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Evaluating The Effect Of PCM Insulation Packaging Design On The Thermal Protection Performance

Kasra Ghasemi[1], Mehran Bozorgi[1], Syeda Tasnim[1], Shohel Mahmud[1]
[1]School of Engineering, University of Guelph, Guelph, Ontario, Canada
kghasemi@uoguelph.ca; mbozorgi@uoguelph.ca; stasnim@uoguelph.ca; smahmud@uoguelph.ca

Abstract – The thermal insulation layer in packaging plays a vital role in thermal protection during food transportation and storage. One of the promising materials applied for insulation is phase change material (PCM) due to its high heat capacity. So, PCM-based insulation can provide almost a constant temperature for a considerable amount of time. However, when PCM is in liquid form, natural convection can shape which affects the heat transfer rate, and consequently, its performance. So, the configuration of PCM is a characteristic factor in increasing the thermal protection time which is evaluated in this paper. For this reason, different designs of PCM insulation with the same amount of PCM are numerically investigated in terms of melting time. It is stated that the bottom part of the PCM-based insulation layer melts faster due to heat penetration caused by free convection. Also, the circular shape provides almost 35% and 15% more protection time than the triangular and square models, respectively, which are supposed to be considered in thermal insulation packaging design.

Keywords**:** Thermal insulation packaging; Phase change Material; Melting time; Natural convection.

1. Introduction

Thermal-insulated packaging (TIP) is one of the important factors in energy management and used to transport temperature-sensitive products such as chocolates, wine, pharmaceuticals, butter, seafood, fresh flowers, meat, cheese, gourmet meals and fresh herbs [1]. Indeed, finding suitable insulation design [2], material [3] and configuration [4] are of great importance that can provide long protection time with several characteristic parameters such as compatibility, weight, safety and handling. TIP is designed to maintain the inside temperature of the packaging within a specific range by decreasing the heat transfer rate between the outside environment and the packaging. In other words, the TIP is used to minimize the heat flow through the walls. Indeed, the product's preservation time improves, and optimal temperatures maintain until it reaches the final destination. In this regard, advanced insulation systems restrict heat transfer through all heat transfer mechanisms, including conduction, convection and radiation [5]. To efficiently minimize heat transfer, it is important to strictly consider all these aspects.

So far several insulation materials have been applied for TIP. The conventional insulation designs and materials used in the industry are mainly work based applying material with low thermal conductivity to reduce heat transfer rate. Cotton fabric, mineral wood, insulating fibres like fibreglass, bubble films/gas column films, and cellulose, plastic foams (polyurethane (PU) and polystyrene (PS) foams), wool, cold packs and aluminium foil are among the available materials for TIP [6]–[9]. So, the thermal conductivity and thickness of the insulation layer are supposed to be selected to keep the temperature within a certain range for the required time. For temperature-sensitive products, usually, the required temperature ranges from -20 to -5 °C for frozen, 2 to 8°C for refrigerated and 16 to 24 for room temperature items [10].

In this regard, a relatively new concept is using Phase change materials (PCMs) which have exclusive characteristics to increase the thermal buffer and control temperature variations [11]. PCM has high latent heat and long thermal cycle life and are available with different melting/solidification temperatures making them a suitable concept to be applied in a wide range of applications. PCMs are also known as passive thermal energy storage materials that can be used in the TIP industry to maintain a temperature-sensitive product within the required temperature range specified by the manufacturer during the transportation and storage phases until it reaches the consumer. Several key factors should be considered before applying PCM for TIP, including the latent heat of fusion or enthalpy, the existence of a sharp melting/freezing point, the phase change temperature, flash point, material purity, vapour pressure, toxicity, odour, corrosiveness and thermal stability [11], [12]. To enhance the performance of PCM in TIP, the PCMs with melting temperatures within the required shipping temperature for the products are selected. As the phase of the PCM change (from solid to liquid by absorbing heat), it effectively keeps the packaging temperature constant and extends the duration of thermal protection time via latent heat. Besides the temperature, the melting progress is a distinguished factor in this insulation material compared to other TIP models. While the PCM melts by absorbing heat, natural convection occurs in the liquid portion of the PCM which significantly affects the insulation performance. Indeed, the configuration of the PCM layer is another important factor that needs further investigation.

Based on the literature, PCM has a high potential for TIP which can increase the protection time compared to other available materials. However, since natural convection is among the heat transfer mechanism in the PCM layer, the placement of the insulation layer needs to be optimized to decrease the melting rate. So, this study is dedicated to comparing different forms of insulation layer designs and corresponding results on the melting time.

