Numerical Heat Transfer Modelling for Improving Thermal Protection of Fish Packaging

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Abstract. *Thermal protection of fresh fish packaging can substantially reduce negative effects of poor temperature control in chill chains. The aim of the current study was to apply numerical heat transfer modelling to improve such packaging by redesigning an expanded polystyrene (EPS) fish box. By thickening the walls at the corners the insulation performance of the box was enhanced and to counterbalance the weight of the new box, the walls were made thinner further away from the corners. By this means, the reference box was optimised in a step-by-step procedure using a 'trial and error' method. A trial was conducted to compare the improved and the reference EPS boxes, using fresh fish products subjected to thermal loads likely to occur during air- and land based multimodal transport from a processor in North-Iceland to a wholesaler in Europe. The improved EPS box weighed around 11% less than the reference EPS box. The performance of the EPS boxes was evaluated by means of temperature monitoring, chemical- and microbial measurements and sensory evaluation. Finally, the shelf life of fish loins subjected to air transport simulation was compared to continuous containerised sea transport (around -1 °C).*

The improved EPS boxes provided significantly better thermal protection compared to the reference boxes. Sensory evaluation gave approximately 2-3 days longer freshness period and prolonged shelf life up to 1-2 days (8 days v. 6 – 7 days). Steady storage at -1 °C resulted in shelf life of 11-12 days. The conclusion is that the improved packaging can increase the value of fresh fish by a significant amount.

Keywords. Heat transfer modelling, expanded polystyrene (EPS), packaging design, insulation, fresh fish, shelf life.

Introduction

The quality of perishable foodstuffs such as fresh fish can be greatly affected by temperature control during storage and transport from processor to market. Experiments have shown that the chill chain from processor to market is discontinuous and therefore packaging plays an important role in preserving the quality of the product (Martinsdóttir, Lauzon, Margeirsson, Sveinsdóttir, Þorvaldsson, Magnússon, et al., 2010; Mai, Margeirsson, Margeirsson, Bogason & Arason, 2010). Different transport modes, e.g. land transport, air and sea freight with variable ambient temperature profiles, require different packaging solutions. Consistent quality is a critical factor to marketing fresh seafood, and reliable temperature control is important, being reflected by the resulting shelf life.

The insulation of packaging limits heat transfer from the surroundings to the fish and vice versa. Heat transfer takes place through convection, conduction and radiation. The insulation value of the packaging is controlled by the physical properties and shape of the packaging, mainly thermal conductivity and wall thickness. This study was focused on changing the wall thickness of an already well insulated EPS box and verifying the effects by using a numerical heat transfer model. Such modelling has proved to be an efficient tool for improving the thermal protection of packaging (Moureh, Laguerre, Flick & Commere, 2002, Margeirsson, Gospavic, Pálsson, Arason & Popov, 2011; Margeirsson, Lauzon, Reynisson, Magnússon, Arason & Martinsdóttir, 2010). The EPS box was optimised by changing various parameters in the numerical heat transfer model, using a ‘trial and error’ method to find the optimal parameters.

The paper is organised as follows: in the material and methods the properties of the reference EPS box and the fresh fish are listed, and then the constraints of the design are discussed followed by the construction of the numerical heat transfer model, ending with optimisation of the design. Results and discussion are shown graphically with conclusions in the end.

Material and methods

The properties of the original EPS box and fresh fish

The packaging used for this study was an EPS box with 5 kg capacity. EPS boxes are usually white, manufactured from moulded polystyrene beads and up to 98% of the boxes consist of air pores. The air decreases density and increases insulation performance of the boxes, but the downside is that it decreases strength and increases the required storage volume for the boxes. From here on the reference box will be referred to as the original box. The inner dimensions of the original box were (L x W x H) = 355.5 x 220 x 85 in millimetres and the outer dimensions were (L x W x H) = 400 x 264.5 x 135, also in millimetres. The thermal properties of the box and fresh haddock fillets are shown in Table 1. The thermal properties of fresh haddock fillets given in the table are valid over the temperature range 0 to 10 °C.

Table 1. Thermal properties of the EPS box and the fresh fish (haddock)

Material	*ρ (kg m^{-3})*	*c_p (kJ kg^{-1} K^{-1})*	*k (W m^{-1} K^{-1})*
EPS	23[a]	1.28 ± 0.05[b]	0.0345[a]
Fresh haddock	1054[c]	3.73[d]	0.43[c]

a See Gudmundsson (2009), b See Al-Ajlan (2006),
c See Zueco, Alhama & Gonzalez Fernandez (2004), d See Rao & Rizvi (1995)

Constraints of the design

The new design was restricted by material choice, weight, capacity and outer dimensions of the original box. The restrictions were formulated in cooperation with the manufacturer of the original EPS box (PROMENS TEMPRA) and a fresh fish processing plant in Iceland. Thus the only parameter of interest for improving the EPS box was the wall thickness, leaving the original and improved box with the same material properties, outer dimensions, weight (m_{EPS} ± 5 g) and capacity.

