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Experimental Investigation on the Performance Analysis of Cold Storage Plant Using with and without Phase Change Material (PCM)

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Abstract: ***As the demand for refrigeration and Air conditioning has been increased during the last decade, the cold storage system can be used to the economic advantage over conventional plants. Loss of electrical power for cold storage facilities leads to an increase in temperature and can result in the loss in quality and value of stored products and thus reduce in Coefficient of performance (COP). This paper proposes the use of a passive system integrated into the walls of the cold storage facility i.e., PCM (Ethylene Glycol) is located behind the five sides of the evaporator cabinet in which the evaporator coils are immersed. Experimental application of PCM into a cold storage has shown that the temperature rise during loss of power is limited. With PCM, the air temperature is kept constant at -8°C for 8 hours, compared to without PCM where the air temperature rises continuously and rises above -8°C in just 1 hour. Experimental result also compares the Coefficient of performance (COP) with and without PCM for the cold storage plant. Hence proposed system could be a new option for performance improvement of a cold storage by enhancing heat transfer of the evaporator and useful for commercial establishments as presently there are frequent power cuts.***

Keywords: Phase change material (Ethylene Glycol), Vapor compression cycle, Poly Urethane foam, Coefficient of performance, cold storage**.**

1. Introduction

Refrigeration and Air conditioning systems are directly or indirectly responsible for present energy crisis problem as their use in household, commercial and transportation sector are increasing rapidly. Now-a-days power cuts are very often due to accidents, or could be due to implementation of demand side management schemes (DSM) to shift power usage to avoid high loads by the electricity supplier, or by the user to shift their electricity usage to off-peak pricing periods (electrical load shifting) and it is important to maintain regular temperatures inside cold storage facilities and cold transport vehicles (Purdue, 2010 et al, [17]). Most frozen and chilled foods are sensitive to temperature fluctuations. A major contribution to the heat loadings for a cold store comes from heat penetrating the walls. The refrigeration system removes this heat load, but if there is a power failure, cooling is not provided to the stored product (DR. Manoj Kumar Chourasia, 2009 et al, [16]). Thermal Energy storage systems (TES) will use phase change materials for storage of heat and cold at shifted time. Phase change material (PCM) melts within a narrow temperature range, and absorbs a large amount of energy while in the transition state, thus minimizing the rise in the environment temperature. PCM with a suitable melting temperature may be used to provide thermal capacity to maintain suitable internal temperature during power failure. (Mohammed Farid, 2010 et al, [15]) PCM may also be used in load shedding applications to shift electricity usage to an optimum time. Many Cold Thermal Energy Storage (CTES) systems have gained attention in recent years. Cold Storage is a special kind of room, the temperature of which is kept very low with the help of machines and precision instruments. India is having a unique geographical position and a wide range of soil thus producing variety of fruits and vegetables like apples, grapes, oranges, potatoes, chilies, ginger, etc. Marine products are also being produced in large quantities due to large coastal areas. (Amit M Patel et al [25]). The present production level of fruits and vegetables is more than 100 million MT and keeping in view the growth rate of population and demand, the production of risible commodities is increasing every year. The cold storage facilities are the prime infrastructural component for such perishable commodities. Besides the role of stabilizing market prices and evenly distributing both on demand basis and time basis, the cold storage industry renders other advantages and benefits to both the farmers and the consumers.

This paper aims to combination of 3D cold store using without and with the inclusion of PCM panels in its walls. The effect on the change in air temperature during loss of electrical power (and thus loss of cooling) is investigated and validated for a cold store and then extended to predict the transient performance of a typical cold store.

2. Experimental Methodology

2.1 Refrigeration cycle

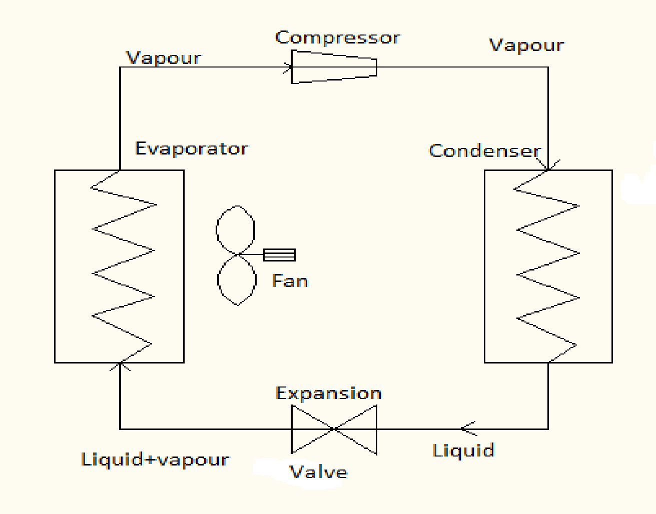

Figure 1: Schematic Diagram of a VCRS

The vapor compression uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. Figure 1 depicts a typical, single-stage vapor compression system. All such systems have four components: a compressor, a condenser, a thermal expansion valve (also called a throttle valve), and an evaporator. Circulating refrigerant enters the compressor in the thermodynamic state known as a saturated vapor] and is compressed to a higher pressure, resulting in a higher temperature as well. The hot, compressed vapor is then in the thermodynamic state known as a superheated vapor and it is at a temperature and pressure at which it can be condensed with either cooling water or cooling air. That hot vapor is routed through a condenser where it is cooled and condensed into a liquid by flowing through a coil or tubes with cool water or cool air flowing across the coil or tubes. This is where the circulating refrigerant rejects heat from the system and the rejected heat is carried away by either the water or the air (whichever may be the case). The condensed liquid refrigerant, in the thermodynamic state known as a saturated liquid, is next routed through an expansion valve where it undergoes an abrupt reduction in pressure. That pressure reduction results in the adiabatic flash evaporation of a part of the liquid refrigerant. The auto-refrigeration effect of the adiabatic flash evaporation lowers the temperature of the liquid and vapor refrigerant mixture to where it is colder than the temperature of the enclosed space to be refrigerated. The cold mixture is then routed through the coil or tubes in the evaporator. A fan circulates the warm air in the enclosed space across the coil or tubes carrying the cold refrigerant liquid and vapor mixture. That warm air evaporates the liquid part of the cold refrigerant mixture. At the same time, the circulating air is cooled and thus lowers the temperature of the enclosed space to the desired temperature. The evaporator is where the circulating refrigerant absorbs and removes heat which is subsequently rejected in the condenser and transferred elsewhere by the water or air used in the condenser. To complete the refrigeration cycle, the refrigerant vapor from the evaporator is again a saturated vapor and is routed back into the compressor.

2.2 Characteristics and Classification of PCM

PCMs latent heat storage can be achieved through solid–solid, solid–liquid, solid–gas and liquid–gas phase change. However, the only phase change used for PCMs is the solid–liquid change. Liquid-gas phase changes are not practical for use as thermal storage. Liquid–gas transitions do have a higher heat of transformation than solid–liquid transitions. Solid–solid phase changes are typically very slow and have a rather low heat of transformation. PCM stores 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry or rock. The classification of PCM is shown in figure 2.

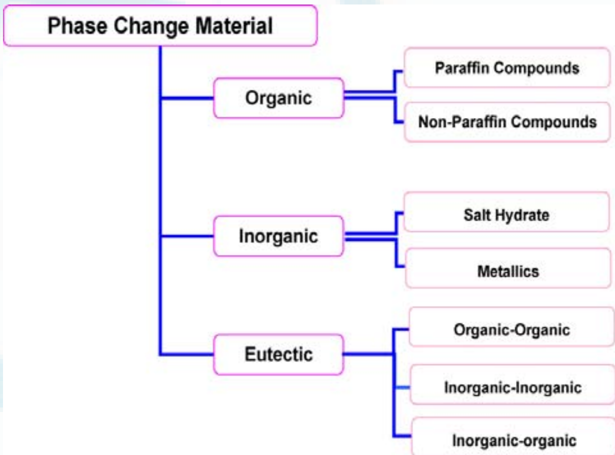

Figure 2: Classification of PCM

2.2.1 Important properties required for PCM

- High latent heat of fusion per unit mass, so that a lesser amount of materials stores a given amount of energy.
- High thermal conductivity so that the temperature gradient required for charging the storage material is small.
- High density, so that a smaller container volume holds the material to obtain compact encapsulation.
- A melting point in the desired operating range of temperature as per the application.
- The phase change material should be non poisonous, non-flammable, and non explosive.
- No chemical decomposition, so that the system life is assured.
- No corrosiveness to the encapsulation material.

