The effects of different precooling techniques and improved packaging design on fresh fish temperature control

Kristín Líf Valtýsdóttir

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
University of Iceland
2011

THE EFFECTS OF DIFFERENT PRECOOLING TECHNIQUES AND IMPROVED PACKAGING DESIGN ON FRESH FISH TEMPERATURE CONTROL

Kristín Líf Valtýsdóttir

60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Mechanical Engineering

Advisors
Sigurjón Arason
Halldór Pálsson
Björn Margeirsson

Faculty Representative
Gunnar Stefánsson

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, October 2011

The effects of different precooling techniques and improved packaging design on fresh fish temperature control
Precooling techniques and packaging design for fresh fish
60 ECTS thesis submitted in partial fulfillment of a M.Sc. degree in Mechanical Engineering

Copyright © 2011 Kristín Líf Valtýsdóttir
All rights reserved

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Hjarðarhagi 2-6
107, Reykjavik, Reykjavik
Iceland

Telephone: 525 4700

Bibliographic information:
Kristín Líf Valtýsdóttir, 2011, The effects of different precooling techniques and improved packaging design on fresh fish temperature control, M.Sc. thesis, Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland.

Printing: Háskólaprent, Fálkagata 2, 107 Reykjavík
Reykjavik, Iceland, October 2011

Abstract

The focus of this study was on the effects of different precooling techniques and improved packaging design on fresh fish temperature control. Insufficient temperature control in fresh fish supply chains has negative effects on the quality of fresh fish. It is therefore desirable to cool the product down to its intended storage temperature before packaging using some precooling technique, resulting in an efficient and rapid cooling. The insulation property of the packaging limits heat transfer from the surroundings to the fish. Fresh fish temperature was mapped while exploring different precooling techniques and numerical heat transfer modelling was used to improve expanded polystyrene (EPS) packaging. The precooling experiments resulted in fresh fish temperature profiles which provide guidelines for how to precool fresh fish effectively. The insulation performance of the EPS box was enhanced by increasing the radius of curvature in the corners, thereby increasing material. By these means, the original box was optimised in a 'trial and error' method using numerical heat transfer modelling. Experiments were performed with fresh fish using prototypes and later the new improved box. The result was significantly improved thermal protection during a period of temperature abuse. The conclusion is that by precooling the product to its intended storage temperature and utilising the new improved packaging, the temperature control in fresh fish supply chains can be increased significantly.

Útdráttur

Markmið þessa verkefnis var að kanna áhrif mismunandi forkæliaðferða og endurhönnununar pakkninga á hitastýringu ferskra fiskafurða. Ófullnægjandi hitastýring í kælikeðju ferskra fiskafurða frá framleiðanda til kaupanda hefur neikvæð áhrif á gæði afurðanna og því er ákjósanlegt að forkæla fiskafurðir hratt og örugglega niður að geymsluhitastigi fyrir pökkun. Varmaeinangrun pakkninga takmarkar varmaflutning frá umhverfi til vöru. Hitadreifing í fiski var kortlögð fyrir mismunandi forkæliaðferðir og varmaflutningslíkön voru notuð til að endurhanna frauðplastpakkningar (EPS). Niðurstöður forkælitilrauna voru hitaprófílar sem þjóna sem leiðbeiningar að árangursríkri forkælingu. Varmaeinangrun pakkninga var bætt með því að auka bogaradíus í hornum. Þannig var upphaflegi EPS kassinn endurbættur með aðstoð tölvuvæddra varmaflutningslíkana. Tilraunir sem framkvæmdar voru með ferskum fisk með frumgerðum og síðar nýja endurhannaða kassanum sýndu fram á bætta varmaeinangrun. Lokaniðurstöður eru þær að með því að forkæla vöruna niður að geymsluhitastigi og með notkun endurbættra pakkninga er hægt að bæta hitastýringu í kælikeðju fiskafurða töluvert.

Contents

List of Figures

List of Tables

Abbreviations

Air	air temperature, °C
Amb	ambient temperature, °C
CBC	combined blast and contact
CBCC	combined blast and contact cooling
CFD	computational fluid dynamics
Co	corner box samples
CP	corrugated plastic
c_p	specific heat, kJ kg^{-1} K^{-1}
DT	dynamic storage temperature
EPS	expanded polystyrene
Flo	floor temperature
FOB	free on board
H	height, m, mm
h	convective heat transfer coefficient, W m^{-2} K^{-1}
ISK	national currency of Iceland
k	thermal conductivity, W m^{-1} K^{-1}
L	length, m, mm
LC	liquid cooling
LSW	lightly salted water
m	mass, kg, g
Mi	middle box samples
New	new box
Org	original box
PCMs	phase changing materials
q	vector of heat flow per unit area, W m^{-2}
R	thermal contact resistance, m^2 K W^{-1}
Ra	Rayleigh number
Ref	reference box
SIC	slurry ice cooling
ST	steady storage temperature
Sur	surface temperature, °C
T	temperature, °C, K
T_f	initial freezing temperature, °C
T_{film}	film temperature, °C
TMA	trimethylamine
W	width, m, mm

Greek symbols

α	proportion of frozen water
β	coefficient of thermal expansion, K^{-1}
δ	gap between fish surface and inner surface of EPS lid, m
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}

Subscripts

amb	ambient
box	box
eps	expanded polystyrene
fish	fish fillet
init	initial
p	prototype
top	top of box
v	vertical sides of box

Acknowledgments

The author would like to thank for the support and guidance of the advisors, Björn Margeirsson, Sigurjón Arason and Halldór Pálsson. The author would like to thank for the financial support from the AVS R&D Fund of Ministry of Fisheries in Iceland (project no. R-037 08), the Technology Developement Fund of The Icelandic Centre for Research (project no. 08134508) and the University of Iceland Research Fund through the national project Hermun kæliferla.

1 Introduction

The quality of fresh seafood depends on various factors such as hygiene and handling, during pre- and post-processing (from catch to on shore processing). Bacterial growth, enzyme activity, physical damage, dehydration, chemical reactions and contamination are the main causes of quality loss in fish. These properties are dependant upon temperature and it is well known that the shelf life of fish products is markedly extended when products are stored at low temperatures. The questions raised in this thesis are;

- Can the temperature of fresh fish be lowered efficiently down to the initial freezing temperature by use of some precooling technique?

- Does the design of new packaging improve the thermal insulation of the packaging?

The main focus of the thesis is on packaging design but the reason for combining the precooling techniques with the packaging design is that if the product temperature is not lowered to the storage temperature before packaging, then the positive effects of improved thermal insulation are reversed.

According to the Statistics Iceland (2010) the export of fresh fish fillets from Iceland has grown for the last two decades as well as the free on board (FOB) export value. In 2010, 13.8 thousand tons of fresh fish fillets with a total value of 14 FOB billion Icelandic kronas were exported. Export of fresh fish fillets via sea freight has increased at the expense of air freight. This development can partially be explained by the difference in the quality of temperature control in cold chains during transport from Iceland to Europe (Mai et al., 2011). The advantage of faster transport mode can be lost if the temperature control during transport is inadequate (Magnússon et al., 2009a; Martinsdóttir et al., 2010). As a result the need for efficient thermal insulation of packaging is greater for air shipped fish than for fish transported by sea in refrigerated containers.

The demand for efficient temperature control in cold chains for fresh fish products has increased for the last decades. An agreement, ATP, was concluded in the 1970, concerning the international carriage of perishable foodstuffs and the special equipment to be used for such carriage. In 2010, over 40 countries were parties to the ATP agreement including two from outside the UNECE region, Morocco and Tunisia. Briefly, the agreement details conditions that have to be fulfilled in temperature control during transport of perishable foodstuffs. Research has shown that temperature control in cold chains of fresh fish products is insufficient compared to the requirements in the ATP agreement, i.e. that the temperature should be as close to 0 °C as possible without going below the initial freezing temperature of the product (Giannakourou et al., 2005; Mai et al., 2011; Margeirsson et al., 2008).

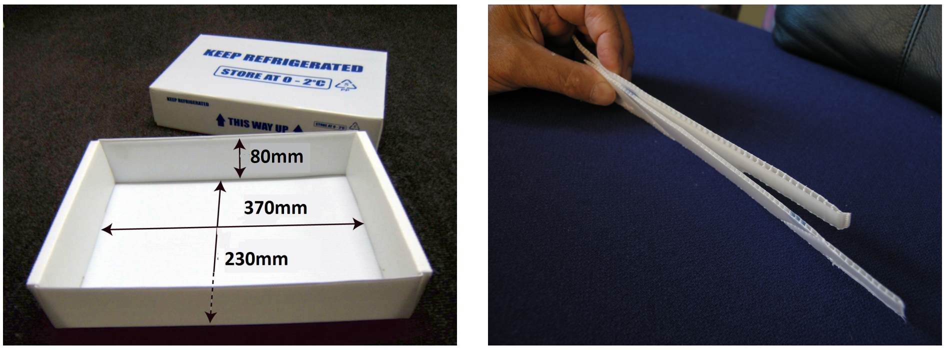
It is desirable to cool the product down to its intended storage temperature before packaging using some precooling techniques, which guarantee efficient and rapid cooling. Otherwise, cooling of an already packaged fish product in an insulated box will require more time to achieve the targeted product temperature. This cooling time is even prolonged by palletisation of boxes. Fresh fish processors can choose between different precooling techniques, packaging solutions and transport modes.

Some processors apply extra cooling immediately before packaging in the form of ice/gel-packs, dry ice or water ice. The cooling ability of gel packs and other PCMs have been evaluated by Labranque and Kacimi (2007) as well as Elliott and Halbert (2005). Zalba et al. (2003) provides a good overview of usage of phase change materials in the field of preservation of perishable products. Arnþórsdóttir et al. (2008) and Margeirsson et al. (2009, 2011) have demonstrated the importance of using ice packs during transport to maintain desirable product temperature. Icelandic fresh fish processors have shown great interest in further study of precooling techniques for fresh fish before packaging. Temperature fluctuations observed during storage and transport from processor to wholesaler can generally be better maintained by precooling fillets than if no precooling technique is used. Figure 1.1 shows fresh cod fillets placed in packaging with dry ice and ice pack put on top of a plastic film, covering the fillets.

(a) (b) (c)

Figure 1.1: Fresh cod fillets placed in an EPS box (a), covered with a plastic film (b) and a cooling medium which consists of a combination of dry ice and an ice pack (c).

The ambient temperature during transport and storage can fluctuate and different transport modes, i.e. by land, air or sea, require different packaging solutions. Expanded polystyrene (EPS) has been the most utilised packaging solution for export of fresh fish products during the last decades. Another type of packaging for fresh fish, which is particularly popular because of environmental aspects, is corrugated plastic (CP). The boxes are extruded twin wall plastic sheet products (about 2 to 3.5 mm thick) produced from high impact polypropylene resin. Corrugated plastic can easily be compacted in standard waste compaction equipment and are readily recycled, whereas expanded polystyrene requires specialised compaction equipment and the contaminated polystyrene material is difficult to recycle. The CP boxes can be folded, which saves storage space, but the strength and thermal performance are not as good as in the EPS boxes according to Margeirsson et al. (2009, 2011) and Anyadiegwu and Archer (2002). The CP box used by Margeirsson et al. (2009, 2011) are shown in Figure 1.2.



(a) *(b)*

Figure 1.2: Corrugated plastic box from Coolseal, dimensions (a) and folded (b).

Because the CP box is relatively new on the market, it has not received as much attention in the research field as the EPS box. Froese (1998) investigated the thermal performance of EPS boxes, which contained life fish in water. Burgess (1999) calculated and compared R-values (a measure of thermal resistance) for different packaging at a constant ambient temperature by using ice-melt test, because of the well known physical properties of ice. Further comparison between packaging solutions was performed by Singh et al. (2008) by using the ice-melt tests. Not only was the R-value calculated for different packaging solutions, but the melting point and latent heat (and thereby the cooling ability) of twelve different gel packs and phase change materials (PCMs) were also evaluated. One of the research findings was that the thermal resistance (R-value) is not only dependent on the packaging but also its contents. This indicates that it is desirable to investigate the thermal resistance of different packaging for fresh fish by experimenting with real fish instead of ice.

Numerical heat transfer modelling has proved to be an efficient tool for improving the thermal insulation of packaging (Margeirsson et al., 2010, 2011; Moureh et al., 2002). The focus of this study is on how to lower the temperature of fresh fish down to a desired level and maintain it during storage and transport, with special focus on precooling techniques and packaging design. Experiments were performed in the field, where temperature of air, liquid and fish were mapped during precooling.

Sufficient thermal protection of fresh fish packaging can substantially reduce negative effects of poor temperature control in cold chains. The design of new improved packaging was performed with numerical heat transfer modelling. In relation to that, an optimisation procedure consisted of thickening the walls of an original EPS box where enhanced thermal protection was needed. The radius of curvature in the corners and the wall thickness were different for each design, the goal being to improve the insulation performance of the packaging. By this means, the original box was optimised in a step-by-step procedure using a 'trial and error' method.

