Evaluation on performance of cold storage box enveloped with phase change materials

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Abstract. Retailing temperature-sensitive-products such as sausages, milk, fishes, poultry, etc. requires extra energy for cooling. It is necessary to develop an-energy-efficient-design of cold storage box to preserve these products during transportation and retailing. This research aims to study the heat flow, temperature distribution and temperature changes within a 5 litter cold box featured by phase change material (PCM). The study begins with design and fabrication of cold box followed by testing and evaluation using computational fluid dynamics (CFD) simulation. As energy storage, there are four models of 300 ml plastic-bottle filled with PCM i.e (i) plain bottles without holes and grooves, (ii) bottles with one hole, (iii) two-holes bottles with curvatures, and (iv) bottles with four holes without curvatures. There are two type of PCM was prepared to observe the temperature changes in the box, 100 % H2O and 10 vol.% NaCl in H2O. Experimental results show that adding 10 vol.% of NaCl enhances the effectiveness of energy discharging by 73% compared with pure water. CFD simulation explains in detail the temperature distribution and heat flow pattern of each PCM bottles types highlighting an important influence of the shape and number of holes on the rate of heat flow. The best performance of cold box is exhibited by 10% NaCl in H2O filled into plain bottle.

1. Introduction
Food products such as sausage, milk, fish, poultry, etc. is having a low resistance against bacteria and easily be decayed at room temperature, thus an effort to guarantee food safety is necessary. To keep these products fresh and guarantee the quality, a cold-storage box is designed according to of food safety requirement. Cold storage benefits more in the preservation of perishables especially fruits and vegetables [1]. The use of the freezer or refrigerator is not practical and economical, as the cost for electricity tends to increase.

During last few decades, fossil fuels depletion is against the increase in the energy demand broadening the gap between energy demand and its supply. To bridge this energy demand/supply gap excess energy stored in a suitable form is more effective and beneficial [2]. There are a large number of studies have been devoted to develop phase change materials (PCMs) as thermal energy storage within a wide range of application [3]. since energy conservation and environmental protection becomes most important issues for humanity.
In recent years, many researchers have used CFD numerical simulation and experiments to improve uniform cooling of food products and optimize the design of cold storage-boxes [4]. Investigation on the effect of box materials has been performed to assess the possibility of dose reduction and obtain insight into the fate of the 1-Methylcyclopropene when fruit are stored in wooden boxes [5]. Combined experimental and CFD simulations have been also used to explain the charge and discharge phenomena of paraffin RT35 as PCM for a tube-and-shell heat exchanger design [6]. However, for understanding the heat transfer phenomena and design optimization, combination of CFD simulation and experimental works are still insufficient and need more investigation.

The purpose of this research is to evaluate a purpose built cold-box for retailing temperature-sensitive-products. Design optimization is then performed by study the heat flow, temperature distribution and temperature changes within a cold-box using CFD modelling. Additionally, CFD models are also used to study the effect of the shape of PCM bottle on the heat transfer rate and distribution of temperature inside the cold-box.

2. Methodology

2.1. Material

In this study, there are two samples have been prepared as material for energy storage, i.e. (i) H₂O and (ii) 10 vol.% NaCl in H₂O. The properties of both samples is defined as reported in the literature [5] and tabulated in table 1.

| Table 1. PCM properties |
|-------------------------|
| Properties               | H₂O  | 10 vol.% NaCl in H₂O |
| Conductivity [W/(m.K)]   | 0,6  | 0,53                |
| Density (kg/m³)          | 995,6| 1074                |
| Specific heat (J/kg.K)   | 4182 | 3720                |
| Emissivity               | 1    | -                   |
| Electrical conductivity σ(S/m)| <10⁻³ | 16                  |
| Viscosity (Pa.s)         | 1,14 | 1,3                 |
| Compressibility (MPa)   | 2185,65 | -               |
| Freezing point (°C)     | 0    | -6,5                |

Source: [7]

2.2. Experimental

Initially, a cold storage box has been design for storage volume capacity of 5 litre with outside dimensions of 452x299x237 mm. The box comprises a layer of wood (16 mm thick) as casing, a layer of styrofoam (22 mm thick), six plastic-bottles filled with PCM, and 1.2 mm aluminium plate. Figure 1 shows cold-box design with various type of PCM bottles. For experimental investigation, type-b bottle was used and then followed by model development and validation.