2. Methodology

In this section, the designed insulation layers are described, material properties and geometrical dimensions are defined, and the required mathematical modellings are presented.

2.1. Designed TIP Models

To evaluate the effects of packaging design on thermal protection performance, three different TIP designs as circular, square and triangular shown in Fig. 1 are considered. The insulation layer filled with PCM and its thermophysical properties are given in Table 1. The protected area and PCM layer volume are set 0.02 m^2 to in all cases to have a better analysis between the cases, as a result, the insulation layer thickness varies for each case. Since the melting temperature of the PCM is 10 ℃, the initial temperature of the packaging is assumed equal to this value. The boundaries of each case are exposed to a constant 15 ℃ and natural convection effects are considered in the simulation. Also, the incompressible and Newtonian fluid assumptions are applied for the free convection in the liquid phase to simplify the calculations with acceptable error.

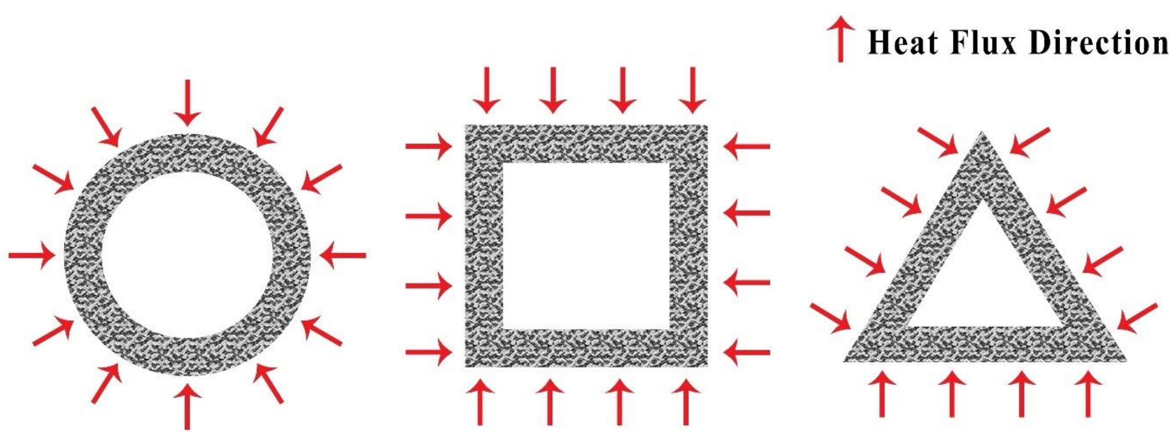

Fig. 1: Schematic of the different insulation layers in (a) circular, (b) square and (b) triangular forms.

Table 1: Thermophysical properties of considered PCM [13].

	ρ (kg/m^3)	k (W/m.K)	c_p (J/kg.K)	β (1/K)	υ (m^2/s)	T_m (℃)	L (kJ/kg)
PCM	780	0.12	2400	5×10^{-6}	0.001	10	240

2.2. Governing Equations

The governing equations, including continuity, momentum and energy, for the heat and mass transfer in the described problem in section 2.1 are [14]:

$$\nabla.\vec{U} = 0 \tag{1}$$

$$\frac{\partial\vec{U}}{\partial t} + \left(\vec{U}.\nabla\right)\left(\vec{U}\right) = -\frac{1}{\rho}\nabla(P) + \nu_{PCM}\nabla^2\vec{U} - \vec{g}\beta(T - T_{ave}) \tag{2}$$

$$\frac{\partial T}{\partial t} + \vec{U}.\nabla T = \nabla.\left(\frac{k}{\rho c_p}\nabla T\right) - \frac{L_{sl}}{c_p}\frac{\partial f_l}{\partial t} \tag{3}$$

Where T, $\vec{U}$, P, f_l and L_{sl} are temperature, velocity vector, pressure, liquid fraction and latent heat of fusion, respectively. Also, the average temperature is calculated as $T_{ave} = \frac{T_{initial}+T_{boudary}}{2}$.

By using the enthalpy (H), the melting fraction of PCM is defined as:

$$f_l = \begin{cases} 0 & H < H_s \\ \frac{L-L_s}{H_l-H_s} & H_s \leq H \leq H_l \\ 1 & H_l < H \end{cases} \tag{4}$$

Where $H = c_pT + L_{sl}f_l$. Detailed information regarding the governing equation are provided in [15].