Parts of this thesis have been published in the following papers, referred to in the text by their respective Roman numerals. The papers are appended at the end of the thesis.

I Guidelines for precooling of fresh fish during processing and choice of packaging with respect to temperature control in cold chains. Matís report 40-10. (Valtýsdóttir et al., 2010).

II Numerical Heat Transfer Modelling for Improving Thermal Protection of Fish Packaging. Proceedings of the 6th CIGR Section VI International Symposium, "Towards a Sustainable Food Chain", Food Process Bioprocessing and Food Quality Management, Nantes, France - April 18-20. (Valtýsdóttir et al., 2011).

The first paper is written by Kristín Líf Valtýsdóttir under the supervision of the co-authors. The thesis author performed and participated in most of the experiments by monitoring and recording fish temperature during processing, from beheading to trimming and packaging. The experiments were performed under the supervision of Sigurjón Arason and Björn Margeirsson in cooperation with fresh fish processors and the results serve as guidelines on how to precool fillets and maintain low temperature during storage and transport. The second paper is written by Kristín Líf Valtýsdóttir under the supervision of the co-authors. The focus is on the design of new improved packaging using the computational fluid dynamics software Fluent. The author presented the results of paper number II at the 6^{6} CIGR Section VI International Symposium "Towards a Sustainable Food Chain" in Nantes, France - April 18-20, 2011.

2 Material and Methods

In this chapter the theoretical and physical background of the project are stated. First, the material properties of the fresh fish and packaging as well as the monitoring devices used in the experiments are discussed, followed by a description of the experimental setup of the precooling experiments and finally a design of new packaging. The precooling setup involved two experiments which the author performed under the supervision of Sigurjón Arason and Björn Margeirsson using liquid cooling and combined blast and contact cooling. The design process consisted of an optimisation procedure using numerical heat transfer modelling and then two packaging experiments which the author performed under the supervision of Sigurjón Arason and Björn Margeirsson using fresh fish to evaluate prototypes and finally the new EPS box.

2.1 Material properties

In this section, the temperature related properties of fresh fish (lean white fish) are listed followed by a discussion about the packaging material, expanded polystyrene and its insulating properties. Then the measurement devices used in the experiments are described.

2.1.1 Fresh fish

The main threats to fresh fish products during processing, storage and transport are high temperatures, temperature fluctuations and cross-contamination leading to higher loads of specific spoilage bacteria. At temperatures below 0 °C, there is a significant reduction in microbial growth rates and in the corresponding deterioration of the product due to microbial activity. However going below the initial freezing temperature of fish implies that some of the water is frozen and the concentration of solutes in unfrozen solutions increase. This may lead to denaturation of the muscle proteins as well as structural damage of membranes, which can result in increased drip loss, loss of water holding capacity and textural changes. It has been demonstrated that the temperature of maximum activity is in the region from -2 to -1 °C (Johnston et al., 1994). The initial freezing temperature (T_f) of a product refers to the temperature at which phase change (crystallisation) of water inside the tissue or muscle is initiated. The initial freezing temperature is dependent upon water and fat content of the fish. According to Pham (1996), T_f for most fresh foods is -1 °C. Kolbe and Kramer (2007) state that the temperature at which fish muscle starts to freeze depends on the solutes in the tissue fluids and is -0.9 °C for cod with 82% water content. When the product is cooled very close to its T_f during precooling, rapid cooling is necessary to ensure formation of small ice crystals within the product structure and to minimise textural damages of the muscle (Singh and Heldman, 2003).

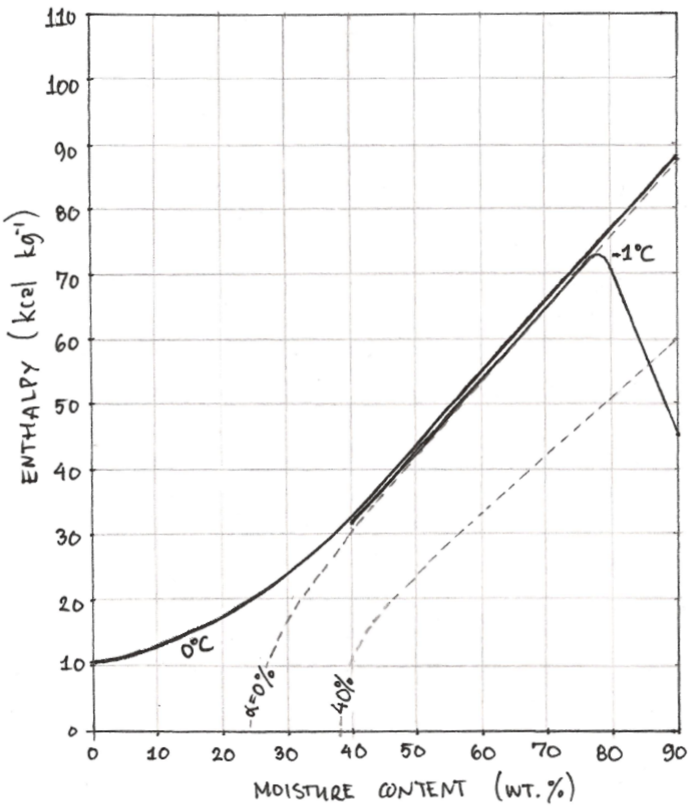


Figure 2.1: A sketch of an enthalpy diagram for a lean fish muscle for the temperature interval from -1 to 0 °C.

The reason for the enhanced resistance of precooled fillets against thermal load is illustrated in Figure 2.1. The figure shows a sketch of the relationship between energy, water content, temperature and percentage of frozen water in lean fish muscle for a temperature interval from -1 to 0 °C based on a diagram by Rha (1975). The water content of white fish (lean fish muscle e.g. cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*)) is approximately 80 to 82% and therefore, it can be read from the figure that by precooling white fish down to -1 °C before packaging, 10 to 20% of the water in the flesh is frozen. Since the latent heat of ice is high (around 335 kJ kg^{-1}), considerable amount of energy is needed from the environment to raise the temperature of the flesh from -1 to 0 °C or around 10 kcal kg^{-1} or 42 kJ kg^{-1}. Consequently, the shelf life of the fish fillet is generally prolonged because of the precooling process.

Both specific heat and thermal conductivity of white fish are temperature dependent. These thermal properties are listed in Table 2.1 according to Johnston et al. (1994). The 'big jump' in specific heat from -1 to 0 °C emphasises even further the amount of energy needed to raise the fish temperature from -1 to 0 °C.

Table 2.1: Temperature dependent thermal properties of white fish; thermal conductivity k (W m^{-1} K^{-1}) and specific heat c_p (kJ kg^{-1} K^{-1}) (Johnston et al., 1994)

T, °C	-6	-4	-3	-2	-1	0	5	10
k	1.400	1.361	1.341	1.322	1.302	0.430	0.430	0.430
c_p	7.744	15.111	26.539	65.636	102.72	4.144	3.641	3.683

Figure 2.2 shows a fresh fish fillet from one of the precooling experiments before trimming. The fresh fish used in this study was cod (*Gadus morhua*) for the precooling experiments and golden redfish (*Sebastes marinus*) for the packaging experiment.

Figure 2.2: Fresh cod (Gadus morhua) fillet before trimming.

2.1.2 Packaging material

The insulation property of the packaging will limit 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 of the packaging material and wall thickness. The packaging type used in this study is an EPS box manufactured from moulded polystyrene beads. The capacity of the EPS box is five kilograms and it was manufactured by Promens Tempra, see Figure 2.3. The beads comprise 98% air by volume which makes them light and contributes to their insulation but also makes them bulky to store. EPS boxes are usually white and the lid and box are manufactured in the same manner, designed to interlock, creating a tight seal.

Figure 2.3: EPS box with capacity for five kilograms of fresh fish.

Since this study involves the design of new improved packaging, the 'old' box will be referred to as the original box. The inner dimensions of the original box are (L × W × H) = 355.5 × 220 × 85 in millimetres and the outer dimensions are (L × W × H) = 400 × 264.5 × 135, also in millimetres. The properties of the original box are as follows; weight m = 181 grams, density ρ = 23 kg m^{-3} (Gudmundsson, 2009), specific heat c_p = (1.28 ± 0.05) kJ kg^{-1} K^{-1} (Al-Ajlan, 2006) and thermal conductivity k = 0.031 to 0.036 W m^{-1} K^{-1} (Al-Ajlan, 2006; Holman, 2002; BASF SE, 2001).

2.1.3 Monitoring devices

Temperature was monitored with DS1922L temperature logger iButtons from Maxim (Sunnyvale, CA, U.S.). The loggers measure temperature and record the result in a protected memory section and have accuracy of ± 0.5 °C, resolution of 0.0625 °C and a range of -10 to 65 °C. The loggers are 17 mm in diameter and 6 mm in thickness and each logger can read up to 4096 16-bit readings taken at equidistant intervals ranging from 1 s to 273 hours. The weight of the fish and EPS boxes was measured using a M 1100 C3 scale from Marel (Garðabær, Iceland) with accuracy of ± 2 g and a range from 1.5 to 15 kg. The monitoring devices are shown in Figure 2.4.

The temperature loggers were calibrated by adding crushed ice and distilled water to a clean container to form a watery slush. Then the temperature loggers were placed in the slush for a couple of minutes. After reading the calibration results the experimental data was corrected according to the calibration. Simulation of storage and transport was performed in an air climate chamber shown in Figure 2.5 in facilities at Matís (Reykjavík, Iceland). The dimensions of the chamber are (L × W × H) = 2.10 × 1.50 × 2.25 in metres.

(a) *(b)*

Figure 2.4: Monitoring devices used in the experiments, DS1922L temperature logger iButton (a) and M 1100 C3 scale from Marel (b).

Figure 2.5: Air climate chamber used in the packaging experiments.

2.2 Precooling techniques - experimental setup

There are two main tasks in cooling; the fast reduction of the product temperature down to the desired low temperature, and the maintenance of the desired temperature over a longer period during storage or transport. The fast reduction of the temperature is achieved by use of some precooling technique before packaging. The purpose of precooling is to slow down the process of microbial growth. Precooling has proven to be necessary to ensure that the fresh fish receives optimum handling. There are several factors that affect the quality of fresh fish during processing such as hygiene, relative humidity, handling and temperature. Some factors can not be controlled at the processing stage, such as intrinsic factors inherent to the fish at catch as well as some extrinsic factors affecting further its condition. The focus of the precooling part of this study is on temperature mapping, both ambient and liquid temperature as well as the fish temperature. The flow chart in Figure 2.6 shows a typical Icelandic fresh fish processing line. The processing line consists of different levels of processing as well as precooling before packaging (Step I) and cooling after packaging (Step II).

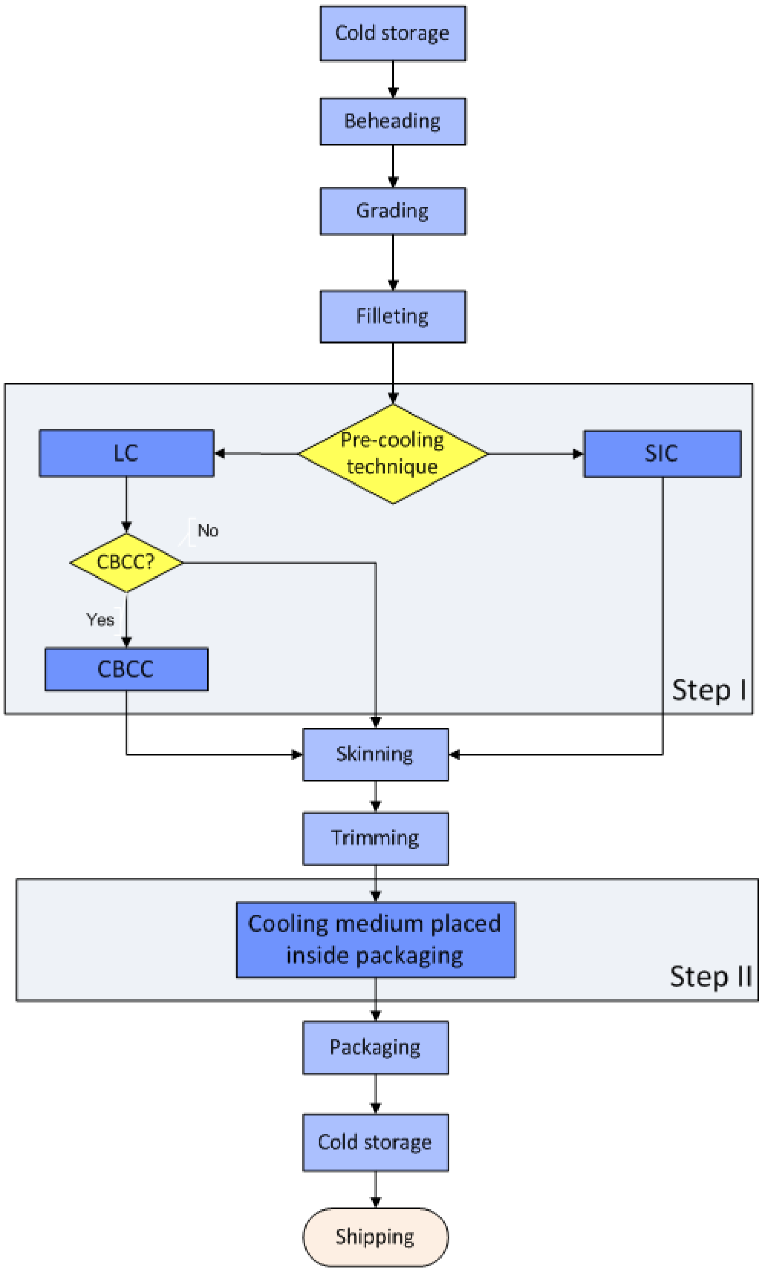


Figure 2.6: Typical fresh fish processing line with precooling in Steps I and II.

As mentioned before, there are mainly three methods of precooling used in the Icelandic fresh fish industry; liquid cooling, slurry ice cooling and combined blast and contact cooling. Each method aims to effectively lower the temperature of the fresh lean fish to its initial freezing temperature. Following are descriptions of the experiments performed, firstly, a description of an experiment using the liquid cooling and then secondly using the combined blast and contact cooling technique.

2.2.1 Liquid cooling

Liquid cooling is a precooling technique which consists of immersing the fresh fish into lightly salted water (LSW). The fish is usually dropped from a conveyor belt into a liquid tank and transported under water via conveyor belt or a turning spiral. During immersion the threat of cross-contamination increases and consequently the number of bacteria increases. In addition to liquid contamination, the fish can also contaminate the liquid.

In the experiment the liquid temperature was recorded using DS1922L temperature logger iButtons. The salt content of the liquid was 1.4% and the temperature was recorded with 10 second intervals. The liquid temperature was recorded for 40 minutes during the experiment at the inlet and outlet of the liquid tank. Two measurements were performed during this 40 minute interval. Each measurement consisted of four fillets, weighing approximately 400 to 650 grams, which were immersed in the liquid cooler for about six minutes. The fillets were numbered from F_0 to F_3. The red circles in Figure 2.7 show the position of the temperature loggers inside the fillets. The temperature loggers were positioned at the thickest part of the fillets, monitoring the temperature where the slowest cooling should be observed in the fillet.

Figure 2.7: Position of temperature loggers inside fillets in the liquid cooling experiment, marked with red circles.

2.2.2 Slurry ice cooling

Slurry ice cooling is similar to liquid cooling but instead of lightly salted water, slurry ice is used as a cooling media.The procedure most often consists of tubs with slurry ice where the fish is dipped into the tubs and immersed in slurry ice. SIC can also be performed exactly the same way as LC, where the fish is dropped from a conveyor belt into a slurry ice tank and transported via under water conveyor belt or a turning spiral. The same problems concerning cross-contamination are present as with LC. Liquid and slurry ice cooling are sometimes used before CBCC. For further information about the properties of slurry ice; e.g. the relation between ice percentage, salinity (salt concentration) and temperature, see paper I.

2.2.3 Combined blast and contact cooling

Combined blast and contact cooling is a processing technique, which the processing company Skaginn hf. (Akranes, Iceland) has developed and holds a patent for. The CBCC technique consists of a combination of blast and contact cooling. A Teflon coated aluminium belt is used for the contact cooling. Before the CBCC, the fish is usually immersed in LSW which lowers the initial freezing temperature of the fish. The fillets are placed skin down on the Teflon coated aluminium belt as they are transferred through the CBC cooler. Fans are positioned above the belt and blow cold air over the fillets. Figure 2.8a shows one of the fans and fillets being transferred through the CBC cooler. The temperature inside the cooler is normally set in the range of -8 to -6 °C and the travel time is about 6 to 10 minutes. The size of the fillets controls the required speed of the conveyor belt, i.e. small fillets require shorter cooling time than large fillets. Relying on the heat resistance of the fish, the core temperature of large fillets can continue to decrease after exiting the CBC cooler.

The fillets exit the CBC cooler at temperature close to -0.9 °C and are then dropped on another conveyor belt which transports them to skinning and trimming, see Figure 2.8b. The skinning has little effect on the fillets, since the fillets become stiff during the CBC cooling. The benefits of this technique are many: the fillets are firm after the cooling which makes skinning easier and the fillets can withstand the necessary handling and preserve the quality all the way through the processing, leading to more valuable products. This rapid cooling process freezes the skin without excessively freezing the flesh and is referred to as superchilling.

The temperature of five fresh cod fillets (numbered from F_1 to F_5) was recorded during the CBCC experiment. The fillet temperature was recorded with DS1922L temperature logger iButtons with 10 second intervals at the centre of the thickest

(a) *(b)*

Figure 2.8: A view inside a CBC cooler, fillets subjected to blast and contact cooling as they are laid skin down on a cold aluminium belt with fans blowing cold air above them (a). Fillets exit a CBC cooler at temperature around -0.9°C, after which they are dropped on another conveyor belt which transports them to skinning and trimming (b).

part of the fillet. Before entering the CBC cooler, the fillets were marked with plastic marks and temperature loggers were inserted into the fillets, the fillets weighed from 600 to 1000 grams.

Before the temperature loggers were placed inside the fillets, the temperature of randomly chosen fillets were measured with a thermometer to ensure that the settings for the CBC cooler ensured exit temperature of approximately -0.9 °C. Figure 2.9a shows a fillet temperature being randomly measured with a thermometer when exiting the cooler. Figure 2.9b shows fillets placed in a plastic box to simulate their journey through the processing hall after exiting the CBC cooler. This was done to see if they continued to cool down after exiting the CBC cooler and also to see when the temperature began to rise again.

The ambient temperature was set to -8.5 °C and it was recorded with 2 minute intervals during the experiment. The placement of the fillets during transfer through the CBC cooler and position of ambient temperature loggers is shown in Figure 2.10. The fillets were positioned along the conveyor belt to observe if they received similar cooling regardless of position. Ambient temperature was recorded at positions marked with orange circles (numbered from Amb_1 to Amb_4) about 10 to 20 cm above the conveyor belt.

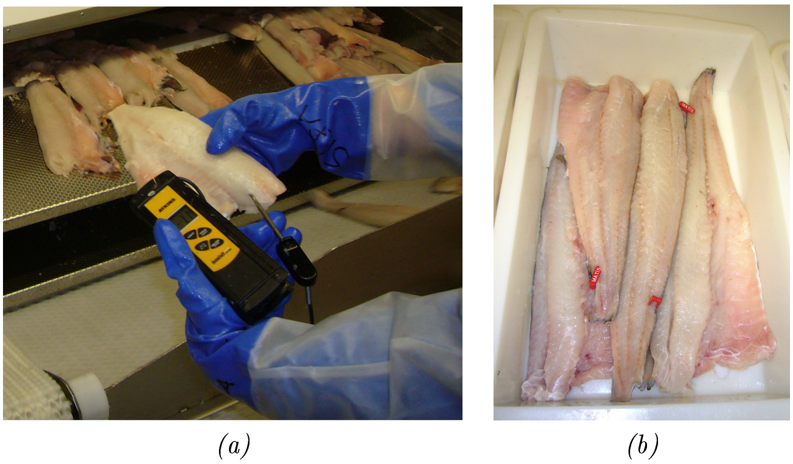


Figure 2.9: Fillet temperature recorded with a thermometer after CBCC (a) and fillets stored in the processing hall after CBCC (b).

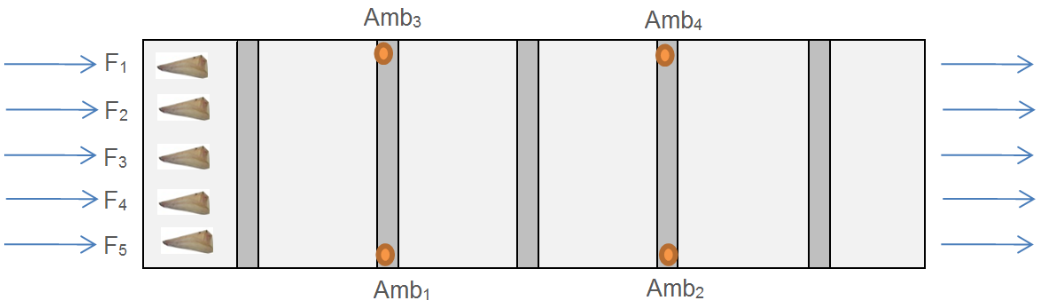


Figure 2.10: Position of five 300 to 1100 g cod fillets (numbered from F_1 to F_5) transferring through a CBC cooler. Ambient temperature was recorded at positions (numbered from Amb_1 to Amb_4) marked with orange circles about 10 to 20 cm above the conveyor belt.

2.3 Design of new packaging

Experiments have shown that the cold chain from processing to market is discontinuous and therefore packaging plays an important role in keeping the fresh fish products safe from temperature fluctuations (Mai et al., 2011; Martinsdóttir et al., 2010). Since consistent quality is a critical factor to marketing fresh seafood, reliable temperature control is important, being reflected by the resulting shelf life. The objective of this section of the study is to present methods used to improve the thermal protection of EPS boxes based on numerical heat transfer modelling. Experiments were performed during the optimisation process, in order to test prototypes, as well as the new improved box after it had beed casted into mold.

2.3.1 Numerical heat transfer modelling

The packaging to be subjected to improvements was a five kilogram EPS box from Promens Tempra (Hafnafjordur, Iceland). The new design was restricted by material choice as well as weight, capacity and outer dimensions of the original box. The shape constraints were specified in cooperation with the manufacturer of the original EPS box and fresh fish processors in Iceland. The only parameter of interest for improving the EPS box was the wall thickness, as a result the original and new box had the same material properties, outer dimensions, weight and capacity.

A three dimensional finite volume heat transfer model was developed using the computational fluid dynamics (CFD) software Fluent for each packaging design. 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 more simple lumped heat capacity models is that not only the mean product temperature during thermal load can be predicted but also the temperature distribution in the whole computational domain (fish + box + air).

Heat flow is a result of a temperature gradient and Fourier's law and states that

$$q = -k\nabla T \tag{2.1}$$

where q is the vector of heat flow per unit area, ∇T is the temperature gradient and k is the thermal conductivity. Assuming constant conductivity and incompressible flow, the energy conservation law results in the incompressible heat-convection equation:

$$\rho c_p \frac{DT}{Dt} = k\nabla^2 T \tag{2.2}$$

For a three dimensional body using the Cartesian coordinate system, the heat-convection equation for the heat transfer inside the fillets can be written as

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{2.3}$$

with c_p and k being the temperature dependent thermal properties, in this case, for white fish. The initial temperature of the fish was set above 1 °C to skip the phase change which occurs at temperatures below 0 °C thereby restricting the models to single-phase flows. The Grashof number (Gr) for the free convection in the enclosed air space between the fish and the inner surface of lid of the EPS box was calculated as

$$Gr_\delta = \frac{g\beta(T_1 - T_2)\delta^3}{\nu^2} \tag{2.4}$$

where δ is the gap between the two surfaces, β is the coefficient of thermal expansion, ν is the kinematic viscosity, g is the gravitational acceleration (g = 9.81 m s^{-2}) and

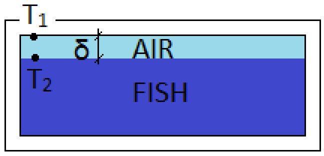


Figure 2.11: The setup for the free convection in the air gap between the fish and EPS box.

$(T_1 - T_2)$ is the temperature difference between the two surfaces. The setup is shown in Figure 2.11.

The coefficient of thermal expansion for ideal gases can be computed from $\beta = 1/T_{film}$. The airflow was considered incompressible ($\rho = constant$) and the film temperature of the air was evaluated by

$$T_{film} = \frac{T_1 - T_2}{2} \tag{2.5}$$

At sufficiently low Grashof numbers (below about 1700), free-convection currents can be neglected and the heat transfer occurs mainly by conduction across the fluid layer (Holman, 2002). Another for excluding air movement is that the fish fillets were maintained at lower temperature than the inside of the EPS lid causing higher-density air to be trapped below lower-density air in the enclosed air space above the fish fillets. Thus, no convection currents are experienced. 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 weight of the fillets positioned inside the packaging in the simulations was $m = (5000 \pm 5)$ g. The simulated time was four hours and the ambient temperature adopted was $T_{amb} = 15\,°C$ which can be expected during transport from a processor to market, according to (Mai et al., 2011). The initial conditions throughout the whole computational domain (fish + box + air) were $T_{init} = 1\,°C$ or above te phase change. The choice of initial temperature above the phase change temperature was chosen to simplify the model.

