Modeling of Temperature Fluctuations in Frozen Fish

Satyam Kumar[1], Subhendu Panigrahi[*,1]
[1]Indian Institute of Technology, Kharagpur
*Corresponding author: B-335, LLR Hall of Residence, IIT Kharagpur, email:subhendu.panigrahi@gmail.com

Abstract:
The novel concept of distributing the food super chilled (partially frozen) in order to prolong the shelf life has been suggested in the project. The temperature of the distribution chain is envisaged to be +5^{0}C. The suggested application has the following advantages:

1) Partial thawing of the product in the distribution chain makes it easier to handle.
2) The unhealthy and labour-demanding operations in professional kitchens can be reduced, therefore, the quality loss can be minimised.

3) High **thermal buffering** capacity of partially frozen foods as compared with chilled foods makes them robust against temperature fluctuations.
4) The temperature gradient is positive throughout the distribution chain because the outside temperature (5^{0}C) is always greater than the product temperature.

The introduction of new technological solutions in the food sector should be sustainable in a broad sense. The solution should give top priority to optimization, while at the same time due considerations must be taken to food safety and the three Ps of sustainability: people, profit and planet earth.

1. Introduction

Many heat transfer models have been developed to study the temperature fluctuations in frozen foods during distribution. Singh *et al.* (1987) predicted the temperature changes in frozen foods exposed to solar radiation. Simultaneous convective and radiative boundary conditions were incorporated into a one-dimensional 3 time level implicit finite difference scheme in rectangular coordinates, which was used to calculate temperature profiles and histories in a packaged frozen food exposed to the sun. The food surface temperature of a pallet of strawberries initially at -18°C reached -5°C in 61 min under ambient conditions of 40°C in full sun. Mathematical models have been developed by Lorentzen (1993) and Sergio (1993) to study temperature abuse affects during distribution of solid frozen foods. Graham (1983) discussed the benefits of using pallet covers for frozen blocks of fish. Comparative tests were done to evaluate the protection of frozen blocks of fish from dehydration during storage and temperature rise during handling outside the cold stores by pallet covers of 62.5 µm LDPE, shaped to fit the pallet load. Oskam (1998) has developed a model to study the thermodynamic behaviour of perishables during flight. Bonacini and Comini (1973) developed a three-level implicit scheme for the numerical solution of the multidimensional heat conduction equations when the thermophysical properties depend on temperature.

The major difficulty in the numerical solution of heat transport equation is in dealing with the large latent heat, which evolves over a very small temperature range. Voller (1996) reviewed the techniques for dealing with phase change. These methods can be divided into *fixed grid* methods and *moving grid* methods. In the latter, the object is divided into a frozen zone and an unfrozen zone. Some nodes, element boundaries or control volume boundaries are put on the freezing front and allowed to move with it. Moving grid methods can give precise, non-oscillating solutions for the temperature and ice front position. However, they are less flexible then the fixed grid methods because most foods do not have a sharp phase change temperature but freeze or thaw gradually, so it is not clear how the freezing front or thawing front should be defined. Of the fixed grid methods, some treat latent heat as a source term. This term is not suitable for most foods for which latent heat is released over a wide range of temperature and hard to distinguish from sensible heat. The most popular technique is the *apparent specific heat method*. Here, latent heat is merged with sensible heat to produce a specific heat curve with a large peak around the freezing point. Because of large variations in the specific heat, iteration must be carefully carried out at each step. However, the discretization of highly non-linear problems such as phase change problem with Galerkin FEM poses serious problems. Therefore, the use of FVM or lumped capacitance FEM is recommended over Galerkin FEM.

.

2. Use of COMSOL Multiphysics

2.1 Model description

Boxes are used to transport fish in frozen form. A cubical box with side 18 cm is used for storage and distribution of frozen fish. A 10 mm thick insulation is used. Both corrugated paperboard as well as expanded polystyrene is used for providing insulation. The initial temperature of the frozen fish is -30^{0}C. The outside temperature is maintained at +2^{0}C. The thermal properties of the fish vary as a function of composition and temperature. Many models have been proposed to analyse the behaviour of frozen fish with variation in temperature. Thermal properties like thermal conductivity, density and specific heat show wide variation with temperature because of a change in the unfrozen water content of the fish. On a general basis, the composition of fish (mass fraction) is: water = 0.8, protein = 0.15, fat = 0.05. The properties can vary with the type of fish as well as the type of processing. The experimental values of enthalpy and unfrozen water fraction as a function of temperature (T) are shown in table 2.1. The unfrozen water content (Unf) varies exponentially with temperature (in K). It can be described by the equation 4.1.

