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

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A B S T R A C T

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

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

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

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Nomenclature

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

Greek symbols

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

Subscripts

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

1. Introduction

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

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

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

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

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

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

2. Materials and methods

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

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

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

2.2. Measurement devices

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

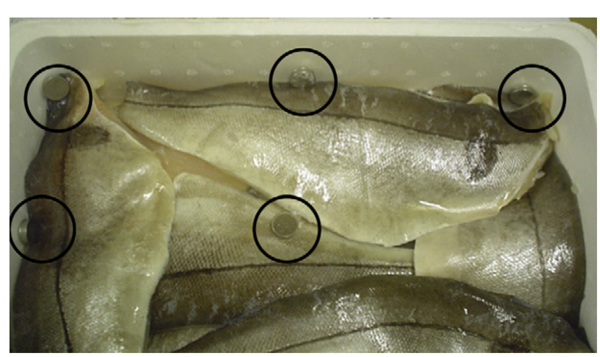

Fig. 2 – Whole haddock fillets in an EPS box. Also shown are temperature loggers used for monitoring temperature on top of fillets.

Table 1 – Dimensions and thermal properties of fish boxes.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.4. *Numerical model for warm up of packaged products*

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

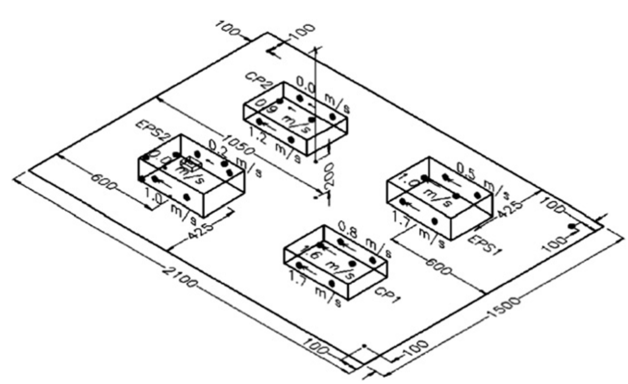

Fig. 3 – Wind speed around free standing wholesale fish boxes positioned on the air climate chamber floor during air blast chilling in Trial 2. Also shown are relative humidity logger on box EPS2, surface temperature loggers on each box and positions of three ambient temperature loggers at the floor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

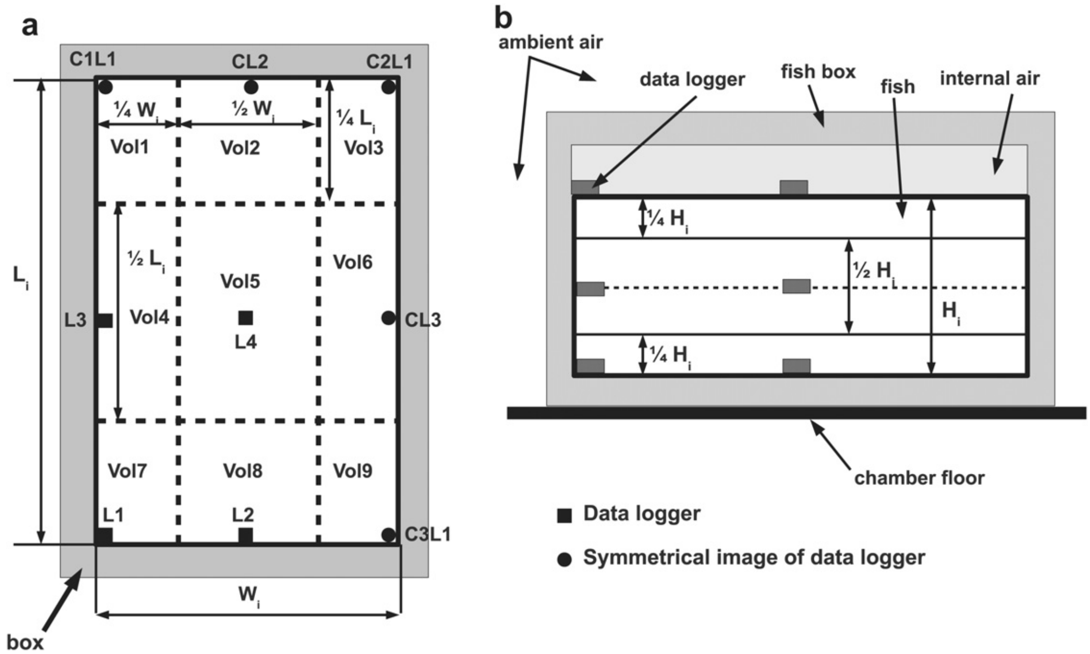

Fig. 4 – Positions of product temperature loggers inside fish boxes along with corresponding copies of the product temperature loggers: a) in horizontal plane, b) in vertical plane.

