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Analyzing the Performance of Phase Change Material Insulation Layer on Food Packaging

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***Abstract*—**One of the main issues affecting the quality and shelf life of food products is temperature fluctuation during transportation and storage. Packaging plays an important role in protecting food from environmental conditions, especially thermal variations. In this study, the performance of using microencapsulated Phase Change Material (PCM) as a promising thermal buffer layer in smart food packaging is investigated. The considered insulation layer is evaluated for different thicknesses and the absorbed heat from the environment. The results are presented in terms of the melting time of PCM or provided thermal protection period.

***Keywords*—**Food packaging, phase change material, thermal buffer, protection time.

I. INTRODUCTION

NOWADAYS, food waste has become a global concern that negatively affects societies. It is estimated that more than one-third of food products are wasted each year with a growing trend [1]. This huge amount of waste results in environmental concerns, such as greenhouse gas production and water resources reduction. Food spoilage due to weak thermal insulation provided by packaging and inappropriate refrigeration system in storage is a prevailing factor in food waste. Having known the global problems regarding insulation materials, such as foam, glass fiber and mineral wool, a sustainable model which is environmentally friendly is of great importance [2].

PCM are substances that can absorb and release a substantial amount of heat without sensible change in their temperature. These materials work based on phase change from solid to liquid and vice versa during melting and solidification processes [3]. As a result, they can be used for insulation and temperature control applications. Although they are not still as affordable as common insulation materials, a wide range of available options and long thermal cycling life make them a promising concept for future studies and industrial applications. Based on the melting temperature of PCM, they can be used for frozen (-10 °C to -3 °C), refrigerated (2 °C to 10 °C) and room temperature (15 °C to 25 °C) food packaging [3].

In the last two decades, PCM casings, nettings and bags have been implemented in several food-processing and food-packaging applications. This active and intelligent packaging is compatible with various types of food products cheeses, meats, soups, stews, sauces, produce and bread without reducing the quality. However, apart from the considerable potential of PCM in damping temperature variation in packaging systems, it has challenges regarding performance and applying for a wide range of applications. Firstly, these materials will be in the liquid state during the melting process which can disperse in and make a reaction with the environment. So, they must be embedded in a container in macro, micro and nano sizes. Moreover, the performance of the PCM packaging is highly dependent on the shape and configuration of PCM embedded insulation layers.

The challenges of PCM-based food packaging have been under scrutiny by numerous researchers. In this regard, Hoang et al. [4] produced microencapsulated PCM and evaluated their performance for food packaging. Under a heating and cooling cycle, they claimed that the produced particles provide a better thermal buffering capacity compared to the bulk use of PCM. Later, Singh et al. [5] explored the challenges of the commercial use of PCM in food packaging systems for transportation purposes. They nominated the manufacturing costs as the main reason why the concept has not been used worldwide. They also suggested some configurations like reducing the diameter of PCM particles to increase the surface area which results in a better performance at a lower amount of PCM. In another study, Unel et al. [6] also compared the performance of microencapsulated PCM with its bulk for providing thermal buffering for 160 g of chocolate. They stated that encapsulated PCM with improved properties can maintain the temperature for 6-8 hours more under the same environmental conditions. Meanwhile, Johnston et al. [7] designed a container structure using nanoencapsulated PCM for maintaining the temperature of asparagus as a food product. According to their test, it kept the temperature inside the container to 10 °C for more than 5 hours at an environmental temperature of 23 °C. Vennapusa et al. [8] produced PCM embedded in a porous matrix known as shaped stabilized PCM to apply for food packaging. The produced composite is then used to maintain the temperature of a 360 g chocolate under 25 °C. The results revealed that the model has the capability of providing 349 min thermal insulation for the product.

PCM is an intelligent material that can provide high-grade thermal protection in food packaging. However, this relatively new concept still demands further investigations to increase the performance and reduce the costs. In this study, food packaging consisting of a PCM layer is investigated in terms of melting time and protection provided for the food product. In this order, 3D models are designed and numerically analyzed by

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considering the effects of PCM layer thickness and heat flux from surrounding to the box.

II. PROBLEM DESCRIPTION

For this simulation, a cubic container with dimensions of $10 \times 10 \times 10$ cm surrounded by PCM particles is considered according to Fig. 1. The insulation layer consists of microencapsulated PCM with thermo-physical properties shown in Table I. The effect of PCM layer thickness and the amount of heat flux from the environment on the melting time and inside temperature is evaluated. The applied thickness and heat flux values are t = 5 mm, 10 mm and 15 mm and q''= 200 W/m^2, 400 W/m^{2}and 600 W/m^2, respectively. The impact of natural convection within the liquid phase of PCM is assumed negligible. Also, the heat flux direction is assumed normal to each side of the cubic box.

III. MATHEMATICAL MODELLING

A. Governing Equations

The energy transfer in this modelling consists of both conduction and latent heat throughout the domain. So, it can be defined as [9]:

$$\frac{\partial T}{\partial t'} = \nabla.(\alpha \nabla T) - \frac{L_{sl}}{c_p}\frac{\partial f_l}{\partial t} \quad (1)$$

where t', T, α, c_p, L_{sl} and f_l are time (s), temperature (°C), thermal diffusivity (m^2/s), latent heat (J/kg) and liquid fraction of PCM, respectively. The convection term is eliminated since the fluid flow is assumed negligible, and correspondingly, the momentum equations are not solved for the current problem.

By using the total enthalpy definition as $H = c_p T + L_{sl} f_l$ and substituting it into (1) the energy equation based on enthalpy can be written as:

$$\frac{\partial (H/c_p)}{\partial t} = \alpha \nabla^2 T \quad (2)$$

The liquid fraction of PCM during energy absorption from the environment is calculated according to the enthalpy of the solid and liquid states of the PCM as:

$$f_l = \begin{cases} 0 & H < H_s = c_p T_s \\ \frac{H - H_s}{H_l - H_s} & H_s \le H \le H_l = c_p T_l + L_{sl} \\ 1 & H_l < H \end{cases} \quad (3)$$

B. Numerical Model

To solve the governing equation, thermal LBM is used in this simulation that is defined as:

$$g_i(\vec{x} + c_i \Delta t, t + \Delta t) - g_i(\vec{x}, t) = -\frac{g_i(\vec{x}, t) - g_i^{(eq)}(\vec{x}, t)}{\tau_g} \quad (4)$$

where g_i, c_i and τ_g are distribution functions, the discrete velocity in i direction and relation time, respectively.

To calculate enthalpy (*H*) as shown in (2), the equilibrium distribution function introduced by Huang et al. [10] is applied as:

$$g_i^{(eq)} = \begin{cases} H - c_p T + \omega_i c_p T & i = 0 \\ \omega_i c_p T & i \neq 0 \end{cases} \quad (5)$$

The thermal relaxation time is defined as a function of effective thermal diffusivity:

$$\tau_g = \frac{\alpha_e}{c_s^2 \Delta t} + 0.5 \quad (6)$$

Then, the macroscopic values for temperature for the are written as [10]:

$$H = \sum_i g_i \quad (7)$$

$$T = \begin{cases} \frac{H}{c_p} & H < H_s = c_p T_s \\ T_s + \frac{H - H_s}{H_l - H_s}(T_l - T_s) & H_s \le H \le H_l = c_p T_l + L_{sl} \\ T_s + \frac{H - H_l}{c_p} & H_l < H \end{cases} \quad (8)$$

In (4) and (5), the weighting factors (ω_i) and lattice directions ($\vec{c}_i$) for D2Q9 lattice are given as [9]:

$$\omega_i = \begin{cases} \omega_0 = \frac{4}{9} & i = 0 \\ \omega_i = \frac{1}{9} & i = 1,2,3,4 \\ \omega_i = \frac{1}{36} & i = 5,6,7,8 \end{cases} \quad (9)$$

Also, c_i for the same lattice is defined as:

$$\vec{c}_i = \begin{cases} (0,0) & i = 0 \\ c\left(\cos\left[\frac{(i-1)\pi}{2}\right] i, \sin\left[\frac{(i-1)\pi}{2}\right] j\right) & i = 1,2,3,4 \\ c\left(\sqrt{2}\cos\left[\frac{(i-5)\pi}{2} + \frac{\pi}{4}\right] i, \sin\left[\frac{(i-5)\pi}{2} + \frac{\pi}{4}\right] j\right) & i = 5,6,7,8 \end{cases} \quad (10)$$

TABLE I
ENCAPSULATED PCM PROPERTIES [11]

Symbol	Quantity	Value
ρ	Density	770 (kg/m^3)
c_p	Specific Heat	2300 (J/kg.K)
k	Thermal Conductivity	0.15 (W/m.K)
L_{sl}	Latent Heat	243000 (J/kg)
T_s	Solidification Temperature	9 (°C)
T_l	Melting Temperature	10 (°C)

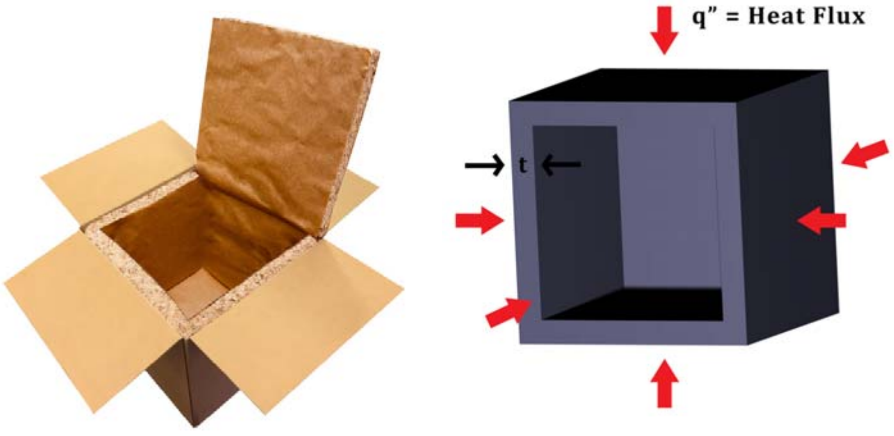
IV. VALIDATION AND RESULTS

A. Validation of Numerical Model

The written LBM code in the FORTRAN language is validated by [12] for melting progress over dimensionless time (Fo$=\frac{t'\alpha}{L^2}$). As presented in Fig. 2, the results are in a good match with [12].

