

Use of phase change material (PCM) for the improvement of thermal performance of cold storage

Abstract

The project deals with the development of cold storage facility for improvement of its thermal performance by application of polyethylene glycol 400 (PEG400) as a Phase change material (PCM). PCM are the materials which generally have low melting point and they change their phase by absorbing the latent heat from the system so as to maintain the temperature of system. Present study was done to determine the rise in the temperature of air inside the cold space in the situations like frequent door openings and electrical power failures. The main aim of this project was to observe the lowering in the rise of temperature when there is PCM used inside the cold space of the cold storage. The experimental result showed that with the application of PCM temperature maintained inside the cold space was 1-4 °C lower than without PCM in case of frequent door openings. And also in case of electrical power failures with the use of PCM, temperature maintained was 1-4.5 °C lower than without application of PCM. The maximum power savings observed in case of door openings was 1021.88 kJ/h when the door was opened 3 times for 10 seconds with an interval of 20 minutes each and for electrical power failure for 1 hour the power saved was 3.115 kJ/h which was higher than the rate of energy absorbed by PCM in other cases.

Keywords: Cold storage, Phase change material (PCM), Polyethylene glycol 400 (PEG 400), Door openings, Electrical power failures

Volume 1 Issue 2 - 2018

Vivek Raj, Goswami TK

Department of Agricultural and Food Engineering, University of IIT Kharagpur, India

Correspondence: Goswami TK, Department of Agricultural and Food Engineering, University of IIT, Kharagpur, India, Email tkg@agfe.iitkgp.ernet.in

Received: October 18, 2017 | **Published:** March 29, 2018

Introduction

Background

Latent heat storage using phase change materials (PCMs) is one of the most efficient methods to store thermal energy. Therefore, PCM have been applied to increase thermal energy storage capacity of different systems. The use of PCM provides higher heat storage capacity and more isothermal behaviour during charging and discharging compared to sensible heat storage. Moreover, thermal energy storage (TES) systems for both heat and cold are necessary for good performance of many industrial processes. High energy storage density and high power capacity for charging and discharging are desirable properties of any storage system. These storage systems have been studied for many years addressing different problems of the used materials such as low thermal conductivity and segregation of the PCM. As regards to the criteria for selecting a suitable storage medium, the phase change materials (PCMs) are very attractive candidates in a thermal energy storage system and has drawn huge interest in recent years.¹ The criteria include but not limited to the thermo-physical benefits, environmental effects and economy. The use of PCMs as storage media is by far the most effective and efficient way to storing thermal energy by exploiting the enthalpy of phase change as the storage mechanism.² Among all possible phase change processes, the solid-liquid phase change is considered as the most suitable form for TES applications. The use of PCM in TES has many advantages over other forms of energy storage mediums, especially the sensible heat storage.³ Because of PCM's high energy density (amount of heat energy storage per unit mass), it is possible to have much smaller and compact storage facilities compared to sensible heat storage types. The characteristic ability of PCM's narrow temperature

range during thermal energy charging and discharging periods has made it a suitable candidate for applications where smaller range of temperature variations are important.

Thermal energy storage (TES)

Heat and thermal energy are often used as synonyms but based on strict thermodynamic definition, they are not the same. Thermal energy describes the thermal content of a substance or a system, while, heat is the content of thermal energy that is transferred from one material or system to another as a consequence of the temperature difference between the two. Thermal energy can also be generated, at the expense of converting energy from one form to another. In general, temperature is an indicator which determines the ability for a physical system (i.e. certain amount of mass of a substance) to transmit thermal energy to another physical system. Presence of heat can only be realized when there is a difference in temperature and the energy crosses the system boundary. Thus, the heat transfer deals with the determination of the rates of thermal energy transfer by taking into account the variations in temperatures. TES system is in practice for centuries. It is essentially a means by which thermal energy is 'hold' for a certain period of time. Storing thermal energy (in the form of heat or cold) in an appropriate form and in a suitable media when it is surplus, and extracting the same at a later time when needed is the basic principle of a TES. TES is proved to be an effective and practical solution to address the issues of intermittency and can play a vital role in efficient energy management system. The main purpose of TES is to overcome the mismatch between the energy generation and its utilization.⁴ TES is gaining enormous importance and is becoming a noteworthy topic due to its growing importance in various areas of engineering and general applications. TES has the enormous potential

in conserving energy which in turn can minimize the carbon footprint on the environment.

Benefits of thermal energy storage (TES)

The primary benefits of a TES are summarized below:

1. Efficiency: help achieve a better and efficient use of energy.
2. Environmental effects: lower environment pollution, less GHG emissions.
3. Sustainability: improved system performance and reliability via inclusion of more renewable energies.
4. Economics: large savings following reduction in capital and operational costs.

Physical methods of thermal energy/heat storage

There are three basic and distinct modes of heat transfer used for storing thermal energy; the sensible heat, the latent heat or the thermo chemical energy.⁵ The sensible component accounts for the translational, rotational and vibration motions of the atoms and molecules. The latent component is the consequences of the intermolecular forces of the material that influence the phase change between solid, liquid and gaseous states. The chemical component accounts for the energy stored in the chemical bonds between atoms.⁶

Sensible heat storage

When the energy is stored or released by increasing or decreasing the temperature of the storage material respectively, it is considered as the sensible heat storage. The amount of thermal energy stored is dependent on the temperature change in the material, mass of the material, m (kg) and its heat storage capacity C_p (kJ / kg °C) and can be expressed as:

$$Q = m \int_{T_1}^{T_2} C_p \Delta T \quad (1.1)$$

Where, T_1 and T_2 are the lower (initial) and upper (final) temperature levels between which the storage system is operating. Benato et al.⁷ however has showed improved method to consider sensible heat.

Latent heat storage

Latent heat storage system involves material's phase transition i.e. the energy is stored or released due to the change in the enthalpy of the phase change. Due to the involvement of the phase change, the thermal energy storage operates almost isothermally at the phase change temperature of the material. The amount of thermal energy stored, Q in this case depends upon the mass, m and the latent heat of the phase change of the material and is expressed in the form:

$$Q = m \Delta h_m \quad (1.2)$$

where, m is the mas of storage material (kg), and Δh_m is the phase change enthalpy or alternately, the latent heat of fusion/solidification (kJ/kg).

Total amount of heat storage:

When a material is heated from its solid state to complete melting and beyond (over a range of temperatures T_s to T_l that passes through the melting point T_m), the total thermal energy stored in the form of heat can be calculated as:

$$Q = m \left[\left\{ \int_{T_s}^{T_m} C_{ps} dt \right\} + \Delta h_m + \left\{ \int_{T_m}^{T_l} C_{pl} dt \right\} \right] \quad (1.3)$$

where, C_{ps} and C_{pl} represents the specific heats of the solid and liquid phases and T_s , T_l and T_m are the temperature of the solid, liquid and melting/fusion of the material respectively. During the initial stage, the PCM behave as a sensible heat storage material where its temperature increase as they absorb heat. But when the PCM reaches its melting temperature, unlike conventional sensible heat storage material, the PCM absorbs large amount of heat at nearly a constant temperature, which is in fact, the latent heat of fusion of that particular PCM. The PCM continue to absorb heat maintaining this near constant temperature until the PCM is completely melted to the liquid phase. After complete melting, the liquid PCM temperature again starts increasing above its melting temperature as sensible heat storage and continues to rise depending on the input temperature. Theoretically, all phase-change processes can be employed for storage and release of energy. There are four types of changes between phases that are of significance: solid-liquid (melting and solidification), liquid-gas (evaporation and condensation), solid-gas (sublimation and re-sublimation), and solid-solid transformations. The absolute value of latent heat of phase change for a solid-solid transition is usually less than that of solid-liquid conversation. Solid-gas and liquid-gas transitions are generally not employed for energy storage, in spite of their high latent heat, only because of their (gases) occupations of large volumes, requiring a big space for storage or conversely stored at high pressure to keep smaller volume, which introduces critical and costly constraints on the storage design. Hence, a solid-liquid transition, which involves only a small change in volume and negligible pressure issues, is quite promising for phase change energy storage.