2.4.1. *Computational domain and mesh*

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

2.4.2. *Modelling approach*

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

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

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

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

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

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

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

- Box top (horizontal plane):

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

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

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

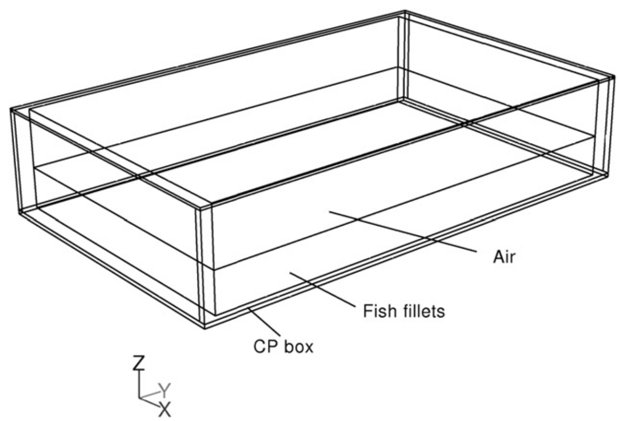

Fig. 5 – Geometry of the numerical FLUENT model consisting of a CP box, fish fillets and an air layer above the fish fillets.

- Box sides (vertical planes):

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

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

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

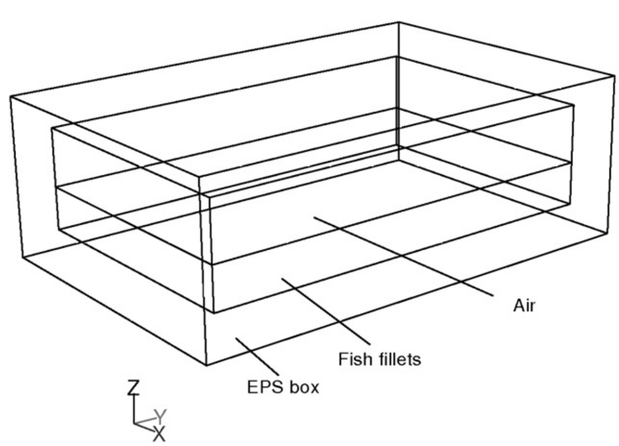

Fig. 6 – Geometry of the numerical FLUENT model consisting of an EPS box, fish fillets and an air layer above the fish fillets.

Table 3 – Calculated equivalent thermal properties of CP walls.

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

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

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

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

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

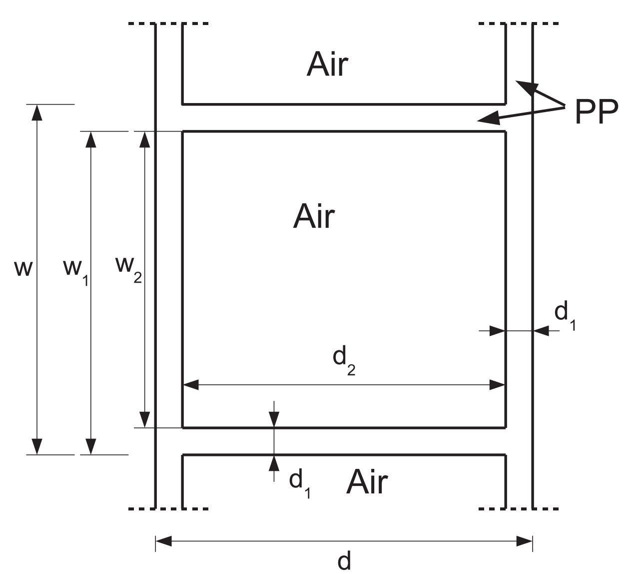

Fig. 7 – Schematic cut through a corrugated plastic (CP) box wall consisting of polypropylene (PP) and air displaying necessary dimensions for calculating equivalent thermal properties of the corrugated box walls. The equivalent thermal properties for different walls (top, bottom, short side, long side)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

