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Experimental and numerical analysis of a chilly bin incorporating phase change material

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HIGHLIGHTS

- The enhancement of temperature sensitive products conditions is studied.
- Phase change materials are used to enhance the thermal performance of chilly bins.
- A mathematical model for chilly bin used to store cold or hot food is developed.
- The numerical model is validated with experimental data.
- The mathematical model proposed may be used for effective design of chilly bins.

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ABSTRACT

In this paper the enhancement of temperature sensitive product conditions when the product is placed in chilly bins is studied. The aim is to develop a numerical model for a bin used to store cold or hot food. Phase change materials (PCM) were used to allow longer time for transport and storage without affecting the quality of perishable products. The mathematical model is validated with the measured experimental data which proved the usefulness of using PCM in cold storage. The benefit of using PCM was demonstrated since it maintained product temperature constant for longer periods. The numerical model may be used for effective design of new chilly bins for use in storage of food.

1. Introduction

The domestic transport of temperature sensitive products is commonly conducted with the use of insulated boxes. It is well known that one of the most important factors affecting the quality of low temperature sensitive products is the temperature variation and fluctuation during storage and transport of ice cream [1] or frozen meat [2], which results in a reduction in the quality of food and reduce shelf life of frozen products. The same may be said for hot products, a temperature drop due to heat losses through the packaging may affect the final consumption. Hence a wide range of packaging solutions exists in the available market for products that must be kept within a specific temperature range throughout the distribution chain. However many of the food service operations which offer take-away meals do not offer this type of food transportation. In order to maintain food safety, the Food and Drug Administration code from the United States (FDA) [3] specifies serving temperature standards of 5 °C or less for cold foods and 60 °C or higher for hot foods as security temperatures. Outside these temperatures bacteria does not grow for prolonged periods. Hutson et al. [4] measured internal temperatures of hot and cold food items immediately after purchase and after 25 min (paper, aluminium foil, polystyrene foam and polyethylene plastic were used as packaging materials). Only 19 out of 39 food items met FDA temperature standards at time of purchase while after 25 min only 3 of them met the requirements. After 25 min, the mean decrease in food temperature for hot food was between 7 and 16 °C while for cold foods the mean increase was 4 °C.

Because of the continuous increase in demand of packaging methods, some researchers have been working in the development of new packaging solutions for use in the different application. East el al. [5] developed a mathematical model of heat transfer to quantify the performance of three different insulated packages transported by road in Australia. On the same way, Margeirsson

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et al. [6] studied the thermal performance of fresh fish boxes with two different insulation materials: corrugated plastic (CP) and expanded polystyrene (EPS). They concluded that the insulating performance of EPS is significantly better than the insulating capacity of CP. Moreover, Singh et al. [7] studied the thermal response of a wide range of packaging solutions including those with gel packs. They calculated the average *R*-values ($m^2 {}^\circ C\ W^{-1}$) for all the packages analysed and compared them with each other.

The use of thermal energy storage (TES) by the addition of phase change materials (PCM) is a possible solution due to its ability in maintaining materials within a narrow temperature range by absorbing heat gains during melting process [8]. Farid et al. [9] reviewed most of the PCM for medium temperature applications and Oró et al. [10] performed the same study but for low temperature applications (lower than 20 °C). Many researchers have been investigated both experimentally and numerically the inclusion of PCM in different systems over the years. Kurina et al. [11] evaluated numerically various configurations of PCM TES devices improving existent designs in terms of heat transfer rate during both charging and discharging processes. A new design of heat spreader for electronics cooling incorporating PCM was studied by Jaworski [12]. The results of the study concluded the benefit of using PCM in the structure of heat spreaders. Liu et al. [13] developed a mathematical model to predict temperature changes in a PCM flat slab for cooling applications, in particular for a novel refrigeration unit for refrigerated trucks. The inclusion of PCM in a domestic hot water tank was studied experimentally and numerically by de Gracia et al. [14] proving the efficiency of the use of PCM in these systems. Moreover the authors used the validated numerical simulation to carry on a parametrical study to optimize the PCM distribution inside the hot water tank. Oró et al. [15] designed and tested, both experimentally and numerically, a PCM package for commercial ice cream containers. It was concluded that the use of the PCM package can be beneficial for sustaining ice cream quality when it is placed out of the freezer. Moreover, using molecular alloys as phase change materials (MAPCM) is another solution that has been considered over the years. Some investigations considered different applications of MAPCM for thermal protection of biomedical products [16], sensitive temperature food [17], and drinks [18].

TES systems using PCM in storage and transport of perishable products could potentially become more efficient if the correct PCM (melting temperature and latent heat), its encapsulation, and the amount used are carefully investigated and properly implemented. There are too many parameters to be considered experimentally, and numerical modelling could help in decreasing the number of experiments required for optimizing the design process.

The aim of this paper is to develop a numerical code for use in the prediction of the thermal performance of an insulated chilly bin with and without PCM in order to enhance its thermal performance. The mathematical code is validated with experimental measurements conducted in this work data and used later to optimize the chilly bin design.

2. Materials and methodology

2.1. Chilly bin description

Two identical chilly bins were used in the work presented in this paper (Fig. 1). Each chilly bin has an inner diameter of 110 mm and length of 270 mm and is insulated with polystyrene, as Fig. 2 shows. Both of them were modified, one was extra insulated with PCM (scenario 2) while the other one was extra insulated with glass wool (scenario 1). The insulation material (glass wool) and the PCM were included between the internal wall of the chilly bin and the aluminium cylinder inside it. The aluminium cylinder was used for convenience and is not usually used in real construction of such bins. The product temperature inside the chilly bins, the air gap temperature between the product and the chilly bins cover, and the ambient temperature were measured and monitored continuously using thermocouples and a data logging system. All the thermocouples were previously calibrated.

Fig. 1. Chilly bins used in the experimentation.

2.2. Phase change material

In the experimentation a commercial PCM (RT-2) from Rubitherm was used. The total PCM volume inside the chilly bins was 0.7 L, occupying 28% of their internal volume. The thermophysical properties given by the manufacturer are shown in Table 1.

3. Numerical model

The unsteady heat conduction equation was solved using a fully implicit finite volume method of solution in cylindrical coordinates (Fig. 3).

From the first law of thermodynamics for a closed isotropic system, transient two-dimensional heat transfer in water, PCM, insulation, and polyethylene recipient is governed by the heat conduction equation (Eq. (1)):

$$C_p(T)\cdot\rho\cdot\frac{\partial T}{\partial t} = k\cdot\left(\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial y^2}\right) \tag{1}$$

The effect of natural convection in the fluid in the chilly bin was ignored since heat transfer resistance is controlled by the insulation and PCM rather than by the natural convection in the water. Here a bulk temperature of the air has been considered. For air, heat transfer was assumed to dominate by convection heat transfer following normal correlations developed in textbooks as described later in the paper. Notice the numerical analysis contrast between the stored product (water) which is treated by conduction and air which is treated as a bulk temperature and governed by convection heat transfer.

The governing equation is completed by the following initial and boundary conditions: