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Thermal modelling of processing and transport of fresh fish

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Vinnsla, virðisaukning og eldi

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Ágrip á íslensku:	Meginmarkmið verkefnisins Hermun kæliferla - varmafræðileg hermun vinnslu- og flutningaferla, sem hófst í júní 2008, var að setja fram endurbætur á verklagi og búnaði tengdum flutningi á sjávarafurðum með ferlagreiningu, tilraunum og tölvuvæddum varma- og straumfræðilíkönum. Afleiðingar bættrar hitastýringar í vinnslu- og flutningaferlum eru aukin gæði, stöðugleiki og öryggi, sem auka um leið verðmæti vörunnar. Samstarfsaðilar í verkefninu voru Matís, Háskóli Íslands, Promens Tempra, Eimskip Ísland, Samherji, Brim (ÚA), Festi, Völusteinn og Eskja. Í þessari skýrslu er helstu niðurstöðum og afurðum verkefnisins lýst. Dæmi um afurðir eru varmaflutningslíkön af ferskfiskafurðum í frauðkassa, sem gera kleift að spá fyrir um fiskhita út frá umhverfishitasögu. Varmaflutningslíkön voru notuð til að endurhanna 3, 5 og 7 kg frauðkassa Promens Tempra með lágmörkun hæsta fiskhita í kössunum undir hitaálagi að markmiði. Tilraunir staðfestu yfirburði nýju kassanna umfram hefðbundnar kassagerðir, bæði m.t.t. hitastýringar og gæða vöru undir hitaálagi. Niðurstöður annarrar tilraunar sýna að geymsluþol ferskra fiskflaka í hornkössum heils bretti í flugflutningskeðju getur verið um 1-1,5 dögum styttra en flaka í kössum í miðju brettastaflans. Hitadreifing í mismunandi kælikeðjum var kortlögð og sérstök áhersla lögð á forkælingu flaka fyrir pökkun og hitadreifingu í mismunandi tegundum kæligáma með mismunandi hleðslumynstur.		
Lykilorð á íslensku:	*Fiskur, hitastig, varmaflutningslíkan, pakkningar , forkæling, kæligámur*		
Summary in English:	The main aim of the research project Hermun kæliferla – Thermal modelling of processing and transport of fresh fish, which was launched in June 2008, was to improve technology and practices used for fish processing and transport by means of analysis of chill chains, experiments and computational modelling. Improved temperature control in fish chill chains leads to increased product quality, stability and safety and thereby increased product value. This report describes the main results and products of the project. Examples include heat transfer models of fresh fish fillets packaged in boxes, which can be used to predict product temperature evolution as a function of variable ambient temperature. Numerical heat transfer models were used to optimise the design of 3, 5 and 7-kg expanded polystyrene boxes manufactured by Promens Tempra with the aim of minimising the maximum fish temperature in boxes under thermal load. Improved thermal protection of the new box design was confirmed in different experiments, both with regard to lesser product temperature variations and prolonged freshness period and storage life of products. The results from another storage study suggest that the storage life of fresh fish products in a corner box can be more than 1-1.5 days shorter than in the centre boxes of a full size pallet stack in a real air transport chain, depending on the level of ambient thermal load. Environmental and product temperatures were mapped in different chill chains with special emphasis laid on precooling during processing and temperature distribution in reefer containers of different types and loading patterns.		
English keywords:	*Fish, temperature, heat transfer model, packaging, precooling, refrigerated container*		

EFNISYFIRLIT

1 INTRODUCTION

The purpose of this report is to review the most important results obtained in the R&D project "Hermun kæliferla" (e. Thermal modelling of processing and transport of fresh fish). The main aim of the project was to improve technology and practices used for fish processing and transport by means of analysis of chill chains, experiments and computational modelling. Temperature control is a key word since it is a critical parameter to retard quality deterioration of perishable foodstuffs, such as fresh fish, in the whole chill chain from catch, through processing and distribution to consumers.