Comparison: Sensible and latent heat TES

Each system has its own advantage and disadvantage, which may vary drastically with changes in the thermos-physical conditions as well as the adaptability.⁸ Thus; it is difficult to generalize the superiority of one over the other. Several explicit factors in a given application dictate the suitability and selection of a heat storage type. These factors may include type, size, location, duration, frequency, repeatability etc. of the TES's use. In other words, choice of TES is exclusively need specific. Although the heat transport and the design philosophy of a latent heat thermal storage system (LHTES) are much more complex than sensible heat thermal storage system (SHTES), from the technical point of view, LHTES has some major advantages over sensible type. Firstly, LHTES has the advantage of storing large amount of heat (energy storage density) in the same amount of mass of the thermal storage media by exploiting the enthalpy of phase change. Secondly, an attractive feature of a LHTES system is that, the operating temperature can be anchored in a narrow band around the phase-change temperature of the media, making the system very suitable for most of the applications. Another notable advantage the LHTES possess is that, even if there is a small temperature difference (ΔT) between the sink and the source, a large amount of heat can still be possible to store. Whereas, the effectiveness of a SHTES system solely depends on the temperature differences, i.e. higher the ΔT , more is the heat storage as seen in Figure 1.

SHTES has the advantage of being relatively simple in design and cheap, but the energy storage density is low and there is a gliding discharging temperature that immensely affect its performance.

LHTES is found in a wide range of applications, which include space heating and cooling, metal processing, thermal energy storage, temperature control in miniature electronics devices, food processing and storage, spacecraft thermal system applications etc.

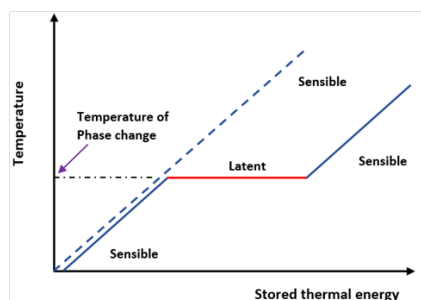


Figure 1 A schematic of sensible and latent heat storage principles.

Requirements of a LHTES

A single PCM or a design of a LHTES cannot fulfil all the desired requisites. During designing a LHTES system, various requirements need to be addressed. These include: high energy density of the storage material (storage capacity), good heat transfers between the HTF and the storage material, mechanical and chemical stability of the storage material, compatibility between storage media and the container material, complete reversibility and the number of cycles, low thermal losses during the storage period, impact on environment and easy control. Moreover, cost, operational strategy, maximum load and integration with other systems are also important.

Complexities with LHTES

As mentioned earlier, the LHTES has some excellent favourable criteria, but they have complex heat transfer aspects and have difficulty in tracking and predicting the solid-liquid interface during the phase change process making it a really challenging problem. These complexities and challenges can be summarized as:

1. Nonlinearity in the phase transition resulting from the unpredictable motion of the solid-liquid interface during phase change,
2. Inadequate knowledge of the heat transfers within the liquid domain and across the solid-liquid interface,
3. Unpredictable volume changes and structural behaviour within the PCM upon phase transition especially during solidification, such as formation of void/cavities, super cooling, nucleation etc. that may arise in the solid phase and can significantly reduce the heat transfer rate both during melting and solidification cycles.

A good understanding on these aspects is of immense importance for LHTES system design perspectives. However, there is scarcity of available information in the literature concerning these issues.

Concerns with the thermal conductivity of PCM

Almost all phase change materials (PCMs), whether organic or inorganic, have a drawback of having low heat transfer rates during melting and freezing processes due to their inherent low thermal conductivity. Low thermal conductivity in PCM hinders the heat transfer process within its domain by prolonging the charging (heat addition) or discharging (heat rejection) period. This problem not only drastically affects the melting and solidification performance of the LHTES system, but also limits their widespread use as latent heat

storage material. The thermal conductivities of organic and inorganic materials usually swing around approximately 0.2 W/m°C and 0.5 W/m°C, respectively. To have these PCMs successfully utilized commercially, some mechanism needs to be incorporated that can enhance the thermal conductivity. Enhancing the heat transfer rate through a PCM is a present day challenge. Different approaches have been proposed to enhance the thermal conductivity of PCM. For example, the placement of metal structure (i.e. fins) inside a PCM, use of porous material, metal foams, carbon fibres and dispersion of high thermal conductivity nanoparticles in the PCM are among the common techniques used to enhance the effective thermal conductivity of PCMs. Although there are many merits in these methods/applications, however, most of these enhancement techniques suffer from increased weight and volume in the system, except for the use of nanoparticles. Nanoparticles possess physical and chemical properties, which are quite different from their bulk form.

Producing various types of nanoparticles has become cheaper due to rapid advancement in nanotechnology. There is a growing use of nanotechnology in different engineering, electronics and industrial processes. The presence of a mere amount of nanoparticles in the PCM significantly increases the effective thermal conductivity of the PCM, and consequently enhances the heat transfer characteristics. A fluid containing Nano particles, generally less than 100 nm sizes is termed as Nano fluid. Nano fluids are prepared by dispersing such tiny particles (1-100 nm) in a base fluid such as water, ethylene glycol, propylene glycol, oil and other conventional heat transfer fluids. Preserving the intended properties, holding nanoparticles in the fluid suspended after repetitive cycles and the cost of bulk volume of nanoparticles are the few major problems of widespread use of these nanoparticles. Based on the above facts the following objectives have been targeted for the present study:

Classification of PCM

The phase change materials (PCMs) are generally divided into two groups: organic and inorganic. Inorganic compounds show a volumetric latent TES capacity twice that of organic compounds. But the organic substances could serve as important heat storage media because of several advantages from their natural properties like, ability to melt congruently, self-nucleation, non-toxic and non-corrosiveness, environment friendly etc. Alkanes and paraffin are in the latter category. Figure 2 shows various common materials for sensible and latent heat storage systems.

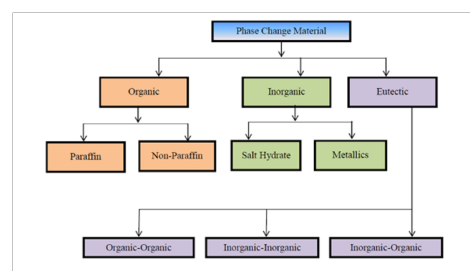


Figure 2 Classification of PCM materials.

Paraffin

Paraffin is one of the most studied phase change materials in thermal energy storage application because of their availability, relatively low-cost and non-corrosive nature. Paraffin is normally composed of straight long chain alkanes, the heat release and melting

point of this paraffin depends on the chain length. Though it has few advantages but the bottlenecks i.e. low thermal conductivity and moderate flammability made it only applicable to small scale and only for small temperature application.

Non-Paraffin

Among the non-paraffins some of the fatty acids, alcohol and glycol are suitable for thermal energy storage, but all of the non-paraffin has a major drawback, that is their flammability and they should be handled carefully under high temperature environment. Some of the potential organic PCM are: Ammediol (melting point 112 °C and heat of fusion 285 kJ/kg), neopentyl glycol, isomalt, adipic acid, tromethamine etc.