In our model we have used ethylene glycol as a phase change material. The physical and chemical properties of ethylene glycol are shown below.

2.2.2 Properties of ethylene glycol

2.2.2.1 Antifreeze

Due to its low freezing point ethylene glycol resists freezing. Ethylene glycol disrupts hydrogen bonding when dissolved in water. Pure ethylene glycol freezes at about −12 °C (10.4 °F), but when mixed with water molecules forms a solid crystal structure, and therefore the freezing point of the mixture is depressed significantly. The minimum freezing point is observed when the ethylene glycol percent in water is about 70%, as shown below.

Table 1: Ethylene Glycol Freezing Point Vs Concentration in Water

S.No	*Water Wt %*	*Freezing Point(°C)*	*S.No*	*Water Wt%*	*Freezing Point(°C)*
1	0	0	7	60	-48
2	10	-4	8	70	-51
3	20	-7	9	80	-45
4	30	-15	10	90	-29
5	40	-23	11	100	-12
6	50	-34			

However, the boiling point for aqueous ethylene glycol increases monotonically with increasing ethylene glycol percentage. Thus, the use of ethylene glycol not only depresses the freezing point, but also elevates the boiling point such that the operating range for the heat transfer fluid is broadened on both ends of the temperature scale. The increase in boiling temperature is due to pure ethylene glycol having a much higher boiling point and lower vapor pressure than pure water.

2.2.2.2 Physical Properties

Ethylene glycol is a clear, colorless, odorless liquid with a sweet taste. It is hygroscopic and completely miscible with many polar solvents such as water, alcohols, glycol ethers, and acetone. Its solubility is low however, in non polar solvents, such as benzene, toluene, dichloromethane, and chloroform. Following are some of the physical properties of ethylene glycol as shown in table 3.

Table 2: Ethylene Glycol Boiling Point Vs Concentration of Water

S.No	*Water Wt %*	*Boiling Point(°C)*	*S.No*	*Water Wt%*	*Boiling Point(°C)*
1	0	100	7	60	110
2	10	102	8	70	116
3	20	102	9	80	124
4	30	104	10	90	140
5	40	104	11	100	197
6	50	107			

Ethylene glycol is difficult to crystallize; when cooled, it forms a highly viscous, super cooled mass that finally solidifies to produce a glass like substance. The widespread use of ethylene glycol as antifreeze is based on its ability to lower the freezing point when mixed water. The physical properties of ethylene glycol- water mixtures are therefore, extremely important in this regard.

2.3 Design of Cold Cabin

For the application of PCM to improve temperature stability during power loss in cold store, a vertical cabin of dimensions 0.2794mH x 0.2794mW x 0.325m D (11”x11”x11”) and a storage volume of 25.7 L was used. Anodized aluminium panels filled with PCM (a ethylene glycol solution with a melting point of -23°C) were placed against the walls of the cold cabin in the arrangement shown in Figure. The PCM in an aluminium panels with dimensions of 0.0254x0.33x0.38m (thkXwideXheight) i.e;1”x13”x15” contained 3 liters of ethylene glycol and 12 liters of water as a PCM occupying a volume of 4.735 L was used for experimental investigation. The PCM panels were placed vertically against the entire walls to minimize the amount of usable storage space lost as shown in Figure 1. This PCM panels was covered entirely with poly urethane foam panels of dimensions 0.05x0.43x0.43m (thkxwidexht). This will reduce the heat transfer from outside to inside the cabin as shown in figure. As evaporator coil and phase change material (PCM) are present in one panel, the PCM will absorbs the energy as evaporator coil cools and stores the energy by changing its phase. During power cuts or off peak time the PCM will releases its energy and maintains the cold cabin at constant require temperature for -8°C for about 7-8 hours depending upon the outside condition as it is proved by experiment. Thus a small difference in temperature can be used for storing energy and releasing the stored energy. In order to avoid the above stated problem, in this paper it is clearly analyzed experimentally that the thermal storage capacity can be improved by using phase change material panels incorporated in the walls of the cold storage.