The experiment is carried-out for two types of liquids, i.e H₂O and 10 vol.% NaCl in H₂O. Liquid sample is filled into six pieces of type-b plastic bottle at a volume of 300 ml each. For charging, the bottles were placed in the freezer for 8 h and then inserted into the box for discharging test as shown in Figure 2(a). As energy recipient (loaded media) a 180 ml of H₂O was filled at room temperature into an aluminium flask and placed in the middle of the box. To record temperature changes, there are six thermocouples installed during experiment as pointed out in Figure 2(b).
Figure 1. Cold-box with various types of plastic bottles for PCM. (a) plain bottle without holes and grooves, (b) one-hole bottle without grooves, (c) two-holes bottle with grooves, and (d) four-holes bottle without grooves.

Figure 2. Experimental setup of cold box. (a) Arrangement of the PCM bottles (b) location of thermocouple probe: (1) Loaded media, 2. Space inside the box, 3. PCM plastic bottle, 4. Styrofoam, 5. Wooden casing, and 6. Environment

2.3. Simulation modeling

A CFD models are developed using Autodesk CFD software to analyse the flow pattern and temperature distribution inside the cooler. The finite element method is used to solve partial differential equations for different amounts. In the finite element method, the equilibrium residual Galerkin method is generally used. The algorithm in this equation is using the segregated solver. Pressure equation derived from the continuity equation. Integral equilibrium and the continuity equation where integration with parts used to reduce the order of integration in Equation 1 as follows:

\[ \begin{align*}
\frac{\partial N}{\partial t} &= -\nabla \cdot \left( \rho \mathbf{U} \right) - \nabla \cdot \left( \rho \mathbf{V} \right) - \nabla \cdot \left( \rho \mathbf{W} \right) \\
&= \frac{\partial N}{\partial t} \mathbf{U} + \frac{\partial N}{\partial t} \mathbf{V} + \frac{\partial N}{\partial t} \mathbf{W} \\
&= \int \left( \frac{\partial \mathbf{N}}{\partial x} \rho \mathbf{U} + \frac{\partial \mathbf{N}}{\partial y} \rho \mathbf{V} + \frac{\partial \mathbf{N}}{\partial z} \rho \mathbf{W} \right) d\Omega
\end{align*} \]  

(1)

This equation represents the mass flux that crosses the boundaries of the element. This will cancel the integral part of interior elements and will be zero for all boundaries where no mass (symmetry, wall). This term represents a natural boundary conditions for the pressure equation. To display the
pressure in this equation, using semi-discretized form of the equation of momentum, velocity-pressure relationship in Equation 2 below:

\[
U = U_h - K_u \frac{\partial p}{\partial x} / V = V_h - K_v \frac{\partial p}{\partial y} / W = W_h - K_w \frac{\partial p}{\partial z}
\]  

(2)

The term \(U_h, V_h, W_h\) with all the off-diagonal terms in the momentum equation. If the three equations have changed to the previous continuity equation, the result of pressure Equation 3 below:

\[
\int \left( \frac{\partial N}{\partial x} \rho K_u \frac{\partial p}{\partial x} + \frac{\partial N}{\partial y} \rho K_v \frac{\partial p}{\partial y} + \frac{\partial N}{\partial z} \rho K_w \frac{\partial p}{\partial z} \right) d\Omega = - \oint N_p Ud\Gamma - \oint N_p Vd\Gamma -
\]

\[
\oint N_p Wd\Gamma + \int \rho \left( U_h \frac{\partial N}{\partial x} + V_h \frac{\partial N}{\partial y} + W_h \frac{\partial N}{\partial z} \right) d\Omega
\]