Convection boundary conditions were applied for both top and sides according to (Margeirsson et al., 2011). The convective heat transfer coefficients (h) for laminar natural convection in air ($Ra < 10^9$) were estimated using correlations from Holman (2002): $h_{top} = 2.1$ W m^{-2} K^{-1} and $h_v = 3.0$ W m^{-2} K^{-1} for top and vertical sides, respectively. 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, $R_{box,fish}$, was used. A resistance value of $R_{box,fish} = 0.05$ m^2 K W^{-1} was adopted according to Margeirsson et al. (2011).

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 are listed in Table 2.2. Each design had different radius of curvature in the corners and at the top and bottom, as well as different wall thickness at the bottom, top and walls.

Table 2.2: The radius and wall thickness, weight and number of cells for the original and designs A to H

Design	**Radius [mm]**			**Wall thickness [mm]**			**Weight**	**Computa-**
	Corners	Bottom	Top	Bottom	Top	Walls	**[g]**	**tional Cells**
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

The mesh was refined until the solution was considered independent upon the number of cells. The number of cells required to achieve grid independence was 200,000 to 300,000 for each design. The mesh was refined in areas where high temperature gradient was expected, i.e. near boundaries. Since the geometry became more complex when the radius of curvature was increased, an unstructured grid which consisted of tetrahedral cells was used for all designs. An attempt was made to use a structured grid using hexahedron cells to create a mapped mesh but it turned out to be unsuccessful. Figure 2.12 shows the mesh on the boundaries for design G.

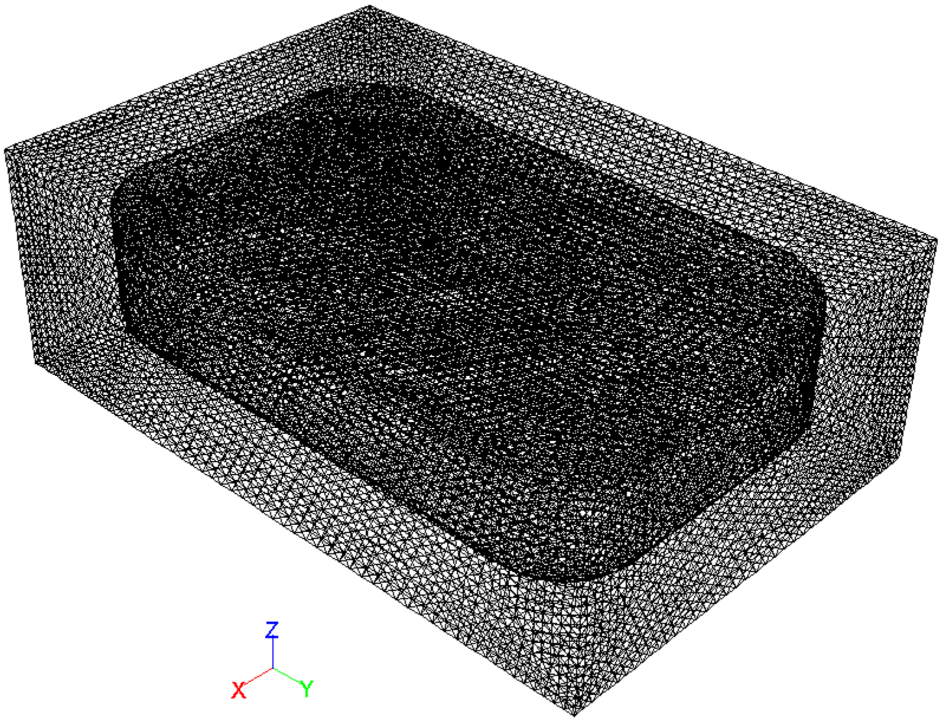


Figure 2.12: Tetrahedral mesh for design G with 247,400 cells.

Figure 2.13a and 2.13b show the outlines of the original box and design E in Fluent. Design E has rounded corners opposed to the sharp edges in the original box. The radius of curvature at the bottom was also increased from 5 to 10 mm. The figures show the layer of fish with air above inside the EPS box.

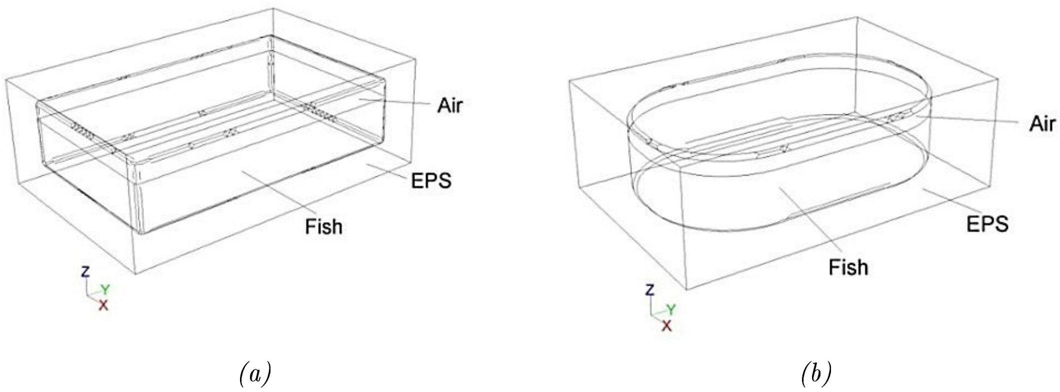


Figure 2.13: Geometries of the original box (a) and design E (b), each containing fish fillets with layer of air above.

2.3.2 Packaging experiments

Two packaging experiments were performed, the first one using two prototype boxes and the latter one using the new EPS box. Fresh fish was used in both experiments and temperature was monitored with eight temperature loggers in each box. The positions of loggers differed between experiments. Two air climate chambers were used in the experiments, one was set to low steady temperature to reach homogeneous fish temperature before the boxes were placed in the other chamber where dynamic temperature storage was simulated.

The two prototypes were not casted directly into mold as that would have been too expensive and also unneccessary. Instead the original box was adjusted to the new designs by decreasing wall thickness and adding material in the corners. These boxes had the same design as G and H, except for that no material was added to the bottom corners and the original wall thickness was maintained. Figure 2.14a and 2.14b show the two prototypes with extra material glued to the corners. They will be refered to as prototypes G_p and H_p, where the subscript p refers to prototype. The radius of curvature of G_p and H_p was 50 mm and 75 mm, respectively.

(a) (b)

Figure 2.14: Prototypes of design G and H, prototype G_p (a) and prototype G_p (b).

Six EPS boxes were used in the prototype experiment, two reference boxes, two boxes from Promens Tempra and two prototypes, G_p and H_p. The reference boxes were different from the original boxes in a way that they had less material in the corners and at the bottom, which decreases thermal protection. The reference boxes were used to see if they would give the worst thermal protection which would further establish the importance of proper insulation in the corners. Five kilograms of fresh cod fillets were placed in each box along with eight DS1922L temperature logger iButtons. The position of the temperature loggers inside the boxes is shown in Figure 2.15. Four loggers were placed on top of approximately 0.5 cm layer of fish at the bottom and another four loggers were placed under approximately 0.5 cm of fish at the top of the fish block. The loggers were positioned in the corner (number 4 and 8), at mid-length (number 2 and 6), mid-width (number 3 and 7) and in the middle of the x-y plane (number 1 and 5).

The temperature was recorded with 3 minute intervals, which was considered to be enough to capture the evolution of the fish temperature during the experiment. The boxes were put in a steady temperature storage in an air climate chamber at 2 °C for 48 hours after the temperature loggers had been placed inside the packaging. Thereby ensuring that a uniform fish temperature was reached before the dynamic temperature storage began.

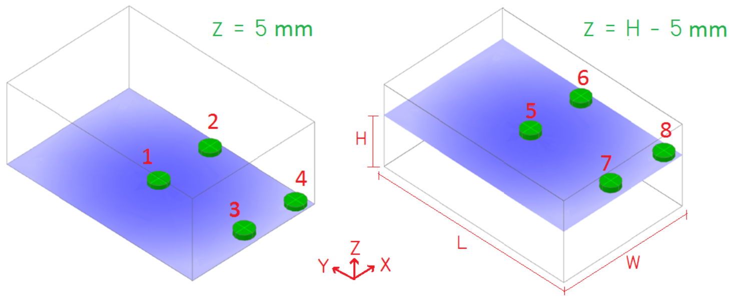


Figure 2.15: The position of eight temperature loggers (numbered from 1 to 8) in the prototype experiment. The first four temperature loggers are placed 5 mm above the bottom surface of the box (z = 5 mm) and the last four loggers are placed 5 mm below the top of the fish block (z = H - 5 mm), where H refers to the height of the fish block.

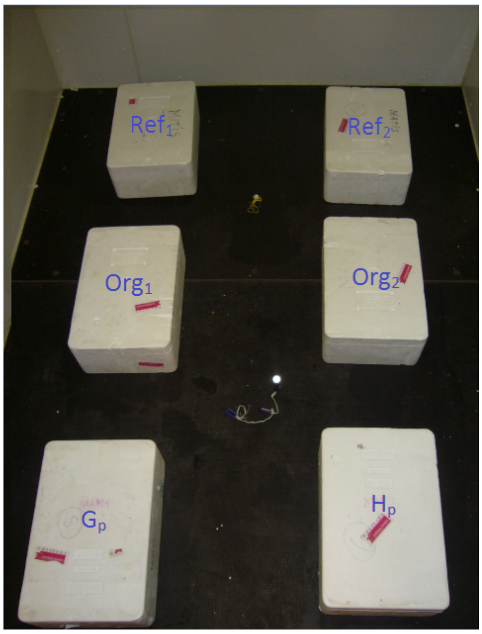


Figure 2.16: Six boxes inside an air climate chamber in the prototype experiment.

After 48 hours in the steady temperature storage, the boxes were moved to an air climate chamber at room temperature. Some difficulties were experienced in controlling such high ambient temperatures in the chamber so in order to successfully reach room temperature the chamber was turned off and left with the door open. Figure 2.16 shows the internals of the chamber where the six boxes were stored during the dynamic temperature storage. Ambient temperature was recorded both on the floor (Flo) and in the air (Air) above the boxes at five positions (numbered Flo_1, Flo_2, Air_1, Air_2 and Air_3).

After consulting with the manufacturer and fresh fish processors, some of the designs were ruled out and one final design was chosen. The manufacturer of the original EPS box, Promens Tempra, invested in a mold and casted the new improved EPS box into the mold. After the new box was ready for use, an experiment was performed to compare the thermal protection of new box to the original one. Four boxes were used in the experiment, two original and two new boxes and five kilograms of fresh fish (*Sebastes marinus*) was placed in each box along with eight temperature loggers which were numbered and their position documented as they were placed inside the EPS box. Figure 2.17 and 2.18 show the original and new box with temperature loggers placed at the bottom and on the top of the fillets.

(a) *(b)* *(c)*

Figure 2.17: Position of temperature loggers placed inside the original box in the new box experiment. Loggers positioned at the bottom (z = 0) to the left and on top of fillets (z = H) to the right.

(a) *(b)*

Figure 2.18: Position of temperature loggers inside the new improved box in the new box experiment. Loggers positioned at the bottom (z = 0) to the left and on top of fillets (z = H) to the right.

Figure 2.19 shows the position of the loggers (numbered from 1 to 8) where the two columns represent the original box and new box, with each line representing different position in the z plane (H is the height of the fish block). In order to obtain more consistency in the positions of temperature loggers in z direction, the loggers were not placed on top of a thin layer of fish as in the prototype experiment but rather they were placed below and above the fish block. The loggers were positioned at the bottom of each box (number 1, 2 and 3), at mid height of the block (number 4 and 5) and on top of the fillets (number 6,7 and 8). Since the box is axisymmetric about both the x and y axis, the results from the loggers could be mirrored about these axis.