Inorganic Salt and Salt Composites

Salt hydrates are the most extensively studied PCM because of their highest potential in terms of moderately higher thermal conductivity, inexpensiveness and safe operation. But one of the major challenges of using salt hydrates PCM in TES is its incongruent melting. When salts are not soluble by its associated water then incongruent melting occurs leaving the salt solution supersaturated after melting. This phenomenon creates loss of salt due to settling after several melting-freezing cycles. But there are ways to avoid it such as using stirrer, using water so those melt portions do not get supersaturated. Liu et al.¹² in his study listed several inorganic salt composites as a potential PCM storage application due to their higher energy density, heat of fusion and relatively lower cost. Among those NaNO_3 , NaOH , KNO_3 , KOH , Na_2CO_3 have been used extensively for research purpose. In terms of cost KOH proved to be the best choice and in terms of energy density NaNO_3 proved to be the best choice. NaNO_3 proved to be the best choice for producing high pressure steam around 100 bar. Sole et al.¹⁰ reported that though fluoride salts have much higher heat capacity but in terms of cost and material compatibility, they are not the best choice for PCM salt selection and same is the case for KOH which is very cost effective but impose very high corrosion with the containing material.

Metal and Metal Alloys (Metallics)

Metals and metal alloys are attracting researcher's attention now days because of their some highly favourable characteristics over salt hydrates such as high thermal conductivity, higher heat of fusion per unit of volume and small volume change during phase change. But in most of the case they are not in the final consideration list because of their weight penalties as well as cost. But recently as a thermal conductivity enhancement technique these metals are used with the other PCM materials as additives. Among the metals and metal alloys Al-Si alloy (88%Al, 12%Si) and 6Al-Mg-Zn (60-34-6) alloy has been tested the most because of their higher energy density and thermal conductivity.

Donhowe & Hartel¹¹ studied ice recrystallization during bulk storage of ice cream in containers. The temperature of the freezer was controlled with and without fluctuations (with different levels of temperature control of ± 1.0 °C and ± 0.01 °C) at set temperatures between -15 and -5 °C. They concluded that recrystallization rate increased with the increase in storage temperature and extent of temperature fluctuations.

Phimolsiripol et al.¹² also studied the effects of freezing and temperature fluctuations on frozen dough and bread quality. The rates of quality and weight losses were significantly greater when temperature

fluctuation was high (-18 ± 5 °C). Since temperature fluctuation is unavoidable, the same authors suggested that temperature variations should be kept minimum and not higher than ± 3 °C.

Gormley et al.¹³ studied the effect of temperature fluctuation (cycling between -30 and -10 °C) versus constant frozen storage temperatures regimes (-60 or -30 °C) on quality parameters of selected food products. Temperature fluctuation is expected to produce stress damage and other deleterious effects such as fat oxidation and changes in colour and texture. Moreover, temperature fluctuation could lead to high peroxide and free fatty acid contents in food.

Nagpo et al.¹⁴ studied the effect of freezing and thawing rate on moisture drip loss from samples of pork. They compared a fresh sample to a sample frozen at slow and fast freezing rates and the drip loss was significantly reduced in the sample frozen at high rate.

Onyejekwe¹⁵ incorporated PCM into a domestic freezer. Their work was based on using an easily available and very cheap PCM ($\text{NaCl} + \text{H}_2\text{O}$) for thermal energy storage (TES). However, such type of PCM suffers severe corrosion and sub-cooling.

Wang et al.^{16,17} developed and tested a prototype refrigeration system that incorporates PCM. They placed a PCM heat exchanger at different locations in the refrigerator such as at the back the compressor, and the condenser. The experimental results showed that the integration of PCM heat exchangers into the refrigeration system could improve the COP of the system by 6-8%.

Wang et al.¹⁸ developed a dynamic novel system which can be used to design and optimize the performance of the refrigeration system.

Farid et al.¹⁹ designed a method of a novel dual evaporator for domestic refrigerator with PCM which provided thermal storage in order to improve food quality and prolong compressor off time.

Azzouz et al.²⁰ Using numerical investigations, showed that the addition of a thick slab of PCM on the back side of a refrigerator evaporator may result in a higher evaporating temperature leading to 5-15% increase in the COP, a significant decrease in the number of starts and stops of the compressor, and lower freezer indoor air temperature.

Azzouz et al.²¹ experimentally showed that the use of PCM behind the evaporator in a household refrigerator improves its performance and allows several hours of refrigeration without the need for electrical power supply.

Cheralathan et al.²² Using bigger chambers, carried out an experimental investigation on the performance of an industrial refrigeration system integrated with encapsulated PCM based on cold TES system. In the experimental set-up a vertical storage tank is integrated with the evaporator of the vapour compression refrigeration system. They reported the effects of inlet HTF temperature on system performance and demonstrated the useful addition of PCM TES to the system.

Gin et al.²³ investigated the incorporation of PCM panels placed against the internal walls of a domestic freezer to maintain stable temperatures in the presence of heat loads. Moreover, energy consumption tests showed that the inclusion of PCM into the freezer decreased the energy consumption during a defrost cycle by 8%, and by 7% during door openings. Furthermore they observed that the introduction of PCM improved the quality of the frozen foods during storage.

Based on the above facts the following objectives have been targeted for the present study:

1. Theoretical heat load calculation of a lab model Cold Storage System.
2. To select PCM by observing the melting behaviour and transient heat transfer in phase change materials.
3. To develop a PCM incorporated Cold Storage.
4. To analyse the power saving by using PCM in the Cold storage

Materials and methods

Model cold storage

For the application of PCM to improve thermal stability during power loss in cold store, a model cold cabin having storage space dimensions $0.61 \text{ m} \times 0.60 \text{ m} \times 0.83 \text{ m}$ and a storage volume of 303.78 litre was used. The boundary condition for load calculations was taken as 45°C outside ambient temperature and 70% RH. The temperature and relative humidity that should be maintained inside the storage space was 4°C and 95% respectively. Thickness of wall was 9 cm containing 3.5 cm thick sheet of stainless steel, 5 cm thick insulation of PUF and 0.5 cm mild steel plate. The door was 6 cm thick containing 0.5 cm thick stainless steel sheet, 5 cm thick PUF insulation and 0.5 cm thick mild steel plate. In-between door and storage space there was a rubber seal of thickness 1.5 cm which helped to provide leakage.

