ISSN 2229-5518

Performance Enhancement of a Domestic Refrigerator using Phase Change Materials

Deni Thomas Boban, Jijo George, Akhil Geo Biju, Binu chacko, Easwaran Nampoothiry K

Abstract—This work investigates about the performance enhancement of a domestic refrigerator by incorporating phase change materials (PCM) inside the evaporator. A U-shaped PCM box is used to contain the PCM, to improve its efficiency and to provide a storage capacity allowing several hours of refrigeration without power supply. This system has been tested with water, ethylene glycol mixture and eutectic solution as PCM. It has been found that the addition of PCM results in an enhanced conduction heat transfer from the PCM to the evaporator coil. The result shows that the performance of the system has improved upto 19%. The energy stoted in the PCM is yielded to the refrigerator during the off time and allows for several hours of continuous operation without power supply. This model shows a 5 to 19% increase in coefficient of performance(COP) and significant decrease in no.of starts and stops of the compressor and consequently of the temperature fluctuation inside the evaporator. The experimental studies with water, ethylene glycol mixture and eutectic solution have confirmed these results.

Index Terms—Coefficient of performance, Compressor on/off cycle, Heat transfer, Domestic refrigerator, Latent heat of fusion, Phase change materials, Thermodynamic analysis

—————————— ◆ ——————————

1 INTRODUCTION

THE household refrigerators are the most extensively used appliances in the present world and its consuming massive portion of the total world energy. In this scenario improving the energy efficiency of household refrigerator is an imperative issue in terms of energy savings. Scientists, engineers, researchers in the field of refrigeration and air conditioning are now involving themselves to develop different technical options for enhancing the energy efficiency of household refrigerators. Following are the well-known technical options in this regard,

1) Improve the performance of compressor
2) Development of heat exchangers having very high effectiveness.
3) Utilization of good insulation materials to decrease heat loss.

. The refrigerant inside the evaporator coil takes the cabinet heat during compressor on mode. During the off mode of the compressor, the temperature inside the evaporator cabinet starts rising due to heat released from the materials inside the refrigerator and also due heat inleak from atmosphere. This on and off makes a temperature fluctuation (temperature rapidly rise and drop) inside the evaporator cabinet which ultimately decrease the quality of the perishable items.

The physical and chemical changes caused the loss of quality of the product. Temperature fluctuations during freez ing are prior responsible of that re- crystallization and surface drying, although the importance of these physical changes decreases at lower storage temperature.

Among the above mentioned technical options, improving the efficiency of heat exchanger (Condenser and Evaporator) has got many researches in this field. So in this work we are using a PCM incorporeated box inside the evaporator of the refrigerator to enhance the heat transfer.

So reduction of temperature fluctuation inside the evaporator cabinet, i.e. make a continuous or stable temperature inside the cabinet would be the most important issue in terms of designing a household refrigerator. A phase change material (PCM) is a latent heat thermal energy storage system which, melting and solidifying at a certain temperature. During the phase change time, the material is capable of storing and releasing large amounts of heat energy and that's why it is called Latent heat storage system (LHS).

NOMENCLATURE

TABLE 1
NOMENCLATURE

Symbol	Quantity
COP	Coefficient of performance(-)
h_1	Enthalpy at compressor inlet(kJ/kg)
h_2	Enthalpy at compressor outlet(kJ/kg)
h_3	Enthalpy at condenser inlet(kJ/kg)
h_4	Enthalpy at condenser outlet(kJ/kg)
P_1	Pressure at evaporator side(bar)
P_2	Pressure at condenser side(bar)
T_1	Temperature at compressor inlet(°C)
T_2	Temperature at compressor outlet(°C)
T_3	Temperature at condenser inlet(°C)
T_4	Temperature at condenser outlet(°C)

2 LITERATURE REVIEW

Earlier works in vapour compression systems comes under two categories: those that focus on the performance

————————————————

• *Deni Thomas Boban, Jijo George, Akhil Geo Biju, Binu Chacko U G Students, Department of Mechanical Engineering Saintgits College of Engineering, Kerala, India*
• *Easwaran Nampoothiry K, Assistant professor, Department of Mechanical Engineering, Saintgits College of Engineering, Kerala, India*

ISSN 2229-5518

improvement and those that focus on the reduction of power consumed.

