An Experimental Evaluation of Application of Phase Change Material for Energy Conservation in Refrigeration System

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Abstract- *The refrigerator and cold storages are generally found in most of the countries and they are one of the most energy demanding appliances because of their continuous operation. The paper investigates the improvement in performance provided by a phase change material (PCM) in refrigerator systems. As the PCM cool off, they release the stored heat and while solidifying they absorb the heat from surrounding in the same fashion. The phase change takes place without a change in the temperature of the material. So, PCM with a suitable melting temperature may be used to provide thermal capacity to maintain suitable internal temperature during power failure. Water, mixture of ethylene glycol and water and mixture of propylene glycol and water with different proportionate can be used as PCM for the experimental purpose to maintain the recommended temperature of 0°C and -11°C in the storage compartment. Experimentally to maintain 0° C storage temperature, it is found that 31.8% power is saved with water as PCM as compared to run the system without PCM during 24 hours. Also to maintain -11°C temperature in the evaporator for 24 hours by using ethylene glycol water mixture 23.83% and by application of propylene glycol water mixture 19.23% of power is saved as compared to evaporator without PCM.*

Keywords- Phase change material (PCM), refrigeration, thermal energy storage.

I. INTRODUCTION

The Refrigeration systems are directly or indirectly responsible for Global Warming problems which refer to the rise in temperature of Earth's atmosphere and ocean. During early 1990, after water heater a frost freezer was the second most expensive and energy consuming home appliance. It was compulsory for appliance makers to include labels which list an estimate of the annual cost of running the appliance, so consumers could compare energy usage and costs. [1]

Most frozen and chilled foods are sensitive to temperature fluctuations. Thermal Energy storage systems (TES) will use phase change materials (PCM) for storage of heat and cold at shifted time. Phase change material (PCM) melts within a narrow temperature range, and while in transition state absorbs a large amount of heat, thus rise in the refrigerator temperature is minimum. PCM with a suitable melting temperature may be used to provide thermal capacity for maintaining suitable recommended internal temperature during power failure. TES could be the most appropriate way and method to correct the gap between the demand and supply of energy and therefore it has become a very attractive technology.

II. PHASE CHANGING MATERIAL

The materials which absorb and release heat as it undergoes a change in phase are known as phase changing materials (PCM). They should have a melting/freezing temperature lying in the practical range of operation, melt/freeze congruently within minimum subcooling and be chemically stable, low in cost, nontoxic and non-corrosive. [2] Latent heat of PCM is many orders higher than the specific heat of materials. As heat exchange takes place in narrow band of temperature the phenomenon can be used for temperature smoothening also.

A. PCM CLASSIFICATION

Figure 1 shows the families of phase change heat storage materials: divided as organic and inorganic materials. Organic materials are further classified as paraffin and nonparaffins. (fatty acids, eutectics, and mixtures). Experiments (melting and freezing cycles) using these materials showed that they crystallize with little or no subcooling and are usually non-corrosive and very stable.

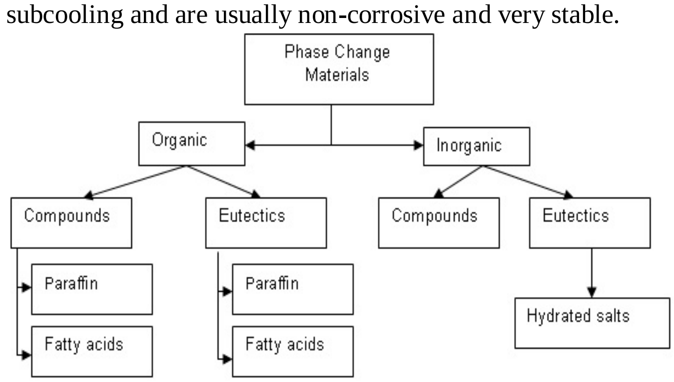

Fig.1 Families of phase change heat storage materials [2]