Heat load calculations

The sources of heat coming inside the cold space of our model cold cabin was due to transmission through walls, respiration heat of the product and infiltration heat due to door openings. These heats on summation gave the total heat of the evaporator.²² Some design parameters which were considered for calculation are appended below:²³

1. thermal conductivity of PUF insulation, $k_{\text{ins}} = 0.023 \text{ W/m } ^\circ\text{C}$
2. thickness of PUF insulation, $x_{\text{ins}} = 0.05 \text{ m}$
3. thermal conductivity of stainless steel, $k_{\text{ss}} = 16 \text{ W/m } ^\circ\text{C}$
4. thermal conductivity of mild steel, $k_{\text{ms}} = 54 \text{ W/m } ^\circ\text{C}$
5. operating time = 24 h
6. come-up time = 3 h
7. outside air flow rate = 2 m/sec , density = 1.1108 kg/m^3 , coefficient of friction = 0.000018 Specific heat = $1039.6 \text{ J/kg } ^\circ\text{C}$
8. inside air flow rate = 4 m/sec , density = 1.2842 kg/m^3 , coefficient of friction = 0.000017 , Specific heat = $1005 \text{ J/kg } ^\circ\text{C}$
9. no. of air changes per day = 4
10. capacity of product, $m_p = 163 \text{ kg}$ (assumed for potato having bulk density of 641 kg/m^3)
11. For side walls
12. thickness of stainless steel, $x_{\text{ss}} = 0.035 \text{ m}$
13. thickness of mild steel, $x_{\text{ms}} = 0.05 \text{ m}$
14. For door

15. thickness of stainless steel, $x_{\text{ss}} = 0.05 \text{ m}$

16. thickness of mild steel, $x_{\text{ms}} = 0.05 \text{ m}$

Heat transmission through walls:

The heat transmission through walls can be calculated by the following formula:

$$Q = UA (T_o - T_i)$$

$$\text{where, } \frac{1}{U} = \frac{1}{h_o} + \sum_{i=1}^n \frac{x_i}{k_i} + \frac{1}{h_i} \quad (2.1)$$

where, U = Overall heat transfer coefficient, $\text{W/m}^2 ^\circ\text{C}$

A = Area, m^2

$(T_o - T_i)$ = Temperature gradient, $^\circ\text{C}$

h_o = Outside air convective heat transfer coefficient $\text{W/m}^2 ^\circ\text{C}$

h_i = Inside air convective heat transfer coefficient $\text{W/m}^2 ^\circ\text{C}$

x_i = Thickness of the materials, m

k_i = Thermal conductivities of the materials, $\text{W/m } ^\circ\text{C}$

For outside air

$$N_{re} = \frac{\rho v l}{\mu} = \frac{1.1108 \times 0.91 \times 2}{0.000018} = 112314.22 \quad N_{re} < 30000$$

$$N_{pr} = \frac{\mu C_p}{k} = \frac{0.000018 \times 1039.6}{0.05} = 0.3742$$

$$N_{nu} = (N_{re})^{1/2} (N_{pr})^{1/3} = 160.356$$

$$h_o = \frac{\mu k}{t} = \frac{160.36 \times 0.005}{0.91} = 8.81 \text{ W/m}^2 ^\circ\text{C}$$

For inside air

$$N_{re} = \frac{\rho v l}{\mu} = \frac{1.2842 \times 0.73 \times 4}{0.000017} = 220580.23, \quad N_{re} > 3000$$

$$N_{pr} = \frac{\mu C_p}{k} = \frac{0.000017 \times 1005}{0.0244} = 0.7002$$

$$N_{nu} = (N_{re})^{0.8} (N_{pr})^{0.33} = 612.714$$

$$h_i = \frac{\mu k}{t} = \frac{612.714 \times 0.0244}{0.73} = 20.5 \text{ W/m}^2 ^\circ\text{C}$$

For walls,

$$\frac{1}{U} = \frac{1}{20.5} + \frac{0.035}{16} + \frac{0.05}{0.023} + \frac{0.005}{54} + \frac{1}{8.81}$$

$$U = 0.427 \text{ W/m}^2 ^\circ\text{C}$$

$$\text{Area of wall} = 2 (0.74 \times 0.91 + 0.61 \times 0.74) + 0.91 \times 0.61 \text{ m}^2 \\ = 2.8047 \text{ m}^2$$

Heat load from walls:

$$Q_1 = 0.427 \times 2.8047 \times (45-4) \\ = 49.1 \text{ Watts} \cong 50 \text{ W}$$

For door,

$$\frac{1}{U} = \frac{1}{20.5} + \frac{0.005}{16} + \frac{0.05}{0.023} + \frac{0.005}{54} + \frac{1}{8.81}$$

$$U = 0.428 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$\text{Area of walls} = 0.79 \times 0.91 \text{ m}^2 \\ = 0.7189 \text{ m}^2$$

Heat load from walls:

$$Q_2 = 0.428 \times 0.7189 (45-4) \\ = 12.61 \text{ Watts} \cong 13 \text{ W}$$

$$\text{Heat load transmitted} = Q_1 + Q_2 = 63 \text{ W}$$

Also, specific heat in potato at the time of entrance $C_p = 3430 \text{ J/kg}^\circ\text{C}$ (assuming entrance temperature to be 25°C)

$$\text{Come up time} = 3 \text{ hours} = 10800 \text{ seconds}$$

So, heat transferred at initial state = $(m \times C_p \times \Delta T) / \text{time}$

$$Q_{\text{initial}} = 162 \times 3430 (45-4) / 10800 \\ = 2109.45 \text{ W}$$

Heat Load through respiration

Storing 162 kg potatoes having heat of respiration to be 0.1 kJ/kg/h would generate heat as given below:

$$Q_r = m \times \text{respiration heat} \\ Q_r = 162 \times 0.1 \times 1000 / 3600 \\ Q_r = 4.523 \text{ W}$$

Heat load due to infiltration

Considering the rate of air change was 4 times fresh air change per day

Outside air enthalpy, $h_{\text{out}} = 99.173 \text{ kJ/kg}$ (at 45°C DBT & 30°C WBT)

Inside air enthalpy, $h_{\text{in}} = 21.79 \text{ kJ/kg}$ (at 4°C and 95% RH)

Enthalpy difference = $(99.173 - 21.79) \text{ kJ/kg}$

$$\Delta h = 77.383 \text{ kJ/kg}$$

$$\text{Amount of ventilated air (l/s)} = \frac{\text{volume of air per change} \times \text{no. of changes}}{\text{time duration}}$$

$$= (0.254 \times 4) / (24 \times 3.6)$$

$$= 0.01176 \text{ l/s}$$

$$\text{Standard formula for heat load due to infiltration} = 1.2 \times \text{l/s} \times$$

$\Delta h \text{ W}$

$$Q_{\text{inf}} = 1.2 \times 0.01176 \times 77.383 \text{ W}$$

$$Q_{\text{inf}} = 1.092 \text{ W}$$

Total heat load

Total heat load are the summation of transmission, initial, respiration and infiltration heat loads calculated above:

$$\text{Total heat load} = Q_t + Q_{\text{initial}} + Q_r + Q_{\text{inf}}$$

$$Q_e = 2176.775 \text{ W}$$

To overcome experimental errors, we took factor of safety of 10%

$$\text{Thus total heat load inside the evaporator was } (2176.775 + 217.67) \\ = 2394.445 \text{ W} \cong 2500 \text{ W} = 2.5 \text{ kW}$$

Calculation for COP

Evaporator temperature, $T_e = 4^\circ\text{C}$

Pressure correspond to Evaporator temperature, $P_e = 3.152 \text{ bar}$

Saturated vapour enthalpy corresponding to Evaporator temperature, $h_1 = 401.1 \text{ kJ/kg}$

Saturated vapour entropy correspond to Evaporator temperature, $s_1 = 1.7257 \text{ kJ/kg} = s_2$

Condenser temperature, $T_2 = 60^\circ\text{C}$ (superheated)

Pressure correspond to h_3 , $P_3 = 5.07 \text{ kPa} = P_2$

Saturation Temperature corresponds to $P_3 = T_c = 18^\circ\text{C}$ = condenser temperature

Enthalpy at $T_c = h_c = 408.9 \text{ kJ/kg}$ (vapour)

Specific heat of R134a = $0.204 \text{ kCal/kg } ^\circ\text{C} = 0.853 \text{ kJ/kg } ^\circ\text{C}$