2.3. Numerical Modelling

Lattice Boltzmann Method (LBM) is used to solve the governing equations, and correspondingly, an in-house code is developed in the Fortran language.

In the numerical simulation, natural convection happens in the liquid part of the PCM, and so, as PCM melts, the liquid region changes and requires a moving boundary. The moving boundary effects are added in the collision step, and also, for the heat transfer in the domain, Huang et al.'s [16] model is applied as follows for the D2Q9 lattice [17], [18]:

$$f_i(x + c_i\Delta t, t + \Delta t) - f_i(x,t) = -\frac{1-B}{\tau_f}\left[f_i(x,t) - f_i^{(eq)}(x,t)\right] + B\Omega_i^s + \Delta t.F_i \tag{5}$$

$$g_i(x + c_i\Delta t, t + \Delta t) - g_i(x,t) = -\frac{g_i(x,t)-g_i^{(eq)}(x,t)}{\tau_g} \tag{6}$$

Where F_i, τ_f and τ_g are represents the body forces, flow and thermal relaxation times, respectively. The equilibrium distribution function ($g_i^{(eq)}$) in Eq. (6) is defined as:

$$g_i^{(eq)} = \begin{cases} H - c_pT + \omega_i c_pT\left(1 - \frac{\vec{U}^2}{2c_s^2}\right) & i = 0 \\ \omega_i c_pT\left[1 + \frac{\vec{c}_i.\vec{U}}{c_s^2} + \frac{\vec{U}\vec{U}:(\vec{c}_i\vec{c}_i - c_s^2 I)}{2\varepsilon c_s^4}\right] & i \neq 0 \end{cases} \tag{7}$$

In which $\vec{c}_i$, ω_i, and c_s are lattice speed, weighting factor, and sound speed, respectively. Detailed information regarding the governing equation are provided in [16].

3. Results and Discussion

The same amount of PCM for insulation is used in different shapes to thermally protect the same inside area. To have a better understanding of melting progress during the time in each shape, liquid fraction contours are presented in Fig. 2. In this figure, while the red colour represents the liquid region, the solid part is in blue for three different times as 240, 480 and 720 s. At the first glance, it can be observed that in all shapes, the melting rate is higher at the bottom region of the TIP.

After that, the top and the lateral areas melt, respectively, which highlights the importance of natural convection in the liquid region.

Natural convection starts from the bottom region in all designed TIPs and a wavy trend in the melted region has been formed. Compared to the other sides in which the melting mainly occurs by conductive heat transfer, natural convection in the bottom has increased the heat transfer. From a practical point of the view, the bottom of the PCM-based TIP is the weakest part and the maximum possible protection time have to be defined based on this region.