Limited emphasis is put on describing materials and methods used since these are described in each reference. The main results comprise assessment of temperature control during air and sea transport, precooling during processing, insulation performance of packaging and utilisation of numerical heat transfer modelling for predicting product temperature variations and improving packaging design.

2 MATERIALS AND METHODS

In this section, commonalities in measurement devices on one hand and in the numerical modelling on the other hand will be mentioned. The detailed configuration of measurement devices in each study is described in each reference (see Section 3). In all transport simulation studies, i.e. the ones that were not conducted in real supply chains, ambient conditions were controlled in controllable air climate chambers (Celsius, Reykjavík, Iceland).

2.1 Measurement devices

The specification of the different measurement devices used is presented in Table 1. Ibutton temperature loggers (DS1922L, see Figure 1) from Maxim Integrated Products (Sunnyvale, CA, USA) were used to monitor the fish temperature inside the insulated boxes (Figure 2) in addition to the surface and ambient temperatures in some trials. Its diameter is 17.35 mm and the thickness is 5.89 mm. Tidbit v2 temperature loggers (Figure 3) 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 (Figure 4) from Onset Computer Corporation (Bourne,

MA, USA). Finally, air velocity was measured with Thermo-Anemometer Datalogger (model 451126) from Extech Instruments (Waltham, MA, USA).

Table 1. Specification of measurement devices

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

Figure 1. Ibutton DS1922L temperature datalogger.

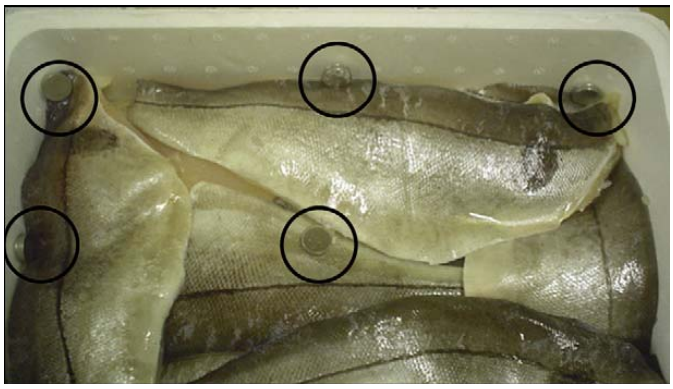

Figure 2. Whole haddock fillets in an EPS box. Also shown are temperature loggers used for monitoring temperature on top of fillets.[1]

Figure 3. Tidbit v2 temperature datalogger.

Figure 4. HoBo U12 temperature and relative humidity datalogger.

2.2 Numerical heat transfer modelling

Three dimensional heat transfer models were developed using the Computational Fluid Dynamics software FLUENT. Models were developed for single packages containing chilled fish[1], superchilled fish and a cooling pack[2], frozen fish in multiple packages assembled on a pallet[3] and chilled fish in multiple packages assembled on a pallet.[4] 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 whole packages/pallet stack. Examples of computational grids are presented in Figure 5 and Figure 6 and more details on the modelling development are accessible in each article/report.

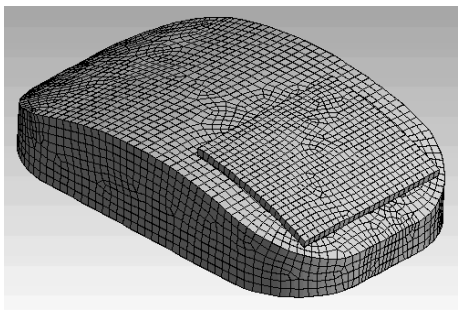

Figure 5. Computational mesh for superchilled fish and cooling pack inside an EPS box with rounded corners.[2]

[1] Margeirsson, B., Gospavic, R., Pálsson, H., Arason, S., Popov, V. 2011a. 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.