Enthalpy at point 4; $h_4 = h_f(\text{liquid}) + x h_{fg}$

(Assuming $x = 0.1$, because refrigerant entered in evaporator was almost in liquid state)

$$h_4 = 205.4 + 0.1 \times 195.7$$

$$h_4 = 224.97 \text{ kJ/kg} = h_3$$

$$h_2 = h_f(\text{vapour}) + c_p \Delta t$$

$$h_2 = 408.9 + 0.853 \times (60-18)$$

$$h_2 = 444.73 \text{ kJ/kg}$$

For mass flow rate,

$$Q_e = m_r (h_1 - h_4)$$

$$2.5 \text{ kW} = m_r (401.1 - 224.97)$$

$$m_r = (176.13) / 2.5$$

$$m_r = 0.0142 \text{ kg/s}$$

At 4°C density of R134a vapour, $\rho = 16.569 \text{ kg/m}^3$

$$v_r = m_r / \rho$$

$$v_r = 0.857 \text{ l/s}$$

Work done by the compressor,

$$W_c = m_r (h_2 - h_1)$$

$$W_c = 0.0142 (444.73 - 401.1)$$

$$W_c = 619.55 \text{ W}$$

(Assuming compressor efficiency to be 80%)

$$W_c = 619.55 / 0.8 = 774.43 \text{ W} \approx 775 \text{ W}$$

$$COP = \frac{Q_e}{W_c} = \frac{2500}{775} = 3.2$$

Study of melting behaviour and transient heat transfer in phase change materials

The main principle of cooling with PCMs is the receiving or releasing of a high amount of cold during a phase change at an extremely low temperature difference and relatively constant temperature. This phenomenon occurs during the solidification and melting processes. During the cold storage process, the PCM is solidified and during the cold release process the PCM is melted (Figure 3). Curve A represents an actual solidification or melting process, where the slope of the curve is increased during the phase change. However, in theoretical studies the solidification or melting process appears at a constant temperature and is shown by the vertical (B) curve.

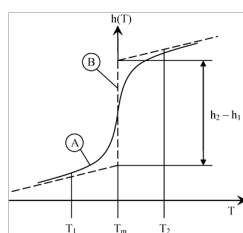


Figure 3 Phase change during the solidification or melting process: A: actual process; B: ideal process.

Theoretically, the total amount of cold is stored at the temperature difference is $\Delta T = T_2 - T_1$ and is expressed by Equation (1)

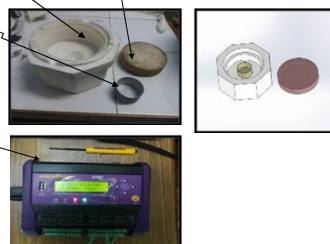
$$Q_{pcm} = m \left[\int_{T_1}^{T_m} c_{p,s}(T) dT + (h_2 - h_1) + \int_{T_m}^{T_2} C_{p,l}(T) dT \right]$$

Experimental setup

An experimental set-up for the analysis of melting temperature and latent heat transfer of different PCM were conducted.

Materials used

- Insulated thermocol container and cap
- Metal container
- Thermocouples
- DataTaker DT800
- Delogger
- Water
- PCM



Method

1. A known amount of water in a thermocol container was poured (Figure 4).
2. A known amount of PCM in the metal container was taken and frozen it (with Liquid Nitrogen (LN₂)).
3. The PCM containing container was placed in the water in a thermocol container.
4. Water level should be above the PCM level for heat transfer to take place.
5. One thermocouple was placed into the water, two thermocouples in the PCM.
6. The top was covered by thermocol cap.
7. The data logger was run till whole PCM got melted.
8. The data was loaded to excel and the graph between average temperatures of PCM versus heat loss ($m \times c_p \times \Delta T$) by water was plotted.
9. From the graph similar to that as shown in Figure 3, we get the melting temperature (T_m) and latent heat of fusion ($h_2 - h_1$) of the PCM.



Figure 4 Setup for determination of melting temperature of PCM.

Experimentation for PCM selection

Material used:

1. A model cold storage
2. Thermocouples
3. DataTaker DT800
4. Delogger

Method:

1. Three thermocouples were put at top, middle and bottom of the Cold Storage (Figure 5).
2. The Data Taker was run for 1 hour approx.
3. The data was uploaded to excel and the graph between temperature versus time was plotted.
4. From the graph we got the range of air temperature variations.
5. Accordingly, a PCM having melting temperature between this air temperature ranges was selected.



Figure 5 Setup for determination of changes in air temperature and effect of PCM incorporation on it.

Experimentation of PCM incorporation

Sets of experiments conducted with and without incorporation of PCM are shown in Tables 1 & 2 as shown below:

Table 1 Set of experiments related to door openings conducted for experimentation.

Test scenarios	Number of door openings	Time for that the door was opened for (s)	Time between openings (min)
Test 1a. Door opening	3	10	20
Test 1b. Door Opening	3	30	20
Test 1c. Door Opening	3	180	20
Test 1e. Door Opening	1	600	-

Table 2 Set of experiments conducted during electrical power failure (simulated).

Test scenarios	Time of electrical power failure (min)
Test 2a. Electrical power failure	15
Test 2b. Electrical power failure	30
Test 2c. Electrical power failure	60
Test 2d. Electrical power failure	120

Results and discussions

The present study was conducted to find the effect on air temperature inside the cold space of a Model cold storage with the application of phase change material in it.

Model Cold Storage

Theoretical design is completed for a lab model cold storage

containing R134a as an operating refrigerant. The design gives the data of operating parameters as follow:

1. Refrigeration effect = 2500 W, which is the heat load that has to be removed from cold space inside the evaporator.
2. Compressor work = 775 W, which is the power utilised by compressor for extracting 2500 W of heat.
3. Coefficient of Performance (COP) = 3.2

Melting behaviour of PCM

The tests are run and graphs are plotted between temperature and time of two PCM namely, water and ethylene glycol gives the melting behaviour of PCM. According to theoretical concept the melting point is the constant temperature at which the phase transition takes place is not possible practically, so we are taking the average temperature of extreme temperatures on the phase transition profile.

Melting profile of water

The graph plotted between temperature and time for water for observing the melting behaviour is shown in Figure 6. From the graph we observed that the water in the form of ice initially at - 25 °C is taking heat from the water and starts melting. In the beginning, curve follows a regular trend of increasing temperature from - 25 °C up to - 4.2 °C, and then a sinusoidal behaviour is shown in the curve up to 4.2 °C which is the phase transition of ice to water. After that the curve changes trend and temperature is increasing further. To get the melting point we have to take the average of - 4.2 °C and 4.2 °C.

$$\text{Melting temperature} = (-4.2 + 4.2) / 2$$

$$T_m = 0^\circ\text{C}$$

Thus melting point of ice is 0 °C (approx.)

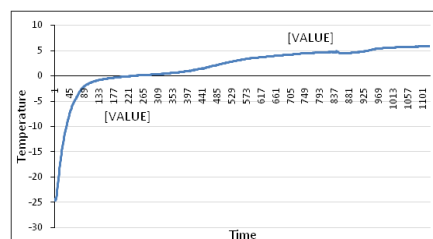


Figure 6 Temperature profile of melting behaviour of ice.

