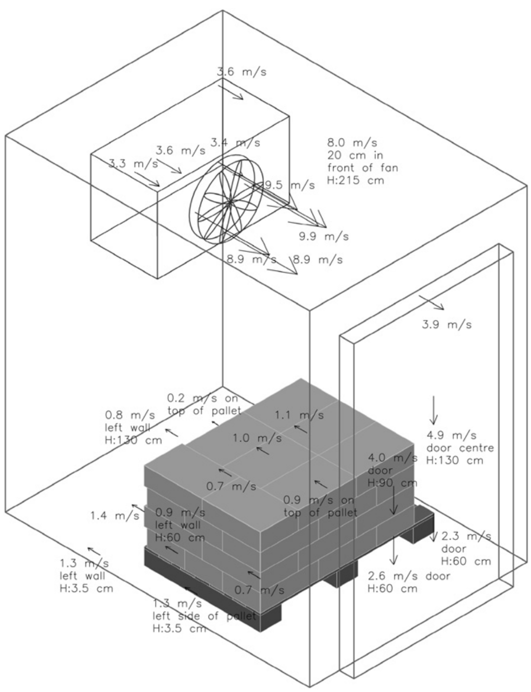

Fig. 3 – Velocity inside the chamber with the EPS pallet during air blast chilling in the second dynamic period, left view.

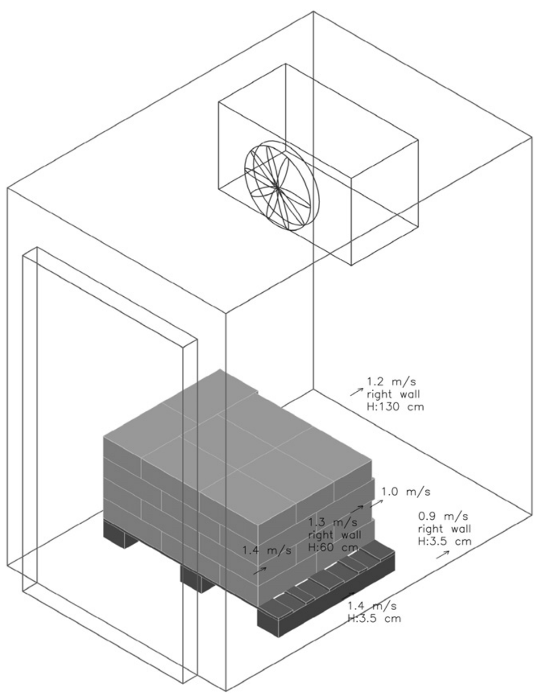

Fig. 4 – Velocity inside the chamber with the EPS pallet during air blast chilling in the second dynamic period, right view.

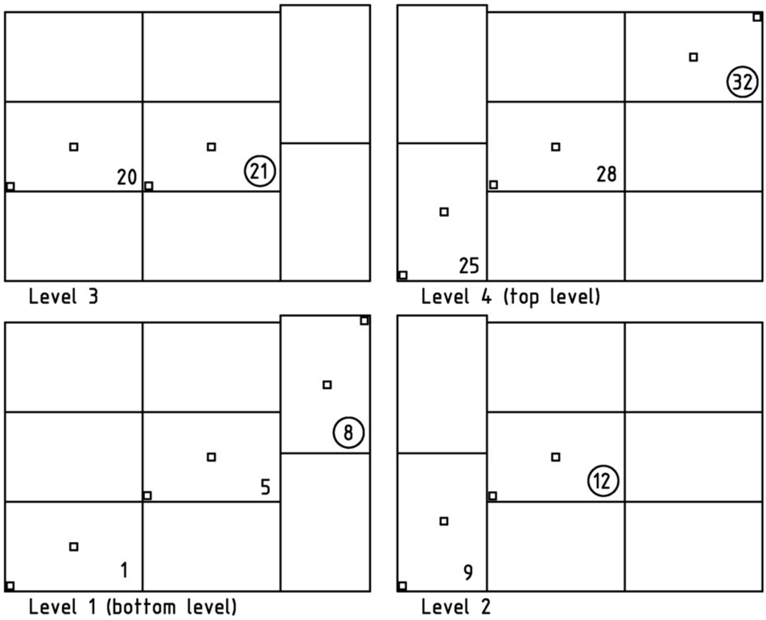

Fig. 5 – Configuration of fish boxes and numbering of ten temperature-monitored EPS boxes and four CP boxes (circled numbers) at the four layers on each pallet. Small squares represent the horizontal positions of temperature data loggers, see vertical positions in Fig. 6.

2.4. *Storage life study*

Six experimental groups are presented in Table 3 along with the sampling days. Day 0 represents the day of processing and packaging (one day post-catch). For microbiological analysis, two fillets were pooled into one sample, where three parts of each fillet were aseptically cut and minced. Duplicate samples were obtained from upper and lower positions in the box. Minced flesh (20 g) was mixed with 180 g of chilled Maximum Recovery Diluent (MRD, Oxoid) in a stomacher for 1 min.

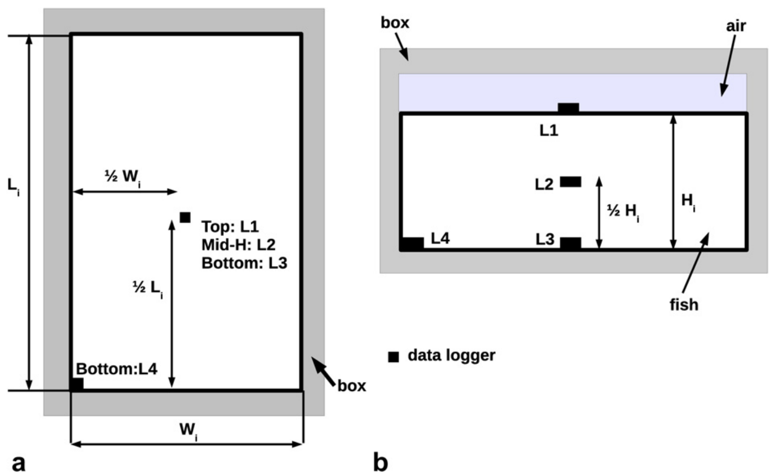

Fig. 6 – Positions of product temperature loggers in nine out of ten temperature-monitored EPS boxes and four CP boxes: a) in horizontal plane, b) in vertical plane. Product temperature in the bottom corner (L4) was not monitored in EPS box no. 28 (see Fig. 5).

Table 3 – Experimental groups evaluated throughout storage. ST: steady storage temperature, DT: dynamic storage temperature, Mi/Co: samples taken from boxes at the middle/corners of the pallet stack. Sampling days in parentheses refer to days with microbial sampling only.

Group	Sampling days, post-packaging
EPS-ST	(1), 4, 8, 12
EPS-DT-Mi	5, (11)
EPS-DT-Co	(1), 4, 7, (11)
CP-ST	(1), 4, 7, 12
CP-DT-Mi	5, (11)
CP-DT-Co	(1), 4, 7, (11)

Successive 10-fold dilutions were done as required. Total viable psychrotrophic counts (TVC, 17 °C for 5 days) were evaluated from Iron Agar (IA), as described by Gram et al. (1987) but with 1% NaCl and no overlay. Enumeration of specific spoilage organisms (SSO) in cod was performed using IA (counting black colonies as H_2S-producing bacteria) and cephaloridine fucidin cetrimide (CFC) agar (modified according to Stanbridge and Board (1994)) for detection of presumptive pseudomonads (incubated at 22 °C for 3–4 days). All agar media were surface-plated and incubated aerobically. Furthermore, counts of *Photobacterium phosphoreum* were estimated by the PPDM-Malthus conductance method (Dalgaard et al., 1996). Mean results are reported as log colony-forming units (CFU) g^{-1}. The rest of the mince was used for trimethylamine (TMA) measurements. The method of Malle and Tao (1987) was used. TMA was measured in TCA extract by adding 20 ml of 35% formaldehyde, an alkaline binding mono- and diamine, TMA being the only volatile and measurable amine.

Sensory analysis of fish in palletised boxes was only performed early storage (days 4 and 7 for corner boxes, and day 5 for inner boxes) to compare freshness among groups, since a restricted number of boxes could be used without disturbing the temperature profile of the pallets. Any box removed from the pallet for analysis was replaced by another one that contained fish and had been maintained in the same chamber. Quantitative Descriptive Analysis (QDA), introduced by Stone and Sidel (2004), was used to assess the sensory characteristics of cooked samples. Ten panellists were trained according to international standards (ISO 8586, 1993). The members of the panel were familiar with the QDA method and experienced in sensory analysis of cod. Thirty sensory attributes for appearance (3), odour (10), flavour (9) and texture (8) were evaluated using an unstructured scale (0–100%) as described in Sveinsdóttir et al. (2009). Storage life determination was based on the mean QDA score for spoilage related attributes (sour and TMA odour and/or flavour) reaching above 20%, indicating that the sample is approaching the end of storage life. Freshness equivalence was determined based on QDA mean data for all odour attributes of cooked fish, comparing the freshness stage of steady and corner boxes to those in the middle of the pallets which were analysed on day 5. This allowed the determination of the days at which steady and corner boxes had similar QDA odour scores compared to the centre boxes on day 5. Samples taken towards the box centre were cut from the loin part of the fillets into 40-g portions, placed in aluminium boxes coded with three-digit random numbers and cooked for 6 min in a pre-warmed oven (Convotherm Elektrogeräte GmbH, Eglfing, Germany) at 95–100 °C with air circulation and steam. Each panellist evaluated duplicates of each sample group in a random order during eight sessions (maximum of four samples per session). A computerised system (FIZZ, Version 2.0, 1994–2000, Biosystèmes) was used for data recording.

Statistical analysis of data was carried out with NCSS 2000 (UT, USA) using one-way ANOVA. Comparison of data with respect to treatments was performed using the Tukey–Kramer multiple comparison test. The threshold level for significance was 0.05.

3. Results and discussion

3.1. *Effect of air blast on ambient conditions*

Evolution of ambient temperature around the two pallets during the whole storage period is presented in Fig. 7. The figure shows that the dynamic ambient temperature profile applied in the current study represents a relatively well-controlled air transport chain with two main thermal loads no more hazardous than Mai et al. (2011) reported (up to 20 h at mean ambient temperature of 10–15 °C). Similarly, the mean ambient temperature of −0.4 °C for the steady storage represents a well temperature-controlled, containerised sea transport according to Mai et al. (2011). Table 4 presents the duration and ambient temperature at 0.8 to 0.9 m height at each step of the storage period shown in Fig. 7. The short peaks in Fig. 7 represent short warm-up periods outside chambers (periods no. 5 and 9 in Table 4). The ambient temperature at three different heights is zoomed up in Fig. 8 for both pallets during the dynamic temperature periods on days 3 and 6.

It is generally observed that during the dynamic periods, the floor temperature was around 2–3 °C lower than close to the top of the chambers at 2.1 m height. The third location was

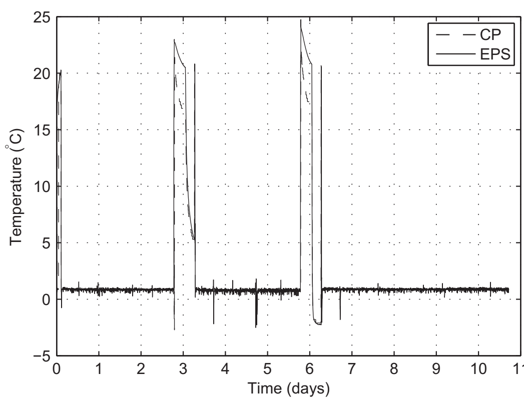

Fig. 7 – Ambient temperature evolution at 0.8 to 0.9 m height during storage of cod fillets packaged in EPS and CP boxes palletised separately.

Table 4 – Ambient temperature 0.3 m above pallets and duration of each storage period for the two pallets (EPS/CP).

Period no.	Cooling conditions	Start of period (h from packaging)	Duration (h)	Mean ambient temp. (°C)	Std. dev. ambient temp. (°C)
1	Warm-up outside chamber	1.0/1.0	2.6/2.6	18.9/13.1	1.0/8.6
2	Cooling in same chamber	3.6/3.6	64.3/64.5	0.8/0.8	0.3/0.3
3	Non-blast warm-up in separate chambers	67.9/68.1	6.4/6.3	21.4/17.8	0.7/1.3
4	Non-blast cooling in separate chambers	74.3/74.4	5.3/5.1	8.5/7.5	3.5/2.6
5	Warm-up outside chambers	79.6/79.5	0.2/0.2	11.1/12.2	9.0/7.9
6	Cooling in same chamber	79.8/79.7	60.0/60.2	0.7/0.8	0.3/0.4
7	Non-blast warm-up in separate chambers	139.8/139.9	6.4/6.4	22.1/18.5	1.0/1.5
8	Blast cooling in separate chambers	146.2/146.3	5.4/5.1	−1.3/−1.4	2.9/2.3
9	Warm-up outside chambers	151.6/151.4	0.1/0.1	20.6/20.7	0.0/0.0
10	Cooling in same chamber	151.7/151.5	106.5/106.7	0.9/0.9	0.2/0.2

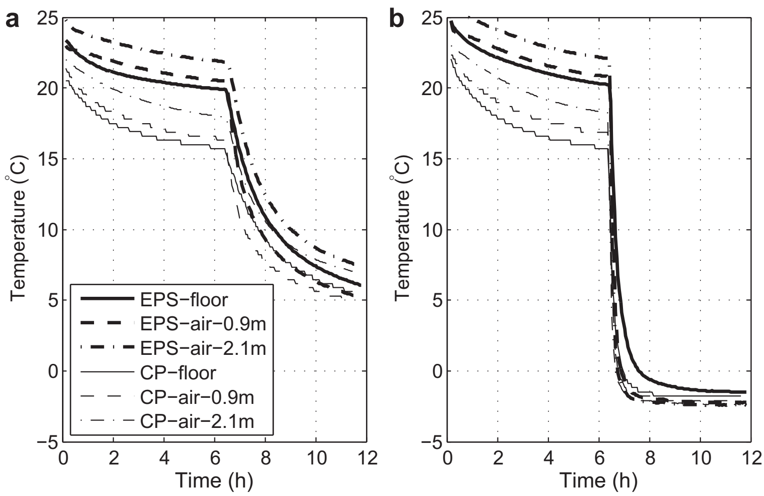

Fig. 8 – Ambient temperature evolution for the two dynamic periods during storage of cod fillets packaged in EPS and CP boxes on pallets: a) first dynamic period on day 3 with non-air blast chilling, b) second dynamic period on day 6 with air blast chilling. Note that the legend is valid for both a) and b).

around 0.3 m above the top centre of each pallet. This is close to being directly below the front of the cooling unit causing the temperature at this location to decrease fastest during the non-blast chilling period. The mean air temperature around 0.3 m above the top centre of each pallet is given in Table 5 along with the air temperature decrease due to the chilling effect of the fish. The mean air temperature was 3.6 °C lower above the CP pallet than above the EPS pallet during the warm-up part of both dynamic periods. The higher air temperatures 0.3 m above the EPS pallet just before transfer of the pallets (1.6 and 2.4 °C, respectively) were not planned and were caused by a mechanical failure of the EPS chamber during these periods. Clearly, this ambient temperature difference makes the comparison between the insulation value of the two packaging types harder. Another thing worth noting is the considerably larger air temperature decrease above the CP pallet during the warm-up time (5.1–5.5 °C for CP vs. 2.5–4.0 °C for EPS, see Table 5), which implies that the EPS packaging is better insulated while the fish in the CP packaging has more chilling effect on its environment. Regarding this it should be noted that the heat capacity of single EPS and

Table 5 – Ambient temperature 0.3 m above pallets during warm-up in the two dynamic periods (no. 3 and 7 in Table 4).