(3)

This equation is in the form of the discretized Poisson equation and therefore will result in a symmetric coefficient matrix. For compressible flow, pressure density relationship should also be considered. This relationship is defined in Equation 4 as follows:

\[
\rho U = \frac{(\rho U^o + \rho U)}{2}
\]

Where \(o\) refers to the old values. This relationship is used when the continuity equation is integrated with the parts. Then replace the results of the speed defined in equation 5 as follows:

\[
\int \left( \frac{\partial N}{\partial x} \rho^o K_u \frac{\partial p^o}{\partial x} + \frac{\partial N}{\partial y} \rho^o K_v \frac{\partial p^o}{\partial y} + \frac{\partial N}{\partial z} \rho^o K_w \frac{\partial p^o}{\partial z} + N \frac{\partial \rho U^o}{\partial x} + N \frac{\partial \rho V^o}{\partial y} + N \frac{\partial \rho W^o}{\partial z} \right) d\Omega = - \oint N_p \rho^o U^o d\Gamma - \oint N_p \rho^o V^o d\Gamma -
\]

\[
\oint N_p \rho^o W^o d\Gamma + \int \left[ \rho \left( U_h \frac{\partial \rho}{\partial x} + V_h \frac{\partial \rho}{\partial y} + W_h \frac{\partial \rho}{\partial z} \right) + N \frac{\partial \rho U^o}{\partial x} + N \frac{\partial \rho V^o}{\partial y} + N \frac{\partial \rho W^o}{\partial z} \right] d\Omega
\]

(5)

With explicit pressure equations, each governing equations can be solved separately. That is, the X-momentum equation can be solved for \(U\) in all nodes, \(Y\) momentum equations can be solved for \(V\) on all nodes, \(Z\)-momentum equation can be solved for \(W\) on all nodes, the equation can be solved for \(P\) pressure on all nodes, etc. This approach is called Segregated Solver for each dependent variable separately resolved.

In the CFD simulation process input data must first determine the initial conditions and boundary conditions of the experimental test results of the cooler. Data input initial conditions and boundary conditions are shown in table 2.

3. Results and discussions

3.1. The results of experimental tests

Figure 3 shows the minutes of temperature changes occured during discharging process of \(H_2O\) PCM. Temperature changes versus time are also plotted for 10 vol% NaCl in \(H_2O\) PCM in Figure 4. Comparing both figures, \(H_2O\) sample has a freezing temperature of -12 °C while water is frozen at -15.9 °C. Once the test is started, loaded media absorbs energy from sample reaching the equilibrium condition. \(H_2O\) sample exhibits an increase in temperature from -12 °C to -0.9 °C over 300 minutes. Data of 10 vol. % NaCl in \(H_2O\) indicates a process of discharging energy as can be observed by a change in sample temperature from 15.9 °C to -6.4 °C. Indeed, the heat charged into PCM sample gradually removes the heat from loaded media resulting an equilibrium temperature of 3.4 °C and -3.1 °C for \(H_2O\) and vol.% NaCl in \(H_2O\), respectively. In term of time, PCM of 100% \(H_2O\) reaches equilibrium at 335 minutes while 10 vol.% NaCl in \(H_2O\) takes 240 minutes to reach equilibrium.
Table 2. Initial conditions and boundary conditions CFD simulation

| Input                                      | PCM                  |
|--------------------------------------------|----------------------|
| **Initial conditions**                     |                      |
| Media load (°C)                            | H₂O                  |
| In the aluminum space (°C)                 | 32.1                 |
| In the space of styrofoam (°C)             | 28.3                 |
| The outside walls styrofoam (°C)           | 26.5                 |
| The outside walls Wood (°C)                | 28.3                 |
| **boundary conditions**                    |                      |
| PCM cooling medium (°C)                    | -12                  |
| Environment (°C)                           | 33.5                 |
| PCM cooling medium volume (ml)             | 1800 ml              |
| media load                                 | Water (H₂O)          |
| Load the media volume (ml)                 | 180 ml               |
| **Meshing**                                | Automatic            |