Melting profile of ethylene glycol

The graph plotted between temperature and time for ethylene glycol for observing the melting behaviour is shown in Figure 7. From the graph we observed that the ethylene glycol in the form of solid, initially at - 22 °C, was taking heat from water and started melting. In the beginning, the curve follows a regular trend of increasing temperature from - 25 °C up to -17.3 °C, and then a sinusoidal behaviour is observed in the curve up to - 8.5 °C, which is the phase transition temperature of solid ethylene glycol to be transformed to its liquid form. After that, the curve again changes its trend and temperature increases further. To get the melting point we have to take the average of -17.3 °C and - 8.5 °C.

$$\text{Melting temperature} = [(-17.3) + (-8.5)] / 2$$

$$T_m = -12.9^\circ\text{C}$$

Thus melting point of ethylene glycol is -12.9°C

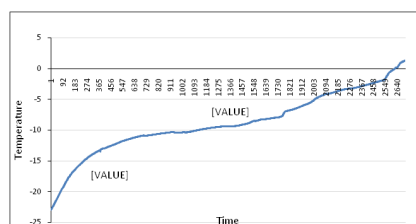


Figure 7 Temperature profile of melting behaviour of ethylene glycol.

PCM selection

For selection of PCM, the range of temperature of air inside the storage space of cold storage is obtained from the graph between temperatures of air versus time. The PCM is then selected according to its melting temperature which should be within the range of air temperature as shown in Figure 8.

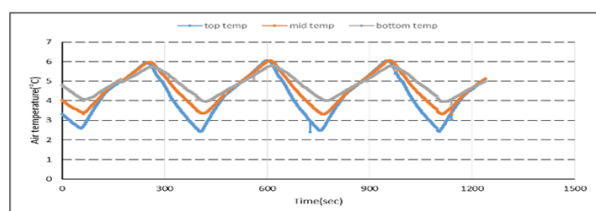


Figure 8 Air temperature profile inside the storage chamber.

Polyethylene glycol 400 (PEG 400)

From Figure 8 & Figure 9, we find that temperature fluctuates between the temperature ranges of 3°C to 6°C . The PCM studied in this work was Polyethylene glycol 400 (PEG 400), which has melting temperature of 5°C as obtained from the manufacturing company Merckmillipore. The chemical formula of PEG 400 is $\text{HO}(\text{C}_2\text{H}_4\text{O})_n\text{H}$.

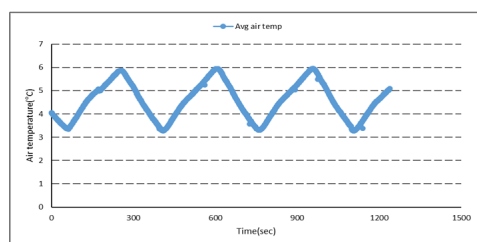


Figure 9 Average air temperature profile inside the storage chamber.

Amount of PCM required

Heat load that has to be removed from the cold space inside the evaporator = 2.5 kW

$$\text{Initial heat load} = 2.11\text{ kW}$$

$$\text{Amount of heat considered to be removed, } Q = 2.5 - 2.11 = 0.39\text{ kW} \approx 400\text{ W}$$

$$\text{Latent heat of polyethylene glycol 400, } \lambda = 150.98\text{ kJ/kg}$$

$$\text{Density of polyethylene glycol 400, } \rho = 1125.5\text{ kg/m}^3$$

Now, heat considered to be removed should be equal to the latent heat of polyethylene glycol 400 per hour basis.

$$\therefore Q = m \times \lambda$$

$$400\text{ (J/s)} = m \times 150.98 \times 1000$$

$$m = 400 \times 3600 / (150.98 \times 1000)$$

$$m = 9.537\text{ kg}$$

$$\text{Volume (v)} = \text{mass (m)} / \text{density (}\rho\text{)}$$

$$\therefore v = 9.537 / 1125.5$$

$$v = 8.474 \times 10^{-3}\text{ m}^3$$

$$\therefore v = 8.5\text{ l (per hour basis)}$$

Design of Trays to hold PCM

The PCM containing trays were designed such that they can be placed in the shelves of the cold storage (Figure. 10) (Figure 11). Their size was made slightly smaller than the cross sectional area of the shelves, leaving enough gap for air circulation inside the storage space of the cold storage. The material for the construction of trays used is GI sheet 1.25 mm thick. The total volume of each tray ($40\text{cm} \times 40\text{cm} \times 2\text{cm}$) was 3.2×10^{-3} and PCM in each tray was $2.8 \times 10^{-3}\text{ m}^3$, occupying a total of only 2.76% of internal volume of the cold storage. Each tray weighed 3.1 kg and contained 2.833 kg of Polyethylene glycol 400; therefore the total amount of PCM inside the cold storage was 9.537 kg.



Figure 10 Pictorial views of PCM trays.



Figure 11 Pictorial view showing PCM trays inside cold storage model.

Cold storage's inside air temperature response to door openings

A series of door openings have been done with and without incorporation of Polyethylene glycol 400 as a Phase change material. Four different tests (Table 1) were performed in order to study the behaviour of cold storage.

Test 1a: Door opening

Test was conducted for opening the door 3 times for 10 seconds each. The duration between openings of door was 20 minutes. The graph plotted between air temperature and time is given in Figure 12: From Figure 12, it is revealed that the temperature rises on opening the door and it reaches to 17 °C when the door remained open for 10 seconds. It was observed that the use of PCM maintained the air temperature 3 °C lower (14 °C) than that without PCM.

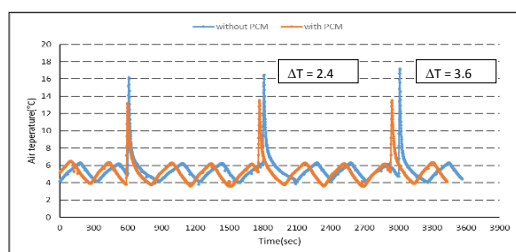


Figure 12 Test 1a: Door opening.

Test 1b: Door opening

Test was conducted for opening the door 3 times for 30 seconds each. The duration between openings of door is 20 minutes. The graph plotted between air temperature and time is given in Figure 13: Figure 13 reveals that the peak of temperature rises to 21 °C during door opening for 30 seconds and it is observed that the use of PCM maintained the air temperature 1.04 °C lower than that without PCM.

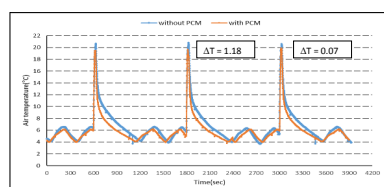


Figure 13 Test 1b: Door opening.

Test 1c: Door opening

Test conducted for opening the door 3 times for 3 minutes each. The duration between openings of door is 20 minutes. The graph plotted between air temperature and time is given in Fig. 3.9. It is clear from Figure 14 that the use of PCM maintained the air temperature 1.11 °C lower during door openings for 3 minutes.

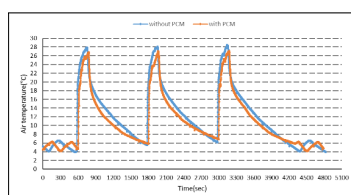


Figure 14 Test 1c: Door opening.

Test 1d: Door opening

Test conducted for opening the door for 10 minutes. The graph plotted between air temperature and time is given in Figure 15: From Figure 15, it is observed that the temperature rises to 32 °C during door opening for 10 minutes. The use of PCM maintained the air temperature 3.5 °C lower than that of without PCM.

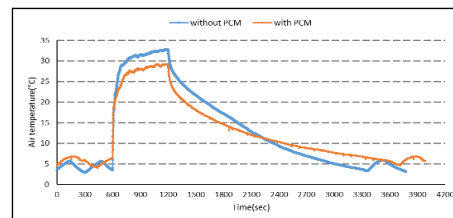


Figure 15 Test 1d: Door opening.

Air temperature response to electrical power failure

A series of electrical power failures have been done with and without incorporation of Polyethylene glycol as Phase change material. Four different tests (Table 2) were performed in order to study the behaviour of cold storage.