Dyn. Period no. (box type)	Mean ambient temp. (°C)	Warm-up time (h)	Ambient temp. decrease during warm-up time (°C)
1 (EPS)	21.4	6.4	2.5
1 (CP)	17.8	6.3	5.1
2 (EPS)	22.1	6.4	4.0
2 (CP)	18.5	6.4	5.5

Table 6 – Ambient temperature 0.3 m above pallets during chilling in the two dynamic periods (no. 4 and 8 in Table 4).

Dynamic period no. (box type)	Ambient temp. at start of cooling period (°C)	Ambient temp. decrease during first 15 min of chilling (°C)	Air blast condition
1 (EPS)	20.5	3.3	No air blast
1 (CP)	16.3	2.6	No air blast
2 (EPS	20.8	16.6	With air blast
2 (CP)	16.9	14.5	With air blast

CP boxes is around 0.22 and 0.34 kJ/K, respectively, which can be seen as negligible compared to around 11.2 kJ/K for the 3-kg fish fillets inside each box.

The importance of air blast during the chilling periods on the air temperature distribution inside the two chambers is evident by comparing the results in Fig. 8b (second dynamic period with air blast) and 8a, where air blast led to a greater cooling rate. Furthermore, the difference between the temperature decrease during the first 15 min of chilling time in the two dynamic periods is presented in Table 6.

Relative humidity during the two dynamic periods, both in the ambience of the fish boxes and at the surface of an EPS box at layer 2, is presented in Fig. 9. The results shown are for humidity measured at 0.3 and 2.1 m height at the chambers walls in addition to the aforementioned EPS box surface. During most of the non-blast periods, the relative humidity was 6.5–10.5% higher at 0.3 m height than at 2.1 m height in the two chambers (Fig. 9a and left part of Fig. 9b). According to Still et al. (1998), this fact alone should generally lead to an increased convective heat transfer from the ambient air to the packages at the bottom during warm-up (thereby increasing the fish heating rate) compared to higher-layer packages. The main effect of relative air humidity is the latent heat effect of condensation, which tends to increase the heating rate due to condensed moisture from the air onto the packages. Only four box layers were used on the pallets in the current study, but the number of layers is often 10 to 13 in real fish industry applications (Þóroddsson, 2008), yielding package stack height of approximately 1.4–1.8 m. According to the current study, a few percentage relative air humidity difference should therefore be expected between the bottom and top packages on a fully loaded pallet in non-blast conditions.

3.2. *Product temperature distribution on the pallets*

The initial maximum product temperature differences on the EPS pallet were 1.0 °C and 1.8 °C for the first and second dynamic periods, respectively. The corresponding values for the CP pallet were 0.5 °C and 0.6 °C, respectively. The ambient thermal load and thermal inertia of the fish and packages caused the maximum product temperature differences in the pallet at a given time to rise to 8.3 °C and 8.5 °C for EPS boxes compared to 9.9 °C and 10.5 °C for CP boxes during the first and second dynamic periods, respectively. These product temperature differences were the absolute maximum temperature differences found on the pallets, i.e. the temperature differences between the most sensitive position L4 in the bottom corner boxes (no. 8, shown in Figs. 10 and 11) and the least sensitive position L2 of the mid-layer boxes (no. 12 and 21, shown in Figs. 12 and 13). Comparison of Figs. 10–13 reveals that the largest maximum temperature difference

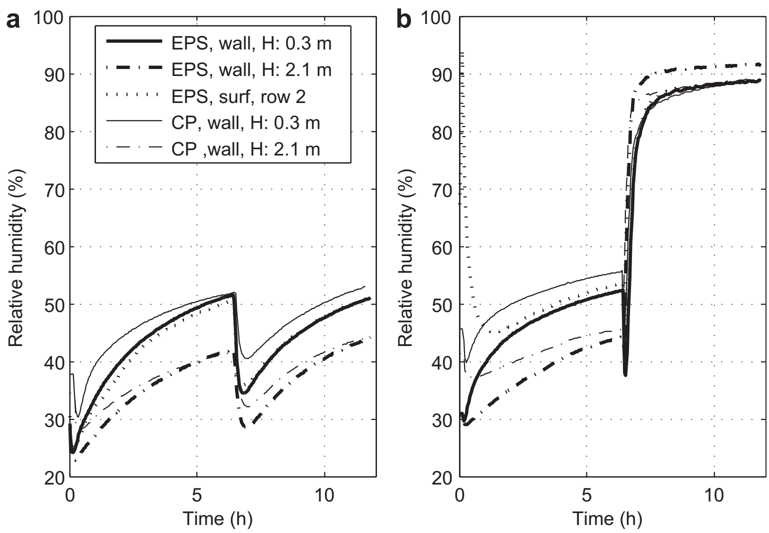

Fig. 9 – Relative humidity evolution during two dynamic temperature periods with cod fillets packaged in thirty two EPS and CP fish boxes: a) first dynamic period on day 3 with non-air blast chilling, b) second dynamic period on day 6 with air blast chilling. Note that the legend is valid for both a) and b).

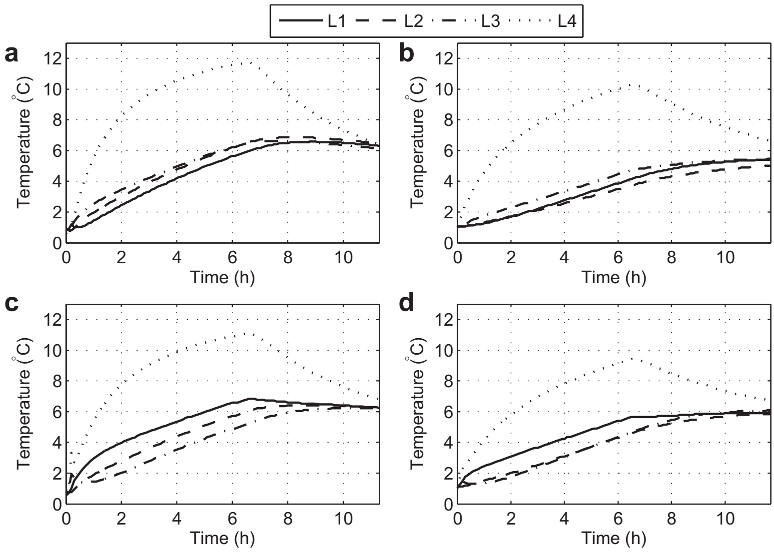

Fig. 10 – Product temperature evolution in two of the most temperature sensitive boxes on each pallet during the first dynamic period with no air blast chilling: a) Box CP-8 at bottom corner, b) Box EPS-8 at bottom corner, c) Box CP-32 at top corner, d) Box EPS-32 at top corner (see box configuration in Fig. 5).

inside each box in the two dynamic periods was found inside the bottom corner boxes (6.6–6.7 °C in EPS-8 and 6.4–6.9 °C in CP-8) compared to 4.9 °C (EPS-32) and 6.4–6.6 °C (CP-32) in the top corner boxes. The corresponding temperature differences inside the mid-layer boxes were only 0.4–1.1 °C in EPS-12/21 and 0.9–1.2 °C in CP-12/21.

The position, which best represents the fish fillets evaluated by sensory analysis, is the mid-height centre position (L2)

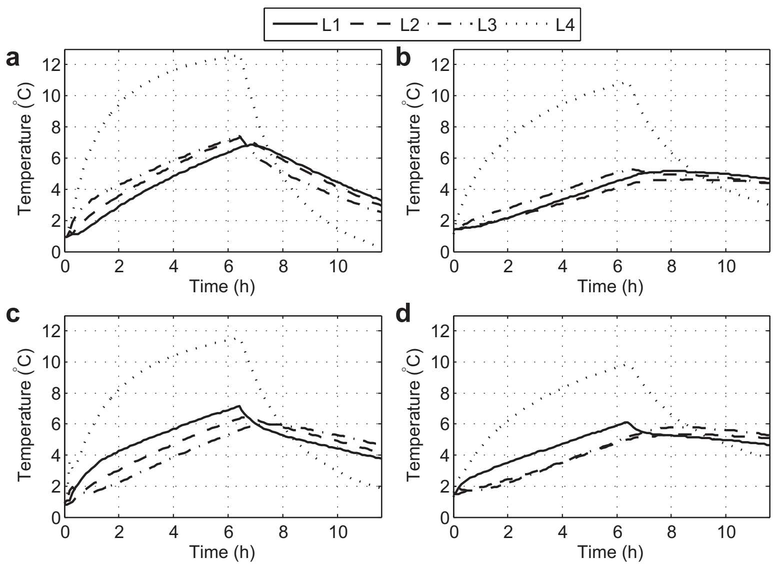

Fig. 11 – Product temperature evolution in two of the most temperature sensitive boxes on each pallet during the second dynamic period with air blast chilling: a) Box CP-8 at bottom corner, b) Box EPS-8 at bottom corner, c) Box CP-32 at top corner, d) Box EPS-32 at top corner (see box configuration in Fig. 5).

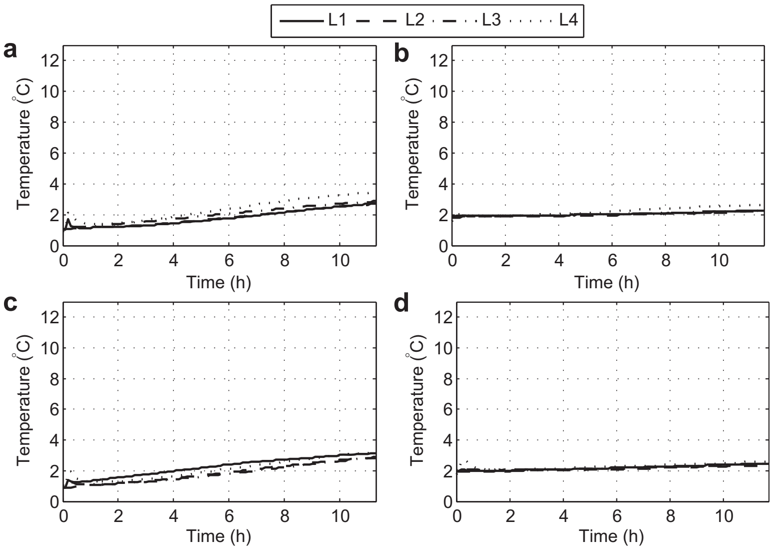

Fig. 12 – Product temperature evolution in the two least temperature sensitive boxes on each pallet during the first dynamic period with no air blast chilling: a) Box CP-12 at centre of layer 2, b) Box EPS-12 at centre of layer 2, c) Box CP-21 at centre of layer 3, d) Box EPS-21 at centre of layer 3 (see box configuration in Fig. 5).

since the samples were taken towards the box centres. The product temperature evolution for this particular centre position during the dynamic periods is shown in Fig. 14. The maximum centre temperatures (L2) in the top corner boxes EPS-25/32 were 0.5–1.2 °C higher than in EPS-1/8. The largest temperature rise in the top corner boxes is in good agreement with the findings of Moureh and Derens (2000), who recorded temperature at the centre of the outermost frozen fish portions only at top, medium and bottom corners of a pallet stack. However, the maximum temperatures of the EPS pallet

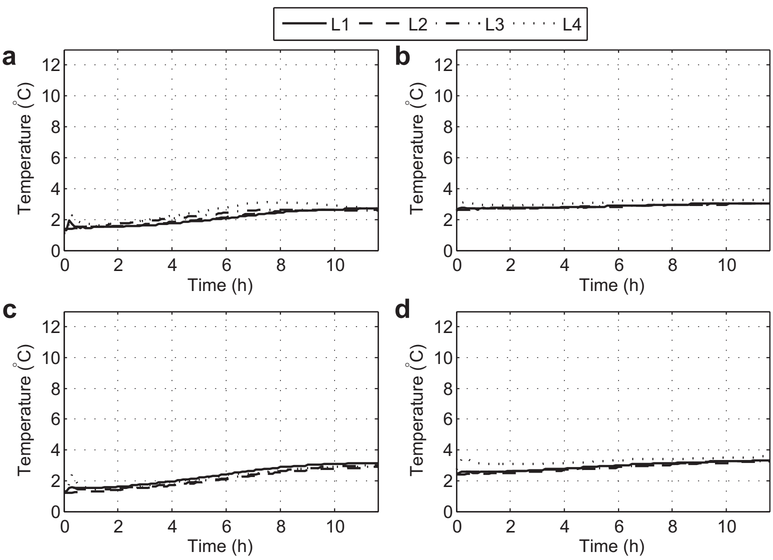

Fig. 13 – Product temperature evolution in the two least temperature sensitive boxes on each pallet during the second dynamic period with air blast chilling: a) Box CP-12 at centre of layer 2, b) Box EPS-12 at centre of layer 2, c) Box CP-21 at centre of layer 3, d) Box EPS-21 at centre of layer 3 (see box configuration in Fig. 5).