Unf = 3.866 * (10^(-29))*exp(0.2565*T) … 2.1

The ice fraction (x_ice) at any temperature can be obtained by subtracting Unf from 0.8. Similarly, the variation of enthalpy as a function of temperature (in K) can be given by equation 2.2.

$$H = 7.685 * (10^{(-22)}) * \exp(0.2*T) \quad \ldots \quad 2.2$$

Both the above equations have been developed by using the curve fitting toolbox of MATLAB software.

Temperature (^{0}C)	% unfrozen water	Enthalpy (kJ/kg)
-40	10	0
-30	10	19
-20	11	42
-18	12	47
-16	12	53
-14	13	66
-12	14	74
-10	16	79
-9	17	84
-8	18	89
-7	19	96
-6	21	105
-5	23	118
-4	27	137
-3	34	177
-2	48	298
-1	92	323
0	100	_

Table 2.1: Experimental values of unfrozen water content and specific enthalpy for haddock variety of fish.

The box containing frozen fish is kept in a surrounding environment of temperature 2^{0}C. The air outside is assumed to be static. There is perfect contact between the frozen fish and inside of the insulating cover. As a result, the heat transfer coefficient between these two surfaces is assumed to be very large. The overall heat transfer coefficient U is given by equation 2.3.

$$1/U = 1/h1 + d/k\_cover + 1/h2 \quad \ldots. \quad 2.3$$

where h1 is the heat transfer coefficient between outside environment and insulating material, h2 is the heat transfer coefficient between frozen fish and inside of the insulating cover, d is the thickness of the insulating cover, k_cover is the thermal conductivity of the insulating cover.

Substitituting the values of h1= 8 W/(m^2)*K, h2=infinite, d=.01m and k_cover=.007, the value of U is 0.839. The value of U would have been different if air was assumed to be present between package and the food because the value of h2 would not be infinite.

The value of Biot Number (B) can be calculated using equation 2.4

$$B = U * r / k \quad \ldots.. \quad 2.4$$

where r is the characteristic length of the box (half the side of cube)

The value of Biot number comes out to be .0599, taking the value of k to be 1.4 for totally frozen fish. The value of k will decrease with time as more ice melts into water. Hence, the value of Biot number will increase with time. Since this value is less than 0.1, it is safe to assume that the temperature at every point inside the box is same at a particular time.

2.2 Variation of thermal properties of fish

The thermal conductivity (k), specific heat (C_p) and density (ρ) of fish varies as follows:

k = k_pro*X_pro + k_fat*X_fat + k_w*X_w +k_ice*X_ice

where k_pro (.1788 W/m*K) , k_fat (.1807 W/m*K) , k_w (.571 W/m*K) and k_ice (2.2 W/m*K) are the thermal conductivity values of proteins, fat , unfrozen water and ice respectively. The thermal conductivity values for protein and fat vary slightly with temperature. Therefore, the main change is due to change in unfrozen water fraction as temperature increases with time.

ρ = rho_pro*x_pro + rho_fat*x_fat+rho_w*x_w+rho_ice*x_ice

where rho_pro (1330 kg/m^3) , rho_fat (926 kg/m^3) , rho_w (1000 kg/m^3) and rho_ice (920 kg/m^3) are the densities of protein, fat, unfrozen water and ice respectively.

C_p = cp_pro*x_pro+cp_fat*x_fat+cp_w*x_w+cp_ice*x_ice

cp_pro (2.0082 kJ/kg*K), cp_fat (1.9842 kJ/kg*K), cp_w (4.18 kJ/kg*K) and cp_ice (2.0623 kJ/kg*K) are specific heat values of protein, fat , water and ice respectively. The specific heat values for protein and fat remain almost same with temperature fluctuations, therefore, only the proportion of unfrozen water has significant impact on its value.

X is the volume fraction and x is the mass fraction of various components.

$$X_i = \frac{\frac{x_i}{\rho_i}}{\sum \frac{x_i}{\rho_i}}$$

, i denotes the individual component.

The density of water at 273 K is 1000 kg/m^3 and for ice it is 920 kg/m^3 at subzero temperatures. The average density for fish throughout the supply chain can be taken to be 1040 kg/m^3 as there is a difference of only 10 % between totally frozen state and totally thawed condition.