Test 2a: Power failure

Test conducted for electrical power failure for 15 minutes. The graph plotted between air temperature and time is given in Figure 16: From Figure 16 it is observed that electrical failure of 15 minutes could cause rise in temperature to 11.38 °C. The use of PCM maintained the air temperature 0.38 °C lower than that without PCM.

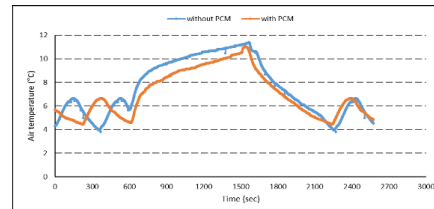


Figure 16 Test 2a: Power failure.

Test 2b: Power failure

Test conducted for electrical power failure for 30 minutes. The graph plotted between air temperature and time is given in Figure 17: From Figure 17 it is observed that on power failure of 30 minutes the temperature rises to 14 °C. The use of PCM maintained the air temperature 1 °C lower than that of without PCM.

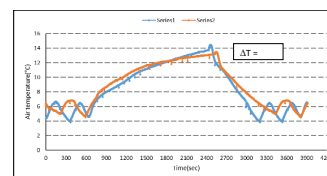


Figure 17 Test 2b: Power failure.

Test 2c: Power failure

Test conducted for electrical power failure for 1 hour. The graph plotted between air temperature and time is given in Figure 18: From Figure 18 it is observed that electrical failure of 1 hour could cause

rise in temperature to 18 °C. The use of PCM maintained the air temperature 3.1 °C lower (up to 15 °C) than that without PCM.

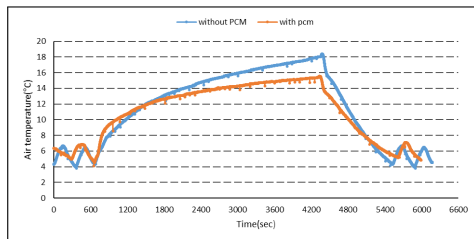


Figure 18 Test 2c: Power failure.

Test 2d: Power failure

Test conducted for electrical power failure for 2 hours. The graph plotted between air temperature and time is given in Figure 19: From Figure 19 it is observed that the temperature rises to 21 °C during power failure for 2 hours. The use of PCM maintained the air temperature 4.5 °C lower (up to 17 °C) than that without PCM.

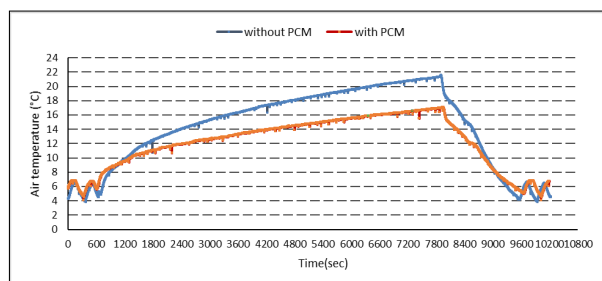


Figure 19 Test 2d: Power failure.

Analysis of Power savings

For the analysis of power saving we have calculated the compressor work in both cases i.e. with and without incorporation of PCM. The net power saving due to PCM incorporation in a cold storage system can be calculated by finding the difference between the compressor work done with and without PCM. This compression work when divided by time taken for analysis gives the net power saving. The theoretical power saving can be obtained by dividing the net power saved by the efficiency of the compressor system which can be as much as 70% in this case. The detailed calculations and the results of net power saving for each set of experiments is presented below:

Power saving in case of power cut

Test 1a: Door opening for 10 seconds after 20 minutes of interval

Without PCM

Peak temperature attained, $T_c = 17\text{ °C}$

Enthalpy of refrigerant before entering the compressor, $h_1 = 425\text{ kJ/kg}$

Entropy of refrigerant before entering the compressor, $S_1 = 1.71923\text{ kJ/kg °C}$

Enthalpy of refrigerant at the exit of compressor, $h_2 = 450\text{ kJ/kg}$

Enthalpy of refrigerant at the exit of condenser, $h_3 = 240\text{ kJ/kg} = h_4$

Condenser temperature, $T_c = 30\text{ °C}$

Heat load in the evaporator, $Q_e = 2500\text{ W}$

$$Q_e = m_r (h_1 - h_4)$$

$$m_r = 0.0135\text{ kg/s}$$

$$\text{Compressor work} = W_{c1} = m_r (h_2 - h_1)$$

$$= 337.5\text{ W}$$

With PCM

$$T_c = 14\text{ °C}$$

$$h_1 = 420\text{ kJ/kg}$$

$$S_1 = 1.718\text{ kJ/kg °C}$$

$$h_2 = 450\text{ kJ/kg}$$

$$h_3 = 240\text{ kJ/kg} = h_4$$

$$Q_e = 2500\text{ W}$$

$$Q_e = m_r (h_1 - h_4)$$

$$m_r = 0.01388\text{ kg/s}$$

$$\text{Compressor power} = W_{c2} = m_r (h_2 - h_1)$$

$$= 138.88\text{ W}$$

$$\text{Net compressor power} = W_{c1} - W_{c2} = 337.5 - 138.88 = 198.7\text{ W}$$

$$\text{Theoretical compressor power} = 198.7/0.7 = 283.86\text{ W}$$

$$\text{Net energy saved in one hr} = 0.283 \times 3600 = 1021.88\text{ kJ}$$

Test 1b: Door opening for 30 s after 20 minutes of interval

Without PCM

$$T_c = 21\text{ °C}$$

$$h_1 = 432\text{ kJ/kg}$$

$$S_1 = 1.7177\text{ kJ/kg °C}$$

$$h_2 = 450\text{ kJ/kg}$$

$$h_3 = 240\text{ kJ/kg} = h_4$$

$$T_c = 30\text{ °C}$$

$$Q_e = 2500\text{ W}$$

$$Q_e = m_r (h_1 - h_4)$$

$$m_r = 0.01316\text{ kg/s}$$

$$\text{Compressor work} = W_{c1} = m_r (h_2 - h_1) = 234.4\text{ W}$$

With PCM

$$T_c = 19.9\text{ °C}$$

$$h_1 = 429\text{ kJ/kg}$$

$$S_1 = 1.718\text{ kJ/kg °C}$$

$$h_2 = 440\text{ kJ/kg}$$

$$h_3 = 240\text{ kJ/kg} = h_4$$

$$Q_e = 2500\text{ W} = m_r (h_1 - h_4)$$

$$m_r = 0.01323\text{ kg/s}$$

$$\text{Compressor power} = W_{c2} = m_r (h_2 - h_1) \\ = 145.5 \text{ W}$$

$$\text{Net compressor power} = 88.9 \text{ W}$$

$$\text{Theoretical compressor power} = 127 \text{ W}$$

$$\text{Theoretical energy saved in one hr} = 457.2 \text{ kJ}$$

Test 1c: Door opening for 3 minutes after 20 minutes of interval

Similar calculations can be done

We get,

$$W_{c1} = 264.6 \text{ W}$$

$$W_{c2} = 240.6 \text{ W}$$

$$\text{Net compressor power} = 23.96 \text{ W}$$

$$\text{Theoretical compressor power} = 34 \text{ W}$$

$$\text{Theoretical energy saved in one hr} = 123 \text{ kJ}$$

Test 1d: Door opening for 10 minutes.

Similarly we get,

$$W_{c1} = 192.3 \text{ W}$$

$$W_{c2} = 197.3 \text{ W}$$

$$\text{Net compressor power} = 5.1 \text{ W}$$

$$\text{Theoretical compressor power} = 7.3 \text{ W}$$

$$\text{Theoretical energy saved in one hr} = 26.2 \text{ kJ}$$

Power saving in case of power cut

Test 2a: when power failure was for 15 minutes.