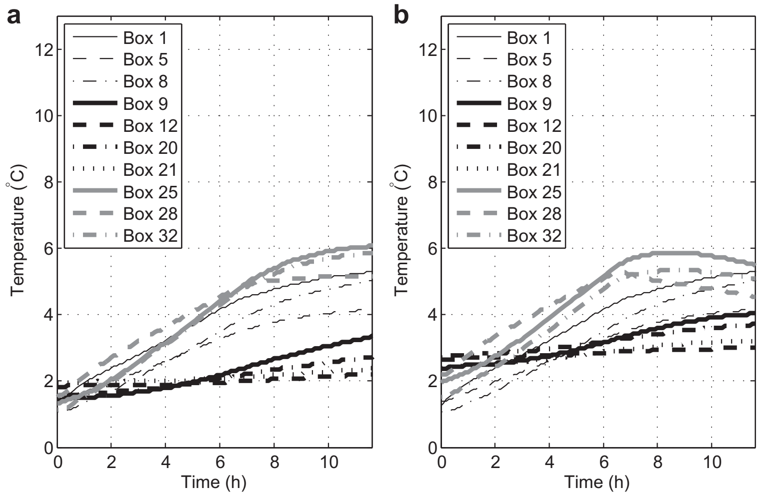

Fig. 14 – Product temperature evolution at the mid-height centre (L2) in all ten EPS boxes during the dynamic periods: a) First dynamic period on day 3 with no air blast chilling, b) Latter dynamic period on day 6 with air blast chilling (see box configuration in Fig. 5).

in the current study were experienced at L4 in the bottom corner boxes EPS-1/8 but not the top corner boxes EPS-25/32. This could be explained by the lack of temperature monitoring at the top corners above L4 in the top corner boxes, which should be the hottest spots according to Moureh and Derens (2000).

As could be expected and explained by the thermal inertia of the fish and packages, smaller differences were obtained for the centre temperatures between different boxes on the pallet, compared to the absolute maximum temperature differences on the pallet. The maximum centre temperature differences on the EPS pallet were 3.9 °C and 2.9 °C during the first and second dynamic periods, respectively. The corresponding values for the CP pallet were 4.8 °C and 5.2 °C.

It should also be noted that the maximum centre temperature differences between boxes were less than the temperature differences measured inside the corner boxes (up to 6.7 °C in EPS-8 and 6.9 °C in CP-8). This implies that the largest temperature gradients are found close to the boundaries of the pallet stack and that larger quality variation can be expected inside the corner boxes than between different box positions on the pallets. This also underlines the bigger risk for the outside boxes of the pallet stack and the accompanying need for master packaging solutions such as the insulated pallet covers that Moureh et al. (2002) studied both experimentally and numerically.

3.3. *Influence of packaging solution on temperature evolution*

The mean initial product temperatures during the first dynamic warm-up period were 1.1–1.9 °C in the EPS boxes and 0.7–1.0 °C in the CP boxes. The corresponding mean initial product temperatures during the second dynamic period were 1.3–2.7 °C in the EPS boxes and 0.9–1.3 °C in the CP boxes.

Figs. 10 and 11 show how the product temperature evolved at four locations inside the four corner boxes of the pallets in the first and second dynamic periods, respectively. Despite the fact that the ambient temperature was 3.6 °C lower above the CP pallet than the EPS pallet, the temperature increase inside the latter packaging type was smaller at all positions inside the fish boxes during both trials. This is in good agreement with the results by Margeirsson et al. (2009, 2011a), who reported the insulation performance of single EPS packages to be significantly better than for single CP packages. A comparison between the product temperature rise in the bottom corner of each of the four corner boxes during the second dynamic period is given in Table 7. As noted in Section 3.2, these are among the most thermally sensitive positions on each pallet.

The maximum product temperatures in the EPS and CP pallets during the first dynamic period were 10.3 °C and 11.8 °C, respectively. The corresponding maximum product temperatures during the second dynamic period were 10.9 °C

Table 7 – Product temperature changes in bottom corner of four of the most vulnerable boxes during the warm-up part of the second dynamic period, with mean ambient temperature of 22.1 °C (EPS) and 18.5 °C (CP) and warm-up time of 6.4 h.

Box	Bottom corner temp. before warm-up (°C)	Max. bottom corner temp. during trial (°C)	Temp. increase during warm-up (°C)
EPS-8	1.1	10.9	9.8
CP-8	0.9	12.6	11.7
EPS-32	1.3	9.9	8.6
CP-32	0.9	11.5	10.6

and 12.6 °C for the EPS and CP pallets, respectively. These maximum temperatures were measured in the bottom corner boxes on both pallets, i.e. EPS-8 and CP-8, during both dynamic periods. The difference between the two packaging types was similar in both dynamic periods.

The relatively good insulation of the EPS box is of greatest importance for the boxes in contact with the warm surrounding air. This can be noted from Figs. 12 and 13, which present the product temperature evolution of best protected centre boxes during the two dynamic periods due to their inner position on the pallets. Hardly any difference is seen between the temperature evolution at different points in these boxes during both dynamic periods. However, a clear upward trend is evidenced throughout the trials for the centre CP boxes while the temperature in the corresponding EPS boxes is relatively stable. The maximum product temperature inside CP-12 and CP-21 boxes increased during the whole first dynamic period by 2.4 °C and 2.2 °C, respectively, compared to 0.7 °C and 0.6 °C for EPS-12 and EPS-21, respectively. These results imply that during distribution of un-broken fish pallets, less insulated boxes could be used inside the outermost layer of better insulated boxes without increasing the thermal load on the inner boxes. However, the outer dimensions of the boxes put certain restrictions on this idea since too large box size variability on the same pallet can prevent secure box assembly on the pallet.

3.4. *Effect of box position on pallet and packaging type on fish quality deterioration*

Sensory data revealed that the storage life of the products stored under steady conditions was estimated to 11 days, based on QDA data obtained (not shown) and independently of the box type used. At this time point, spoilage indicators demonstrated that *P. phosphoreum* (Pp) was prevailing among other SSO and TMA was being produced to high levels 12 days post-packaging (Fig. 15). It is also noticed that at sensory rejection, Pp counts were close to log 7.5 CFU g^{-1} in both products. Based on this count, the storage life of cod products in palletised boxes was determined as reported in Table 8.

It is observed that the box position on the pallets influences the microbiological storage life obtained while the box type has no or little influence under the conditions tested. Indeed, a 3-day storage life reduction was seen for products stored at the most sensitive position (corners) on the pallets compared to those stored at steady storage conditions representing well-controlled, containerised sea transport.

At the least sensitive position (inner centre) of the pallets, the storage life was only reduced by about 2 days. This quality loss is explained by a 1000-fold increase in *P. phosphoreum* numbers 4 days post-packaging in corner boxes compared to boxes from steady conditions (Fig. 16). A lesser increase was measured 5 days post-packaging in boxes from the inner pallet centres. Therefore, a difference of at least 1 day in storage life was measured between the most and the least sensitive boxes on the pallets. Regarding this, it should again be noted that only four box layers were used on the pallets in the current study compared to 10 to 13 layers in real industry applications. Because of the extra thermal protection from the extra layers even higher maximum temperature differences should be expected for a full size pallet stack. Thus, it can be suggested that the storage life difference between the most and the least sensitive boxes on a full size pallet is even larger than the 1–1.5 days difference, observed in the current study.

As described under Section 2.4, sensory analysis of fish in palletised boxes was only performed early storage to compare freshness among groups. Based on QDA data for odour attributes of cooked fish a freshness equivalence bar graph was obtained (Fig. 17). It is shown that cod from the CP box positioned in the inner centre of the pallet (CP-DT-Mi) was of similar quality to that from less protected EPS boxes (EPS-ST and EPS-DT-Co), but of better quality than less protected CP boxes (CP-DT-Co). In contrast, fish from the protected EPS box (EPS-DT-Mi) was not of better quality than that from other boxes evaluated. This comparison is carried out two days after the first dynamic period, where air blast was not applied, and therefore only accounts for these effects. According to Fig. 8a, a warmer ambient temperature profile was seen for EPS boxes compared to CP boxes during the first dynamic period, while Fig. 12 shows a steady but initially slightly higher temperature

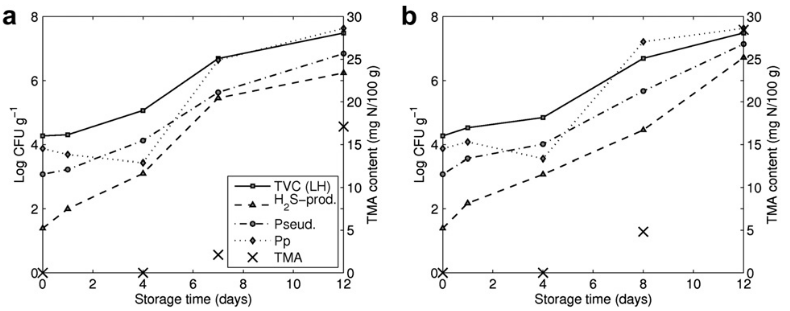

Fig. 15 – Development of microbiological and chemical spoilage indicators in cod fillets stored in CP (a) and EPS (b) boxes under steady conditions. TVC, total psychrotrophic viable counts on LH; H_2S-prod., counts of H_2S-producing bacteria on IA; Pseud., counts of presumptive pseudomonads on modified CFC medium; Pp, counts of *Photobacterium phosphoreum* estimated by the Malthus conductance method; TMA, trimethylamine content. Note that the legend is valid for both a) and b).

Table 8 – Storage life of cod products determined by sensory or microbial analysis. ST: Steady storage temperature, DT: dynamic storage temperature, Mi/Co: samples taken from boxes at the middle/corners of the pallet stack. Product temperature was calculated from box centres (L2) and tops (L1).

Group	Storage life (days)	Prod. temp. at L2 until end of storage life, mean ± std. dev. (°C)	Mean prod. temp. at L1 and L2 until end of storage life, mean ± std. dev. (°C)
EPS-ST	11[a]	0.3 ± 0.7	0.2 ± 0.8
EPS-DT-Mi	9[b]	2.7 ± 0.5	2.8 ± 0.5
EPS-DT-Co	8[b]	2.5 ± 1.2	2.5 ± 1.3
CP-ST	11[a]	0.4 ± 1.0	0.3 ± 1.1
CP-DT-Mi	9.5[b]	2.1 ± 0.7	2.1 ± 0.7
CP-DT-Co	8[b]	1.9 ± 1.6	1.9 ± 1.5

a Based on sensory evaluation.
b Based on microbial limit of log 7.5 CFU g^{-1} for counts of *Photobacterium phosphoreum*.

for EPS fish in the centre of the pallet. Therefore, the overall warmer fish in the EPS box resulted in a slightly lower quality product early post-packaging compared to CP packaged fish.

To conclude, temperature abuse at early storage time resulted in a greater quality deterioration and microbial growth in boxes positioned at corners than at the inner centre of the pallet. Further, the box type used influenced the freshness loss of the fish product stored under dynamic conditions at the most sensitive position as EPS boxes retarded freshness loss compared to CP boxes. The greater insulation of EPS packaging makes it the preferred choice for broken chill chains, especially when pallets are broken up during thermal load. On the other hand, the environmental advantages of the CP packaging can be favoured in well-maintained cold chains.

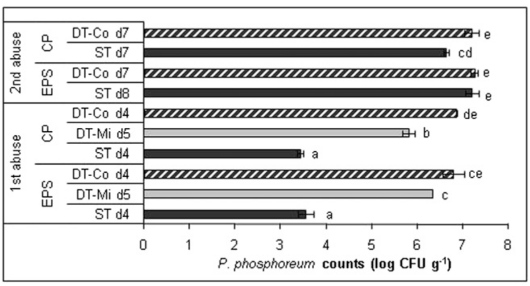

Fig. 16 – Mean counts of *P. phosphoreum* in cod fillets packaged in EPS and CP boxes as influenced by the temperature abuses and the box position on the pallet. Error bars indicate standard deviation and different letters represent significant difference between sample groups ($p < 0.05$). Temperature abuses (DT groups) occurred on day 3 (1st abuse) and day 6 (2nd abuse); ST denotes steady storage conditions; Co, corner box on the abused pallet from the top layer; Mi, box from the centre of the abused pallet.

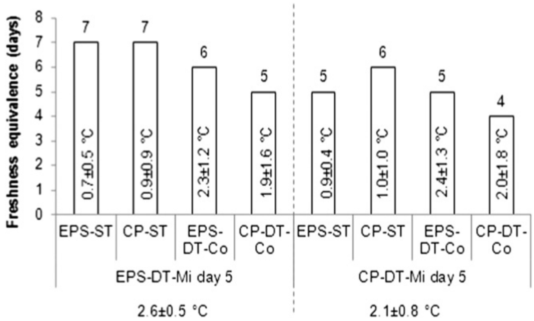

Fig. 17 – Freshness equivalence (in days) among groups based on the QDA odour scores obtained for the centre boxes (EPS-DT-Mi and CP-DT-Mi) on day 5. A value higher than 5 days indicates a retarded deterioration while a lower value depicts a faster deterioration. Product temperature (mean ± st. dev.) is given inside each bar.

4. Conclusions

Temperature variations and quality deterioration of cod fillets packaged and assembled on pallets were studied under simulated air and sea transport conditions. Ambient temperature and relative humidity were strongly influenced by air blast during chilling periods. Product temperature differences of up to 8.5 °C (EPS) and 10.5 °C (CP) were recorded on the pallets thermally loaded for 6.4 h at mean ambient temperature of 18.5–22.1 °C. The maximum temperature differences within single boxes were similar between the box types; 6.7 °C for EPS compared to 6.9 °C for CP. The corresponding maximum temperature differences inside the inner, mid-layer boxes on the pallets were only 1.1–1.2 °C caused by the thermal protection of the outer boxes.

Compared to storage life of fillets stored at temperature conditions simulating well-controlled, containerised sea transport, the dynamic temperature storage resulted in a storage life reduction of 1.5–3 days. The large temperature fluctuations in the boxes positioned at corners resulted in faster quality deterioration and microbial growth than at the inner centre of each pallet. The results from the current study suggest that the storage life difference between the most and the least sensitive boxes on a full size pallet in a real air transport chain can exceed 1–1.5 days, depending on the level of ambient thermal load.

EPS boxes at the most sensitive position proved to retard freshness loss at early storage following abusive temperature conditions. Although better insulating performance of EPS than of CP was confirmed, similar storage life was observed for fish stored in the two box types under variable temperature. Judging from the results of the current study, the greater insulation of EPS packaging makes it the preferred choice for broken chill chains. On the other hand, the environmental advantages of the CP packaging can be favoured in well temperature-controlled supply chains.