Thermal conductivity values for haddock fish have been determined experimentally. Its variation with temperature (in K) can be best described by equation 2.5

k_fish = -.00004645*(T^3) + .03412*(T^2)-8.352*T+683 ... 2.5

2.3 Enthalpy and apparent specific heat

The enthalpy of a food product can be calculated based on a reference temperature of 233 K as follows :

The components of equation 4.6 include sensible heat of product solids at any temperature (T_i). The second component of the equation accounts for the sensible heat of unfrozen water when T_i is above the initial freezing temperature (T_f) of the product. The sensible heat of unfrozen water in the frozen product is the third component of the equation, where the unfrozen water fraction (m_u) and specific heat of unfrozen water (C_{pu}) vary with temperature. The fourth component of the equation accounts for the latent heat contribution to the enthalpy and indicates the changing influence of the unfrozen water fraction (m_u). The contribution of the frozen water fraction (m_i) to enthalpy is the final component of the equation.

$$H = m_p C_{ps} \int_{233}^{T_i} dT + m_u C_{pu} \int_{T_f}^{T_i} dT + \int_{233}^{T_f} m_u(T) C_{pu}(T) dT + m_u(T) L + \int_{233}^{T_f} m_i(T) C_{ps}(T) dT$$

... 2.6

The value of specific heat based on sensible heating only cannot give the correct results because it doesn't incorporate the latent heat term which has a considerable influence on the temperature profile of frozen foods. Therefore, the concept of apparent specific heat has been introduced which takes into account both latent heat release as well as sensible heating. By using the thermodynamic definitions of specific heat, the derivative of enthalpy with respect to temperature produces an apparent specific heat function for frozen foods. The apparent specific heat is given by equation 2.7

$$C_{pA}(T) = \frac{dH}{dT}$$

.... 2.7

It is a significant and unique function of temperature for all frozen foods. The apparent specific heat increases with increasing temperature until reaching the initial freezing temperature, indicating the region where major portions of the latent heat of fusion are removed from the product.

2.4 Subdomain settings and boundary conditions

A cubical box of 18 cm side contains frozen fish at 243 K. A 10 mm thick insulation is provided. Corrugated cardboard and expanded polystyrene is used for insulation purpose. The properties of corrugated cardboard used for packaging frozen fish are as follows :

- Density = 30 - 90 kg/m^3(for non-compact cardboard) and 250kg/m^3 for compacted cardboard
- Thermal conductivity = 0.065 W/m.K
- Specific heat = 1700 J/kg.K

The properties of expanded polystyrene (EPS) used for packaging are as follows :

- Density = 25 kg/m^3
- Thermal conductivity = .04 W/m.K
- Specific heat = 1500 J/kg.K

The values of thermal properties for fish have already been defined in sections 2.2 and 2.3. All the outside boundaries are at a temperature of 271 K (2^0C).

2.5 Heat transfer

Heat is transferred into the box by conduction as well as convection. There is a considerable temperature difference between the surroundings and the product, therefore, transient heat transfer equation is used. The temperature of a point inside the box varies with time.

The equation for unsteady heat transfer can be described by equation 2.8

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q - \rho C_p u.\nabla T \quad \ldots.. \quad 2.8$$

The first terms on right hand sides is for a heat source or sink (if any). The second term accounts for heat transfer due to convection. The value of source term is taken to be zero since the effects of latent heat release have been incorporated in the value of specific heat.

The temperature at the outer surfaces (boundaries) of the box is 2^0C. The heat transfer takes place equally from all the surfaces. The thermal properties of insulating material ie. extended polystyrene and corrugated cardboard is assumed to be constant with temperature and time. The velocity of air outside the box is assumed to be zero. There is only natural convection and no forced convection.

The temperature profile has sharp gradient initially due to sensible heating only. However, it becomes flat when the initial freezing point of the fish is approached. Actually, a *thermal buffer* is created around the initial freezing temperature of the product. There is a large enthalpy difference within a short range of temperature around this temperature due to latent heat of melting. It means that there is a negligible change in temperature with considerable amount of heat input. The obtained values of enthalpy can be verified with the experimental values.

3. Figures

A model predicting the temperature profile of the food inside the box is developed in COMSOL software.

The temperature profile of box with 10mm corrugated cardboard insulation after 2 days of exposure has been shown in fig 3.1. The temperature distribution for 10 equally spaced and parallel slices has been shown. Heat transfer takes place through conduction as well as convection.