Inorganic materials are further classified as compounds and eutectics. Main inorganic materials are salts, salt hydrates, aqueous solutions and water. A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization. Eutectic always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously, again with separation unlikely. Organic materials are categorized as paraffin and non-paraffin materials. These materials include congruent melting; means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion. Paraffin are chemically known as hydrocarbons which are generally found to be as wax at room temperature whereas non-paraffin encompasses fatty acids, glycols, esters and alcohols etc. Non-paraffin materials are flammable and should not be exposed to excessively high temperature, flames or oxidizing agents. Some of the features of these organic materials are high heat of fusion, inflammability, low thermal conductivity, low flash points, varying level of toxicity, and instability at high temperatures.

By far the best-known PCM is water. It has been used for cold storage for more than 2000 years. Today, cold storage with ice is state of the art and even cooling with natural ice and snow is used again. Eutectic water-salt solutions have melting temperatures below 0 ºC, because the addition of the salt reduces the melting temperature, and usually good storage density. Eutectic compositions solidify simultaneously out of the liquid at a minimum freezing point. Therefore, none of the phases can sink down due to a different density.

Rezaur Rahman et al. [1] investigated the performance of domestic refrigerator improvement with application of PCM with the evaporator in a domestic refrigerator. The researcher analyzed that makes use of phase change material enhances the rate of heat transfer and hence improve the COP of refrigeration. Md Imran Hossen Khan et al. [3] have experimented to investigate the improvement in performance of a household refrigerator with three different phase change materials with different quantities at different thermal loads. He has achieved about 20% to 27% COP improvement with the use of PCM in respect to without PCM. MD. Mansoor Ahamed et al. [4] has investigated the performance improvement of a cold storage with and without PCM panels (Ethylene Glycol). C. Marques et al. [5] has analyzed that in conventional refrigerator compressor efficiency improves by increase in compressor displacement for single speed compressor. The method proposed to take advantage of high cooling capacity of large compressor with PCM to increase the refrigerator autonomy i.e. off-cycle period, without power supply, from a few minutes to several hours. Azzouz, K et al. [6] have done experiments to investigate the performance of a household refrigerator using a phase change material (PCM). The PCM is located on the backside of the evaporator in order to improve its efficiency and to provide a storage capacity allowing several hours of refrigeration without power supply.

From the above mention research papers it is clear that a very few experimental works of performance improvement of refrigeration systems by PCM has been done. This research is devoted to obtain the clear concept and more experimental data of performance improvement by saving the compressor power in refrigeration systems like household refrigerator or cold storages by using PCM for different temperatures. Ice plant tutor has been selected to evaluate the performance of vapour compression refrigeration system with PCM and evaluation of % power saving and temperature stability of the system in case of power failure. Ethylene glycol and propylene glycol have been selected due to some advantages like clear, colorless, odorless liquid, inflammable. It is also used as antifreeze so its expansion coefficient is lower so if needed it can be circulated by pump at solid state for lower temperature applications. It is hygroscopic and completely miscible with water and by adding it freezing point of mixture decreases and can be used to store product below 0˚C temperature.

III. OBJECTIVE

The objectives of the performance improvement of the refrigeration systems by using the phase change material (PCM) are given below,

- Experiments to be carried out to improve the performance of refrigeration system by using PCM.
- To analyze the effect of PCM on compressor running time to evaluate the saving in power consumption of compressor.
- To evaluate thermal stability of the system in the case of power failure.

IV. EXPERIMENTAL SETUP AND PROCEDURES

An ice plant tutor as shown in fig. 2-A for the refrigeration laboratory is used to perform the experiment and to evaluate the performance of Phase Changing Material. The PCM material is filled in small polythene bags with dimensions of 4” × 3” and PCM used is water, mixture of water and ethylene glycol and mixture of water and propylene glycol with certain weight percentages. The arrangement of polythene bags and can be seen in fig. 2-B. Polythene bags are attached to copper coil of evaporator because it will increase the contact area of PCM with evaporator coil and maximum heat will be transferred via conduction. Due to this arrangement heat transfer rate is higher in conduction as compared free convection and heat transfer losses will be reduced.