Acknowledgements

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Paper VI

Numerical modelling of temperature fluctuations of chilled and superchilled cod fillets packaged in expanded polystyrene boxes stored on pallets under dynamic temperature conditions

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Abstract

Temperature variations in cod fillets packaged in four levels of EPS boxes stored on pallets under thermal load were studied numerically and experimentally. In the experiment the fillet temperature along with environmental temperature were monitored at 39 positions on the pallets during 9–hour dynamic temperature storage between 7 and 23 °C. A three–dimensional time dependent heat transfer model was developed using the ANSYS FLUENT Computational Fluid Dynamics (CFD) software. The overall mean absolute error of the model was 0.3 °C and the maximum error obtained at a single position over the whole period was 2.4 °C. The model was further developed in order to simulate temperature evolution inside a fully loaded, 12–level pallet under the same dynamic temperature conditions as a four–level pallet studied before. The mean temperature after 9–hour thermal load was 1.0 °C lower in the 12–level pallet but the maximum temperature evolution was similar in both pallets. Finally, the model was used to investigate the temperature–maintaining effect of superchilling fish before the thermal load.

Keywords: Fish, Temperature variation, Heat transfer model, Packaging, Pallet, Precooling

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Nomenclature

b, B	box
c_p	specific heat capacity, $\mathrm{J\,kg^{-1}\,K^{-1}}$
d	thickness of box wall, m
EPS	expanded polystyrene
g	gravitational acceleration, $\mathrm{m\,s^{-2}}$
h_{conv}	convective heat transfer coefficient,$\mathrm{W\,m^{-2}\,K^{-1}}$
h_{rad}	radiative heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
H	height, m
k	thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
L	length, m
m	mass, kg
n	number of time steps
q	number of temperature sensors
Ra	Rayleigh number, dimensionless
R	thermal contact resistance, $\mathrm{m^2\,K\,W^{-1}}$
S	surface area, $\mathrm{m^2}$
t	warm up time, seconds
T	temperature, °C, K
V	volume, $\mathrm{m^3}$
W	width, m
x	characteristic length, m

Greek symbols

ρ	density, $\mathrm{kgm^{-3}}$
σ	Stefan-Boltzmann's constant, $(5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}})$

Subscripts

amb	ambient
b	box
bot	bottom of pallet stack
f	fish fillet
in	inside
init	initial
out	outside
stack	pallet stack
top	top of pallet stack
w	wall

1. Introduction

Quality and storage life of perishable foods, such as chilled and superchilled cod (*Gadus morhua*), is highly temperature–dependent. Temperature of the perishables during transport and storage in the chill chain are affected by different factors, such as initial product temperature (level of precooling), thermal properties of the foodstuff, ambient conditions (e.g. temperature, air flow, solar radiation, humidity and time) and insulative inner and outer (master) packaging. Research has shown that the chill chain is often broken and consequently the products are unprotected and not refrigerated for a substantial part of the transport time from packaging to consumer (Gill et al., 1996; James et al., 2006; Raab et al., 2008; Rediers et al., 2009). Mai et al. (2011) found much more severe temperature control problems in air transport chains than in sea transport chains and James et al. (2006) state that up to 80% of the relatively short air transport time involves waiting on the tarmac and transport to and from the airport. According to both James et al. (2006) and Mai et al. (2011), air temperatures between 15 and 20 °C can be expected in the aircraft hold during flight.

Considerable effort has been put in studying thermal load effects on refrigerated food and to relate product temperature changes to abusive ambient conditions and thermal properties of the food and packaging solutions (Zuritz and Sastry, 1986; Dolan et al., 1987; Almonacid-Merino et al., 1993; Moureh and Derens, 2000; Tanner et al., 2002a,b; Stubbs et al., 2004; Laguerre et al., 2008; Mai et al., 2011; Margeirsson et al., 2011a,b, 2012). Both experimental and numerical methods have been used in these studies to show that the temperature distribution in single packages and in whole pallets subjected to thermal load is in general inhomogeneous, with highest temperatures at the corners of the packages/pallets and the most stable temperatures at the centre of the packages/pallets. Insulated pallet covers are one of the available options for improving the chill chain for air freighted foods but they are actually not always applicable (Bollen et al., 1997; Amos and Bollen, 1998; Moureh et al., 2002). Before being loaded onboard passenger aircrafts, which frequently are used for perishable cargo, pallets are broken up to maximise volume exploitation of the cargo hold of the airplanes (Grétarsson, 2011). None of the aforementioned studies has covered a numerical heat transfer model of fresh (chilled or superchilled) fish assembled on pallets, even though it is an important subject for e.g. Iceland. Air transported, fresh fish from Iceland is a high–value product with a FOB (free on board) export value of around 65 to 96 million EUR (Statistics Iceland, 2011).

Margeirsson et al. (2012) did however examine temperature variations in a storage life study, observing product temperature differences of up to 8.5 °C on a thermally abused pallet with fish in EPS (expanded polystyrene) boxes stored for 6.4 h at mean ambient temperature of 22.1 °C. In this storage life study, three different thermal loads with durations of approximately 3, 6 and 12 h and a mean ambient temperature of 19 to 22 °C resulted in a 1.5 days longer storage life at the least sensitive centre box as compared to the most sensitive corner box. The known temperature control problems and the high value of fresh fish products clearly indicate the need for a three–dimensional heat transfer model to predict more detailed temperature variations within a whole, fresh fish pallet, which could be coupled with storage life models (Amos and Bollen, 1998; Mai et al., 2011). Results from such models could be used to investigate the effect of various dynamic thermal load profiles on storage life in a reasonably accurate and predictive way.

Superchilling is a preservation method for foodstuff, which implies partial freezing, i.e.

lowering the food temperature to no more than 1 to 3 °C below the initial freezing point, $T_{\mathrm{f,init}}$ (Aune, 2003; Magnussen, 2008; Kaale et al., 2011). The initial freezing point of most fresh food is around −1 °C (Pham, 1996) and the initial freezing point of cod is specified by Rahman (2009) as −0.91 °C. Although it does not apply to this paper, the term "superchilling" is actually also used when chilling a product to a temperature between the initial freezing point of the product and 0 °C (Aune, 2003; Ando et al., 2004). Studies have shown that storing both fresh cod and other foods such as salmon, prawn and pork at superchilled temperatures is effective in delaying microbial growth, maintaining freshness and prolonging storage life (Aune, 2003; Ando et al., 2004; Martinsdóttir et al., 2005; Olafsdottir et al., 2006; Duun, 2008; Magnussen, 2008; Kaale et al., 2011). Superchilling cod with water content of 80–82% down to −2 °C implies that around 50–55% of the product's water content is frozen (Rha, 1975). In order to avoid excessive surface freezing and ice crystal growth, which can cause structural damage and negative texture changes to the fish flesh and increase drip loss (Bahuaud et al., 2008; Magnussen, 2008; Kaale et al., 2011), cod is normally superchilled to around −1 °C in modern industrial applications (Valtýsdóttir et al., 2010; Stevik and Claussen, 2011).

The process of precooling has been defined as the removal of field heat (prior to transport and storage) thus slowing deteriorative processes so as to maintain a high level of quality that ensures customer satisfaction (Brosnan and Sun, 2001). Precooling also protects the foodstuff against thermal load during distribution, especially if the food is precooled to a superchilled temperature below the initial freezing point, causing partial freezing and build–up of a cold reservoir in the product. The "SuperChiller" cooling technique by Marel Ltd., Garðabær, Iceland (formerly referred to as combined blast and contact (CBC) cooling technique) is an example of an efficient equipment for precooling fresh fish fillets, requiring only around 8 to 10 min to lower the fillet temperature from around 1 to 4 °C to temperatures between -1.0 and −0.5 °C with the air temperature in the SuperChiller set at −8 °C (Gao, 2007; Valtýsdóttir et al., 2010).

The objective of the present work was to develop and validate a 3–D heat transfer model which could be used to predict product temperature changes in thermally loaded, chilled and superchilled cod fillets packaged in EPS boxes and assembled on a pallet. To validate the model, numerical results were compared with experimental results. Furthermore, the aim was to investigate the effect of pallet stack height and precooling on fish temperature during thermal load. The numerical models developed can be utilised to improve the design of insulative master packaging or estimate storage life in a cost effective way, since it is highly related to the product temperature history and can be related to a storage life prediction model.

2. Materials and methods

2.1. Experimental setup

The experimental setup and results have previously been described in detail by Margeirsson et al. (2012) for a 11–day storage life study. Only the dynamic temperature period on day 3 after packaging is used in the current study to compare experimental results to the numerical results. Thus, only the experimental setup and results related to that specific period are described here.

2.1.1. *Wholesale fresh fish boxes and cod fillets*

Thirty–two 3–kg EPS boxes from Promens Tempra (Hafnarfjörður, Iceland) were assembled into four layers on a Europallet (dimensions: 120 x 80cm), see Figure 1. The boxes weighed 171 g and had inner and outer dimensions of $L_{b,in} \times W_{b,in} \times H_{b,in}$ = 355.5 x 220 x 71 mm and $L_{b,out} \times W_{b,out} \times H_{b,out}$ = 400 x 264.5 x 121 mm, respectively. The thickness of the top and bottom of the EPS boxes was 25.0 mm and the thickness of the vertical side walls was 22.25 mm. The thermal properties adopted in the numerical heat transfer models are presented in Section 2.2.

Each fish box contained 3.01 ±0.16 kg of fresh cod fillets at 1.1 to 2.0 °C at the beginning of the dynamic temperature period under consideration.

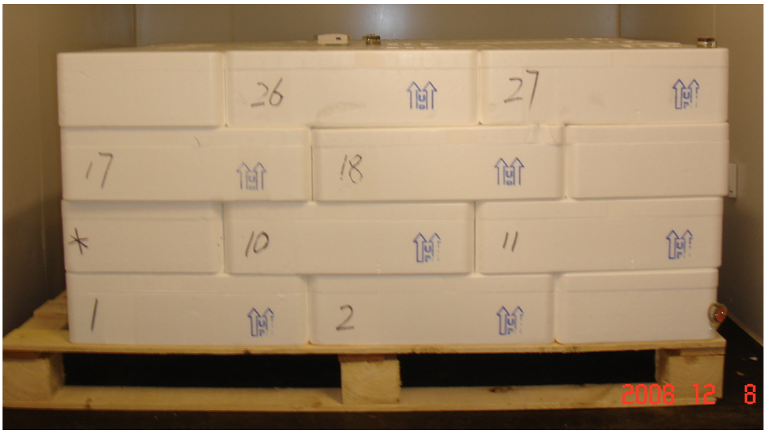

Figure 1: Thirty-two EPS boxes containing cod fillets on a Europallet in an air climate chamber.

2.1.2. *Measurement devices*

The specification of the different measurement devices used is presented in Table 1. Ibutton temperature loggers (DS1922L) from Maxim Integrated Products (Sunnyvale, CA, USA) were used to monitor the temperature inside the insulated boxes under testing. Each logger's diameter is 17 mm and the thickness is 6 mm. Tidbit v2 temperature loggers from Onset Computer Corporation (Bourne, MA, USA) were used to monitor the ambient and surface temperatures. All temperature loggers were factory calibrated and re–calibrated by the authors in a thick mixture of fresh, crushed ice and water to ensure uniformity of the collected data.

2.1.3. *Control of ambient environment and configuration of monitoring devices*

After instrumentation, the pallets were stored for 64 h at 0.8 ±0.3 °C in a temperature–controlled air climate chamber from Celsius (Reykjavík, Iceland) to ensure temperature homogenization within the pallet stack. Then the dynamic temperature conditions were obtained by transferring the palletised fish boxes and the pallet into another climate

Table 1: Specification of temperature data loggers.

Device	Resolution	Range	Accuracy
Ibutton	0.0625 °C	-40 to 85 °C	±0.5 °C [a] between −15 and 65 °C
Tidbit v2	0.02 °C	-20 to 70 °C	±0.2 °C between 0 and 50 °C

[a] equal to the allowed deviation from the set point by standards for food distribution (BS EN 12830, 1999)

chamber of the same type. The applied thermal load period consisted of a 6.4–h warm up period at around 21 °C followed by a 5.3–h cooling period, all performed in still air. The evolution of ambient and surface temperatures at different locations during the whole dynamic period is presented in Figure 2.

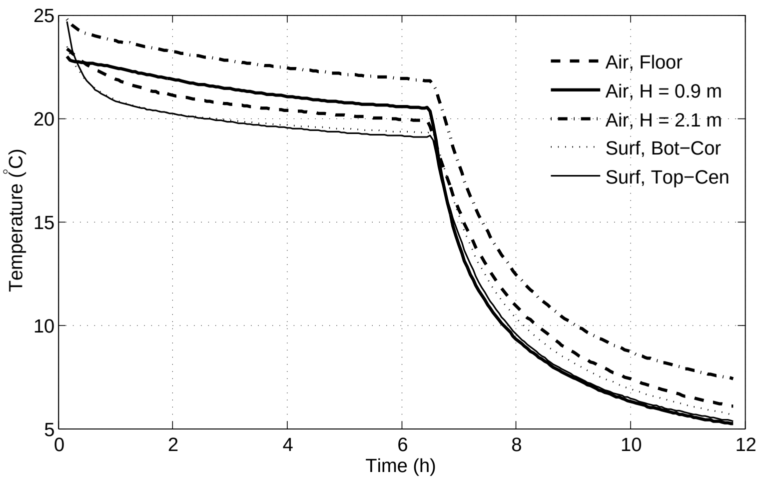

Figure 2: Experimental results: evolution of ambient temperature at three levels and surface temperature at two levels during dynamic temperature storage of packaged and palletised cod fillets.

The product temperatures were monitored at four different positions inside ten fish boxes. The locations of the boxes on the Europallet are shown in Figure 3. The aim of this configuration was to grasp product temperature extremes, i.e. monitor temperature both at the most sensitive (corners) and least sensitive (centre) locations in the pallet stack. The four different positions of temperature data loggers inside each box are shown in Figure 4. Three loggers were located in the middle of the fish bulk in each box: at the top (L1), mid-height (L2) and bottom (L3). The fourth location was at the most temperature sensitive position, i.e. at the bottom corner (L4), as shown in the figure.

2.2. Heat transfer modelling

The numerical heat transfer model for single EPS boxes described by Margeirsson et al. (2011a) was extended in order to take into account an increased number of fish boxes and 14 mm lower boxes with capacity of 3 kg instead of 5 kg.