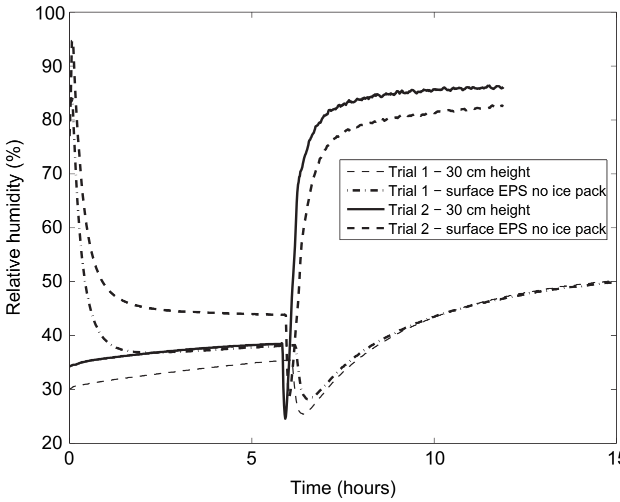

Fig. 8 – Evolution of relative humidity during two temperature abuse trials with fresh haddock fillets in wholesale fish boxes.

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

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

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

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

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

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

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

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

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

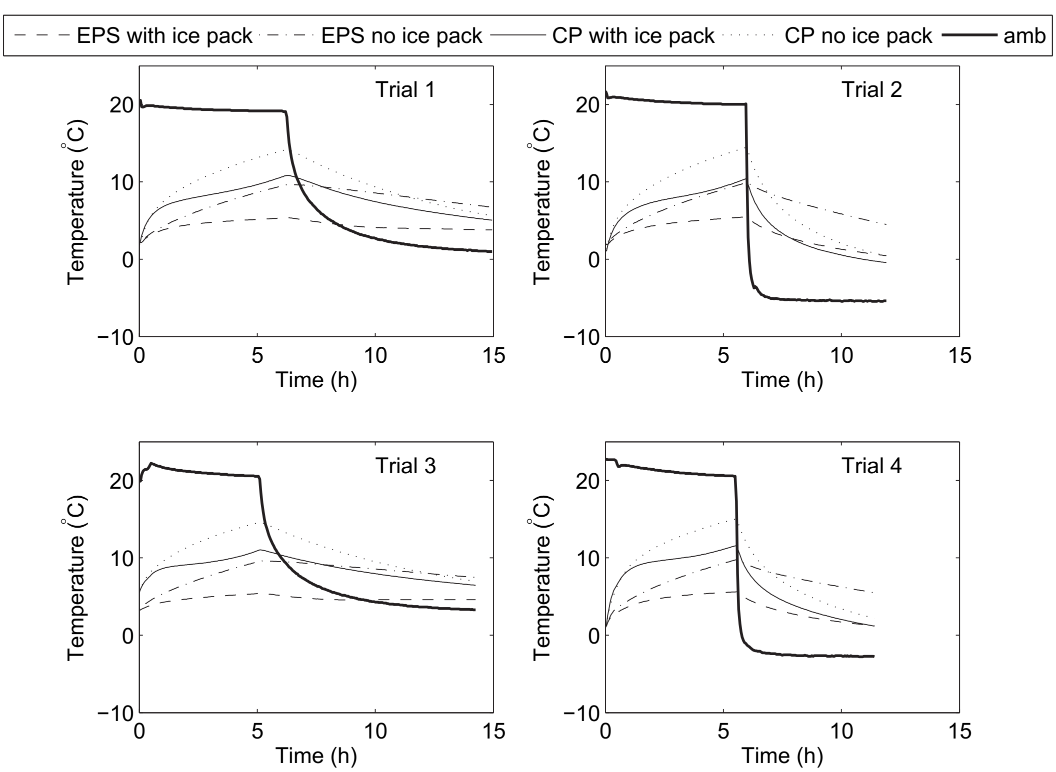

Fig. 9 – Evolution of ambient temperature (amb) and mean product temperature during four temperature abuse trials with haddock fillets in free standing wholesale fresh fish boxes.