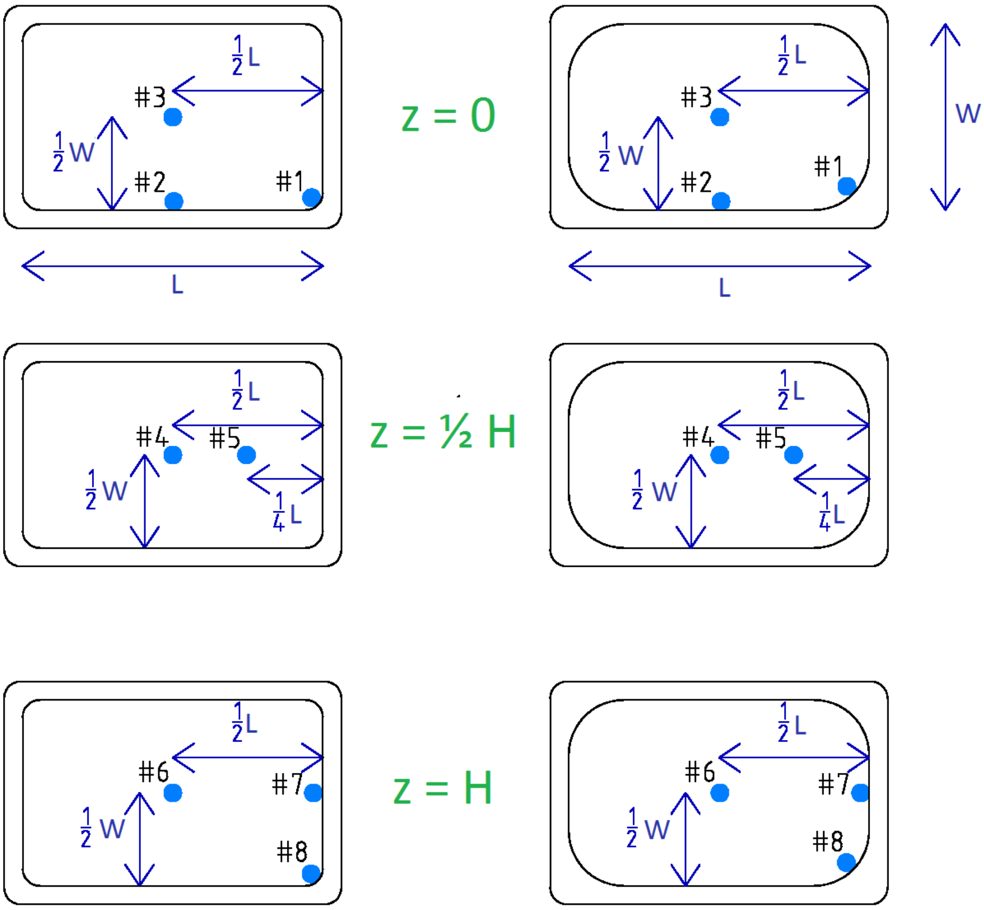


Figure 2.19: The position of eight temperature loggers (numbered from 1 to 8) in the new box experiment. Each line represents different position in the z plane (H is the height of the fish block) for the original box (left) and new box (right).

An ambient temperature profile was constructed in order to simulate real temperature conditions during storage and air freight transport. Figure 2.20 shows the planned profile starting with eight hours of storage at 1 °C followed by 12 hours of

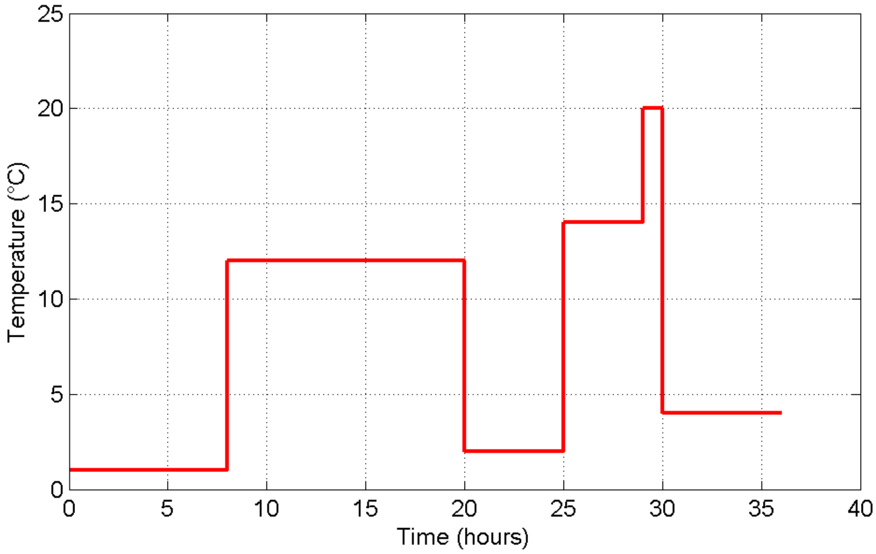


Figure 2.20: Planned ambient temperature profile for the trial.

12 °C during transport and then cold storage for five hours at 2 °C and finally five hours at 14 to 20 °C simulating air freight and then storage at 4 °C. The total time span is thus 36 hours. The ambient temperature was monitored at four positions inside the air climate chamber during the trial. The surface temperature on top of the lid of each box was also monitored.

3 Results

3.1 Precooling experiments

Two experiments were performed in the precooling part and the results from the temperature mapping are presented here, first for the liquid cooling experiment and then for the combined blast and contact cooling experiment.

3.1.1 LC experiment

The LC experiment was performed twice during a 40 minute interval. During the first measurement, the fillet temperature rose too high during insertion of temperature loggers but the second measurement was successful. Figure 3.1 shows the liquid temperature and Figure 3.2 shows the fillet temperature during the experiment. The line representing T_f is reference for the optimum temperature to be reached during precooling before packaging. The measurements reveal the liquid to be inhomogeneous as the temperature at the inlet and outlet differ more than 1 °C at some time instances. The first time the fillets were immersed in the liquid cooler, the initial temperature varied from zero to 3 °C and the cooling proved to be unsuccessful. The second time, the fish temperature was at approximately 1 °C after insertion of temperature loggers.

The temperature loggers inserted in fillet number F_0 failed to give any results for the second immersion. The final temperature of the fillets varied from -0.9 to -0.4 °C and only one fillet sucessfully reached T_f. The average fish temperature before and after immersion in the second measurement was 1.1 °C and -0.6 °C, respectively.

These results show that it seems to be difficult to control the liquid temperature, as it was set to -1 °C during the experiment, but did not reach that goal but once at the inlet. The results also show that the liquid temperature was inhomogeneous. Despite no records reveal the liquid to reach T_f during the two measurements, the temperature of F_2 was lowered to T_f. This suggests that the liquid must have reached T_f somewhere in the tank.

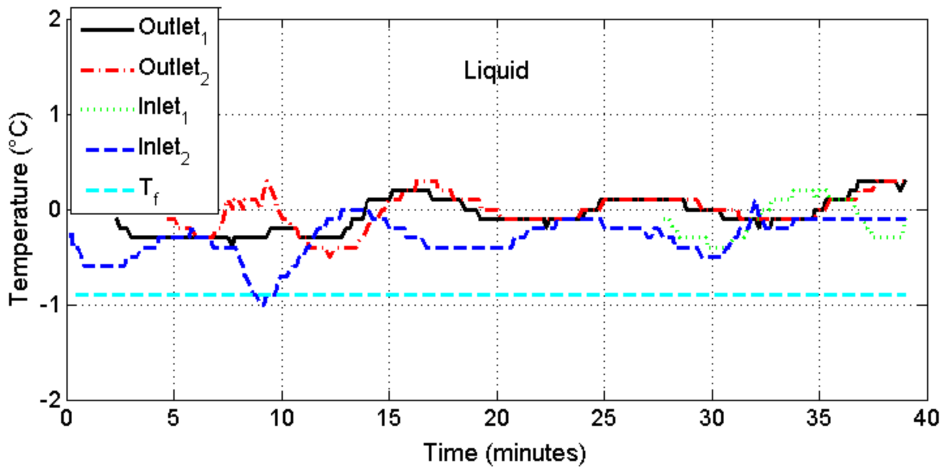


Figure 3.1: Liquid temperature at the inlet and outlet during two LC measurements spanning a total of 40 minutes.

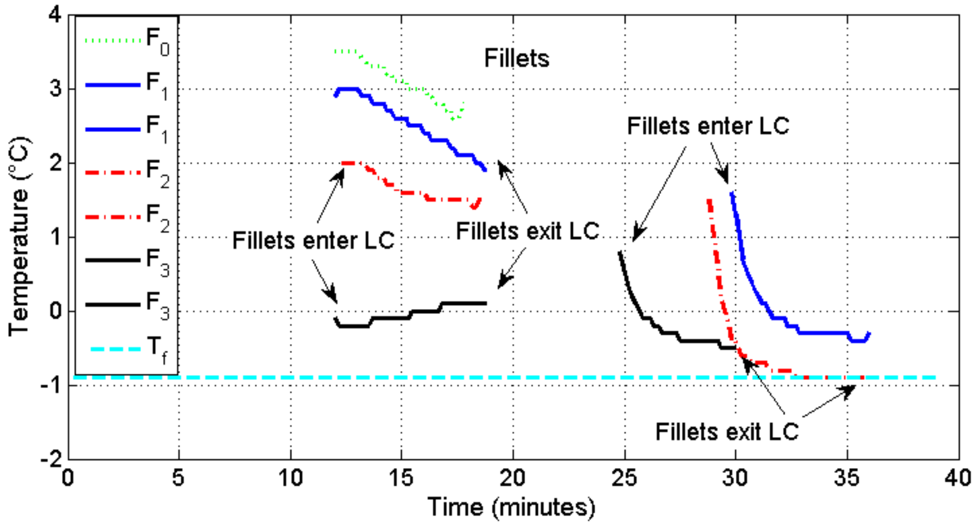


Figure 3.2: Fillet temperature during two LC measurements spanning a total of 40 minutes.

3.1.2 CBCC experiment

The ambient temperature during the CBCC experiment, at the four positions numbered from Amb_1 to Amb_4, is shown in Figure 3.3. The average temperature was around -8 °C and the reason for the inhomogeneous ambient temperature can be explained by the powerful fans, which are located on one side of the cooler above the conveyor belt. Figure 3.4 shows the fish temperature (numbered from F_1 to F_5) transferring through the CBC cooler. Entering and exiting the CBC cooler took about 1 minute and the fillets and it took the fillets 10 minutes to transfer through the cooler. During insertion of temperature loggers the fish temperature rose to 2.0 °C before entering the cooler. During the 10 minutes inside the CBC cooler, the fish temperature dropped by 2.6 °C on average resulting in a final temperature of around -0.3 °C. After the fillets exited the cooler, at ambient temperature of 15 °C, they continued to cool down and reached -0.8 °C ten minutes after exiting the cooler. This is caused by the fillets skin being at temperature below -0.9 °C and thus ice crystals had formed. Fillet temperature around T_f was maintained for about 30 minutes when stored in an open plastic box at ambient temperature in the processing hall.

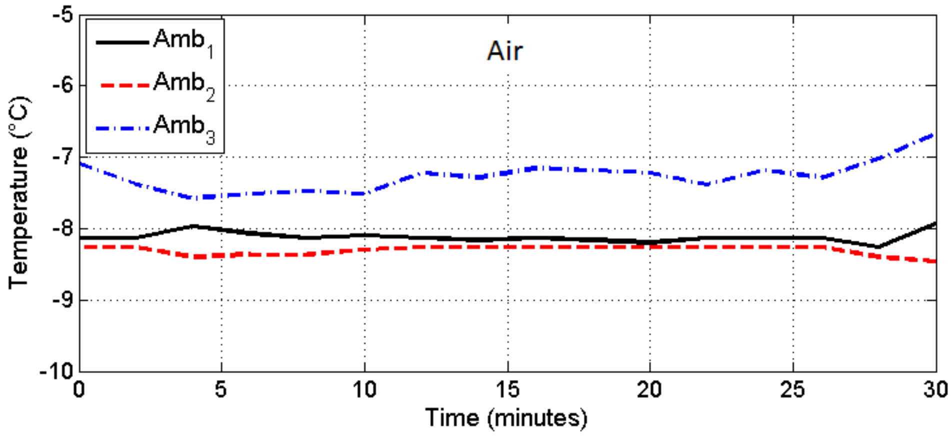


Figure 3.3: Ambient air temperature during the CBCC experiment spanning a total of 30 minutes.

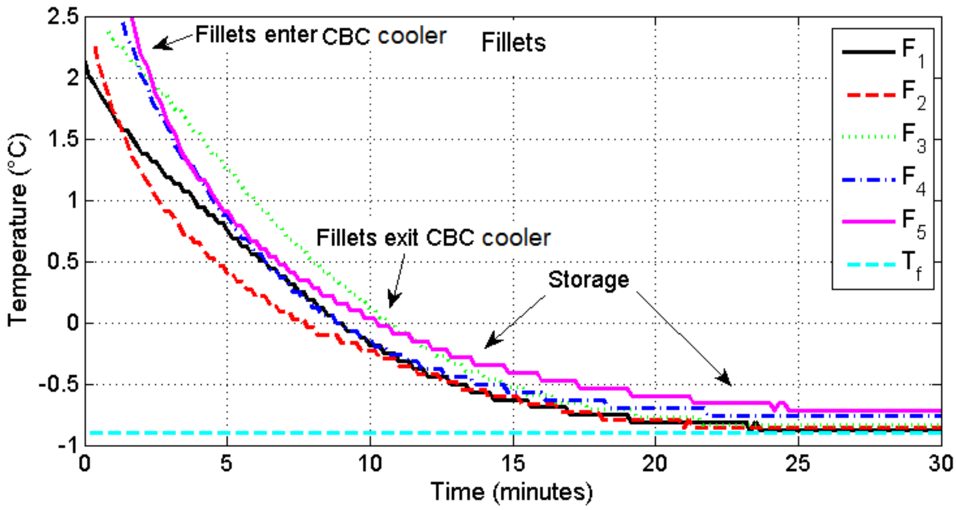


Figure 3.4: Fillet temperature during the CBCC experiment spanning a total of 30 minutes.