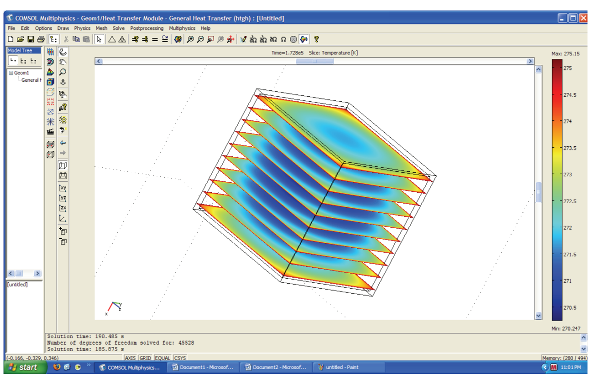

Fig. 3.1: Temperature profile after 2 days of exposure (275 K) for cardboard insulation

The centre temperature (fig 3.2) reaches 270.5 K after 2 days while the corner point (0.9,0.9,0.9) reaches 274.15 K and has a very steep temperature rise initially (Fig 3.3).

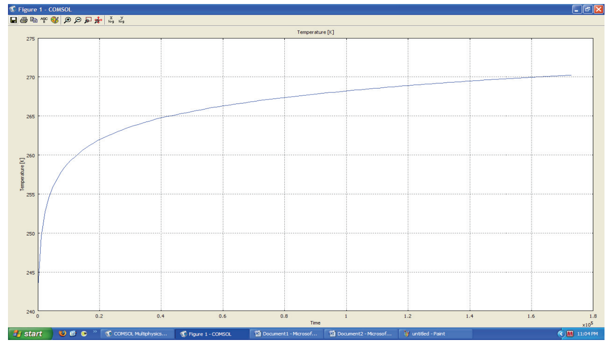

Fig 3.2: Temperature profile of the centre point of the box for cardboard insulation

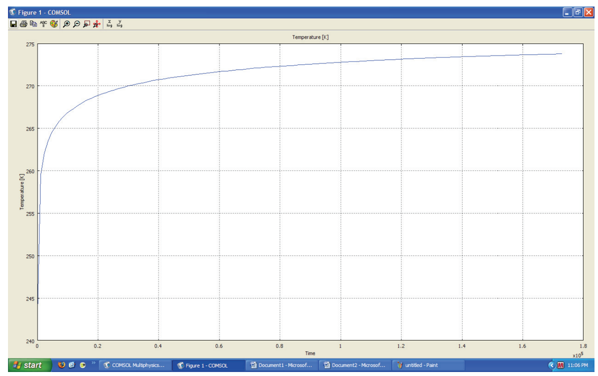

Fig 3.3: Temperature profile of the corner point (0.9,0.9,0.9) of the box

The temperature profile for 10mm thick EPS (Expended Polystyrene) insulation after 2 days of exposure to 275 K is shown in figure 3.4.

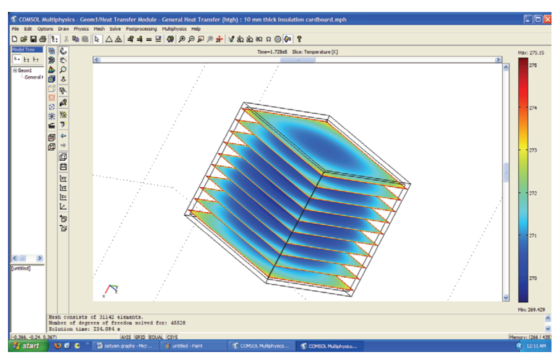

Fig 3.4: Temperature profile of the box for 10mm EPS insulation after 2 days (275 K)

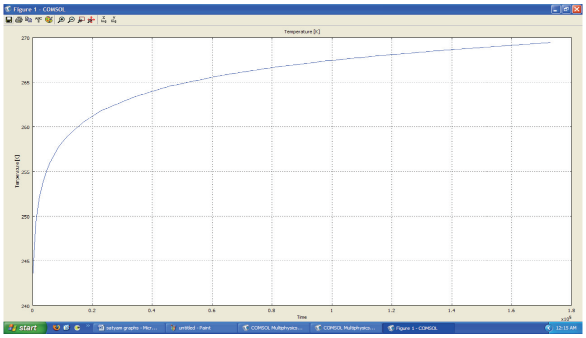

Fig 3.5: Temperature profile of the centre point of box for 10mm EPS insulation.

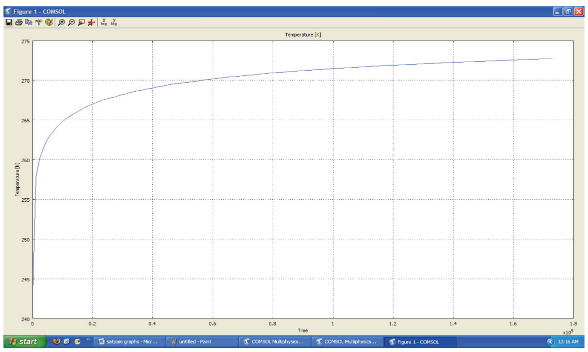

Fig 3.6: Temperature profile of the corner point (.9,.9,.9) of box for EPS insulation.