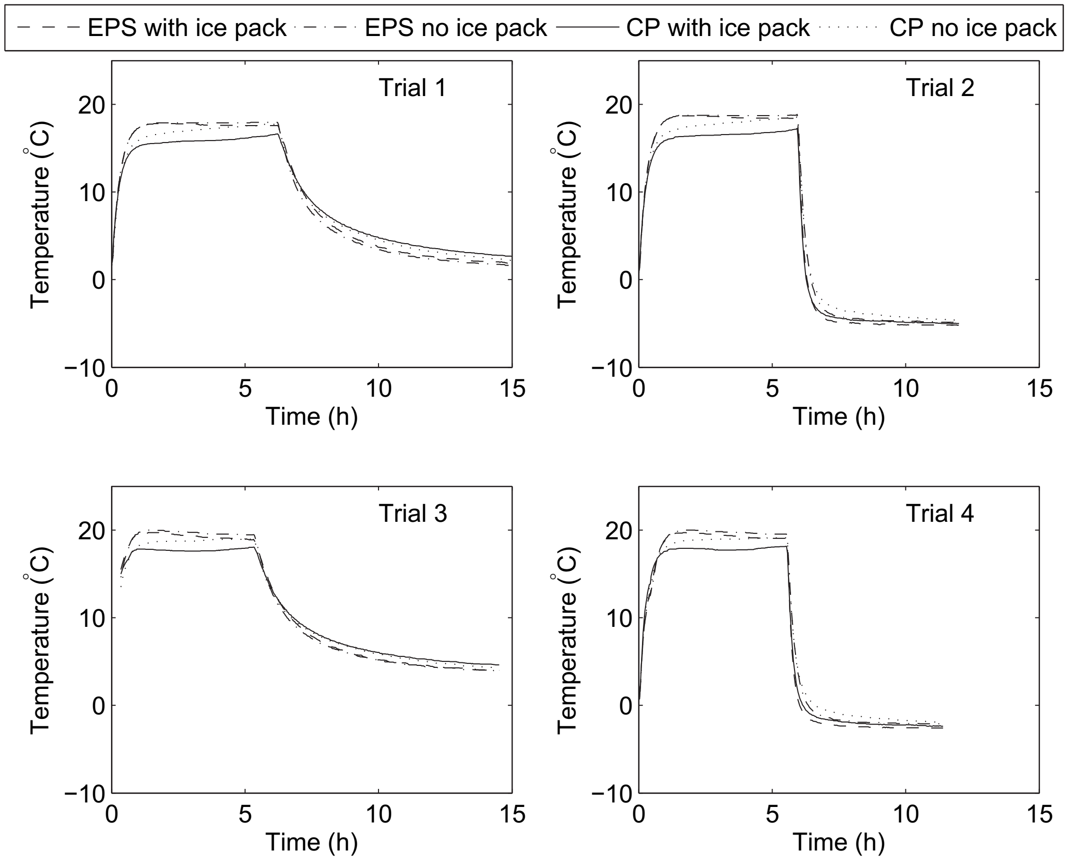

Fig. 10 – Surface temperature (mean from six positions) evolution during four temperature abuse trials with haddock fillets in free standing wholesale fresh fish boxes.