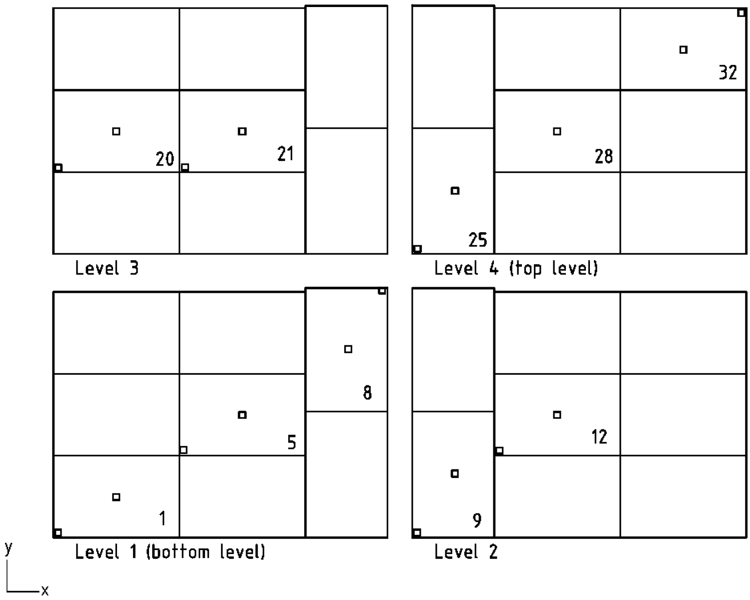

Figure 3: Configuration of fish boxes and numbering of ten temperature-monitored fish boxes at the four layers on the pallet. Small squares represent the horizontal positions of temperature data loggers, see vertical positions in Figure 4.

2.2.1. Computational domain

Two models were built, one for the 32 boxes as used in the experiment and another for a fully loaded pallet with 96 boxes in 12 levels. For both models the lower part of the computational domain was limited to the five deck boards (2.2 cm in thickness and with accumulated area of $0.48\,m^2$ compared to $0.85\,m^2$ bottom surface area of the pallet stack) and three stringer boards (2.2 cm in thickness and with accumulated area of $0.19\,m^2$) perpendicular and below the deck boards, see Figure 5. The EPS boxes containing a 36.5 mm thick fish layer were distributed evenly at the bottom of the box and a 34.5 mm thick air layer was included at the top inside each box. An unstructured computational mesh was used for both pallet stack sizes. The number of cells was 493801 and 932832 for the 4 and 12-level pallet stacks, respectively. Using an unstructured mesh comprised of 651409 cells resulted in less than 0.1 °C deviation in the mean temperature at the most sensitive positions in the 4-level pallet stack as compared to the coarser mesh. In order to spare computational power, the coarser mesh was used. The airflow outside the boxes was not modelled and was taken into account by using convection coefficients and ambient temperatures.

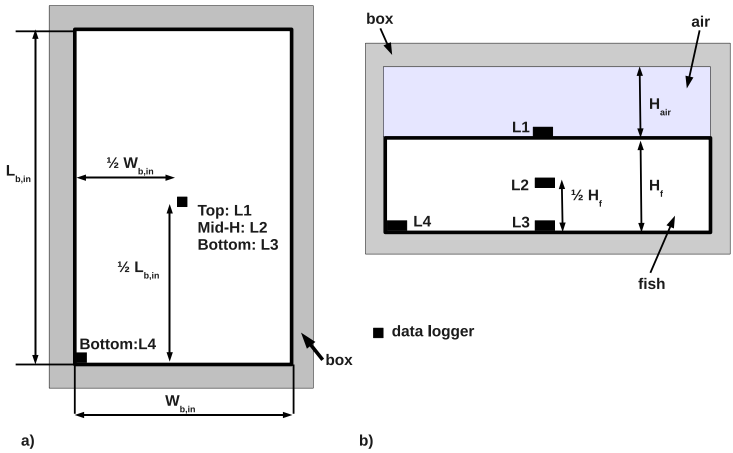

Figure 4: Positions of product temperature loggers in ten temperature-monitored fish boxes: a) in horizontal plane, b) in vertical plane. The temperature sensor in the bottom corner (L4) in box no. 28 failed (see box configuration in Figure 3). Dimensions: $L_{\mathrm{b,in}} = 355.5\,\mathrm{mm}$; $W_{\mathrm{b,in}} = 220\,\mathrm{mm}$; $H_{\mathrm{b,in}} = 71\,\mathrm{mm}$; $H_{\mathrm{air}} = 34\,\mathrm{mm}$; $H_{\mathrm{f}} = 37\,\mathrm{mm}$.

2.2.2. Modelling approach

A three dimensional finite volume heat transfer model was developed using the Computational Fluid Dynamics (CFD) software ANSYS FLUENT for a pallet with 4 box layers. Margeirsson et al. (2012) expected four box layers to suffice for the purpose of calibrating the model, which could then be used to model a full size pallet stack. Thus, after comparison to experimental results the model was further developed/scaled by increasing the number of box layers to 12.

Inside the fish fillets heat is transferred only by conduction described by the following partial differential equation:

$$\rho_{\mathrm{f}} c_{p,\mathrm{f}} \frac{\partial T_{\mathrm{f}}}{\partial t} = \nabla \cdot (k_{\mathrm{f}} \nabla T_{\mathrm{f}}) \tag{1}$$

As in Margeirsson et al. (2011b), the model by Choi and Okos (1986) was used for estimating the temperature dependent apparent specific heat capacity (c_p, both accounting for sensible and latent heat) of cod as shown in Table 2. A constant density of $1054\,\mathrm{kg\,m^{-3}}$ and values for thermal conductivity (k) were adopted from Zueco et al. (2004) assuming a sharp change at the initial freezing point of the fish, $T_{\mathrm{f,init}}$ (Table 2). The temperature dependencies of c_p and k were taken into account by linear interpolation but otherwise, the thermal properties of the fish were assumed to be isotropic and homogeneous in the model. The thermal properties of the remaining components of the computational domain are shown in Table 3.

The air layer above the fish fillets in each box is assumed to be static, implying that

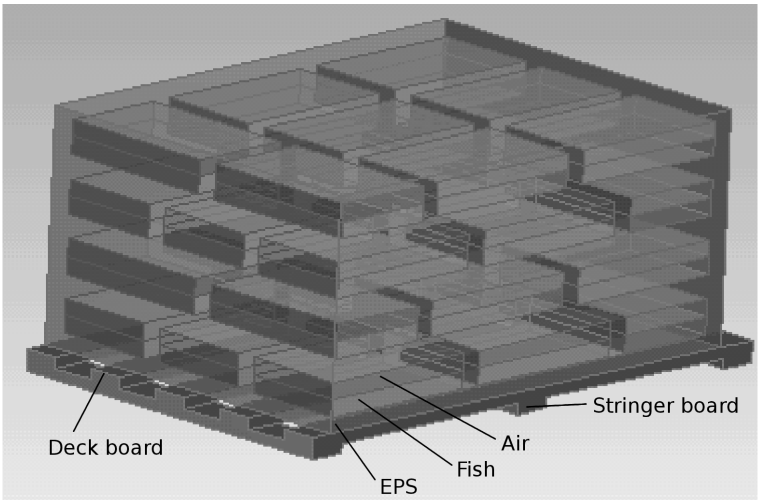

Figure 5: Computational domain comprised of an upper part of a pallet and EPS boxes containing fish and air.

Table 2: Linearly temperature dependent thermal properties of cod fish.

T (°C)	-1.00	-0.92	-0.9	-0.85	0	15
$c_{p,\mathrm{f}}$ (kJ kg^{-1} K^{-1})	189.4	223.0	3.679	3.679	3.675	3.755
k_{f} (W m^{-1} K^{-1})	1.302	1.302	0.43	0.43	0.43	0.43

Table 3: Thermal properties of the principal components of the computational domain except cod (see Table 2).

Domain	ρ (kg m^{-3})	c_p (kJ kg^{-1} K^{-1})	k (W m^{-1} K^{-1})
Air	1.225	1.006	0.0242
EPS	23[a]	1.28[b]	0.0345[a]
Pallet (wood)	500[c]	2.5[d]	0.12[e]

[a] Gudmundsson (2009); [b] Al-Ajlan (2006); [c] The Engineering Toolbox (2011a);
[d] The Engineering Toolbox (2011b); [e] The Engineering Toolbox (2011c)

heat transfer in the air is conductive, according to Eq. 1, and radiative, modelled with a Surface-to-Surface (S2S) radiation model, see Siegel and Howell (1992). The emissivity adopted for the inside surface of EPS boxes and the fish was 0.9 according to Earle and Earle (2004). The assumption of no convection above the fish fillets can be explained by the fact that during the warm up period the fish fillets are maintained at lower temperature than the inside of the box lid. This causes higher–density air to be trapped below lower–density air in the enclosed space above the fish fillets and thus no free convection takes place. During the cooling period the opposite situation is possible, i.e. that the inside of the box lid is colder than the air below in some boxes. However, according to the simulated results, the maximum vertical temperature difference (0.3 °C) in the air layers is too low to result in a Rayleigh number higher than the critical value of 1700, see Holman (2002), p. 337.

2.2.3. Boundary conditions

Mixed convection and external radiation boundary conditions were applied for both the top and the sides of the pallet stack. The convective heat transfer coefficient outside the pallet stack (h_{conv}) can be estimated from well known correlations, see Holman (2002) for laminar natural convection in air ($\text{Ra} < 10^9$), as follows:

- Pallet stack top (horizontal plane):

$$h_{\text{conv,top}} = 1.32 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{2}$$

- Pallet stack bottom (horizontal plane):

$$h_{\text{conv,bot}} = 0.59 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{3}$$

- Pallet stack sides (vertical planes):

$$h_{\text{conv,side}} = 1.42 \left(\frac{\Delta T}{x} \right)^{1/4} \tag{4}$$

  where $\Delta T = T_{\text{amb}} - T_{\text{w,out}}$ ($T_{\text{w,out}}$: outside box wall temperature) and x is the characteristic length (taken as $\frac{L_{\text{stack}} + W_{\text{stack}}}{2} = 0.932\,\text{m}$ in Eqs. 2, 3 and taken as no. of layers $\cdot\, H_{\text{b,out}} = 4 \cdot 0.121\,\text{m} = 0.484\,\text{m}$ in Eq. 4).

In order to estimate h_{conv} at the top, bottom and vertical sides of the pallet load, Eqs. 2 – 4 were used with a constant value of $\Delta T = 3\,\text{K}$. This value was estimated from a similar study by Margeirsson et al. (2011a) in which more precise measurements on T_{w} were performed than in the current study, however not explicitly presenting ΔT. This estimation is supported by the results in Figure 2, which also shows that the surface and ambient temperatures are time dependent, which makes it even harder to estimate ΔT. In addition to this, the surface temperature of each pallet stack plane is not uniform as noted by Moureh and Derens (2000). However, it should be noted that according to Eqs. 2 – 4, h_{conv} is proportional to $(\Delta T)^{1/4}$, which means that a deviation of 1 K from the set value of 3 K results in a relative change in h_{conv} which is lower than 10%. The estimated values for the convective heat transfer coefficients are presented in Table 4.

The time dependent ambient temperature measured 0.3 m above the pallet stack was adopted as the free flow (external) temperature for the convective and radiative boundary conditions at the pallet top and sides. Assuming the same temperature for the chamber wall (the radiation temperature, which was not measured) and for the air inside the chamber is a simplification, which can cause an error. Similarly, the ambient temperature measured at the chamber floor was adopted as the free flow temperature for the convective and radiative boundary conditions at the bottom of the pallet stack.

Table 4: Convective heat transfer coefficients adopted in the numerical heat transfer models of two different pallet sizes.

4/12 levels, plane	h_{conv} ($\mathrm{W\,m^{-2}\,K^{-1}}$)
4 levels, top	1.8
4 levels, bottom	0.8
4 levels, side	2.2
12 levels, top	1.8
12 levels, bottom	0.8
12 levels, side	1.7

The radiative heat transfer coefficient outside the box (h_{rad}) can be expressed according to the following relation (Moureh and Derens, 2000):

$$h_{\mathrm{rad}} = \frac{\sigma}{\frac{1}{\epsilon_{\mathrm{amb}}} + \frac{1}{\epsilon_{\mathrm{b,out}}} - 1} \left(T_{\mathrm{b,out}}^2 + T_{\mathrm{amb}}^2\right)\left(T_{\mathrm{b,out}} + T_{\mathrm{amb}}\right) \tag{5}$$

An emissivity of 0.9 was adopted for both the outside surface of EPS boxes and the chamber walls according to The Engineering Toolbox (2010) and Holman (2002).

2.2.4. Contact resistance

The pallet was made of wood with surface roughness of approximately 1 to 2 mm. Non–ideal surface contact was assumed between the bottom of each box and the pallet, and consequently a thermal contact resistance between the two surfaces, $R_{\mathrm{b,pallet}}$, was estimated. Margeirsson et al. (2011a) explained how the thermal contact resistance between an EPS box and plywood floor was estimated as $0.1\,\mathrm{m^2\,K\,W^{-1}}$ with regard to results for plate freezing applications (Cleland and Valentas, 1997) and pressure dependence of R (Novikov, 1970; Shojaefard and Goudarzi, 2008). The same value, i.e. $0.1\,\mathrm{m^2\,K\,W^{-1}}$, was adopted for $R_{\mathrm{b,pallet}}$ in the current study. BASF (2001) recommends as high as $0.2\,\mathrm{m^2\,K\,W^{-1}}$ for thermal contact resistance between solid food and food package, which further strengthens the choice of a relatively high value for $R_{\mathrm{b,pallet}}$. As Margeirsson et al. (2011a) noted in case of haddock, a lower thermal contact resistance should be expected between the fish fillets and the box ($R_{\mathrm{f,b}}$) than between the box and the pallet since the water content of fresh cod is as high as 80–82%. Thus, as in Margeirsson et al. (2011a) a value of $R_{\mathrm{f,b}} = 0.05\,\mathrm{m^2\,K\,W^{-1}}$ was adopted here.

2.2.5. Initial conditions

For the 4–level model, the mean fish temperature (from the four positions L1-L4) at the beginning of the thermal load in the experiment was adopted as the initial temperature throughout the whole box (EPS + fish + air) for each of the 10 temperature–monitored boxes, see Table 5. The initial temperature of the remaining boxes (including fish and air) and the pallet was defined as the mean fish temperature in the 10 boxes mentioned above at the beginning of the thermal load in the experiment. In order to estimate the effects of pallet stack height (see Section 3.2), the initial conditions were slightly simplified by adopting the mean fish temperature from the 10 temperature–monitored boxes in the 4–level experiment as the initial temperature of the whole domain (fish + air + EPS). The aim was to investigate the difference between the product temperature evolutions (mean, maximum and minimum product temperatures) in the two pallet stack sizes with numerical methods only, since experimental data was not available for the larger stack. The assumption is that, once properly calibrated on the smaller pallet, the model is capable of predicting the temperature evolution in the larger pallet with accuracy comparable to the one obtained for the smaller pallet. Similarly, to explore the effect of superchilling the fish before thermal load with numerical methods only (Section 3.2), the initial temperature of the whole domain was set to $-1.0\,^{\circ}$C.