[2] Margeirsson, B., Pálsson, H., Popov, V., Gospavic, R., Arason, S., Sveinsdóttir, K., Jónsson, M.Þ. 2011b. Numerical Modelling of Temperature Fluctuations in Superchilled Fish Loins Packaged in Expanded Polystyrene and Stored at Dynamic Temperature Conditions. In: The 23rd IIR International Congress of Refrigeration, 21 – 26 August 2011. Prague, Czech Republic.

[3] Margeirsson, B., Thorvaldsson, L., Arason, S. 2009. *Frysting og þíðing grálúðu – tilraunir og CFD hermun*. Matis report 33-09.

[4] Margeirsson, B., Pálsson, H., Gospavic, R., Popov, V., Jónsson, M.Þ., Arason, S. Numerical modelling of temperature fluctuations in chilled fish fillets packaged in pallets and stored at dynamic temperature conditions. Unpublished results.

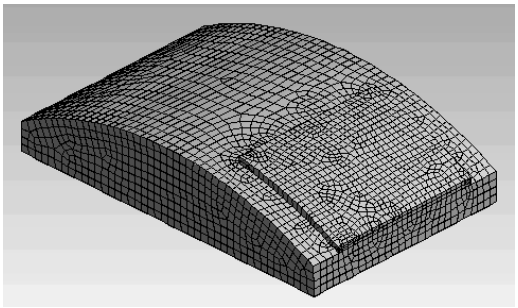

Figure 6. Computational mesh for superchilled fish and cooling pack inside an EPS box with sharp corners.[2]

3 RESULTS AND DISCUSSION

3.1 Temperature control in chill chains – air vs. sea transport

The logistics processes in fresh fish chill chains have been divided into three different areas including handling, storage, and transport.[5,6] Summary of the mean ambient temperatures during the different processes mapped by Mai et al. (2010, 2011) and the time period (in hours:minutes) which the exposure lasted is given in Table 2.

Table 2. Ambient temperature registrations during four temperature mapping trials[6]

Study	Storage	Handling	Transport
Air freight (September 2007)	11,3 °C / 5h:20m	8,6 °C / 2h	9,9 °C / 6h
Air freight (June 2008)	8,8 °C / 10h:10m	4,6 °C / 5h:30m	3,4 °C / 2h:15m
Sea freight (Sept. 23rd – 29th 2008)	3,5 °C / 4h:50m	-0,4 °C / 123h: 30m	
Sea freight (Sept. 24th – Oct 1st 2008)	-0,7 °C / 160h: 35m		

The main conclusion from the different temperature mapping trials is that temperature control in containerised sea transport is generally much better than in multimodal air transport chains. Furthermore, the results demonstrate that differences can also be found in the temperature control in sea transport chains and that efficient precooling of products during processing is very

[5] Mai, N.T.T, 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.

[6] Mai, N., Margeirsson, B., Stefánsson, G. 2010. Temperature controlled transportation alternatives for fresh fish – air or sea? In: The 22nd NOFOMA conference. 10-11 June 2010. Kolding, DK, p. 147 - 162.

important for the temperature control during transport and storage. It is recommended for fresh fish processors to study the temperature management of their export route in order to select a packaging material suiting their needs. The main disadvantage of sea transport is the long transit time, which causes a relatively short remaining shelf life of product in sea freight. This indicates that the trade off between transport 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.

The larger thermal load in air transport chains causes larger fish temperature variations both inside each box and inside each whole pallet stack for air freight as compared to sea freight.

3.1.1 Temperature distribution in reefer containers

Temperature measurements at around 40 – 70 positions inside different types of refrigerated sea containers have revealed that the mean air temperature inside fully loaded containers at ambient temperature of around 15 °C can be 1 to 2 °C above the set point temperature of 0 °C.[7] Furthermore, around 1 °C higher air temperature can be expected in the quadrant at the back of the container as compared to the quadrant closest to the refrigerating equipment at the front of the container. Taking into account that storage life of whitefish products is larger for products stored at -1 °C than at 0 °C,[8] these results imply that the set point temperature should be set to no higher than -1.5 to -1.0 °C during periods when the expected ambient temperature is higher than 10 to 15 °C.