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

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

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

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

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

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

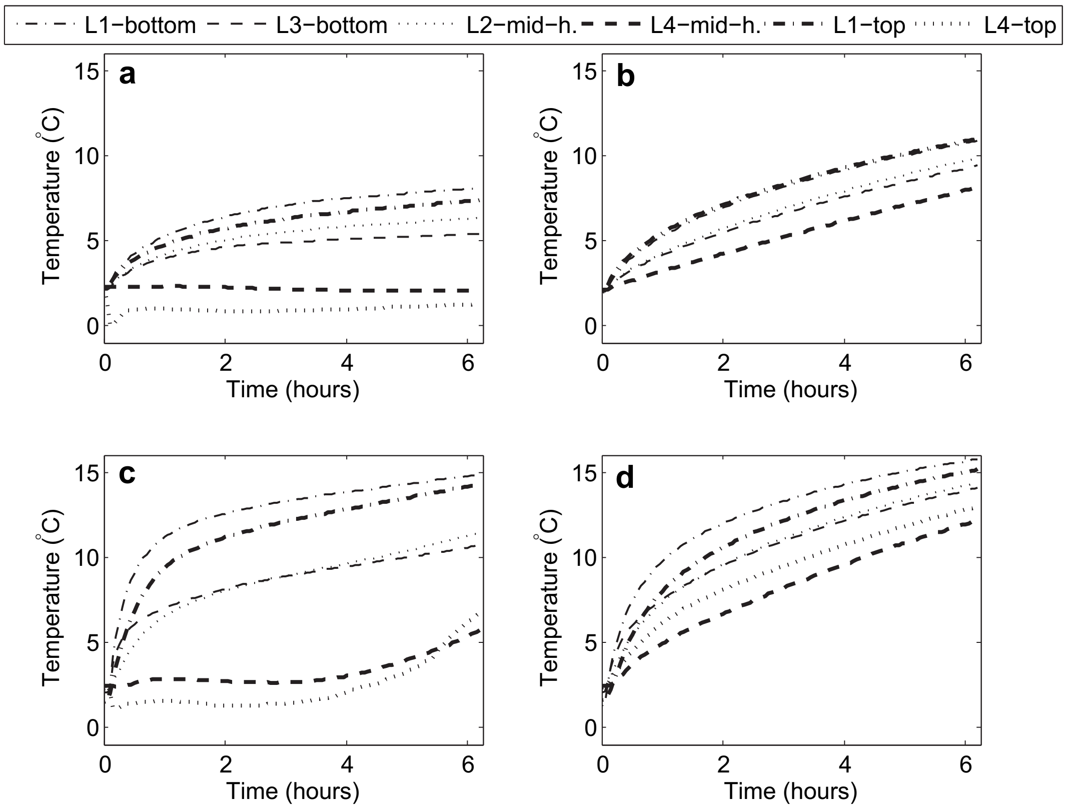

Fig. 11 – Temperature evolution at different positions inside wholesale boxes containing haddock fillets during 6.1 h temperature abuse with mean ambient temperature 19.4 °C in Trial 1: a) EPS with ice pack, b) EPS without ice pack, c) CP with ice pack, d) CP without ice pack.