B. Results and Discussion

In this section, the performance of the insulation layer filled with microencapsulated PCM is investigated. For this purpose, two characteristic parameters are selected as the thickness of the layer and heat flux. Their effects on the provided insulation time or melting time are evaluated.



(a) (b)

Fig. 1 The considered packaging with applied boundary condition

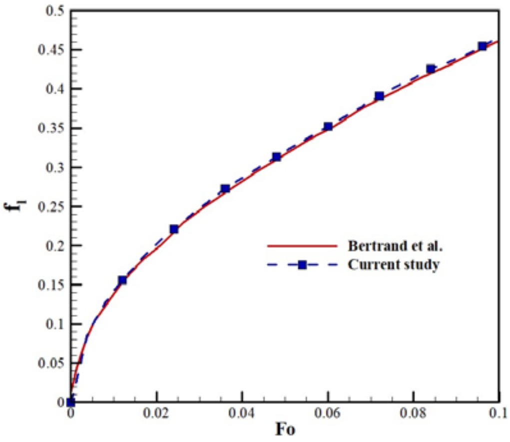


Fig. 2 Comparison of melting fraction for between the current study and [12]

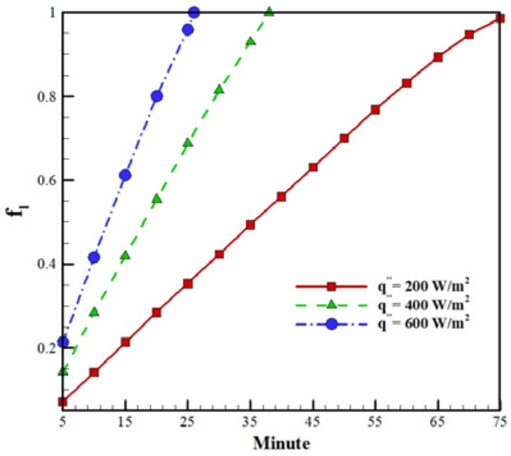


Fig. 3 Variation of the melted fraction of PCM over time for various heat flux values

In Fig. 3, the variation of melting fraction within the PCM layer over time at different heat fluxes for the thickness of 5 mm is demonstrated. Interestingly, even a very small thickness of the PCM layer provides a long insulation time. However, as the heat transfer from the environment to the box increases, the melting time decreases. At the heat flux of 200 W/m^2, the insulation layer can keep the temperature of inside below 10 ℃ for about 75 min. This value reduces to 40 min and 28 min for 400 W/m^2 and 600 W/m^2 heat fluxes, respectively. While there is around 35 min decrease in the insulation time between 200 W/m^2 and 400 W/m^2, it is just 12 min from 400 W/m^2 to 600 W/m^2 heat flux. So, the provided insulation time does not have a linear elation with the absorb heat from the environment.

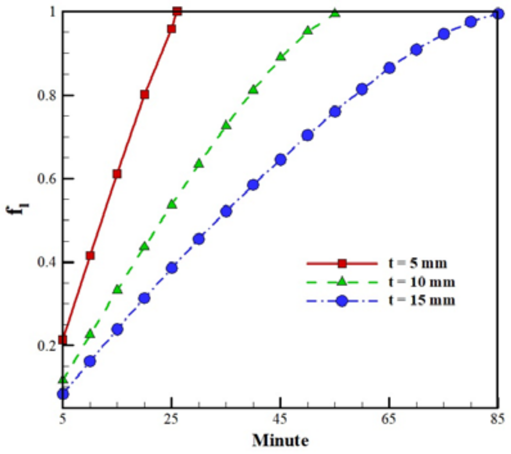


Fig. 4 Variation of the melted fraction of PCM over time for various insulation layer thicknesses

The variation of the melted fraction of the PCM layer over time, or in other words, the provided insulation time for various insulation layer thicknesses is presented in Fig. 4. The worst situation or the lowest protection in Fig. 4 was observed for the heat flux of 600 W/m^2. So, this heat flux is applied to different thicknesses to investigate the possible improvement in the insulation time. By increasing the thickness, the added

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volumetric amount of microencapsulated PCM is proportional to the first-order difference of $(t_2 - t_1)$. Almost the same relation is observed in the melting time of the PCM layer. The provided thermal protection time from 15 mm to 10 mm layer is almost 30 min. The same protection time difference can be seen while decreasing the thickness from 10 mm to 5 mm. So, it can be concluded that the insulation time is proportional to the variation of thickness.

V. CONCLUSION

In this numerical study, the performance of an insulation layer for food packaging using microencapsulated PCM is investigated. For this reason, the impact of two of the main characteristic features, thickness and heat flux, on the provided insulation time in a 3D box is presented. It is observed that the insulation layer can provide long thermal protection, and this thermal insulation time is proportional to the first-order thickness of the layer with non-linear relation to heat flux.

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