On the other hand, according to Elíasson's measurements during the winter time at ambient temperature around -5 to 5 °C, mean air temperature of around 0 to 0.5 °C can be expected under these more favourable conditions. This implies that in order not to risk excessive freezing of whitefish products due to air temperature fluctuations inside containers in the wintertime, the set point temperature should probably not be set at lower temperature than -1.0 °C.

3.2 Precooling

The importance of precooling whitefish fillets and loins during processing has become evident in a number of different studies.[8,9,10] The performance of precooling techniques such as the Marel

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[7] Elíasson, S. 2011. Unpublished results.

[8] Hélène L. Lauzon, Björn Margeirsson, Kolbrún Sveinsdóttir, María Guðjónsdóttir, Magnea G. Karlsdóttir, Emilía Martinsdóttir. 2010. *Overview on fish quality research - Impact of fish handling, processing, storage and logistics on fish quality deterioration*. Matís report 39-10.

[9] Emilía Martinsdóttir, Hélène L. Lauzon, Björn Margeirsson, Kolbrún Sveinsdóttir, Lárus Þorvaldsson, Hannes Magnússon, Eyjólfur Reynisson, Arna Vigdís Jónsdóttir, Sigurjón Arason, Maria Eden. 2010. *The effect of cooling methods at processing and use of gel-*

Super Chiller (formerly referred to as CBC cooler), slurry ice cooling and liquid cooling has been studied in the current project.[11,12, 13,14] Precooling by means of blast and contact cooling in the Super Chiller has been shown to be more effective and more stable than slurry ice- or liquid cooling. The fact that care must be taken that microbiological quality of the fish products is not compromised by the cooling technique further recommends the Super Chiller technique.

3.3 Packaging

Emphasis has been put on investigating thermal insulation of packaging and the effect of cooling packs inside the packaging. Experiments and numerical modelling have been conducted for single and multiple packages made of expanded polystyrene (EPS by different manufacturers), corrugated plastic (CP by Tri-Pack) and solid polypropylene (PP by Cool Blue Box company). [15]

3.3.1 Effect of cooling packs and comparison between CP, EPS and PP

Studies showed that applying frozen cooling packs in fish boxes reduces the negative impact of temperature abuse on fresh fish fillets, [1,16] see Figure 7. Insulating performance of expanded polystyrene was shown to be significantly better than of corrugated plastic. Thus, the insulating properties of the expanded polystyrene boxes make this type of packaging more suitable for the case of chilled chains with insufficient temperature control. However, since the corrugated plastic boxes are less insulating, they offer more rapid product cooling in case of poor precooling and efficient temperature control during transport and storage.

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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.

[10] Magnusson, H., Lauzon, H.L., Sveinsdottir, K., Margeirsson, B., Reynisson, E., Runarsson, A.R., Gudjonsdottir, M., Thorarinsdottir, K.A., Arason, S., Martinsdottir, E. 2009. *The effect of different cooling techniques and temperature fluctuations on the storage life of cod fillets (Gadus morhua).* Matis report 23-09, 37 pages.

[11] Kristín Líf Valtýsdóttir, Björn Margeirsson, Sigurjón Arason, Hélène L. Lauzon, Emilía Martinsdóttir. *Guidelines for precooling of fresh fish during processing and choice of packaging with respect to temperature control in cold chains.* Matís report 40-10.

[12] Valtýsdóttir, K.L. 2011. The effects of different precooling techniques and improved packaging design on fresh fish temperature control. M.Sc. thesis. University of Iceland.