2.3.1 Design Details of Model Cold Storage Plant Using (PCM) Phase Change Material

Mass of refrigerant (R134a) (m) = 250gm.

1. Compressor details:

- Compressor Power = 0.167 H.P

1 H.P = 746 W

Therefore Power = 0.167×746=124.582 W

We use Reciprocating piston type compressor. The specifications of the compressor are as follows:

Table 3: Specification of Compressor

Phase	*Volts*	*Current*	*Speed*	*Cycles*	*Temperature*
Single	160/ 250	4 amp	2850 rpm	50 Hz	40ºC

Theoretical tonne of refrigeration system is 0.5 Ton.

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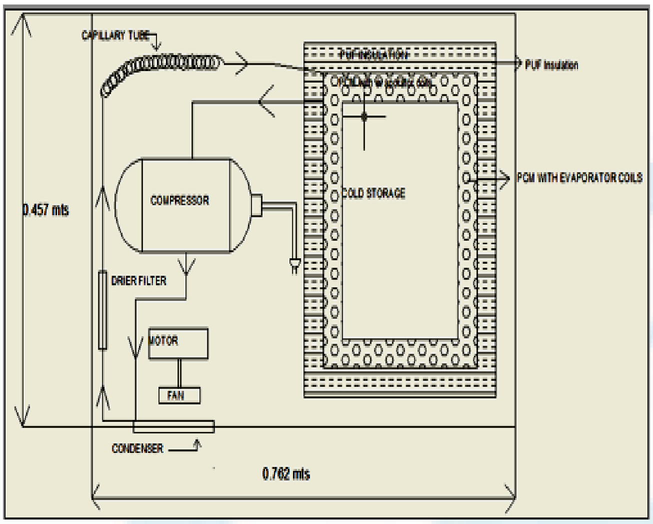


Figure 3: Schematic layout of cold storage plant

Figure 4: Photograph of Fabricated cold storage plant in Thermal lab

2. Condenser Fan details:

Table 4: Specification of Condenser

Type	*Volts*	*Power*	*Speed*	*Current*	*Cycles*
Suction	220/ 240	5W	1300 r.p.m	0.21 A	50/ 60Hz

3. Condenser details:

Fine type 9 inch double row condenser is used
Heat extracted in the condenser = m $c_p \Delta T$
= m $c_p (T_2 - T_1)$
= 0.250×129.98(80-50)
= 974.85 KJ

4. Expander details:

- Diameter of capillary tube = 0.050 inch.
- Length of capillary tube = 5ft.

5. Evaporator:

- Length of the evaporator coil = 30ft.
- Diameter of the evaporating coil = 1/4 inch

6. Capacity of the cold storage plant

Table 5: Dimensions of Cold Cabin

Length (L)	*Breadth (B)*	*Height (H)*	*Volume (LxBxH)*	*Capacity (Volx1000)*
0.2794 m	0.2794m	0.3302m	0.02577m³	25.77liters

7. Phase change material used is Ethylene Glycol

Table 6: Quantity of Water Mixture

Qty of Ethylene Glycol	*Qty of water*	*Ratio Water: ethylene glycol*
3 liters	12 liters	4:1

3. Results and Discussions

The desired working model of cold storage plant using (PCM) phase change material is successfully designed and fabricated. It is also successfully tested for working. Experimental application of PCM into a cold storage has shown that the temperature rise during loss of power is limited. With PCM, the air temperature is kept constant at -8°C for 8 hours, compared to without PCM where the air temperature rises continuously and rises above -8°C in just 1 hour as shown in the figure 6. The PCM temperature rises slowly as the PCM melts over this 8 hour period. Once the PCM has finished melting, the air and PCM temperatures rise steeply.

The model is tested successfully for its working. The following is observed during the testing.