A B

Fig. 2 Ice making plant tutor (Courtesy by S.I.T.E.R.)

The experiments were carried out initially without PCM at 0˚ C and -11˚ C and calculations of ON/OFF cycle times of the compressor and its power consumption are evaluated. Again this experiment is repeated with PCM as water with 1.5 liters quantity at 0˚ C and the power consumption of compressor is evaluated.

Again for the recommended temperature of -11˚ C mixture of water 75% and ethylene glycol 25 % by volume with total quantity of 1.5 liters melting time, freezing time, total power consumption in compressor for 24 hours are calculated. The same is repeated with mixture of water 72% and propylene glycol 28 % by volume with total 1.5 liters. Then the results are compared and best recommended solution is evaluated.

V. EXPERIMENTAL RESULTS

The experiment is performed with consideration of 0˚C recommended temperature. Fig.3 shows the variation in evaporator temperature for the experiments with water as PCM for the recommended temperature of 0 ˚ C. And fig. 4 shows the variation of evaporator temperature without use of PCM material in evaporator with same recommended temperature. Here only temperature of air will vary with time and cycle time is very small as compared to other experiments with PCM.

Table 1 shows the freezing and melting time of the experiments for 0˚ C without PCM and with PCM as water. First column of the table shows the timing of water with 1.5 liter quantity and total cycle time is 375 minutes. Second column of the table shows the timings of freezing and melting cycle without PCM in the evaporator and total cycle timing is 5 minutes. Table 1 also indicates the total power consumption during the 24 hours of experiments for recommended temperature of 0˚ C. And by the experiment power consumption of the compressor is evaluated which is 0.45 KWh per hour for one hour of continues operation. In this experiment the compressor works only during freezing cycle. So from all these data total power consumption in 24 hours is calculated and % of saving of compressor power is evaluated with comparison of experiment of without PCM. Also experimentally found that compressor consumes 0.2 KWh / hour power without use of PCM. Table also indicates %ON time of compressor ($t_{on}/(t_{on} + t_{off})$) of refrigeration system. Also % power saving in 24 hours with use of PCM as water as compared to running the experiments without PCM is calculated.