[13] Björn Margeirsson, Hélène L. Lauzon, Lárus Þorvaldsson, Sveinn Víkingur Árnason, Sigurjón Arason, Kristín Líf Valtýsdóttir, Emilía Martinsdóttir. 2010. *Optimised Chilling Protocols for Fresh Fish.* Matís report 54-10.

[14] Björn Margeirsson, Hannes Magnússon, Kolbrún Sveinsdóttir, Kristín Líf Valtýsdóttir, Eyjólfur Reynisson, Sigurjón Arason. 2010. *The effect of different precooling media during processing and cooling techniques during packaging of cod (Gadus morhua) fillets.* Matís report 15-10, 27 pages.

[15] Kristín Líf Valtýsdóttir, Björn Margeirsson. 2010. *Thermal abuse during transport of fresh fish – experiments concerning thermal insulation of packaging.* Project report, http://www.avs.is/media/avs/Thermal_abuse_during_transport_of_fresh_fish_thermal_insulation_of_packaging_final.pdf

[16] Margeirsson, B., Arason, S., Palsson, H. 2009. *Thermal performance of corrugated plastic boxes and expanded polystyrene boxes*. Matís report 01-09, 24 pages.

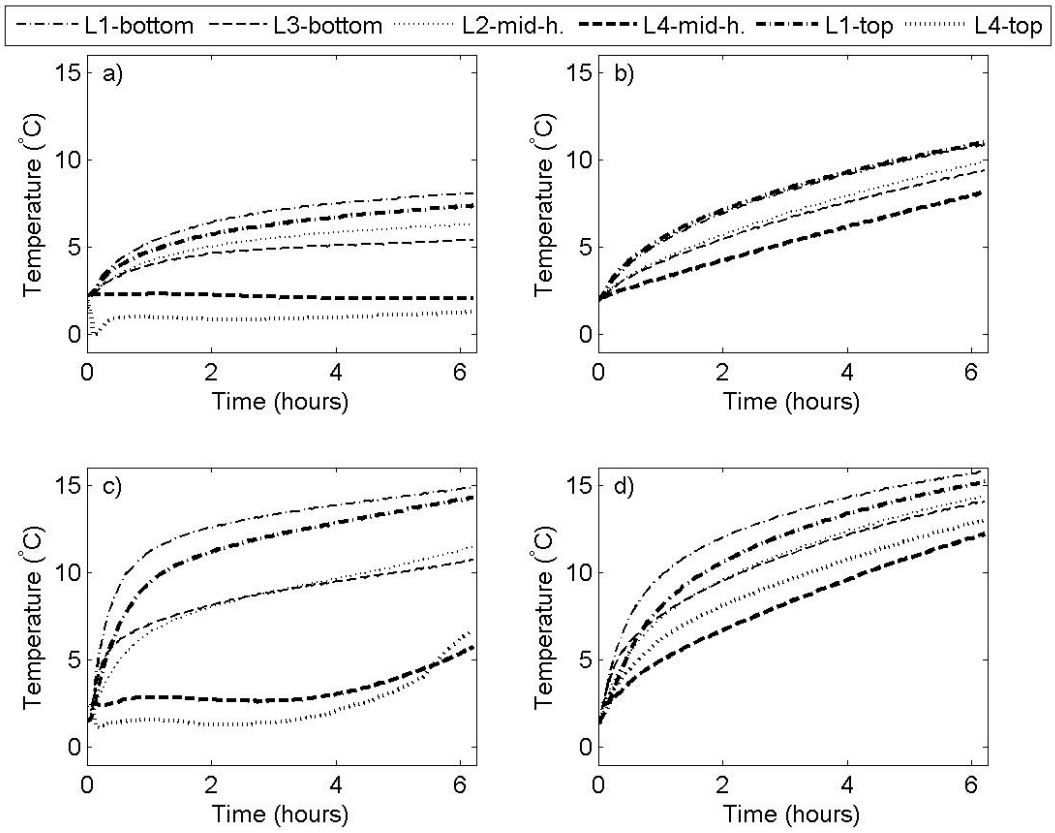

Figure 7. Temperature evolution at different positions inside wholesale boxes containing haddock fillets during 6.1 h temperature abuse with mean ambient temperature 19.4 _C in Trial 1: a) EPS with ice pack, b) EPS without ice pack, c) CP with ice pack, d) CP without ice pack.[1]