The duration of cooling the PCM 24 Hours
Temperature of the cold chamber -25^{0}C

Temperature reducing rate at 1^{0}C per hour up to -8^{0}C and from there the temperature will remains constant for about 7 hours and again temperature will raises steeply.

3.1 Calculation of COP

3.1.1. Without PCM panel:

Experimental results taken on 22/07/13

$$COP_{cooling} = \frac{|Q_C|}{W}$$

Where,
W is the amount of power supplied.

- Q_C Is the heat removed from the cold reservoir

$Q_c = mc_p\Delta T$
Where,
m = mass of water stored, i.e. 0.5Kg
c_p = specific heat of water, i.e. 4.2kj/kg -°C
$\Delta T = T_i - T_f$
T_i = Initial Temperature of water, i.e. 20°C
T_f = Final Temperature of water, i.e. 5°C
Heat rejected $(Q_c) = mc_p\Delta T$

= 0.5x4.2x (20-5)
= 31.5Kj/Kg - ºC
Time required for cooling is 60sec.
Therefore, $Q_c = mc_p\Delta T$/time
= 31.5/80
= 0.394KW
Power consumed by the compressor = VIcosϕ,
Where,
V = Voltage
= 230 volts
I = 1.5 amps
Cosϕ = utilization factor
= 0.857
Therefore, power consumed = 230x1.5x0.857
= 295.665W
= 0.295665 KW

$$C.O.P = \frac{\text{Heat removed from cold cabin}}{\text{power consumed by compressor}}$$

$$C.O.P = \frac{0.394}{0.295665}$$

= **1.333.**

Table 7: Calculation of C.O.P at different loads without pcm panels taken 0n 22-07-13

S.No	*Load (kg)*	*ΔT*	*Time (sec)*	*Heat Rejected Kw*	*Current (Amps)*	*Power (Kw)*	*C.O.P*
1	0.5	15	80	0.394	1.5	0.295	1.333
2	1	15	130	0.485	1.7	0.394	1.221
3	1.5	15	140	0.675	2	0.394	1.713
4	2	15	170	0.741	2.4	0.473	1.567
5	2.5	15	190	0.829	3	0.591	1.401
6	3	15	230	0.828	3.5	0.689	1.192

Table 8: Experimental temperature results without PCM panels taken on 22-07-13

S.No	*Time (hr)*	*Temperature (°C)*	S.No	*Time (hr)*	*Temperature (°C)*
1	0	-25	7	6	-4
2	1	-22	8	7	-5
3	2	-19	9	8	-2
4	3	-13	10	9	0
5	4	-9	11	10	4
6	5	-8			

3.1.2. With PCM Panel

Experimental Results Taken On 22/07/2013

$$COP_{cooling} = \frac{|Q_C|}{W}$$

Where,

- W is the amount of power supplied.
- Q_C Is the heat removed from the cold reservoir

$Q_c = mc_p\Delta T$
Where,
m = mass of water stored, i.e. 0.5Kg
c_p = specific heat of water, i.e. 4.2kj/kg -ºC
$\Delta T = T_i - T_f$
T_i = Initial Temperature of water, i.e. 20ºC
T_f = Final Temperature of water, i.e. 5ºC

Heat rejected $(Q_c) = mc_p\Delta T$
= 0.5x4.2x (20-5)
= 31.5Kj/Kg - ºC
Time required for cooling is 60sec.
Therefore, $Q_c = mc_p\Delta T$/time
= 31.5/60
= 0.525KW
Power consumed by the compressor = VIcosϕ,
Where,
V = Voltage
= 230 volts
I = 1.5 amps
Cosϕ = utilization factor
= 0.857
Therefore, power consumed = 230x1.5x0.857
= 295.665W
= 0.295665 KW

$$C.O.P = \frac{\text{Heat removed from cold cab}}{\text{power consumed by compress}}$$

$$C.O.P = \frac{0.525}{0.2956}$$

= 1.777

Table 9: Calculation of C.O.P at different loads with PCM panels taken on 22-07-2013