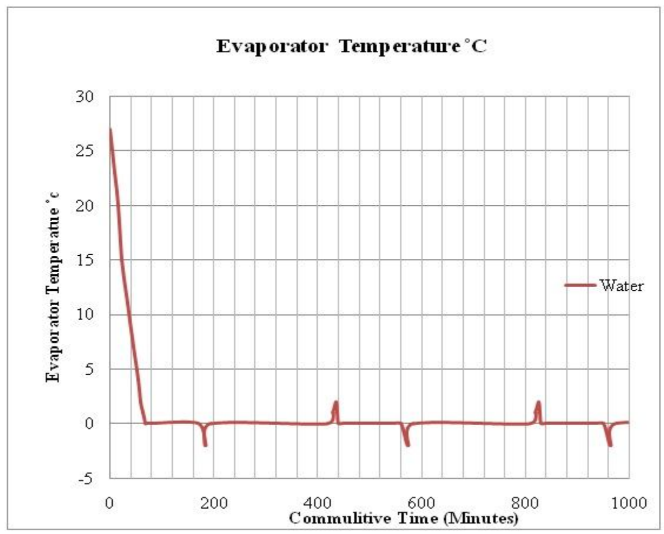

Fig. 3 Variation of evaporator temperature for water as PCM

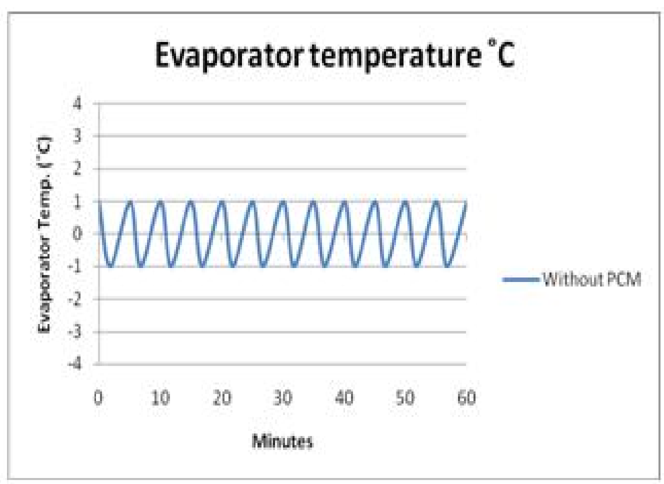

Fig. 4 Variation of evaporator temperature without PCM

TABLE I. RESULT TABLE OF EXPERIMENTS FOR RECOMMENDED TEMPERATURE OF 0˚ C

	Water	*Without PCM*
Freezing time in minutes	125	1.75
Melting time in minutes	250	3.25
Total cycle time in minutes	375	3.25
Power consumption per cycle	0.9375	0.0183
No. of cycle in 24 hours	3.84	288
Total power consumption in 24 hours	3.6	5.28
% ON time of refrigeration system	33.33	35
% power savings in 24 hours	31.8%	--

Figure 5 shows the variation in evaporator temperature for the experiments with PCM (mixture of water and ethylene glycol 25% by volume) and PCM (mixture of water and propylene glycol 28% by volume) for the recommended temperature of -11 ˚C. And figure 7 shows the variation of evaporator temperature without use of PCM material in evaporator with same recommended temperature. Here only temperature of air will vary with time and cycle time of 4.75 minutes is very small as compared to other experiments.

The table 2 shows the analysis of the experiments carried out by the same procedure described above for recommended temperature of -11˚ C. For the experiment without application of PCM to maintain -11˚ C temperature the observed power consumption is 0.3 kWh per hour of operation.

Figure 7 indicated comparison of total power consumption for 24 hours of operation for different recommended temperatures. For the experiments as per the freezing point of the PCM water, ethylene glycol and water mixture and propylene glycol and water mixtures in different proportionate are selected.

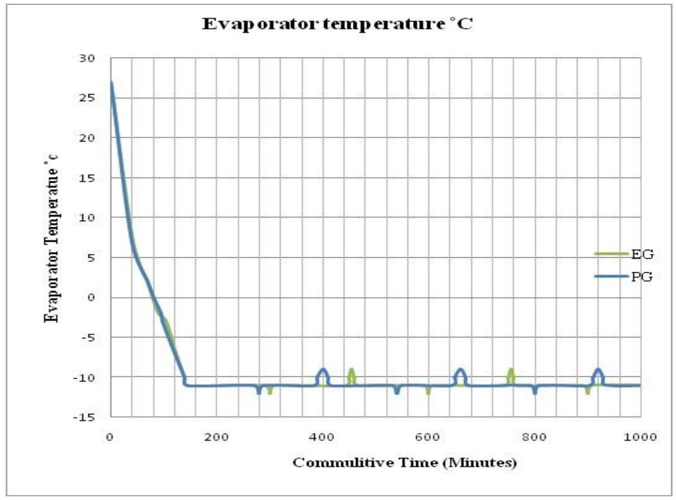

Fig. 5 Variation of evaporator temperature for PCM as mixture of water and ethylene glycol 25% by volume and PCM as mixture of water and propylene glycol 28% by volume

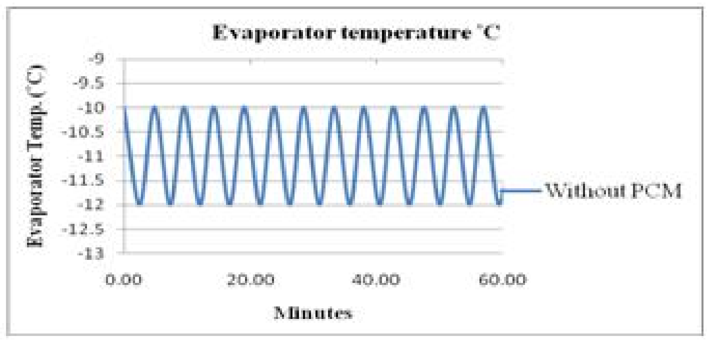

Fig. 6 Variation of evaporator temperature without PCM for recommended temperature of -11˚ C