The temperature profile of the corner point of the box for 10 mm thick EPS insulation is shown in figure 5.6. Fig 5.7 shows the temperature profile of centre point after 1 day of exposure for 10 mm thick corrugated cardboard insulation.

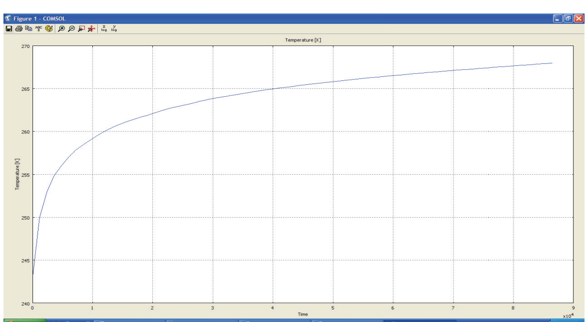

Fig 3.7: Temperature profile of the centre point of box for cardboard insulation.

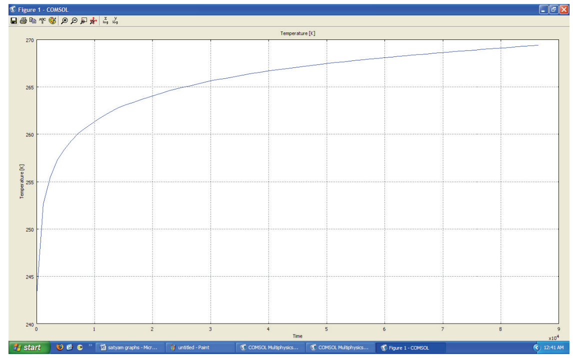

Fig 3.7: Temperature profile of the centre point of box for cardboard insulation

.

4. Conclusions

The obtained graphs show that the centre temperature shows slowest temperature variation whereas the corner points shows rapid increase in temperature. This is because heat transfer occurs through three planes at the corner points. The centre temperature doesn't reach the outside temperature of 275.15 K even after 2 days of exposure. However, if the air outside the fish box is considered to be in motion, then there would be considerable covective heat transfer at the surfaces. Besides, the inside surface of the box has been assumed to be in perfect contact with the insulation. In most of the practical cases, there is an air gap between the two.

EPS (Expanded polystyrene) provides better insulation than same thickness of corrugated cardboard. It can be seen from the temperature profiles of centre points in the two cases. The centre point temperature profile shows that there is sharp increase in the temperature initially before the *initial freezing temperature* (-2^{0}C) of fish is reached. At around the initial freezing point, the graph becomes flat. This is because a large amount of latent heat is absorbed over a very small range of temperature. This leads to the creation of what is commonly referred to as *thermal buffer*. Since freezing point for foods is not sharply defined, we don't obtain a totally flat curve as in the case of water. There is a considerable impact of the thickness of insulation on the temperature profile of the fish box. A thin insulation would mean a faster increse in the temperature as comapred to a thicker one.

5. References

Dolan KD, Singh R.P, Heldman DR. Prediction of temperature in frozen foods exposed to solar radiation. *Journal of Food Processing and Preservation* 1987; 11:135-58

Lorentzen, G. Temperature rise in frozen products during transfer. Proceedings IIF IIR commissions D1, D2 and D3, Barcelona (Spain), 1993.

Sergio, F. Almonacid-Merino, Antonio Torres, J. Mathematical models to evaluate temperature abuse effects during distribution of refrigerated solid foods. *Journal of Food Engineering,* 1993, p. 223-245

Graham J, Roger A. The benefits of using pallet covers for frozen blocks of fish, IIF-IIR, XVI Congres international du froid, Paris, 1983.

Oskam NA, Sillekens JJM, Ceton C. Validated models of the thermodynamic behaviour of perishables during flight.IIf-IIR - D1, D2/3 Cambridge (UK), 1998.

. Bonacini C., Comini G., On the solutions of the nonlinear heat conduction equations by numerical methods. *International journal of heat and mass transfer* (1973) vol. 16 581-589

V. R. Voller, mAn overview of numerical methods for solving phase change problems, in : W. J. Minkowycz, E.M. Sparrow (Eds.), Advances in numerical heat transfer, vol. 1, Taylor & Francis, London, 1996 , pp. 341-375.