Good agreement was obtained by Margeirsson et al. (2011a) between numerical results and experimental results both for the heat transfer model for the EPS box and the CP box without ice pack. It was noted 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 was lower (0.4 °C) than the corresponding error of the numerical model for the CP box (0.7 °C). The study indicated that numerical modelling can be valuable for redesigning thermally insulated packaging in order to minimise temperature differences inside each thermally abused package and thereby further secure even quality of products in each package. To maximise the usefulness of the numerical modelling, boxes with cooling packs were considered in another heat transfer model, see Section 3.3.2.

Figure 8. Ibutton temperature logger on top of a Cool Blue Box.

It has been shown that the insulation of solid polypropylene boxes (brand name Cool Blue Box, see Figure 8) is worse than the insulation of both EPS and CP, see Figure 9.

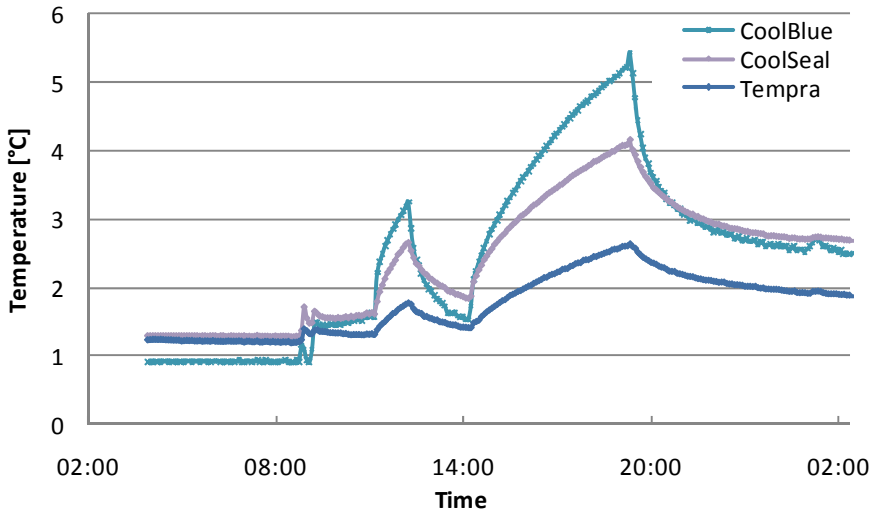

Figure 9. Weighted mean temperature for each box during dynamic temperature storage. [15]

3.3.2 Comparison between different EPS boxes

The heat transfer model for single packages1 was further developed in order to improve the design of 5-kg EPS box manufactured by Promens Tempra (Hafnarfjörður, Iceland) with the aim of minimising the maximum product temperature during thermal load.[17] A follow up study involved two different types of EPS (expanded polystyrene) boxes subjected to temperature fluctuations, simulating real conditions during transport.[2] The study was aimed at experimentally and numerically evaluating the thermal insulation of the packages which contained precooled fresh fish products. One EPS box type was the new, rounded-corner version from Promens Tempra and the other was a box with traditional design (sharp corners). The performance of the EPS boxes was evaluated by means of temperature monitoring and sensory evaluation. The thermal performance of the new EPS boxes was significantly better compared to the old boxes.

[17] 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. In: CIGR Section VI International Symposium on Towards a Sustainable Food Chain Food Process, Bioprocessing and Food Quality Management, 18 – 20 April 2011. Nantes, France.

According to sensory evaluation, storage in the new boxes resulted in approximately 2 days longer storage life (Figure 10).