S.No	*Load (kg)*	*ΔT*	*Time (sec)*	*Heat Rejected Kw*	*Current (Amps)*	*Power (Kw)*	*C.O.P*
1	0.5	15	60	0.525	1.5	0.2956	1.777
2	1	15	90	0.7	1.7	0.3942	1.777
3	1.5	15	120	0.7875	2	0.3942	1.994
4	2	15	150	0.84	2.4	0.473	1.777
5	2.5	15	180	0.875	4	0.591	1.48
6	3	15	210	0.9	3.5	0.6898	1.3

Table 10: Experimental temperature results with PCM panels taken on 22-07-13

S.No	*Time (hr)*	*Temperature (°C)*	S.No	*Time (hr)*	*Temperature (°C)*
1	0	-25	14	13	-8
2	1	-23	15	14	-8
3	2	-22	16	15	-8
4	3	-20	17	16	-8
5	4	-18	18	17	-8
6	5	-16	19	18	-8
7	6	-15	20	19	-7
8	7	-14	21	20	-7
9	8	-12	22	21	-6
10	9	-10	23	22	-4
11	10	-9	24	23	0
12	11	-8	25	24	4
13	12	-8			

Experimental Results Taken On 09/09/2013

Table 11: Calculation of C.O.P at different loads with PCM panels taken on 09-09-2013

S.No	*Load (kg)*	*ΔT*	*Time (sec)*	*Heat Rejected Kw*	*Current (Amps)*	*Power (Kw)*	*C.O.P*
1	0.5	15	60	0.525	1.1	0.216	2.43
2	1	15	90	0.7	1.4	0.275	2.545
3	1.5	15	100	0.945	2.0	0.394	2.398
4	2	15	120	1.05	2.5	0.492	2.134
5	2.5	15	150	1.05	2.7	0.532	1.973
6	3	15	160	1.181	2.9	0.571	2.06

Table 12: Experimental temperature results with PCM panels taken on 09-09-13

S.No	*Time (hr)*	*Temperature (°C)*	*S.No*	*Time (hr)*	*Temperature (°C)*
1	0	-25	17	16	-8
2	1	-24	18	17	-8
3	2	-23	19	18	-8
4	3	-21	20	19	-8
5	4	-20	21	20	-8
6	5	-19	22	21	-8
7	6	-17	23	22	-7
8	7	-15	24	23	-5
9	8	-13	25	24	-4
10	9	-13	26	25	-3
11	10	-11	27	26	-1
12	11	-10	28	27	0
13	12	-9	29	28	2
14	13	-9	30	29	3
15	14	-8	31	30	4
16	15	-8			

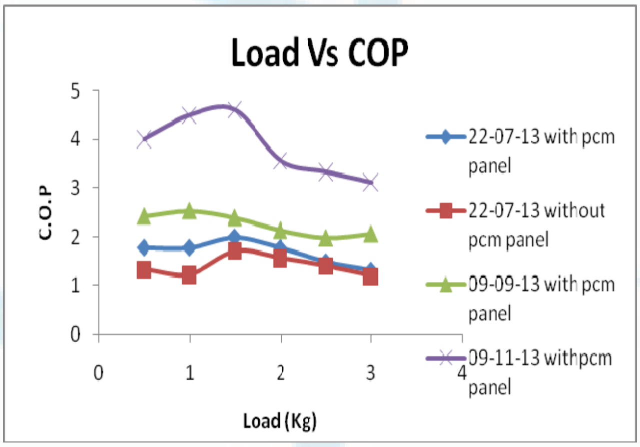
Experimental Results Taken On 09/11/2013

Table 13: Calculation of C.O.P at different loads with PCM panels taken on 09-11-2013