Numerical heat transfer model

A three dimensional finite volume heat transfer model was developed using the computational fluid dynamics (CFD) software FLUENT for each packaging design. The aim of the study was to improve the packaging geometry by minimising the maximum fish temperature under a given thermal load. The computational domain was bounded by the EPS box, carrying a block of fish fillets enclosed with air above. The main advantage of the numerical models compared to lumped heat capacity models is that not only the mean product temperature during thermal load can be predicted but also the temperature distribution inside the whole package.

Heat flow is a result of temperature gradient and Fourier's law states that $q = -k\nabla T$, where q is the vector of heat flow per unit area, ∇T is the temperature gradient and k is the thermal conductivity, which was considered isotropic for this study. The heat transfer inside the fillets was considered to be transferred only by conduction, thus using the following equation

$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} = k_f \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} + \frac{\partial^2 T_f}{\partial z^2} \right) \qquad (1)$$

Radiation was not taken into account in order to reduce computing requirements, which can be severe since calculations have to be performed in large numbers in the optimisation procedure. The fillet-to-air boundary was considered fixed so the heat transfer in the air was assumed to be conductive using eq. (1). The reason for excluding air movement is that the fish fillets were maintained at lower temperature than the inside of the box lid causing higher-density air to be trapped below lower-density air in the enclosed space above the fish fillets. Thus, according to Holman (2002), no convection currents are experienced.

The simulated time was 4 hours and the ambient temperature was considered to be T_{amb}= 15 °C which can be expected during transport from processor to market, according to Mai et al. (2010). The weight of the fillets positioned inside the packaging in the simulations was m_f = (5000 ± 5) g. The initial conditions throughout the whole computational domain (fish + box + air) were T_{init} = 1 °C. Convection boundary conditions were applied for both top and sides. The convective heat transfer coefficients (h_{conv}) for laminar natural convection in air ($Ra < 10^9$) were estimated by Holman (2002) correlations: $h_{conv,t}$ = 2.1 W m^{-2} K^{-1} and $h_{conv,v}$ = 3.0 W m^{-2} K^{-1} for top and vertical sides, respectively, according to Margeirsson et al. (2011). Non-ideal surface contact was assumed between the inner surface of the box and the fish, meaning that a certain thermal contact resistance between the two surfaces, $R_{b,f,}$ was estimated. The resistance value was set to $R_{b,f}$ = 0.05 m^2 K W^{-}1 according to Margeirsson et al. (2011).

Optimisation

A model of the original box was constructed and validated by comparison with data from a specific trial. By analysing the results, i.e. the temperature distribution of the fish inside the box, the critical temperature zones at the box corners were identified. By thickening the walls at the corners the insulation performance of the box was enhanced and to counterbalance the weight of the new box, the walls were made thinner further away from the corners. By this means, the original box was optimised in a step-by-step procedure using a 'trial and error' method.

The designs constructed with FLUENT are listed in Table 2. Each design had different radius of curvature in the corners and at the top and bottom, and wall thickness at the bottom, top and walls. The number of cells for the models was in the range 200-300,000, which was considered to give similar accuracy of results.

Table 2. The radius and wall thickness, weight and no. of cells for the original and A to H designs.

Design no.	*Radius (mm)*			*Wall thickness (mm)*			*Weight (g)*	*No. of cells*
	Corners	Bottom	Top	Bottom	Top	Walls		
ORG	5	5	5	25.00	25.00	22.25	176	292,100
A	75	15	10	22.00	22.00	22.25	177	212,400
B	75	15	10	22.50	22.50	22.25	178	278,100
C	100	10	5	22.50	22.50	22.25	185	279,800
D	85	15	5	22.50	22.50	22.25	180	270,300
E	95	10	5	21.50	21.50	22.25	178	285,900
G	50	20	5	22.50	25.00	21.50	178	247,400
H	75	20	5	22.50	25.00	22.25	183	264,500

Figure 1 shows the geometries of the FLUENT models for the original box and the design C. As the figures shows, design C has rounded corners inside the box where the original one has sharp corners.