Table 5: Initial temperatures adopted in the main heat transfer simulation for a 4–level pallet, see results in Section 3.1. B: box.

Domain	B1	B5	B8	B9	B12	B20	B21	B25	B28	B32	Other boxes	Pallet
T_{init} (°C)	1.3	1.4	1.1	1.4	1.8	1.5	1.9	1.3	1.5	1.1	1.4	1.4

3. Results and discussion

3.1. Comparison between numerical and experimental results

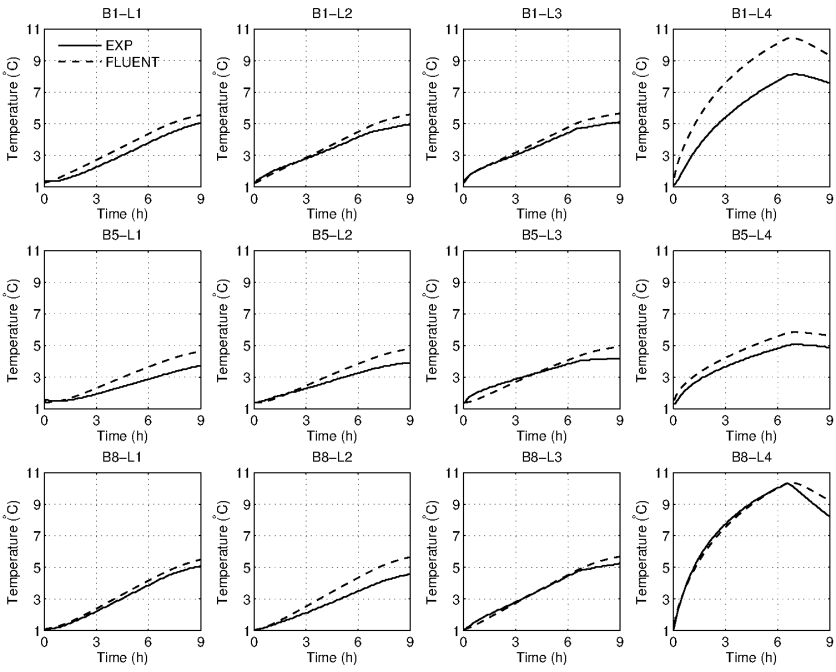

Figure 6: Comparison between simulation results (FLUENT) and experimental results (EXP) for 12 positions (see positions in Figure 4) inside EPS boxes at level 1, see box configuration in Figure 3.

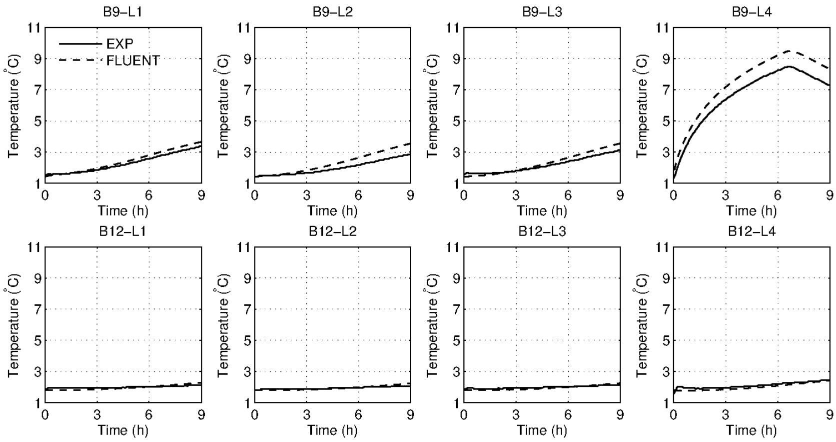

Figure 7: Comparison between simulation results (FLUENT) and experimental results (EXP) for 12 positions (see positions in Figure 4) inside EPS boxes at level 2, see box configuration in Figure 3.

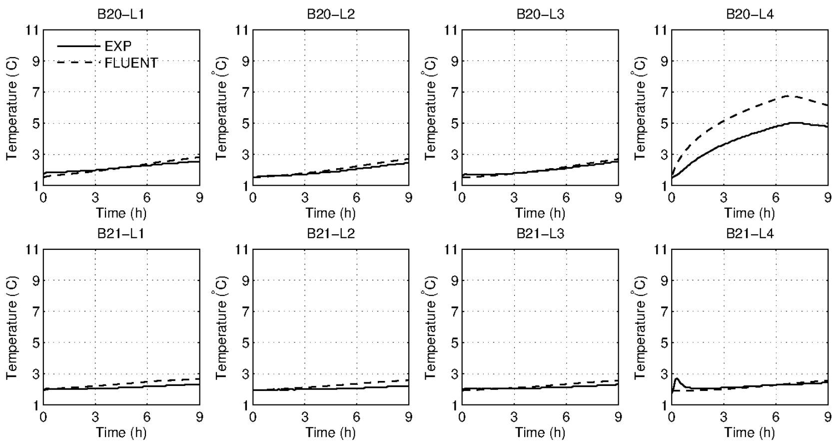

Figure 8: Comparison between simulation results (FLUENT) and experimental results (EXP) for 12 positions (see positions in Figure 4) inside EPS boxes at level 3, see box configuration in Figure 3.

Results from the numerical simulation with four box levels and the experimental results for 39 different positions inside EPS boxes at levels 1 to 4 are compared in Figures 6 to 9. The largest temperature rises within the boxes are in the top and bottom corner boxes, more specifically at the bottom corner position (L4 in Figure 4), as has already been pointed out by Margeirsson et al. (2012). These results are in good agreement with those of Moureh and Derens (2000), who explained this by pointing out the importance

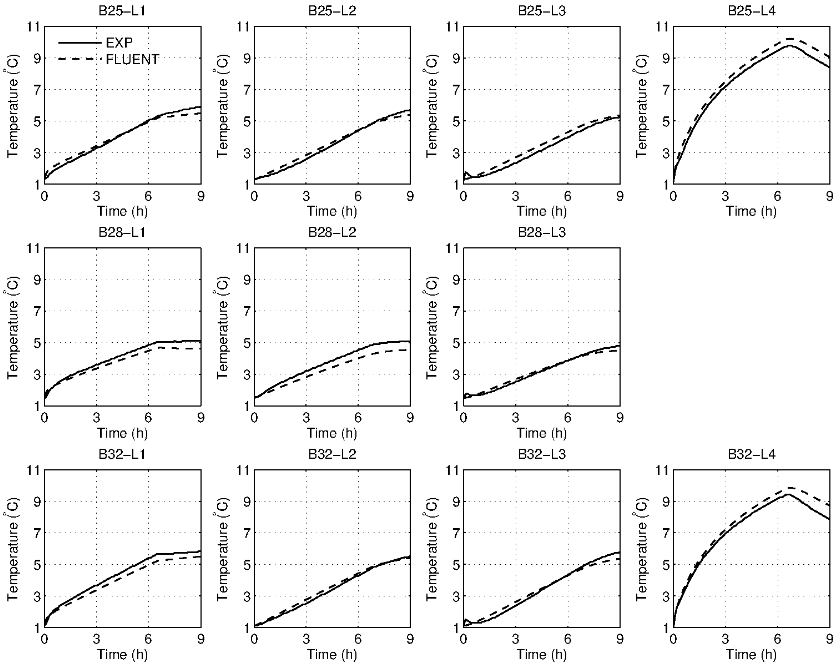

Figure 9: Comparison between simulation results (FLUENT) and experimental results (EXP) for 12 positions (see positions in Figure 4) inside EPS boxes at level 4, see box configuration in Figure 3.

of the number of box surfaces available for heat exchange with the ambience. In other words, the corner boxes are exposed to heat transfer from a greater number of sides than the other boxes. Judging from Figures 6 to 9, it can be stated that a good agreement is obtained between the numerical and experimental data in general and that the largest error is found at the bottom corner position (L4).

The good agreement between the numerical and experimental results is confirmed in Table 6 where the mean and maximum values of the absolute errors during a 9–hour thermal load of numerical results for the 39 data loggers are presented. The mean and maximum absolute errors and overall mean absolute errors in the table are calculated using the following relations:

$$\text{Mean abs. error} = \frac{1}{n}\sum_{i=1}^{n} |T_{\text{exp,i}} - T_{\text{numerical,i}}| \tag{6}$$

$$\text{Max. abs. error} = \max_{i=1}^{n} |T_{\text{exp,i}} - T_{\text{numerical,i}}| \tag{7}$$

$$\text{Overall mean abs. error} = \frac{1}{q \cdot n} \sum_{j=1}^{q} \sum_{i=1}^{n} |T_{\text{exp,i,j}} - T_{\text{numerical,i,j}}| \tag{8}$$

where the number of time steps was $n = 90$ (6 minutes intervals between measurements) and the number of positions (temperature sensors) was $q = 39$.

From Table 6 it can be observed that the mean absolute error at each level is below 0.6 °C for all four levels. The overall mean absolute error of the four levels is 0.3 °C. In this context, it should be noted that the accuracy of the temperature sensors is ±0.5 °C, i.e. larger than the overall mean absolute error. The largest mean and maximum errors in each level are written in boldface in Table 6 and it can be concluded that the largest error is found for position L4 (bottom corner), especially in the outer boxes (B1, B8, B9, B20, B25, B32) as compared to lower errors at the centre positions (L1, L2, L3) and especially in the the middle boxes (B12 and B21). Also, the higher mean absolute error at level 1 as compared to the other levels is noticeable (0.5 °C vs. 0.2 to 0.3 °C).

Table 6: Mean and maximum absolute errors (°C) of numerical results during 9 hours of dynamic temperature storage.

Level 1 Position	Error mean (max.)	Level 2 Position	Error mean (max.)	Level 3 Position	Error mean (max.)	Level 4 Position	Error mean (max.)
B1-L1	0.5 (0.6)	B9-L1	0.2 (0.3)	B20-L1	0.1 (0.3)	B25-L1	0.2 (0.4)
B1-L2	0.3 (0.7)	B9-L2	0.3 (0.7)	B20-L2	0.1 (0.3)	B25-L2	0.2 (0.3)
B1-L3	0.3 (0.6)	B9-L3	0.2 (0.4)	B20-L3	0.1 (0.2)	B25-L3	0.3 (0.4)
B1-L4	**2.1 (2.4)**	B9-L4	**0.9 (1.1)**	B20-L4	**1.5 (1.8)**	B25-L4	**0.4 (0.7)**
B5-L1	0.5 (0.9)	B12-L1	0.1 (0.2)	B21-L1	0.2 (0.4)	B28-L1	0.3 (0.5)
B5-L2	0.4 (0.9)	B12-L2	0.1 (0.2)	B21-L2	0.2 (0.4)	B28-L2	**0.4 (0.6)**
B5-L3	0.3 (0.7)	B12-L3	0.1 (0.1)	B21-L3	0.1 (0.3)	B28-L3	0.1 (0.3)
B5-L4	0.6 (0.8)	B12-L4	0.1 (0.2)	B21-L4	0.1 (0.8)	B28-L4	
B8-L1	0.2 (0.4)					B32-L1	0.3 (0.4)
B8-L2	0.6 (1.1)					B32-L2	0.1 (0.3)
B8-L3	0.2 (0.5)					B32-L3	0.2 (0.4)
B8-L4	0.3 (1.0)					B32-L4	**0.4 (0.9)**
Mean	0.5	Mean	0.2	Mean	0.3	Mean	0.3

Part of the difference between the heat transfer models and the measurements can be attributed to inaccurate placement of the temperature sensors. Since the largest temperature gradients are found close to the outside surfaces of the pallet stack (see Figures 10 and 11), sensor placement is most important for the bottom corner position (L4) in the outer boxes in the pallet stack. In relation to this, the difference between the temperature evolution in the experiment at L4 in the two bottom corner boxes B1 and B8 should also be noted. The much slower temperature rise at B1-L4 and the good agreement between numerical and experimental data for B8-L4 could suggest that the temperature sensor at B1-L4 was not placed correctly at the bottom corner of box B1, i.e. closer to the middle of the box. The relatively good fit between experimental and numerical results for the corner positions B25-L4 and B32-L4 at the top level further strengthens the idea of imprecise positioning of the B1-L4 temperature sensor. However, imprecise positioning alone is probably not enough to fully explain the maximum error of 2.4 °C observed for the B1-L4 sensor since the simulation results imply that a misplacement of 3–4 cm is needed.

Another possible source of error in the heat transfer model is the shape of the fish bulk in each box because in the model, a uniform fish thickness is assumed but in reality the thickness was largest in the middle of each box. The third source of error (also noted by Margeirsson et al. (2011a)) is found in adopting a steady, uniform convective heat transfer coefficient (h_{conv}) for each outside surface of the pallet stack. In reality, h_{conv} is non–uniform for each side and is highest at the beginning of the warm up period when the temperature difference between the ambience and the outside surface is greatest. The last source of error in the heat transfer model is found in the initial conditions. The temperature distribution in each of the temperature-monitored boxes at the beginning of the thermal load in the experiment must not have been completely homogeneous as assumed in the model. Likewise, the initial temperature in the remaining boxes and the pallet in the experiment must not have been a constant as in the model.

Taking all of this into account, it is concluded from the comparison between numerical and experimental results, that the numerical model is capable of predicting the temperature changes at different positions inside thermally abused, palletised fish boxes with sufficient accuracy.

Temperature contours in two vertical cross–sections of the four–level pallet are presented in Figures 10 and 11. The cross–sections were chosen in order to investigate the extreme temperatures found in the pallet stack, i.e. both at the most stable positions close to the centre and at the most vulnerable positions near the outside surfaces of the stack. In Figure 10, the cross–section is taken at the middle of the pallet (through boxes no. 2, 10, 18, 26 etc. in Figure 1) but in the latter figure, the cross–section is taken 2.5 cm from the wall inside the boxes at the left side of the pallet stack shown in Figure 1 (boxes no. 1, 17, etc.). Very inhomogeneous temperature distributions are noticed in Figures 10 and 11, where large temperature gradients are found close to the outside surfaces of the pallet as opposed to the relatively stable temperature in the centre of the pallet stack (Figure 10). Comparison between the temperature distributions in the two cross–sections further emphasises the sensitivity of the outermost boxes in the stack since higher temperatures are seen in Figure 11 than in Figure 10.