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

3. Results and discussion

3.1. *Relative humidity*

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

3.2. *Influence of packaging solution*

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

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

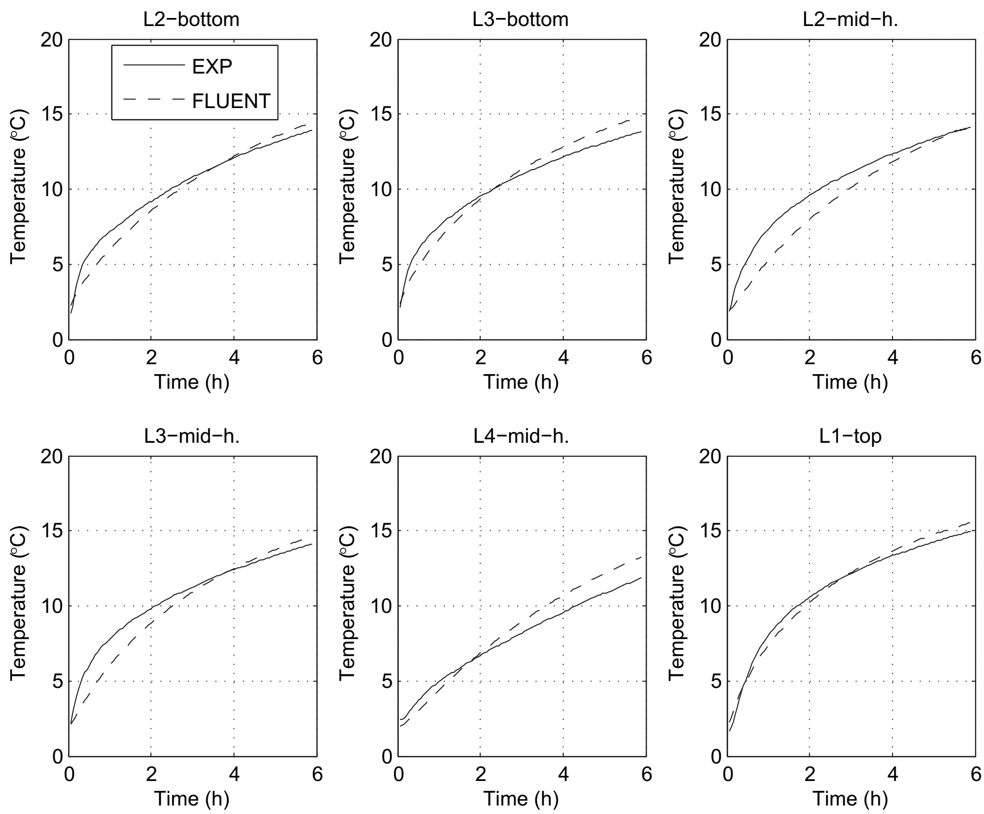

Fig. 12 – Comparison between numerical results obtained with FLUENT and experimental results for 6 selected positions (see positions in Fig. 4) inside the CP box without an ice pack during the first 6 h in Trial 1.

temperature during temperature abuse as CP boxes with ice packs.

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

3.3. *Product temperature distribution*

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

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

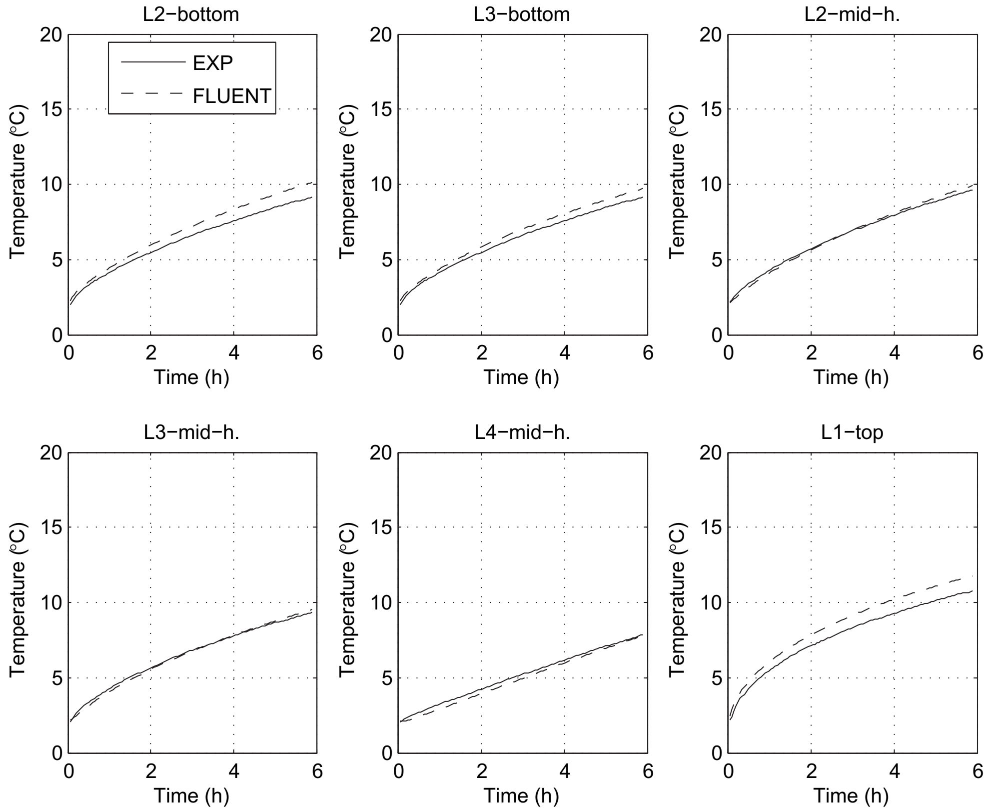

Fig. 13 – Comparison between numerical results obtained with FLUENT and experimental results for 6 positions (see positions in Fig. 4) inside the EPS box without an ice pack during the first 6 h in Trial 1.

3.4. *Numerical heat transfer model*

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

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

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

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

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

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

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

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

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

4. Conclusions

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

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

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

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