3.2 Packaging design

The results from the packaging part of this study was divided into the design of new improved packaging using numerical heat transfer modelling and two experiments, one using first prototypes and another validating the new box which was casted into mold. First, the results from the simulated trial using numerical heat transfer modelling are presented and then the results from the prototype experiment and last but not least, the new box experiment.

3.2.1 Numerical modelling

Before being able to perform improvements, it was necessary to generate a model of the original box and analyse the results. Figure 3.5 shows the temperature distribution at the surface areas of the EPS box, air and fish, forming three domains. The figure does not show the temperature distribution inside the fish block and is mainly presented to help the reader to visualise the setup of the domains. Figure 3.6 shows the temperature distribution in a vertical, diagonal cross section through the original box. It shows the temperature variations inside the fish block, from 2 °C in the core and reaching 6-7 °C in the corners. The layer of air is slightly warmer than the fish block and the EPS box reaches the ambient temperature 15 °C at the surface and corners. Outlines of the computational domain (EPS box) are shown in both figures and the colorbar shows temperature ranging from 2 to 15 °C.

Figure 3.7 shows the temperature contours in a horizontal section through the box and fillets at mid-height of the fillets. The figure clearly displays higher fish temperature in the original box compared to design C. The temperature distribution inside the box was inhomogeneous and the maximum temperature was located in the corners. By analysing the results, i.e. the temperature distribution in the fish block inside the box, the corners were identified to be the most critical temperature areas as expected.

The fish temperature at the bottom corners and at the centre of the fish block was recorded during the simulated time (4 hours with T_{amb} = 15 °C and T_{init} = 1 °C) for all the seven designs. The mean temperature was also computed. Figure 3.8 shows the maximum, mean and minimum temperatures during the simulated time. The minimum temperature was quite similar for all the boxes, compared to the maximum temperature. Design C provided the lowest maximum temperature, i.e. 2.1 °C lower than for the original design.

All the new designs offered significantly improved thermal protection in the corners compared to the original box. The results were however not sensitive, i.e. all the

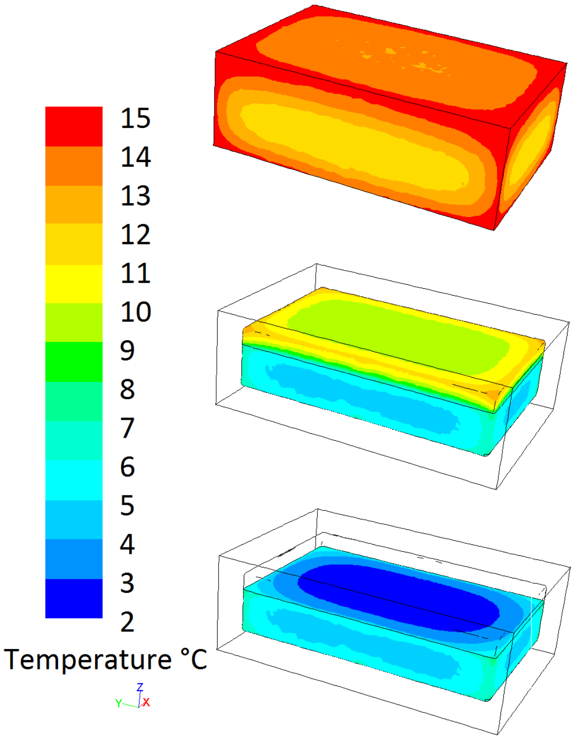


Figure 3.5: Temperature distribution at the surface areas of the original EPS box (top), air and block of fillets (middle) and block of fillets (bottom) after four hours of T_{amb} = 15 °C with T_{init} = 1 °C.

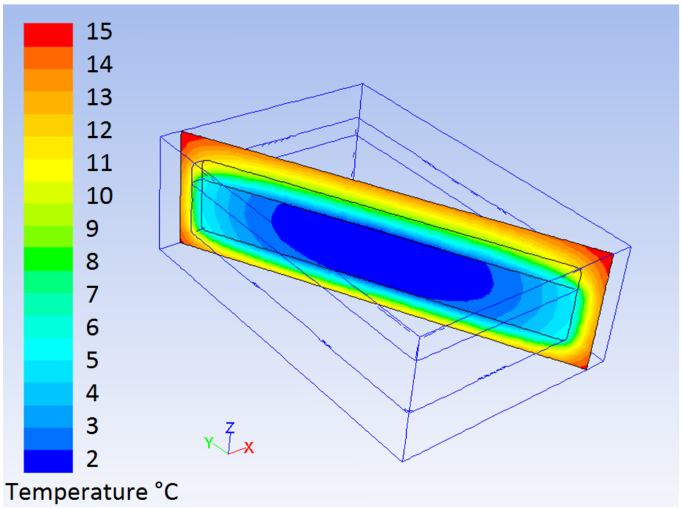


Figure 3.6: Temperature distribution in a diagonal, vertical cross section through the original box after four hours of T_{amb} = 15 °C with T_{init} = 1 °C.

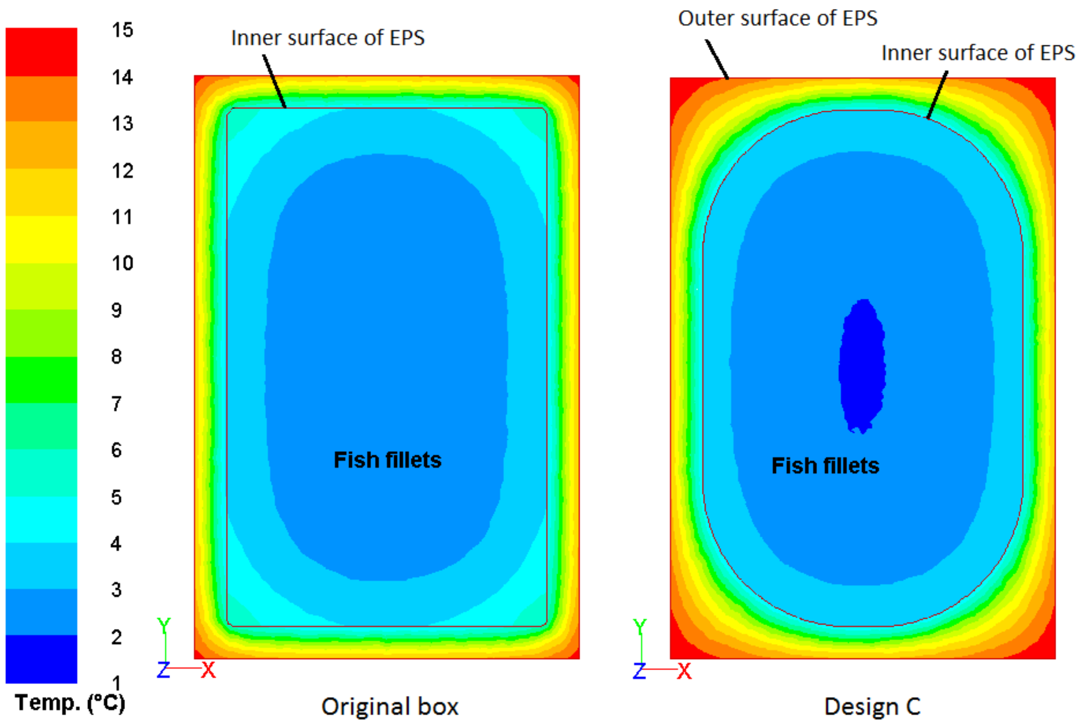


Figure 3.7: Temperature contours in a horizontal section through the original box and design C at mid-height of fillets after four hours at T_{amb} = 15 °C and T_{init} = 1 °C.

designs except for design G gave similar results. Design G was the only design where the wall thickness was reduced, by 0.75 mm, and the radius of curvature in the corners was the smallest or 50 mm. All the other designs had the same wall thickness as the original box and radius of curvature 75 to 100 mm. No significant difference was however observed between their thermal performance.

3.2.2 Packaging experiments

Following are the results from the two packaging experiments, the first one performed with the two prototype boxes (G_p and H_p) and the latter one performed with the new box after it was casted into mold.

Figure 3.9 shows the ambient temperature during the dynamic temperature storage. The temperature of the fish was 2 °C when the boxes entered the chamber and that caused the ambient temperature to gradually drop. During the six hours of temperature abuse the ambient temperature dropped by 1-2 °C. The boxes in the prototype experiment were stored in an air climate chamber at 2 °C for 48 hours

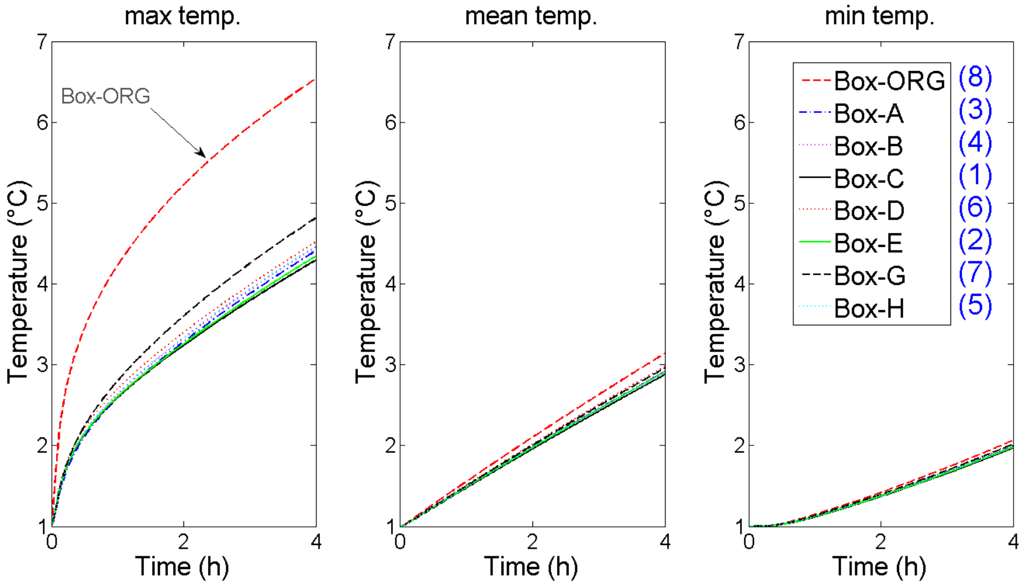


Figure 3.8: Temperature results showing maximum, mean and minimum temperatures to the left, middle and right, respectively. The insulation performance of the designs is shown inside brackets, (1) for C giving the best insulation and (8) for ORG giving the worst insulation.

before subjected to a dynamic temperature. The dynamic temperature was obtained by turning off the air climate chamber and waiting until it reached room temperature of 22.5 °C after which the boxes were put in the chamber.

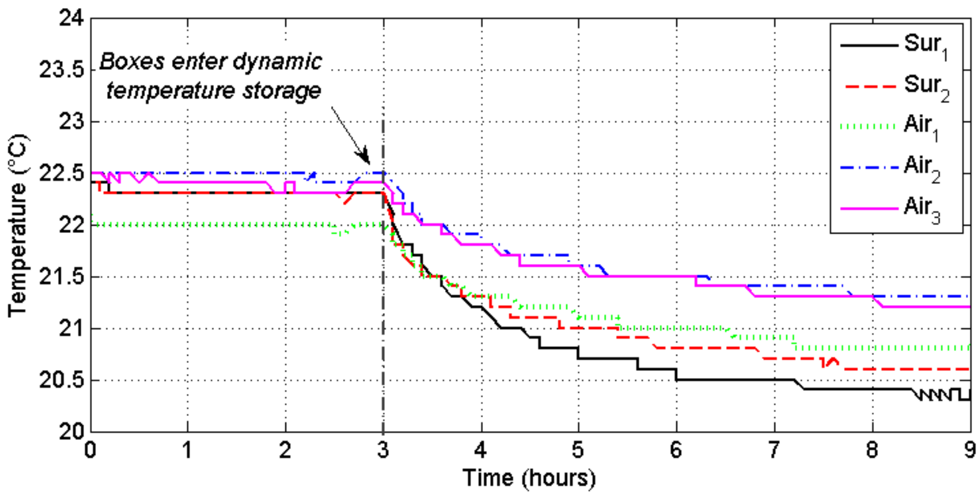


Figure 3.9: Ambient air temperature and surface temperature in the air climate chamber during the prototype experiment.

Figure 3.10 shows the temperature recordings for each box at the eight positions where the temperature loggers were placed. The fish temperature was approximately

2 °C in all boxes before subjected to dynamic temperature. The figures show that the temperature distribution changed quite rapidly during the dynamic temperature storage. The highest temperature in all boxes was in the corners at positions 4 and 8 and the lowest temperature was in the middle of the boxes at positions 1 and 5.