TABLE II. RESULT TABLE OF EXPERIMENTS FOR RECOMMENDED TEMPERATURE OF -11 ˚ C

	EG	*PG*	*Without PCM*
Freezing time in minutes	160	140	2.5
Melting time in minutes	155	120	2.25
Total cycle time in minutes	315	260	4.75
Power Consumption per cycle (kWh)	1.2	1.05	0.02375
No of cycle in 24 hours	4.57	5.538	303.16
Total power consumption in 24 hours (kWh)	5.48	5.82	7.2
% ON time of refrigeration system	50.79	53.84	52.63
% Power savings in 24 hours	23.83%	19.23%	--

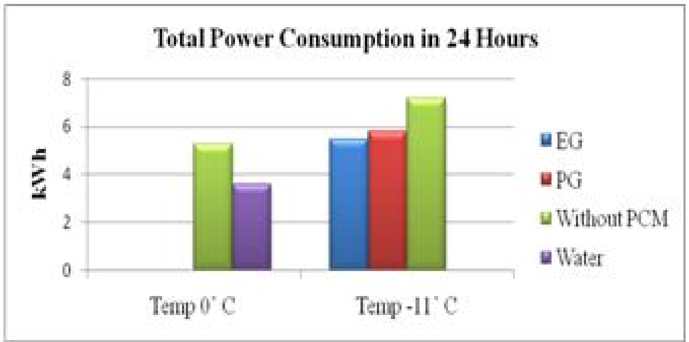

Fig. 7 Variation in total power consumption during 24 hours with different experiments

VI. CONCLUSION

The experimental study of refrigeration system with phase change material shows enhancement of the system performance and reduction of temperature fluctuations in the evaporator.

The integration of latent heat storage maintains the desired temperature of 0 ˚C for 250 minutes with 1.5 liter water as PCM without electrical supply. Experimentally it is found that 31.8% power is saved with water as PCM as compared to run the system without PCM during 24 hours. Some of the known fruits and vegetables like apples, grapes, peaches, pears, plums, lychee, beets, broccoli, carrots, cauliflower, cherries, kiwi, mushroom, spinach, sweet corn, garlics, dry onions etc which can be stored at around 0-2 ˚ C, water can be used as PCM in the evaporator to maintain the recommended temperature of storage as well as power consumption of the system will also decreases.

Now for the storage recommended temperature of -11° C, eutectic mixtures having melting point temperature of -11 °C are selected for the experiments so as the phase change takes place at that particular temperature. For this experiments initially ethylene glycol 25% by volume and water mixture with total 1.5 liter quantity are chosen as PCM. Total power consumption in 24 hours is 5.48 kWh. For same recommended temperature of -11° C another PCM selected for the experiments is mixture of water and propylene glycol 28% by volume with total 1.5 liter quantity. During this experiment for 24 hours of operation using ethylene glycol water mixture 23.83% and by application of propylene glycol water mixture 19.23% of power is saved as compared to evaporator without PCM. So for the cold storage conditions like storage of ice-cream in its cabinet where -11 °C temperature is to be maintained mixture of water and ethylene glycol 25% by volume can be used as PCM to save the power consumption of compressor and maintain the needed temperature in case of power failure also.

The recommended temperature of evaporator or storage depends on the type of the food products or any other storage material. Ethylene glycol with different proportionate should be mixed with water to get the desired melting point of the mixture. This melting point should be slightly below the recommended temperature in evaporator or storage.

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NOMENCLATURE

EG	Ethylene Glycol
PCM	Phase Changing Material
PG	Propylene Glycol
TES	Thermal Energy Storage

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