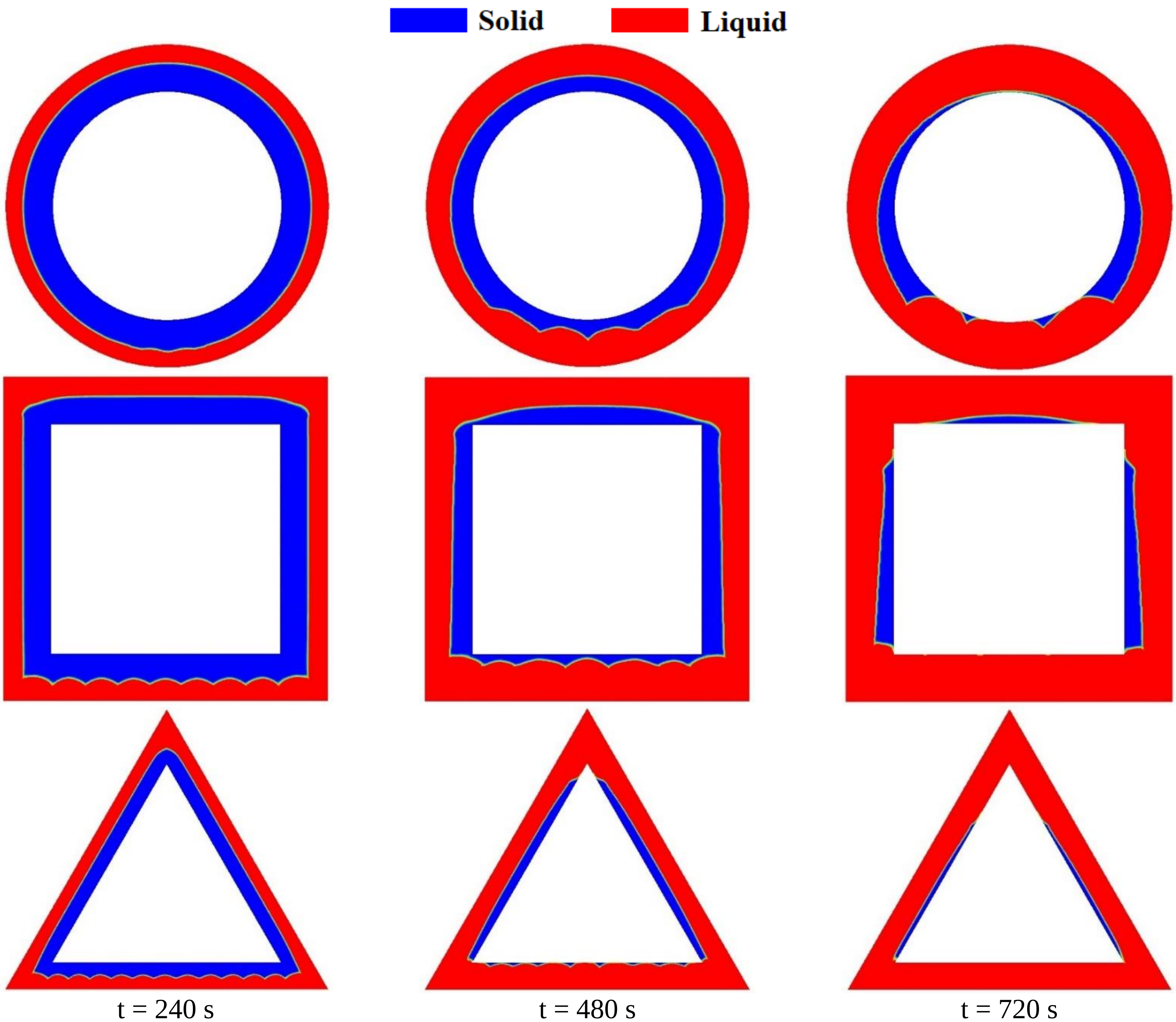

Fig. 2: Melted fraction of the PCM in each considered TIP model.

In addition to the melted fraction, the temperature distribution in each TIP shape is demonstrated in Fig. 3. The temperature is presented in the dimensionless form by using ($T^* = \frac{T - T_{initial}}{T_{boundary} - T_{initial}}$). While there is uniform temperature distribution in the lateral and top regions, a complex temperature profile is observed for the bottom region. Due to flow circulation in this area, heat penetrates into the insulation layer and causes more heat transfer and melting rate. Meanwhile, this heat penetration area is higher in triangular, square and circular TIP modes, respectively. Although the heat is more uniformly with a higher mean temperature moving at the top region, the melted fraction is higher at the bottom.