3.2. Effect of pallet stack height and precooling

Simulated temperature contours in a vertical cross–section 2.5 cm from the wall inside the boxes at the left side of the 12–level pallet are presented in Figure 12. These temperature contours are comparable to the ones for the 4–level pallet in Figure 11. Comparison between Figures 11 and 12 indicates that the additional levels in the 12–level stack should result in a slower temperature rise in the middle of the pallet stack. This is because of higher thermal resistance between the core and the surface in the higher pallet stack.

The effect of pallet stack size can further be observed from Figure 13, which presents maximum, minimum and mean product temperatures for the two pallet stack sizes. The additional box levels have very limited effect on the maximum temperature rise (Figure 13a) because the fish at the most sensitive positions (corners of corner boxes) are still similarly exposed to the ambient thermal load despite the increased number of box layers. The minimum temperature at the middle of the stack is slightly more affected by the stack height, resulting in a 0.5 °C lower minimum temperature for the 12–level pallet after a 9–hour thermal load, see Figure 13b. These small differences indicate that similar absolute maximum temperature differences should be expected for the two pallet stack sizes and further justify the use of only 4 box levels for representing a whole pallet in the storage life study by Margeirsson et al. (2012). The results from the current study thereby indicate that similar maximum storage life difference between the most and the

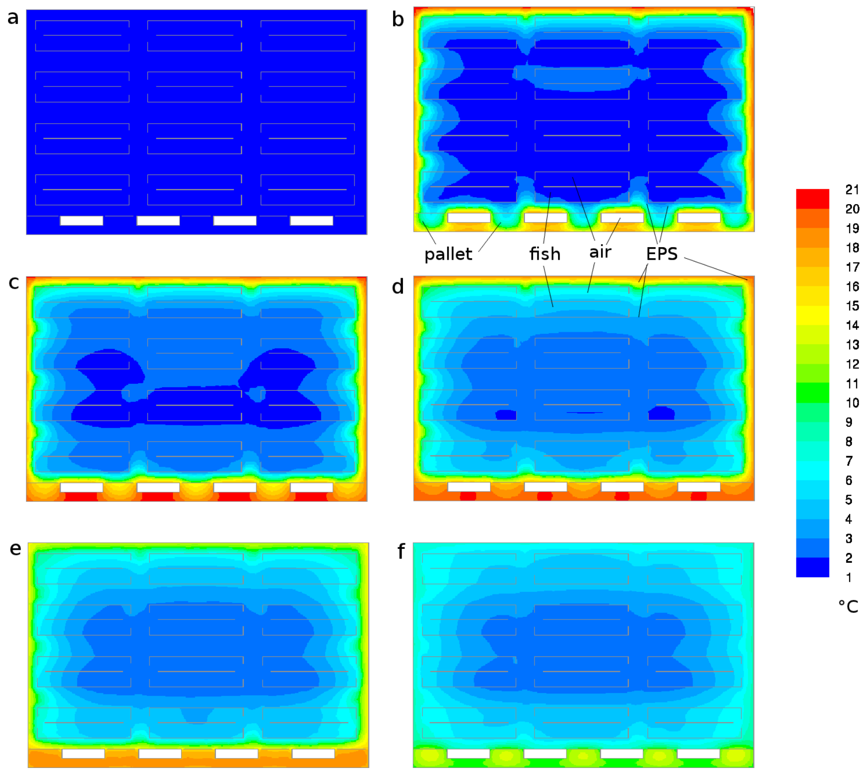

Figure 10: Numerical results: temperature contours in a vertical mid–section of the four–level pallet during dynamic temperature storage a) at the beginning of thermal load and after b) 1 h, c) 3 h, d) 6 h, e) 7 h, f) 9 h of thermal load.

least sensitive boxes are to be expected for a full size pallet under simulated air transport temperature conditions as Margeirsson et al. (2012) obtained, i.e. 1 to 1.5 days.

The largest effect of the added box layers is seen in the mean temperature shown in Figure 13c. The mean temperature after a 9–hour thermal load was 1.0 °C lower in the 12–level pallet, which implies that a more even product quality could be expected for a full size pallet than in case of a 4–level pallet. It should be noted that this does not contradict the prediction of similar maximum storage life differences for the two pallet stack sizes. More even product quality on the full size pallet can be expected because the mean temperature is closer to the minimum temperature (resulting in maximum storage life) meaning that a higher ratio of fish boxes on the full size pallet will have temperature close to the minimum temperature of the pallet.

The slower mean temperature rise in the 12–level pallet can be explained by a lower

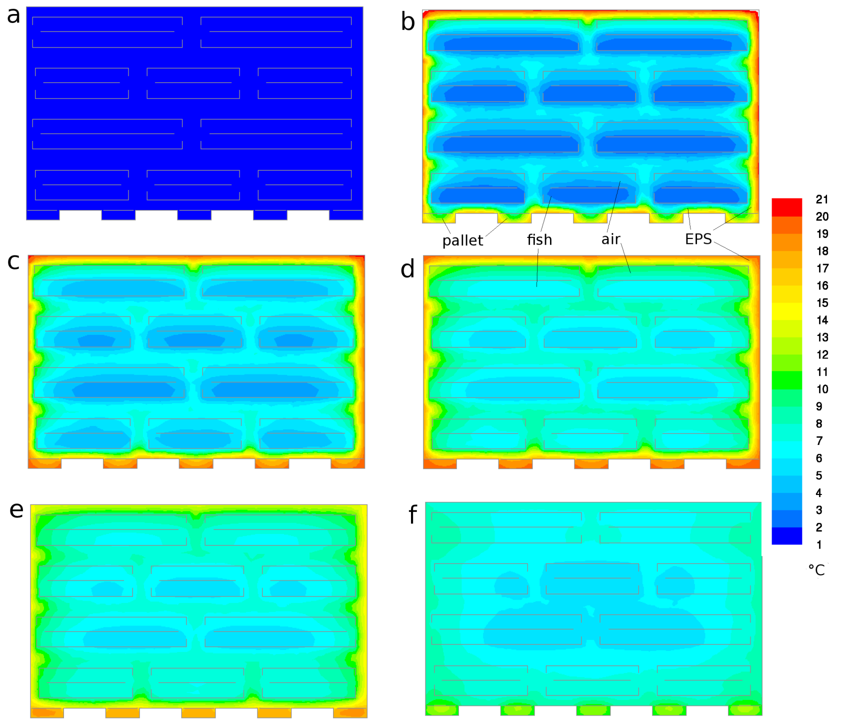

Figure 11: Numerical results: temperature contours in a vertical section 2.5 cm from the wall inside the boxes at the left side of the four–level pallet during dynamic temperature storage a) at the beginning of thermal load and after b) 1 h, c) 3 h, d) 6 h, e) 7 h, f) 9 h of thermal load.

surface area to volume ratio. A larger surface area results in a higher heat transfer rate between the ambient air and the pallet stack while larger volume yields larger heat capacity, thereby reduced temperature rise.

The positive, temperature maintaining effect of precooling the cod fillets to the superchilled (SC) temperature of −1 °C before the thermal load can also be seen in Figure 13. The latent heat of the partially frozen water in the superchilled fish (initial freezing point taken as −0.92 °C and assuming no supercooling) causes a slower fish temperature rise than in case of the non–superchilled (NC) fish at the initial temperature of 1.4 °C (despite the fact that the temperature difference between fish and ambient air is higher for the superchilled fish, which increases heat transfer from the ambience to the fish). The initial mean temperature difference between the NC–fish and the SC–fish was 2.4 °C. The numerical models predict this temperature difference to increase during the 9–hour dynamic temperature period to 4.8 °C while the difference between the maximum temperatures of NC and SC–fish is predicted to be around 3.5 to 4.5 °C throughout

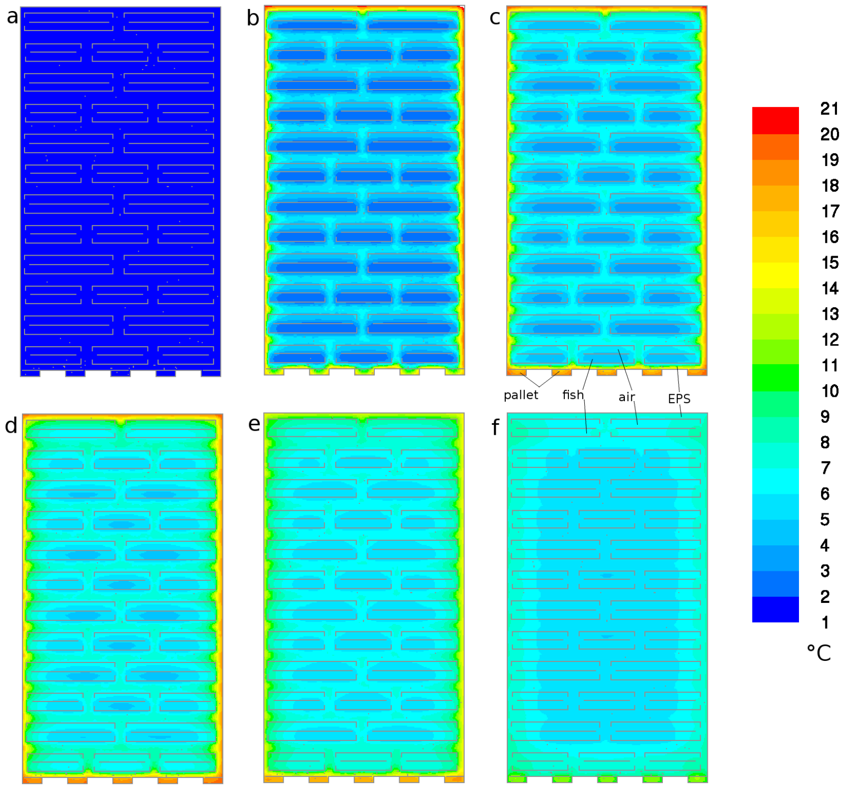

Figure 12: Numerical results: temperature contours in a vertical section 2.5 cm from the wall inside the boxes at the left side of the 12–level pallet during dynamic temperature storage a) at the beginning of thermal load and after b) 1 h, c) 3 h, d) 6 h, e) 7 h, f) 9 h of thermal load.

most of the 9–hour period. Minimising temperature rises in the product by precooling thermally loaded fresh fish has been shown to be important for maximising storage life (Magnússon et al., 2009; Gao, 2007).

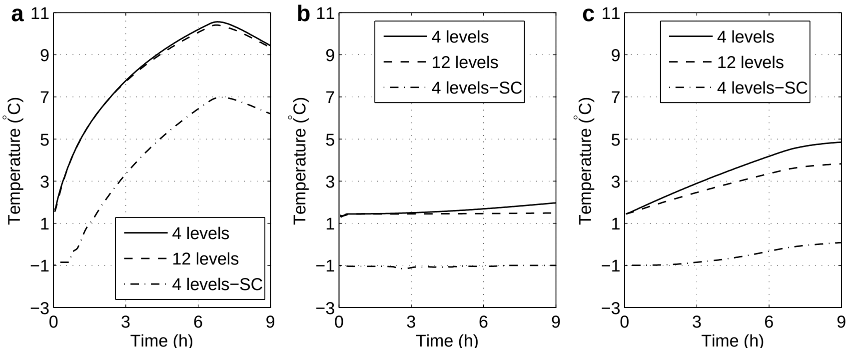

Figure 13: Numerical results: product temperature evolution in 4–level pallet vs. 12–level pallet during 9–hour dynamic storage. a) maximum temperature, b) minimum temperature, c) mean temperature. SC: fillets superchilled at −1 °C at the beginning of thermal load.

4. Conclusions

In this work, temperature variations in cod fillets packaged in both four and twelve levels of palletised EPS boxes under thermal load have been studied numerically and experimentally. In general, good agreement was obtained between numerical and experimental results for four box levels, resulting in an overall mean absolute error around 0.3 °C. The largest errors were obtained at positions close to the pallet stack corners while the mean absolute error was as low as 0.1 °C in the centre boxes. This emphasises the importance of accurate placement of the temperature sensors where the temperature gradients are highest.

The results from the numerical modelling indicate that the fish temperature on a fully loaded, 12–level pallet under thermal load evolves differently as compared to a partially loaded, 4–level pallet. This applies for the mean temperature, which was predicted to be 1.0 °C lower for the larger pallet after the 9–hour dynamic ambient thermal load used in this study. As mentioned before, this should result in a more even product quality on the temperature abused 12–level pallet, compared to the smaller pallet. However, the minimum temperature (found at the pallet stack centre) and the maximum temperature (at the sensitive pallet stack corners) evolve similarly for the different pallet stack heights. Thus, typical ambient thermal load during air transport from Iceland to Europe should result in a similar maximum storage life difference between boxes in a full size pallet as for a 4–level pallet, i.e. 1 to 1.5 days.

The models developed in the current study can give valuable information on the temperature distribution inside a thermally loaded fish pallet. The models could, in conjunction with a product temperature–storage life prediction model, be used to estimate the storage life of thermally loaded cod fish pallets of different sizes and with different initial product temperatures. The model could also be used to predict spatio-temporal temperature changes for other food products, such as salmon or meat, by simply adopting the correct thermal properties of the product. The simulations could also be expanded in order to consider the whole chill chain from processing to market in addition to the broken down portions of the chain as is the case in the current work. This would, however, require some adjustments of the current model to take the storage and transport conditions into account, e.g. by adopting different surface heat transfer coefficients.

Acknowledgements

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Paper VII

Numerical Heat Transfer Modelling for Improving Thermal Protection of Fish Packaging

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Abstract. *Thermal protection of fresh fish packaging can substantially reduce negative effects of poor temperature control in chill chains. The aim of the current study was to apply numerical heat transfer modelling to improve such packaging by redesigning an expanded polystyrene (EPS) fish box. By thickening the walls at the corners the insulation performance of the box was enhanced and to counterbalance the weight of the new box, the walls were made thinner further away from the corners. By this means, the reference box was optimised in a step-by-step procedure using a 'trial and error' method. A trial was conducted to compare the improved and the reference EPS boxes, using fresh fish products subjected to thermal loads likely to occur during air- and land based multimodal transport from a processor in North-Iceland to a wholesaler in Europe. The improved EPS box weighed around 11% less than the reference EPS box. The performance of the EPS boxes was evaluated by means of temperature monitoring, chemical- and microbial measurements and sensory evaluation. Finally, the shelf life of fish loins subjected to air transport simulation was compared to continuous containerised sea transport (around -1 °C).*

The improved EPS boxes provided significantly better thermal protection compared to the reference boxes. Sensory evaluation gave approximately 2-3 days longer freshness period and prolonged shelf life up to 1-2 days (8 days v. 6 – 7 days). Steady storage at -1 °C resulted in shelf life of 11-12 days. The conclusion is that the improved packaging can increase the value of fresh fish by a significant amount.