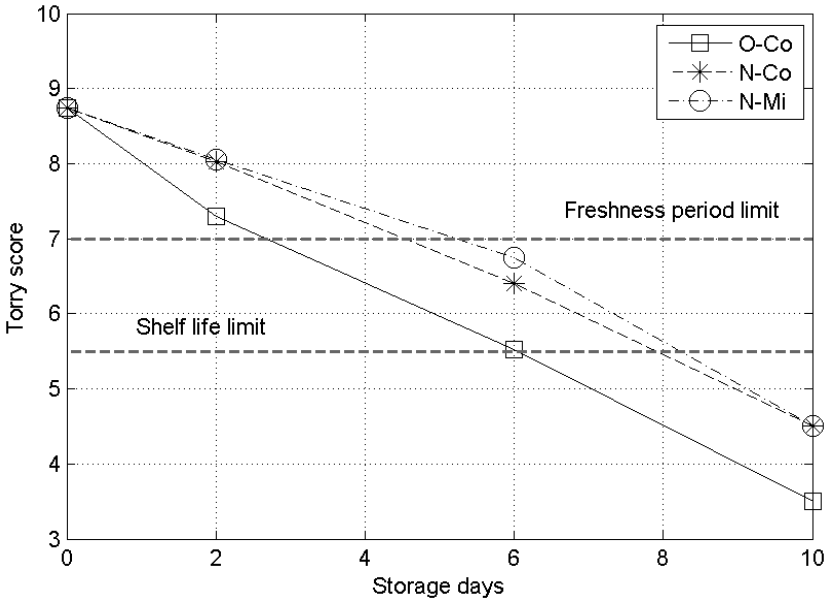

Figure 10. Mean Torry scores. O: Old box, N: New box, Co: Corner samples, Mi: Middle samples. [2]

In Figure 11, the positive effect of the rounded corners in the new design is underlined with the high-temperature fish spots found in the old box type compared to the new box type.