Heat absorbed by air per unit mass without PCM when power failure was for 15 minutes $= C_p \times \Delta t = 1.005 \times (11.38 - 5) = 6.4119 \text{ kJ/kg of air}$

Heat absorbed by air with PCM when power failure was for 15 minutes $= 1.005 \times (11 - 5) = 6.03 \text{ kJ/kg of air}$

Heat absorbed by PCM in 15 minutes of power failure $= 0.389 \text{ kJ} = 1.5276 \text{ kJ/hr}$

Test 2b: when power failure was for ½ hour.

Heat absorbed by air per unit mass without PCM when power failure was for ½ h $= C_p \times \Delta t = 1.005 \times (14 - 5) = 9.045 \text{ kJ/kg of air}$

Heat absorbed by air with PCM when power failure was for ½ hr $= 1.005 \times (13 - 5) = 8.04 \text{ kJ/kg of air}$

Heat absorbed by PCM in ½ hr of power failure $= 1.005 \text{ kJ} = 2.01 \text{ kJ/hr}$

Test 2c: when power cut was for 1 hour.

Heat absorbed by air per unit mass without PCM when power failure was for 1 h $= C_p \times \Delta t = 1.005 \times (18 - 5) = 13.065 \text{ kJ/kg of air}$

Heat absorbed by air with PCM when power failure was for 1 hr $= 1.005 \times (14.9 - 5) = 9.95 \text{ kJ/kg of air}$

Heat absorbed by PCM in 1hr of power failure $= 13.065 - 9.95 = 3.115 \text{ kJ/h}$

Test 2d: when power failure was for 2 hours.

Heat absorbed by air per unit mass without PCM when power failure was for 2 h $= C_p \times \Delta t = 1.005 \times (21 - 5) = 16.08 \text{ kJ/kg of air}$

Heat absorbed by air with PCM when power failure was for 2 hr $= 1.005 \times (16.5 - 5) = 11.56 \text{ kJ/kg of air}$

Heat absorbed by PCM in 2 h of power failure $= 4.52 \text{ kJ} = 2.26 \text{ kJ/h}$

Conclusion

Peak temperature difference was analysed with and without PCM incorporation in cold storage chamber. The benefit of introduction of PCM inside the cold storage is evident. It was observed that the use of PCM maintained the air temperature 1-4 °C lower than without using PCM when frequent door opening condition was considered. The highest difference in temperature rise with and without PCM incorporation was observed when door was opened for 10 seconds with an interval of 20 minutes. It decreases with the increase in the duration of door opening. This may be due to more heat load generation with longer duration of door opening. In case of power cut the PCM maintained air temperature 1-4.5 °C lower than without using PCM. The highest difference in temperature rise with and without PCM incorporation was observed when the power failure was for 2 hr. This difference decreases with decrease in duration of power failure. Power saving analysis results showed that highest power saving in door opening condition was observed when door opened for 10 s at 20 min interval. The total energy saved per hour in this case was 1021.88 kJ. In case of power cut for 1 hr the total energy of 3.115 kJ/h was absorbed by PCM which was higher than the rate of energy absorption in other cases which makes it most efficient in this condition. PCM has higher rate of energy absorption in case of 1 h of power failure as compared to others. More power saving will occur when PCM will absorb energy at higher rates so at 1 h of power failure more energy saving will occur than any other situations.

Acknowledgement

None.

Conflict of interest

None.

References

1. Hasib AMMG. Effect of dispersed particles and branching on the performance of a medium temperature thermal energy storage system. *ProQuest Dissertations Publishing*. 2013;1691104.
2. Mehling H, Cabeza L F. Heat and cold storage with PCM. *Springer*. 2008.
3. Oro E, De Gracia A, Castell A, et al. Review on phase change materials (PCMs) for cold thermal energy storage applications. *Applied Energy*. 2012;99:513–533.
4. Sharma A, Tyagi VV, Chen CR, et al. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable energy reviews*. 2009;13(2):318–345.

5. Tatsidjodoung P, Le Pierrès N, Luo L. A review of potential materials for thermal energy storage in building applications. *Renewable and Sustainable Energy Reviews*. 2013;18:327–349.
6. Zalba B, Marín JM, Cabeza L F, et al. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering*. 2003;23(3):251–283.
7. Benato, Alberto, Stoppato. State-of-the-art and future development of sensible heat thermal electricity storage systems. *IJHT*. 2017;35:S244–S251.
8. Bansal PK, Kruger R. Test standards for household refrigerators and freezers : preliminary comparisons. *International Journal of Refrigeration*. 1995;18(1):4–20.
9. Liu M, Saman W, Bruno F. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. *Renewable and Sustainable Energy Reviews*. 2012;16(4):2118–2132.
10. Sole A, Miro L, Barreneche C, et al. Corrosion of metals and salt hydrates used for thermo chemical energy storage. *Renewable Energy*. 2015;75:519–523.
11. Donhowe DP, Hartel RW. Recrystallization of ice during bulk storage of ice cream. *International Dairy Journal*. 1996;6(11–12):1209–1221.
12. Phimolsiripol Y, Siripatrawan U, Tulyathan V, et al. Effects of freezing and temperature fluctuations during frozen storage on frozen dough and bread quality. *Journal of Food Engineering*. 2008;84(1):48–56.
13. Gormley R, Walshe T, Hussey K, et al. The effect of fluctuating vs. constant frozen storage temperature regimes on some quality parameters of selected food products. *LWT-Food Science and Technology*. (2002);35(2):190–200.
14. Ngapo TM, Babare IH, Reynolds J, et al. Freezing and thawing rate effects on drip loss from samples of pork. *Meat Science*. (1999);53(3):149–158.
15. Onyejekwe DC. Cold storage using eutectic mixture of NaCl/H₂O: An application to photovoltaic compresses or vapour freezers. *Solar and wind technology*. 1989;6(1):11–18.
16. Wang F, Maidment G, Missenden J, et al. The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation. *Applied Thermal Engineering*. 2007;27(17–18):2893–2901.
17. Wang F, Maidment G, Missenden J, et al. The novel use of phase change materials in refrigeration plant. Part 3: PCM for control and energy savings. *Applied Thermal Engineering*. (2007).27(17–18):2911–2918.
18. Wang F, Maidment G, Missenden J, et al. The novel use of phase change materials in refrigeration plant. Part 2: Dynamic simulation model for the combined system. *Applied Thermal Engineering*. 2007;27(17–18):2902–2910.
19. Azzouz K, Leducq D, Gobin D. Performance enhancement of a household refrigerator by addition of latent heat storage. *International Journal of Refrigeration*. 2008;31(5):892–901.
20. Farid MM, Khudair AM, Razack S, et al. A review on phase change energy storage: Materials and applications. *Energy Conversion and Management*. 2004;45(9–10):1597–1615.
21. Azzouz K, Leducq D, Gobin D. Enhancing the performance of household refrigerators with latent heat storage: an experimental investigation. *International journal of refrigeration*. 2009;32(7):1634–1644.
22. Sakare P. Design of Cold Storage Structure For Thousand Tonne Potatoes. *International Journal of Agriculture and Food Science Technology*. 2014;5(3):171–178.
23. Ahamed MM, Kannakumar J, Reddy PM. Design and fabrication of cold Storage plant using Phase change material. *International Journal of Innovative Research in Science, Engineering and Technology*, 2013;2(9).