Figure 3 and 4 also show the temperature changes outside the layer of boxes as well as the environment temperature. From this experimental works, it is learned that PCM’s demonstrate the ability and effectiveness to absorb and release the energy similar to those reported in the literature [8][5]. Our calculation suggests that the highest effectiveness (i.e., 73%) is occurred upon using PCM of 10 vol.% NaCl in H₂O. This means adding 10 vol.% of NaCl enhances the effectiveness of release and adsorb the energy within our cold-box design. The temperatures recorded during this experiment are subsequently used to develop model using AutoDesk CFD together with the properties of each PCMs.

**Figure 3.** Temperature changes of PCM samples and loaded media. × = Temperature of loaded media (T₁); △ = Inside temperature of cold box (T₂); ○ = PCM temperature (T₃); ○ = Outside styrofoam temperature (T₄); + = Temperature of outside wooden casing (T₅); ◊ = room temperature (T₆)
3.2. Simulation results

The simulation shows the flow pattern and temperature distribution that occurs in the cold-box against the variations in PCM bottle model. In Figure 5 (a) variations of plain bottle without hole and groove show flow patterns that occur very well distributed across the cold-box. The pattern of the flow direction is in a straight line parallel without experiencing the intersection of each other. Therefore the rate of movement of the temperature into an aluminium space is maximum and evenly. In Figure 5 (b) one-hole bottle without grooves shows flow patterns that occur across the cold-box is good enough where the flow direction in a straight line parallel. However, there is some flow direction, which coincide. This occurs due to the hole in the bottle[9][10].

In Figure 5 (c) the flow pattern and temperature distribution of two-holes bottle with grooves are shown. This figure shows that in the holes and grooves, the flow pattern of straight lines are not parallel and irregular one to another. From the pattern resulted by simulation, the displacement rate in the aluminium temperature was not optimal and uneven. In Figure 5 (d) four-holes bottle without grooves experiences the flow pattern which is not stable compared to simulation results of two-holes bottle with grooves. In this variation straight lines are not parallel and irregular one another occurs in the hole. This resulted in the displacement rate in the aluminium temperature was not optimal and uneven.

Table 3 summarizes the result of simulation for two kinds of PCM samples. The lowest temperature can be reached under equilibrium condition is -5.9 °C with phase change material made of 10 vol% NaCl in H₂O filled into plain bottle. Simulation of H₂O PCM exhibits the lowest equilibrium temperature of 1.74 °C upon filling this PCM sample into plan bottle.
Figure 5. The flow patterns and temperature distribution in the cold-box on (a) plain bottles without hole and groove, (b) one-hole bottle without grooves, (c) two-holes bottle with grooves, and (d) four-holes bottle without grooves.

Table 3. CFD simulation results loaded medium temperatures for each type of bottles and PCM samples

| Variations Plastic Bottles | Temperature of loaded Media (°C) |
|----------------------------|----------------------------------|
|                            | H₂O                              | 10 vol% NaCl in H₂O              |
| Plain                      | 1.74                             | -5.9                             |
| One hole                   | 2.37                             | -5.77                            |
| Two holes and grooves      | 4.46                             | -4.78                            |
| Four holes                 | 5.37                             | -4.31                            |

4. Conclusion
A purpose built cold-box has been designed and fabricated for retailing food in remote area and villages in Aceh, Indonesia. The experimental results show that adding 10 vol.% of commercial NaCl
into water is able to improve the effectiveness of the release and absorption of heat by up to 73% compared with pure water. Numerical iteration on the flow patterns and temperature distribution of heat within the cold-box concludes that the shape and number of holes of PCM bottle are important factor in optimizing performance of the cold-box. Any PCMs liquids filled into a plain plastic bottle without hole and groove demonstrates the coldest temperature compared to others.

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