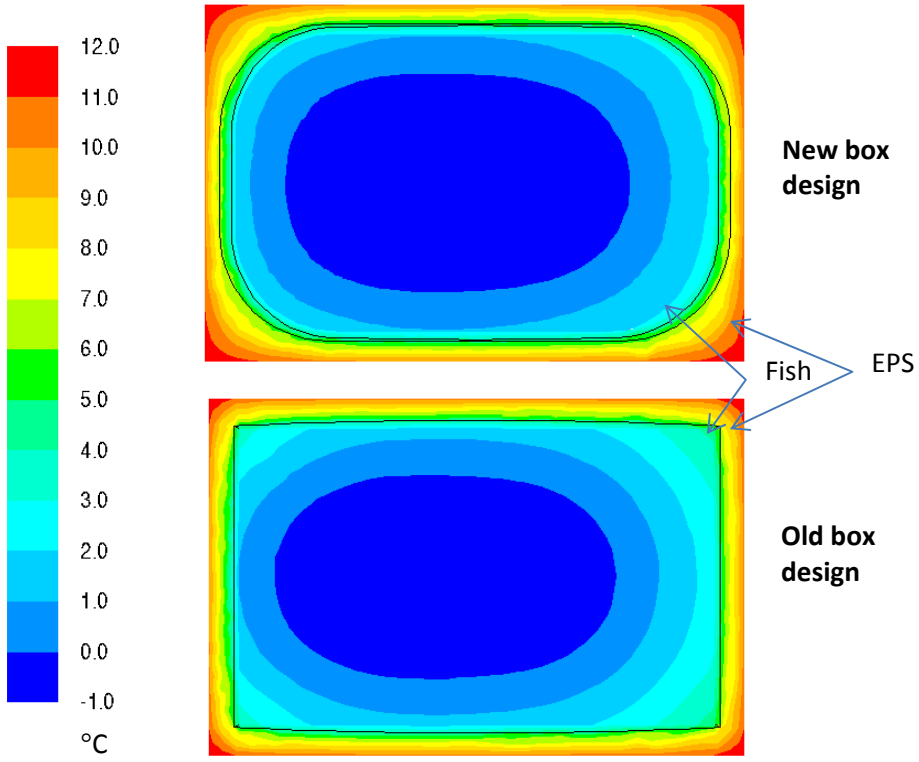

Figure 11. Temperature contour plot in a horizontal plane 5 mm above the bottom of the a) rounded-corner box, b) old-design box after 8 h of thermal load (adopted from Margeirsson et al., 2011b). The black lines represent the box inside surface.

3.3.3 Whole pallets

Measurements have shown that multiple packages assembled on whole pallet stacks with 12 layers of wholesale packages (96 packages in total) are not as sensitive to ambient thermal load as single packages.[16] Product temperature variations in four layers of wholesale packages assembled on pallets (32 packages in total) under dynamic temperature storage have also been studied, both in case of CP packaging and traditional EPS packaging (not the rounded-corner design described in Section 3.3.2).[18] Storage life of thermally abused fillets representing air transport chain conditions was compared to that of fillets stored at steady temperature representing well-controlled sea transport. Thermal performance of fish boxes, made of corrugated plastic on one hand and expanded polystyrene on the other hand, were also compared. 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)

[18] Margeirsson, B., Lauzon, H.L., Pálsson, H., Popov, V., Gospavic, R., Jónsson, M.Þ., Sigurgísladóttir, S., Arason, S. 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*. In press in Sept. 2011.

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 temperature-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.

4 CONCLUSIONS

Sea transport chains have proved to be much better temperature-controlled than air transport chains. This fact makes precooling and well insulated packaging even more important for the latter one. The redesigned EPS box manufactured by Promens Tempra was the best insulated packaging type studied in the current project. The thermal performance of the new EPS boxes was significantly better compared to a traditionally sharp-cornered EPS box type, which still performed thermally better than CP and PP boxes. According to sensory evaluation, storage in the new EPS boxes prolonged storage life by approximately 2 days compared to the traditional EPS box design.

Finally, the results from the current project suggest that the storage life difference between the most and the least sensitive boxes on a full size pallet stack in a real air transport chain can exceed 1-1.5 days, depending on the level of ambient thermal load. 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.

ACKNOWLEDGEMENTS

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PUBLICATIONS

The following has been published on the results of the current project. News and articles in different magazines, websites etc. are not included in the following list.

Theses

2011

Valtýsdóttir, K.L. 2011. The effects of different precooling techniques and improved packaging design on fresh fish temperature control. M.Sc. thesis. University of Iceland.

2010

Mai, N.T.T. 2010. Enhancing quality management of fresh fish supply chains through improved logistics and ensured traceability. Ph.D. thesis. University of Iceland.

Scientific articles, book chapters and papers in conference proceedings

2011

Margeirsson, B., Pálsson, H., Popov, V., Gospavic, R., Arason, S., Sveinsdóttir, K., Jónsson, M.Þ. 2011. Numerical Modelling of Temperature Fluctuations in Superchilled Fish Loins Packaged in Expanded Polystyrene and Stored at Dynamic Temperature Conditions. In: The 23rd IIR International Congress of Refrigeration, 21 – 26 August 2011. Prague, Czech Republic.

Gospavic, R., Margeirsson, B., Popov, V. Mathematical model for estimation of the three-dimensional unsteady temperature variation in chilled packaging. Submitted to International Journal of Refrigeration August 2011.

Margeirsson, B., Lauzon, H.L., Pálsson, H., Popov, V., Gospavic, R., Jónsson, M.Þ., Sigurgísladóttir, S., Arason, S.,. Temperature fluctuations and quality deterioration of chilled cod (*Gadus morhua*) fillets packaged in different boxes stored on pallets under dynamic temperature conditions. In press in September 2011.

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