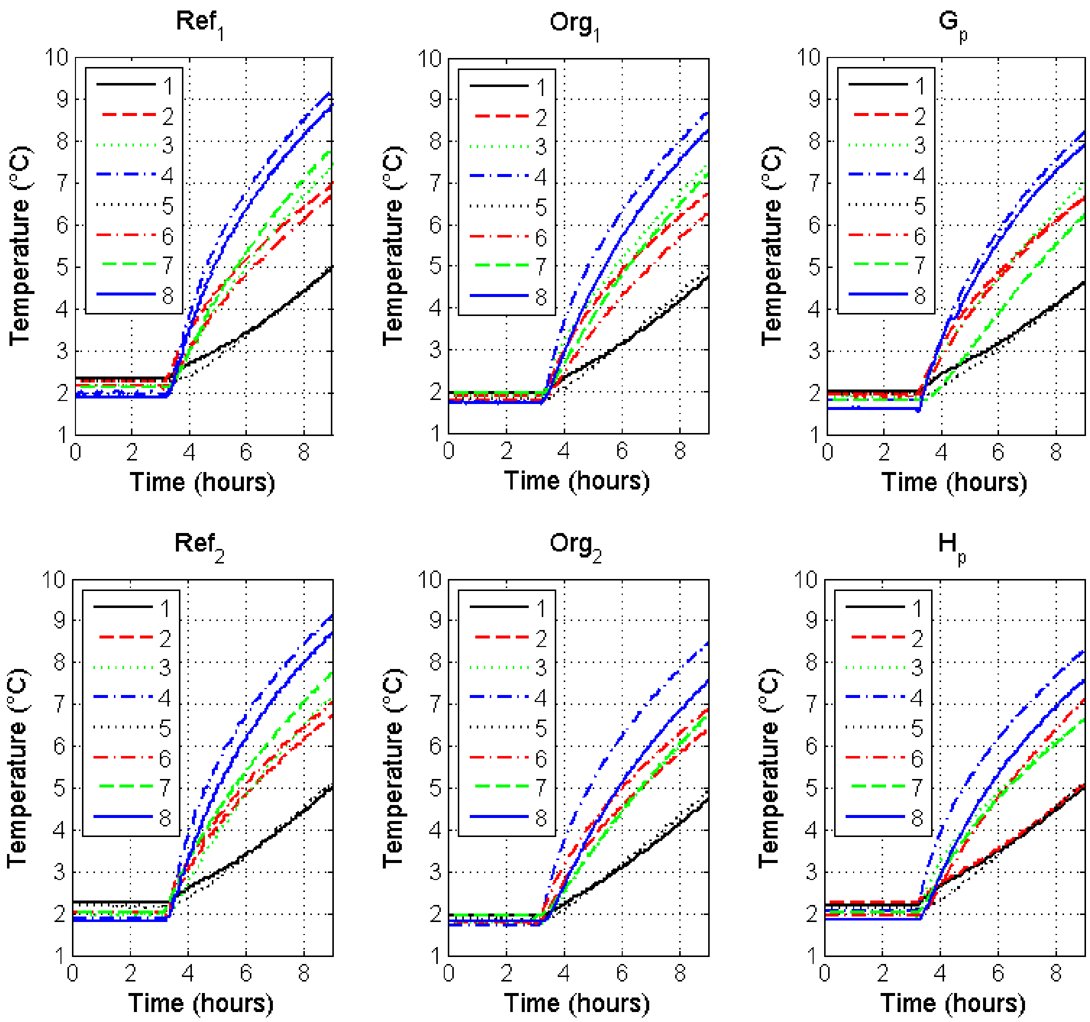


Figure 3.10: Temperature recordings in six boxes, each box with eight loggers, subjected to dynamic temperature storage in the prototype experiment.

These results are in accordance with what was expected, i.e. the rate of heat exchange was the greatest in the corners. The maximum temperature in the reference boxes was 9.1 °C, 8.7 °C in the original boxes, 8.2 °C in G_p and 8.3 °C in H_p. The reference box provided the worst thermal protection in the corners, followed by the original box and then the prototypes. These results are in accordance with previous assumptions, that the box with the least material in the corners (the reference boxes) provides the worst thermal protection. These results further show that the thermal protection can be improved by increasing wall thickness in corners.

After sharing these results with the manufacturer of the original EPS box and fresh fish processors, a final design of the new box was made. The new box was manufactured based both on the results from the numerical heat transfer models and the prototype packaging experiment as well as the experience of the manufacturer and fresh fish processors. Following are the results from the experiment with two original and two new boxes.

Figure 3.11 shows the ambient air temperature (Air), surface temperature (Sur) and floor temperature (Flo) during the experiment. The surface temperature was measured on top of each EPS box.

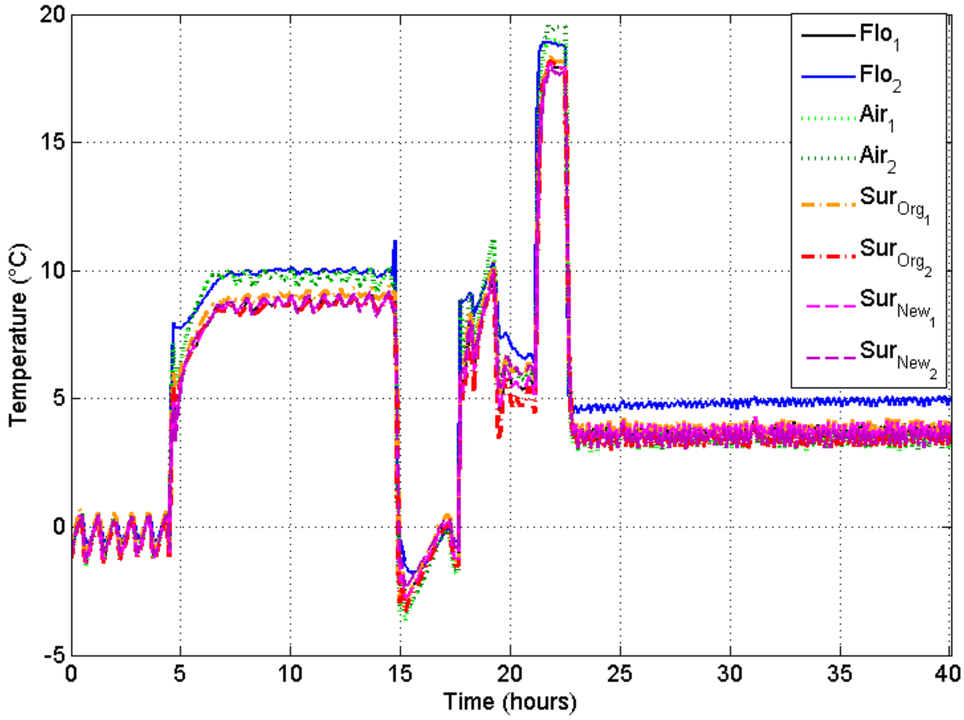


Figure 3.11: Ambient air temperature (Air_1 and Air_1), surface temperature (Sur_{Org1}, Sur_{Org2}, Sur_{Org3} and Sur_{Org4}) and floor temperature (Flo_1 and Flo_2) in the air climate chamber during the new box experiment.

The temperature inside the air climate chamber was inhomogeneous and the surface temperature on top of each EPS box was a bit lower than the floor and air temperature in the chamber. Each EPS box did however experience very similar ambient temperature as the surface temperatures did not vary more than 0.5 °C. Some difficulties were experienced during the experiment in controlling the ambient temperature, and the result was a profile with about 2 °C lower temperature than planned. This did, however, not affect the results as the original and new box were subjected to the same ambient temperature.

The fish temperature at positions 1 to 3 (at the bottom of the EPS box) and 6 to 8 (on top of the fillets) is shown in Figure 3.12. The temperature response time varied between positions, the corners being most sensitive to temperature fluctuations. The evolution of temperature was more smooth at positions surrounded by fish, i.e. positions 3, 4 and 5 shown in Figure 3.13. This has some disadvantages as the temperature at these positions does not react as quickly to a decrease in the ambient temperature.

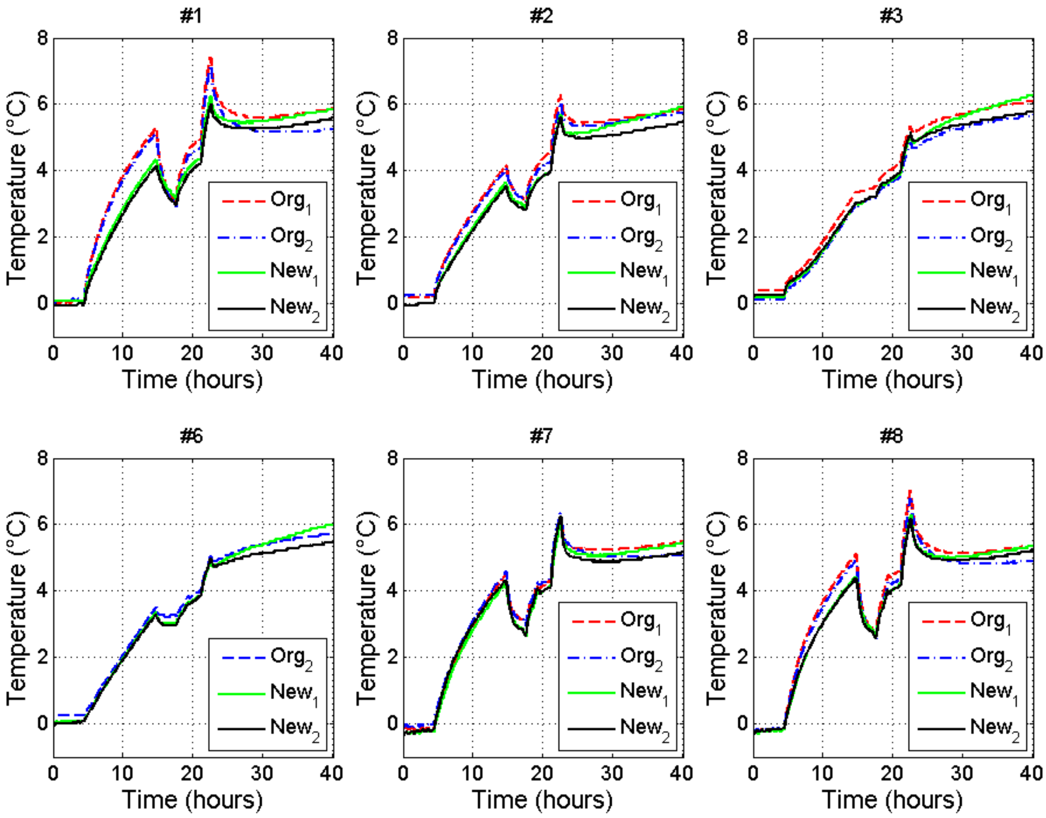


Figure 3.12: Temperature recordings in four boxes (Org_1, Org_2, New_1 and New_2) during dynamic temperature storage in the new box experiment. Temperature was recorded at eight positions, positions 1 to 3 and 6 to 8 are shown.

During the first 10 hours of dynamic temperature storage, at ambient temperature of 10 °C, the thermal protection of the new boxes is significantly better in the corners (positions 1 and 8) and somewhat better at positions 2, 4 and 5. During the cold storage, after the first dynamic temperature storage, the temperature difference between boxes at all positions seems to level off. The fish temperature in the corners drops more rapidly than in the middle (positions 3, 4 and 5) and the reason for this is that the bad thermal protection becomes an advantage when ambient temperature drops. If this would however happen during storage at ambient temperature around T_f then any fluctuations would be very undesirable and rather than lowering the temperature below T_f and then increasing it again above T_f it would be better to just maintain it at a certain temperature around T_f.

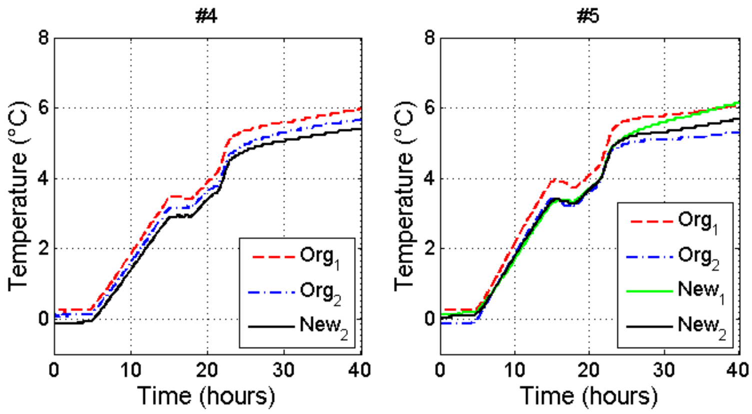


Figure 3.13: Temperature recordings in four boxes (Org_1, Org_2, New_1 and New_2) during dynamic temperature storage in the new box experiment. Temperature was recorded at eight positions, positions 4 and 5 are shown.

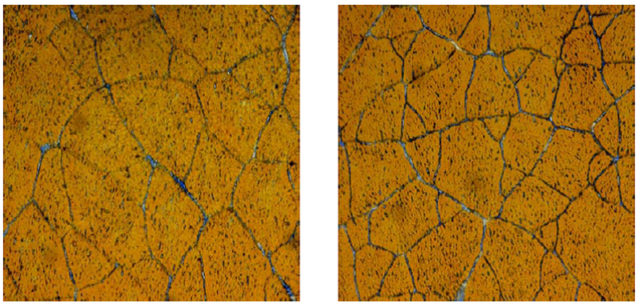
4 Discussion

The results from the precooling experiments revealed that the fillets temperature can be lowered down to T_f by using either LC or CBCC. More difficulties were experienced in controlling the liquid temperature in the liquid cooler. Valtýsdóttir et al. (2010) performed an experiment which reveals the liquid temperature to fluctuate from -0.4 to 4 °C with average between 1-2 °C during a whole day of processing (interval of 8 hours). The LC experiment did not involve the fillets temperature being recorded for half an hour after the LC to see if they continued to cool down. Since the liquid temperature was not below the freezing point, no ice crystals had formed and hence the additional energy (42 kJ kg^{-1}) needed to raise the temperature of the flesh from -1 to 0 °C was not required. In addition to being less efficient, according to Magnússon et al. (2009b), the brine can carry considerable amounts of microbes such as spoilage bacterium Photobacterium phosphoreum which is an active producer of trimethylamine (TMA). The amount of TMA produced is a measure of the activity of spoilage bacteria in the flesh and so is an indicator of the degree of spoilage. Liquid cooling in this poor quality brine resulted in 2-3 days shorter shelf life than a group which received no cooling after.

Martinsdóttir et al. (2004) analysed the effect of CBCC on the physical properties of the fish muscle and concluded that no difference in microstructure was found between CBC superchilled fillets and traditionally processed fillets. Figure 4.1 shows the microstructure of fish fillets, 3 mm from the skin, traditional processed (a), i.e. no cooling and combined blast and contact cooled (b). Figure 4.2 shows the microstructure next to the skin, where contact freezing occurs. The figures show that the walls of the cells are almost intact since the ice crystals which formed during the rapid cooling were small, leaving the flesh free of large holes.

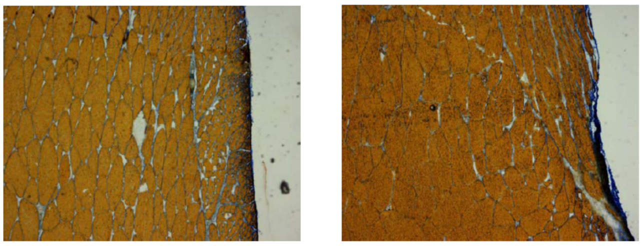
According to another experiment performed by Magnússon et al. (2009a) the CBCC technique clearly resulted in longer freshness period and shelf life extension compared to LC and no cooling. The conclusion from the precooling experiments performed in this study is that CBCC is more preferable than LC in the way that it lowered the fish temperature to its T_f effectively and previous studies indicate that it results in prolonged shelf life and freshness period compared to fillets subjected to LC.

For further work it might be interesting for further work to model a fish fillet subjected to CBCC, taking into account the phase change in the fish muscle which



(a) *(b)*

Figure 4.1: Microstructure of fish fillets 3 mm from the skin, traditional processing (a) and combined blast and contact cooled (b) (Martinsdóttir et al., 2004).



(a) *(b)*

Figure 4.2: Microstructure of fish fillets next to the skin, traditional processing (a) and combined blast and contact cooled (b) (Martinsdóttir et al., 2004).

starts at T_f. The speed of the conveyor belt and the temperature of the air inside the chamber could be controlled in such way that fillets of different size received efficient precooling.

After lowering the temperature of the fish to its intended storage temperature, the packaging plays the role of maintaining that temperature during storage and transport from processor to wholesaler. The main findings in this study are that by re-designing the packaging, without adding material or affecting the outer dimensions of the box, the thermal insulation can be improved significantly. These findings provide opportunities for improvements to other types of packagings, as the method of using numerical heat transfer modelling can be translated to other fields of packaging solutions with some modifications. Margeirsson et al. (2010) performed a trial where the thermal protection of the new improved EPS box was compared to the original box, for simulated air and sea transport, by means of temperature monitoring, chemical-, microbial and sensory analysis. The sea transport was considered to be at constant ambient temperature of -1 °C, which can be achieved during non-interrupted and well temperature-controlled, containerised sea transport. The changes in freshness period and shelf life (in Torry scale) according to sensory evaluation are shown in Table 4.1. Torry score limit of acceptability was considered 5.5 for shelf life and 7 for freshness period.

Table 4.1: Freshness period and shelf life according to sensory evaluation. Org: Original EPS box type, New: New EPS box type, ST: Steady storage temp., DT: Dynamic storage temp., Co: Corner box samples, Mi: Middle box samples (Margeirsson et al., 2010)

Group	Freshness period (days)	Shelf life (days)
Org-ST-Co	6-7	11-12
Org-DT-Co	2-3	6-7
New-DT-Co	5	8
New-DT-Mi	5	8-9

According to sensory evaluation, storage in the new boxes resulted in approximately 2 to 3 days longer freshness period and about two days longer shelf life when comparing samples treated and sampled in the same way, stored in the original and new boxes under dynamic temperature conditions (Org-DT-Co versus New-DT-Co). Furthermore, the sampling position, corner (Co) versus middle (Mi), within the new boxes did not affect the sensory quality significantly. The results further emphasise the importance of proper temperature control in fresh fish supply chains. By cooling the product to its T_f before packaging, and by using the new improved EPS box, the quality and value of fresh fish can be increased considerably.

References

Al-Ajlan, S. A. (2006). Measurements of thermal properties of insulation materials by using transient plane source technique. *Applied Thermal Engineering*, 26(17-18):2184-2191. URL = http://www.sciencedirect.com/science/article/pii/S1359431106001256. Accessed 16. July, 2010.

Anyadiegwu, M., Archer, M. (2002). Trials to Compare the Thermal Performance of a New Design of Tri-pack Corrugated Plastic Nonreusable fish box with Expanded Polystyrene and Single Walled Fibreboard Box. URL = http://www.truefoam.com/site/media/Truefoam/CR192Tri-pack%20report.pdf. Accessed 20 June, 2011.

Arnþórsdóttir, M. G., Arason, S., Margeirsson, B. (2008). Combined blast and contact cooling - effects on physiochemical characteristics of fresh haddock (Melanogrammus aeglefinus) fillets. Matís report 14-08.

BASF SE (2001). Insulation and packaging using strong brands. URL = http://www.plasticsportal.net/wa/plasticsEU~en_GB/function/conversions:/publish/common/upload/foams/Foams_insulation_packaging.pdf. Accessed 10 August, 2010.

Burgess, G. (1999). Practical thermal resistance and ice requirement calculations for insulating packages. *Packaging Technology and Science*, 12(2):75-80.

Elliott, M. A., Halbert, G. W. (2005). Maintaining the cold chain shipping environment for Phase I clinical trial distribution. *International Journal of Pharmaceutics*, 299(1-2):49-54.

Froese, R. (1998). Insulating properties of styrofoam boxes used for transporting life fish. *Aquaculture*, 159(3-4):283-292.

Giannakourou, M. C., Koutsoumanis, K., Nychas G. J. E., Taoukis, P. S. (2005). Field evaluation of the application of time temperature integrators for monitoring fish quality in the chill chain. *International Journal of Food Microbiology*, 102(3):323-336.

Gudmundsson, T. (2009). Personal Communication with the Managing Director of Promens Tempra Iceland.

Holman, J. (2002). *Heat transfer.* McGraw-Hill, 9th edition.

Johnston, W. A., Nicholson, A. R., Stroud, G. D. (1994). Freezing and refrigerated storage in fisheries. FAO Fisheries Technical Paper No. 340. URL = http://www.fao.org/DOCREP/003/V3630E/V3630E00.htm#Contents. Accessed 10 May, 2010.

Kolbe, E., Kramer, D. (2007). *Planning for Seafood Freezing.* Alaska Sea Grant.

Labranque, G. and Kacimi, A. (2007). *Static cooling containers alternative solution for cold chain*, number ICR07-D2-222. International Congress of Refrigeration 2007, Beijing.

Magnússon, H., Lauzon, H. L., Sveinsdóttir, K., Margeirsson, B., Reynisson, E., Rúnarsson, Á. R., Guðjónsdóttir, M., Þórarinsdóttir, K. A., Arason, S., Martinsdóttir, E. (2009a). The effect of different cooling techniques and temperature fluctations on the storage life of cod fillets (Gadus morhua). Matís report 23-09.

Magnússon, H., Þorvaldsson, L., Sveinsdóttir, K., Lauzon, H. L., Þórarinsdóttir, K. A., Arason, S., Martinsdóttir, E. (2009b). The effect of liquid cooling at processing and different cooling techniques during transport of cod (Gadus morhua) fillets. Matís report 34-09.

Mai, N. T. T., Margeirsson, B., Margeirsson, S., Bogason, S. G., Sigurgísladóttir, S., Arason, S. (2011). Temperature mapping of fresh fish supply chains - air and sea transport. *Journal of Food Process Engineering.*

Margeirsson, B., Dornboos, R., Ramirez, A., Mu, W. and Xioli, F., Bogason, S. (2008). D1.10: Flow chart of selected fish supply chains including mapping of temperature and other relevant enviromental parameters.

Margeirsson, B., Arason, S., Pálsson, H. (2009). Thermal Performance of Corrugated Plastic Boxes and Expanded Polystyrene Boxes. Matís report 01-09.

Margeirsson, B., Lauzon, H. L., Reynisson, E., Magnússon, H., Arason, S., Martinsdóttir, E. (2010). Effect of improved design of wholesale EPS fish boxes on thermal insulation and storage life of cod loins - simulation of air and sea transport. Matís report 29-10.

Margeirsson, B. and Gospavic, R. and Pálsson, H. and Arason, S. and 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. URL = http://www.sciencedirect.com/science/article/pii/S0140700710002252. Accessed 10 May, 2010.

Martinsdóttir, E., Guðbjörnsdóttir, B., Lauzon, H. L., Þóroddsson, O., Tryggvadóttir, S. V., Arnarsson, G. Ö. (2004). Effect of contact and blast cooling on quality of fish fillets. Matís report 03-04.

Martinsdóttir, E., Lauzon, H. L., Margeirsson, B., Sveinsdóttir, K., Þorvaldsson, L., Magnússon, H., Eden, M. (2010). The effect of cooling methods at processing and use of gel packs on storage life of cod (Gadus morhua) loins. Effect of transport via air and sea on temperature control and retail-packaging on cod deterioration. Matís report 18–10.

Maxim iButton® Devices DS1922L. URL = http://www.maxim-ic.com/products/ibutton/products/ibuttons.cfm. Accessed 20 June, 2011.

Moureh, J., Laguerre, O., Flick, D., Commere, B. (2002). Analysis of use of insulating pallet covers for shipping heat-sensitive foodstuffs in ambient conditions. *Computers and Electronics in Agriculture*, 34:89-109.

Pham, Q. T. (1996). Prediction of calorimetric properties and freezing time of foods from composition data. *Journal of Food Engineering*, 30(1-2):95-107.

Rha, C. (1975). *Theory, Determination and Control of Physical Properties of Food Materials:Thermal properties of foods.* Reidel Publising.

Singh, R. P., Heldman, D. R. (2003). *Introduction to Food Engineering.* Academic Press, 3rd edition.

Singh, S.P., Burgess, G., Singh, J (2008). Performance comparison of thermal insulated packaging boxes, bags and refrigerants for single-parcel shipments. *Packaging Technology and Science*, 21(1):25-35.

Statistics Iceland (2010). Export of fresh fish by mode of transport 1988-2010. URL = http://www.statice.is/?PageID=1261&src=/temp_en/Dialog/varval.asp?ma=UTA02407%26ti=Export+of+fresh+fish+by+mode+of+transport+1988-2010%26path=../Database/utanrikisverslun/UtflutningurAR/%26lang=1%26units=Fob%20million%20ISK/tonnes. Accessed 18 June, 2011.

Valtýsdóttir, K. L., Margeirsson, B., Arason, S., Lauzon, H. L., Martinsdóttir, E. (2010). Guidelines for precooling of fresh fish during processing and choice of packaging with respect to temperature control in cold chains. Matís report 40-10.

Valtýsdóttir, K. L., Margeirsson, B., Arason, S., Pálsson, H., Gospavic, R., Popov, V. (2011). Numerical Heat Transfer Modelling for Improving Thermal Protection of Fish Packaging. 2011 CIGR Section VI International Symposium on Towards a Sustainable Food Chain Food Process, Bioprocessing and Food Quality Management Nantes, France - April 18-20.

Zalba, B., Marín, J. M., Cabeza, L. F., Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering*, 23(3):251-283.

Appendix A

Paper I: Guidelines for precooling of fresh fish during processing and choice of packaging with respect to temperature control in cold chains

Appendix B

Paper II: Numerical Heat Transfer Modelling for Improving Thermal Protection of Fish Packaging