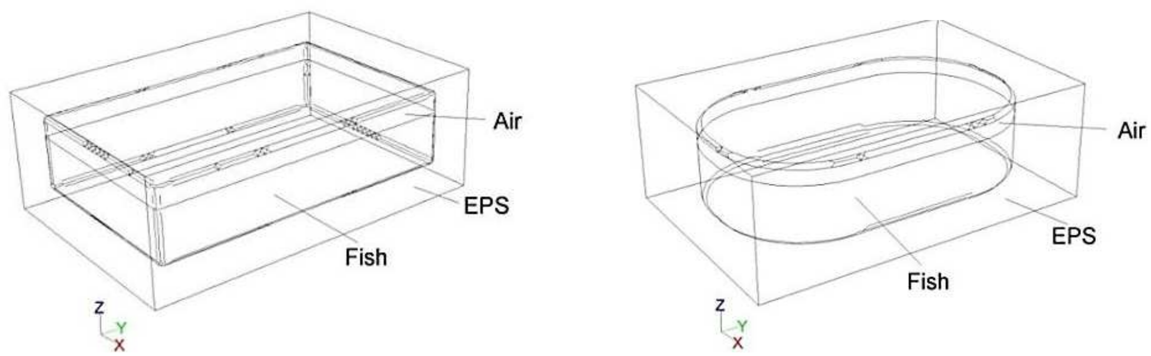

Figure 1. Geometries of the original (left) and design C (right), each containing fish fillets with layer of air above.

Results and discussion

The maximum, mean and minimum temperatures during the 4 hour simulation with T_{amb} = 15 °C and T_{init} = 1 °C are presented in Figure 2. The temperature distribution inside the box was not uniform and varies with position. The minimum temperature was quite similar for all the boxes, compared to the maximum temperature. Design C provided the lowest maximum temperature or 2.1 °C lower than for the original design. Figure 3 shows the temperature contours in a horizontal section through the box and fillets at mid-height of fillets. The figure clearly displays higher fish fillet temperature in the original box compared to the new improved design.

A prototype was manufactured based on designs A, C and E and according to a trial performed by Margeirsson et al. (2010) the freshness period (above 7 on the Torry scale) and shelf life (above 5.5 on the Torry scale) of fresh white lean fish fillets was prolonged by 2-3 days and 2 days, respectively, using the new design. Figure 4 shows the box surface temperatures in the trial where the original box and the new design were subjected to steady temperature (ST) storage or dynamic temperature storage (DT), representing sea and air transport respectively. ST storage (at -1 °C) gave freshness period of 6-7 days and 11-12 days of shelf life using the original boxes but DT storage gave 2-3 days and 5 days freshness period for the original and improved new design, respectively. Shelf life was also prolonged from 6-7 days to 8-9 days using the new improved box.

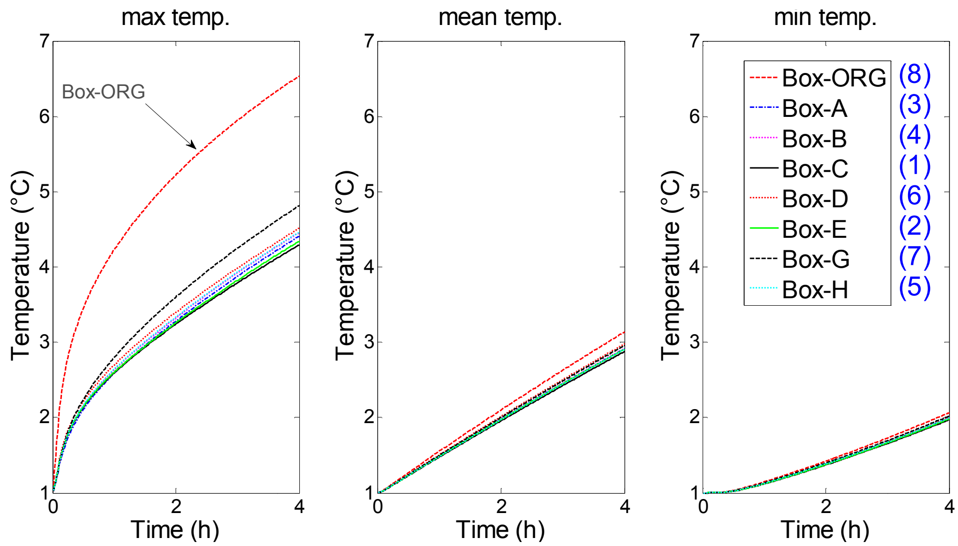

Figure 2. Temperature results showing maximum, mean and minimum temperatures to the left, middle and right, respectively. The insulation performance of the designs is shown inside brackets, (1) for C giving the best insulation and (8) for ORG giving the worst insulation.