Keywords. Heat transfer modelling, expanded polystyrene (EPS), packaging design, insulation, fresh fish, shelf life.

Introduction

The quality of perishable foodstuffs such as fresh fish can be greatly affected by temperature control during storage and transport from processor to market. Experiments have shown that the chill chain from processor to market is discontinuous and therefore packaging plays an important role in preserving the quality of the product (Martinsdóttir, Lauzon, Margeirsson, Sveinsdóttir, Þorvaldsson, Magnússon, et al., 2010; Mai, Margeirsson, Margeirsson, Bogason & Arason, 2010). Different transport modes, e.g. land transport, air and sea freight with variable ambient temperature profiles, require different packaging solutions. Consistent quality is a critical factor to marketing fresh seafood, and reliable temperature control is important, being reflected by the resulting shelf life.

The insulation of packaging limits heat transfer from the surroundings to the fish and vice versa. Heat transfer takes place through convection, conduction and radiation. The insulation value of the packaging is controlled by the physical properties and shape of the packaging, mainly thermal conductivity and wall thickness. This study was focused on changing the wall thickness of an already well insulated EPS box and verifying the effects by using a numerical heat transfer model. Such modelling has proved to be an efficient tool for improving the thermal protection of packaging (Moureh, Laguerre, Flick & Commere, 2002, Margeirsson, Gospavic, Pálsson, Arason & Popov, 2011; Margeirsson, Lauzon, Reynisson, Magnússon, Arason & Martinsdóttir, 2010). The EPS box was optimised by changing various parameters in the numerical heat transfer model, using a 'trial and error' method to find the optimal parameters.

The paper is organised as follows: in the material and methods the properties of the reference EPS box and the fresh fish are listed, and then the constraints of the design are discussed followed by the construction of the numerical heat transfer model, ending with optimisation of the design. Results and discussion are shown graphically with conclusions in the end.

Material and methods

The properties of the original EPS box and fresh fish

The packaging used for this study was an EPS box with 5 kg capacity. EPS boxes are usually white, manufactured from moulded polystyrene beads and up to 98% of the boxes consist of air pores. The air decreases density and increases insulation performance of the boxes, but the downside is that it decreases strength and increases the required storage volume for the boxes. From here on the reference box will be referred to as the original box. The inner dimensions of the original box were (L x W x H) = 355.5 x 220 x 85 in millimetres and the outer dimensions were (L x W x H) = 400 x 264.5 x 135, also in millimetres. The thermal properties of the box and fresh haddock fillets are shown in Table 1. The thermal properties of fresh haddock fillets given in the table are valid over the temperature range 0 to 10 °C.

Table 1. Thermal properties of the EPS box and the fresh fish (haddock)

Material	ρ *(kg m^{-3})*	c_p *(kJ kg^{-1} K^{-1})*	*k (W m^{-1} K^{-1})*
EPS	23[a]	1.28 ± 0.05[b]	0.0345[a]
Fresh haddock	1054[c]	3.73[d]	0.43[c]

a See Gudmundsson (2009), b See Al-Ajlan (2006),
c See Zueco, Alhama & Gonzalez Fernandez (2004), d See Rao & Rizvi (1995)

Constraints of the design

The new design was restricted by material choice, weight, capacity and outer dimensions of the original box. The restrictions were formulated in cooperation with the manufacturer of the original EPS box (PROMENS TEMPRA) and a fresh fish processing plant in Iceland. Thus the only parameter of interest for improving the EPS box was the wall thickness, leaving the original and improved box with the same material properties, outer dimensions, weight (m_{EPS} ± 5 g) and capacity.

Numerical heat transfer model

A three dimensional finite volume heat transfer model was developed using the computational fluid dynamics (CFD) software FLUENT for each packaging design. The aim of the study was to improve the packaging geometry by minimising the maximum fish temperature under a given thermal load. The computational domain was bounded by the EPS box, carrying a block of fish fillets enclosed with air above. The main advantage of the numerical models compared to lumped heat capacity models is that not only the mean product temperature during thermal load can be predicted but also the temperature distribution inside the whole package.

Heat flow is a result of temperature gradient and Fourier's law states that $q = -k\nabla T$, where q is the vector of heat flow per unit area, ∇T is the temperature gradient and k is the thermal conductivity, which was considered isotropic for this study. The heat transfer inside the fillets was considered to be transferred only by conduction, thus using the following equation

$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} = k_f \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} + \frac{\partial^2 T_f}{\partial z^2} \right) \quad (1)$$

Radiation was not taken into account in order to reduce computing requirements, which can be severe since calculations have to be performed in large numbers in the optimisation procedure. The fillet-to-air boundary was considered fixed so the heat transfer in the air was assumed to be conductive using eq. (1). The reason for excluding air movement is that the fish fillets were maintained at lower temperature than the inside of the box lid causing higher-density air to be trapped below lower-density air in the enclosed space above the fish fillets. Thus, according to Holman (2002), no convection currents are experienced.

The simulated time was 4 hours and the ambient temperature was considered to be T_{amb}= 15 °C which can be expected during transport from processor to market, according to Mai et al. (2010). The weight of the fillets positioned inside the packaging in the simulations was m_f = (5000 ± 5) g. The initial conditions throughout the whole computational domain (fish + box + air) were T_{init} = 1 °C. Convection boundary conditions were applied for both top and sides. The convective heat transfer coefficients (h_{conv}) for laminar natural convection in air (Ra < 10^9) were estimated by Holman (2002) correlations: $h_{conv,t}$ = 2.1 W m^{-2} K^{-1} and $h_{conv,v}$ = 3.0 W m^{-2} K^{-1} for top and vertical sides, respectively, according to Margeirsson et al. (2011). Non-ideal surface contact was assumed between the inner surface of the box and the fish, meaning that a certain thermal contact resistance between the two surfaces, $R_{b,f,}$ was estimated. The resistance value was set to $R_{b,f}$ = 0.05 m^2 K W$^-$1 according to Margeirsson et al. (2011).

Optimisation

A model of the original box was constructed and validated by comparison with data from a specific trial. By analysing the results, i.e. the temperature distribution of the fish inside the box, the critical temperature zones at the box corners were identified. By thickening the walls at the corners the insulation performance of the box was enhanced and to counterbalance the weight of the new box, the walls were made thinner further away from the corners. By this means, the original box was optimised in a step-by-step procedure using a 'trial and error' method.

The designs constructed with FLUENT are listed in Table 2. Each design had different radius of curvature in the corners and at the top and bottom, and wall thickness at the bottom, top and walls. The number of cells for the models was in the range 200-300,000, which was considered to give similar accuracy of results.

Table 2. The radius and wall thickness, weight and no. of cells for the original and A to H designs.

Design no.	*Radius (mm)*			*Wall thickness (mm)*			*Weight (g)*	*No. of cells*
	Corners	Bottom	Top	Bottom	Top	Walls		
ORG	5	5	5	25.00	25.00	22.25	176	292,100
A	75	15	10	22.00	22.00	22.25	177	212,400
B	75	15	10	22.50	22.50	22.25	178	278,100
C	100	10	5	22.50	22.50	22.25	185	279,800
D	85	15	5	22.50	22.50	22.25	180	270,300
E	95	10	5	21.50	21.50	22.25	178	285,900
G	50	20	5	22.50	25.00	21.50	178	247,400
H	75	20	5	22.50	25.00	22.25	183	264,500

Figure 1 shows the geometries of the FLUENT models for the original box and the design C. As the figures shows, design C has rounded corners inside the box where the original one has sharp corners.

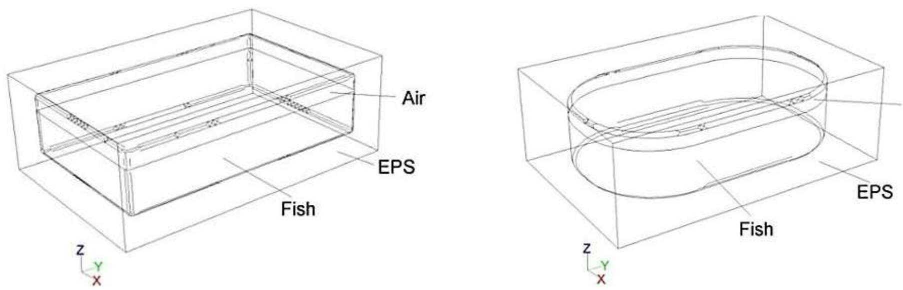

Figure 1. Geometries of the original (left) and design C (right), each containing fish fillets with layer of air above.

Results and discussion

The maximum, mean and minimum temperatures during the 4 hour simulation with T_{amb} = 15 °C and T_{init} = 1 °C are presented in Figure 2. The temperature distribution inside the box was not uniform and varies with position. The minimum temperature was quite similar for all the boxes, compared to the maximum temperature. Design C provided the lowest maximum temperature or 2.1 °C lower than for the original design. Figure 3 shows the temperature contours in a horizontal section through the box and fillets at mid-height of fillets. The figure clearly displays higher fish fillet temperature in the original box compared to the new improved design.

A prototype was manufactured based on designs A, C and E and according to a trial performed by Margeirsson et al. (2010) the freshness period (above 7 on the Torry scale) and shelf life (above 5.5 on the Torry scale) of fresh white lean fish fillets was prolonged by 2-3 days and 2 days, respectively, using the new design. Figure 4 shows the box surface temperatures in the trial where the original box and the new design were subjected to steady temperature (ST) storage or dynamic temperature storage (DT), representing sea and air transport respectively. ST storage (at -1 °C) gave freshness period of 6-7 days and 11-12 days of shelf life using the original boxes but DT storage gave 2-3 days and 5 days freshness period for the original and improved new design, respectively. Shelf life was also prolonged from 6-7 days to 8-9 days using the new improved box.

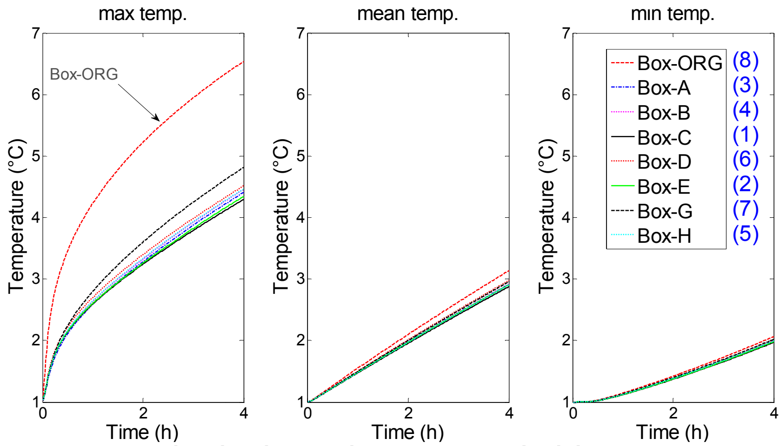

Figure 2. Temperature results showing maximum, mean and minimum temperatures to the left, middle and right, respectively. The insulation performance of the designs is shown inside brackets, (1) for C giving the best insulation and (8) for ORG giving the worst insulation.

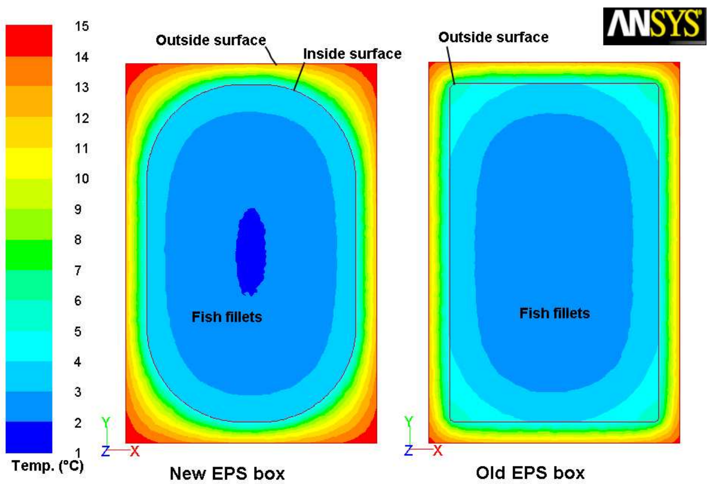

Figure 3. Temperature contours in a horizontal section through design C and the original box at mid-height of fillets after 4 hours at T_{amb} = 15 °C and T_{init} = 1 °C, shown left and right, respectively.

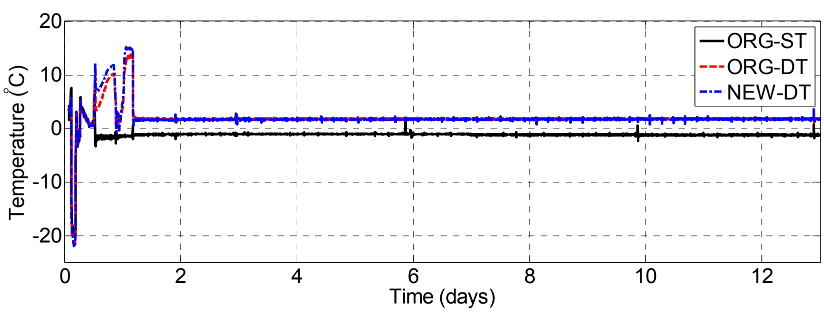

Figure 4. Surface temperature for the original (ORG) and new (NEW) EPS boxes during steady temperature (ST) and dynamic temperature (DT) periods (Margeirsson et al. 2010).

Conclusions

In this study, CFD methods have been applied to design new improved packaging for fresh fish export. The design with the largest radius of curvature provided the best insulation. Thus, results from this study clearly show that the insulation performance of a reference EPS box could be improved by thickening the walls at the critical corner zones, enabling the product to withstand higher ambient temperatures during transport. This results in a prolonged freshness period and shelf life of fresh white lean fish fillets by 2-3 days and 1-2 days, respectively.

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Nomenclature

c_p	specific heat capacity, kJ kg^{-1} K^{-1}
EPS	expanded polystyrene
DT	dynamic temperature
h_{conv}	convective heat transfer coefficient, W m^{-2} K^{-1}
H	box height, m
k	thermal conductivity, W m^{-1} K^{-1}
L	box length, m
M	mass, kg
NEW	new design
ORG	original
q	heat flux, W m^{-2}
Ra	Rayleigh number, dimensionless
ST	steady temperature
T	temperature, °C, K
W	box width, m

Greek symbols

ρ	density, kg m^{-3}

Subscripts

amb	ambient
b	box
f	fish fillet
init	initial
o	outside
w	wall
t	top
v	vertical sides

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