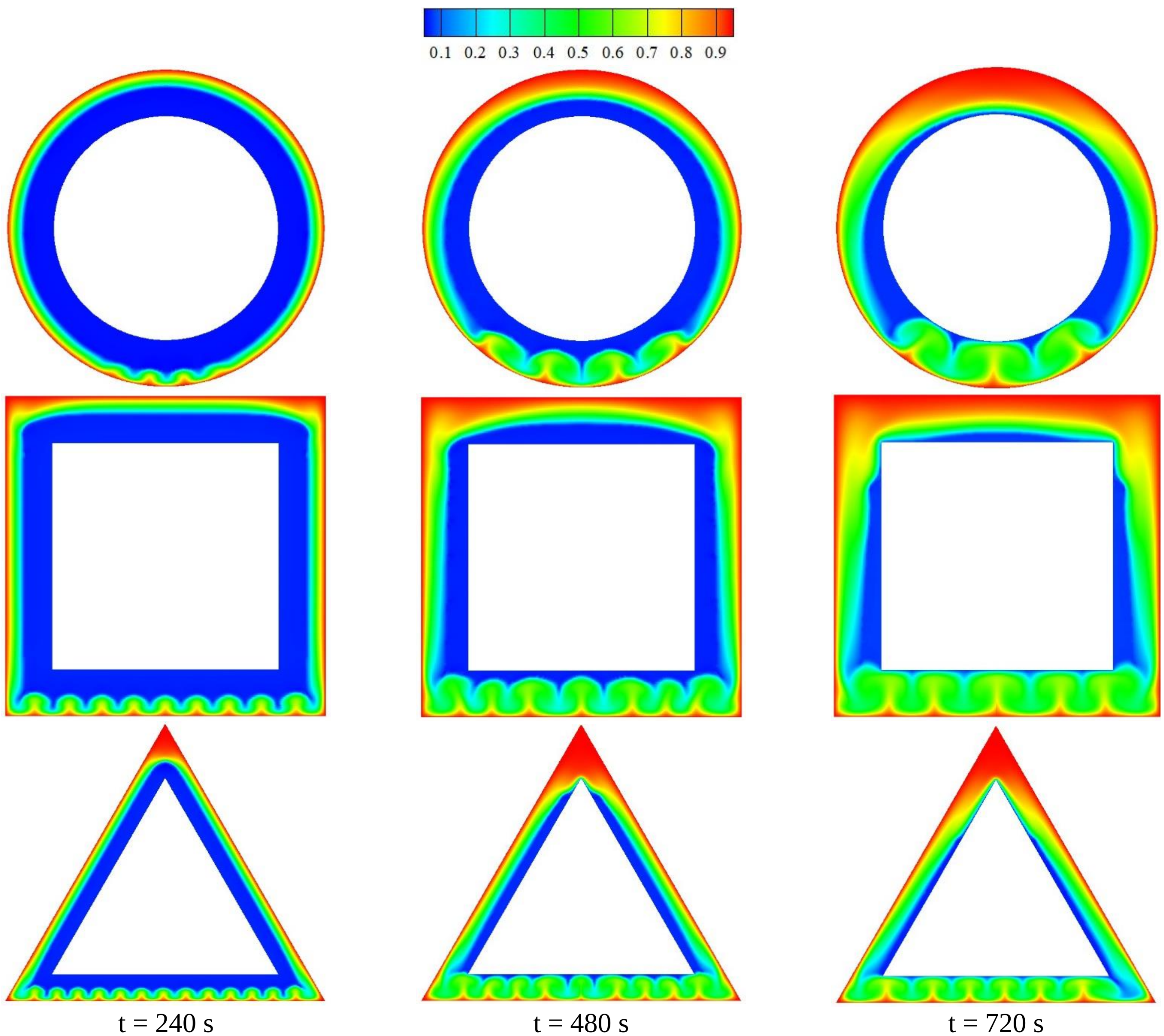

Fig. 3: Temperature distribution in each considered TIP model.

The liquid fraction of PCM over time for all TIP models is reported in Fig. 4 to compare provided thermal protection time. As expected, the PCM layer melts faster in triangular, square and circular models, respectively. In other words, the circular shape provides almost 35% and 15% more protection time than the triangular and square models, respectively. Meanwhile, the natural convection effect on the melting rate is more dominant within 0.3 to 0.8 liquid fraction of PCM each case.

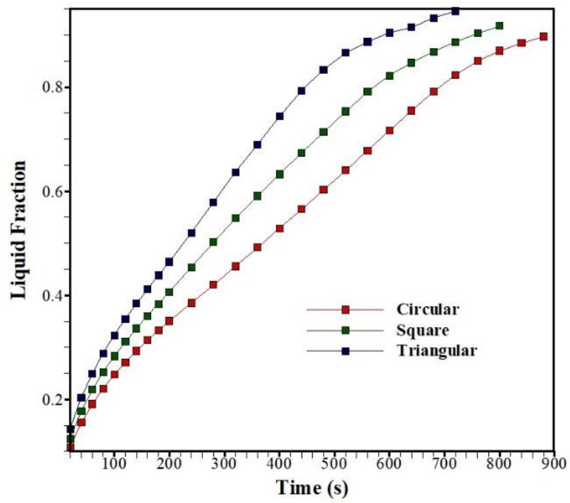

Fig. 4: Liquid fraction over time comparison between considered TIP models.

4. Conclusion

In this study, the effects of the PCM insulation layer for food packaging are investigated by considering three different shapes as circular square and triangular models. The used PCM amount for insulation is set to the same value in all cases and thermal protection time is presented over time. It is observed that the natural convection at the bottom area of each TIP causes a higher heat transfer rate and consequently higher melted PCM. Also, it is stated that the circular TIP model provides considerably higher protection time and is supposed to be considered in PCM-based insulation design.

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