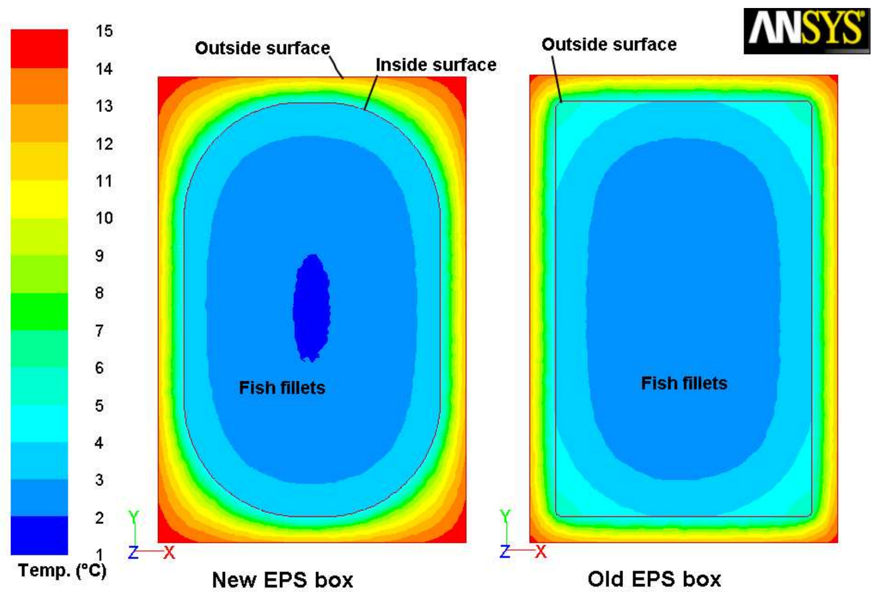

Figure 3. Temperature contours in a horizontal section through design C and the original box at mid-height of fillets after 4 hours at T_{amb} = 15 °C and T_{init} = 1 °C, shown left and right, respectively.

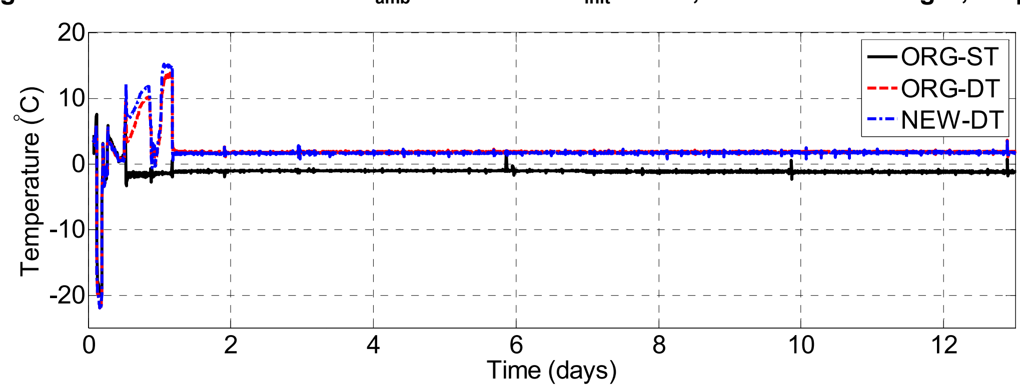

Figure 4. Surface temperature for the original (ORG) and new (NEW) EPS boxes during steady temperature (ST) and dynamic temperature (DT) periods (Margeirsson et al. 2010).

Conclusions

In this study, CFD methods have been applied to design new improved packaging for fresh fish export. The design with the largest radius of curvature provided the best insulation. Thus, results from this study clearly show that the insulation performance of a reference EPS box could be improved by thickening the walls at the critical corner zones, enabling the product to withstand higher ambient temperatures during transport. This results in a prolonged freshness period and shelf life of fresh white lean fish fillets by 2-3 days and 1-2 days, respectively.

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Nomenclature

c_p	specific heat capacity, kJ kg^{-1} K^{-1}
EPS	expanded polystyrene
DT	dynamic temperature
h_{conv}	convective heat transfer coefficient, W m^{-2} K^{-1}
H	box height, m
k	thermal conductivity, W m^{-1} K^{-1}
L	box length, m
M	mass, kg
NEW	new design
ORG	original
q	heat flux, W m^{-2}
Ra	Rayleigh number, dimensionless
ST	steady temperature
T	temperature, °C, K
W	box width, m

Greek symbols

ρ	density, kg m^{-3}

Subscripts

amb	ambient
b	box
f	fish fillet
init	initial
o	outside
w	wall
t	top
v	vertical sides

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