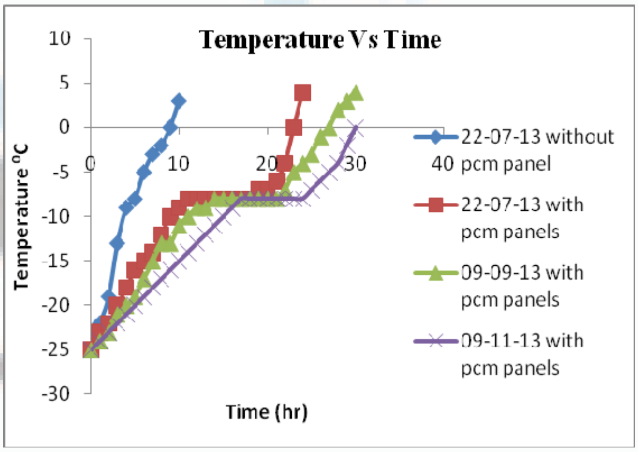
S.No	*Load (kg)*	*ΔT*	*Time (sec)*	*Heat Rejected Kw*	*Current (Amps)*	*Power (Kw)*	*C.O.P*
1	0.5	15	40	0.787	1.0	0.197	4
2	1	15	60	1.05	1.2	0.236	4.5
3	1.5	15	80	1.181	1.3	0.295	4.613
4	2	15	100	1.26	1.8	0.354	3.56
5	2.5	15	120	1.312	2.0	0.394	3.33
6	3	15	140	1.35	2.3	0.433	3.11

Table 14: Experimental temperature results with PCM panels taken on 09-11-13

S.No	*Time (hr)*	*Temperature (°C)*	*S.No*	*Time (hr)*	*Temperature (°C)*
1	0	-25	17	16	-9
2	1	-24	18	17	-8
3	2	-23	19	18	-8
4	3	-22	20	19	-8
5	4	-21	21	20	-8
6	5	-20	22	21	-8
7	6	-19	23	22	-8
8	7	-18	24	23	-8
9	8	-17	25	24	-8
10	9	-16	26	25	-7
11	10	-15	27	26	-6
12	11	-14	28	27	-5
13	12	-13	29	28	-4
14	13	-12	30	29	-2
15	14	-11	31	30	0
16	15	-10			



Graph 1: Comparison results of Load vs COP with and without PCM panels



Graph 2: Comparison results of temperature Vs time with and without PCM panels

4. Conclusions

Experimental tests have been carried out to investigate the performance improvement of a cold storage with and without PCM panels (Ethylene Glycol). For experimentation the quantity of phase change material (Ethylene glycol) used in the ratio of 4:1 i.e. 4 liters of water with 1 liter of ethylene glycol. Experiments were carried out at different loads to investigate the performance of the cold storage. The following conclusions were drawn based on the experimental results.

1) By using phase change material (PCM) panels in the walls of a cold store can limit the raise of temperature and can maintain constant temperature up to 8 hrs.
2) Temperature reduction in cold storage plant by using phase change material (ethylene glycol) panels had observed that reduction of 1ºC for every one hour.
3) Depending on the PCM and thermal load around 11% to 20% of COP improvement has been achieved by the phase change material with respect to without phase change material.
4) Depending on the thermal load with phase change material the average compressor running time per cycle is reduced significantly and it is found about 17% to 30% as compared to without phase change material.
5) Experimental results show that the coefficient of performance (COP) of the refrigeration cycle with PCM is considerably higher than that of without PCM panel. The coefficient of performance (COP) is calculated at different loads and it is found that the coefficient of performance (COP) is optimum at 1.5Kg of thermal load while it decreases with the increase of thermal loads.
6) As the PCM melts, it absorbs the thermal load that enters the cold storage space, thus limiting the rise in the cold store temperature and maintains a constant temperature inside the cold storage during loss of electricity which may occur due to an accidental power loss or done purposely to achieve electrical load shifting.

5. Acknowledgement

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6. Future Scope

More research work is needed in the field of thermal energy storage using phase change materials. Following are recommendations for future research.

1) This experimental work can be extended to investigate the effects of temperature and coefficient of performance by increasing the surface area, and positioning of phase change materials (PCM) panels in different way. It is also observed that when power supply is off this technique is cheapest when compared to other alternate power sources.
2) Investigation of the use of other heat transfer fluids having thermal conductivity higher than that of water.
3) Investigation of thermal losses after thermal storage for a period of time in case of thermal energy storage using phase change materials and compare it with energy storage using without PCM.
4) Investigation of new materials that have a high thermal conductivity in order to be employed as phase change materials for thermal energy storage.

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