PCM may also be used in load shedding applications to shift electricity usage to an optimum time. Modelling of air flow and temperature distribution inside cold storage facilities based on Computational Fluid Dynamics (CFD) has been attempted [11]

Cerri (2003) has simulated a domestic refrigerator including cold storage. His model, based on differential equations, was used to determine appropriate operating conditions in order to achieve a minimum electrical power. From his investigation about 12% COP improvement has been achieved by using PCM. Yet, Cerri used a little amount of PCM in his study [1]. Maltini et al. (2004) experimentally investigated the performance of a household refrigerator using a sodium chloride-water mixture as cooling storage system and he was examined that the PCM decreases the temperature fluctuations inside the cabin, leading to a better preservation of food. Here the PCM work as a temperature damper. An experimental analysis and a statistical analysis were performed by Zalba et al. (2004) to examine phenomena involved in a free-cooling system in which cold from outside air is stored in a phase change material during the night and used during the day for air conditioning. Results indicated that the effect with significant influence in the solidification process was the thickness of the PCM. For the melting process, the air temperature had higher influence than the thickness of the PCM [3].

Azzouz et al. (2005) a mathematical model has been established of the vapour compression cycle with the existence of PCM and showed its experimental justification. The results of this model show that using PCM increase the heat transfer from the evaporator and consent to a higher evaporating temperature which ultimately increases the energy efficiency of the system as compared to without PCM [4].

Xie et al (2006) used a CFD package to simulate the velocity and temperature field in a 2D plane through a cold store. These models were constructed for steady state operation with constant cold air inlets to the cold storage areas [11]. Another experimental study carried out by Cheng et al analysed the performance of a fridge-freezer with a PCM fitted around the condenser pipes, which lowered the condensing temperature and produced energy savings of 12% compared to the same fridge-freezer without thermal storage [12].

Wang et al. (2007) have studied a dynamic mathematical model for coupling a PCM heat exchanger with a refrigeration system and, located between the thermal expansion valve and condenser. His model is capable to calculate the dynamic COP and refrigerant states. Azzouz et al. (2008) design and developed a model of an improved refrigerator using phase change material as a cold storage. He found that about 12% COP has been improved and a 25% decrease m the global working time of the compressor [6]. Azzouz et al. (2009) investigated the performance of a household refrigerator by using PCM. He observed that the thermal loads are strongly affected the efficiency of the refrigerator to the presence of PCM. Experimental results also show the PCM allows 5-9 h of continuous operation without power supply as compared to 1-3 h without PCM and depending on the thermal load about 10-30% more COP improvement has been observed. From the above mention discussion it is clear that a very few experimental works of performance improvement of household refrigerator by PCM has been done [7].

Most of the investigations cited above were focused on the heat transfer in the latent heat storage system. There are only few studies that have been reported in the literature on the behaviour of a refrigerator coupled with a phase change material as a slab applied on the entire area of the evaporator. The purpose of this paper is to propose a model for the dynamic behaviour of a refrigerator using a PCM storage system and to perform a parametric study in order to analyse the consequences of the operating conditions on the energy efficiency.

3 Experimental Setup

A conventional household refrigerator is used in the modified form with PCM box located behind the evaporator cabinet to carry out the necessary experiments. The experimental set up comprised with a refrigerator, pressure transducer, pressure gauge, thermocouple, phase change material box

1) Cabinet : Internal volume, 12.5L
2) Evaporator : Mode of heat transfer - Free convection
Material of the coil/tube - Copper tube
Length of cabin-30cm
Breadth of cabin-20cm
Height of cabin-13cm
3) Condenser : Mode of heat transfer
Material of the coil/tube: Steel and wire tube
4) Compressor : Hermetic reciprocating compressor,
LG NR45LAEG 220-240V, 50Hz
5) Expander : Capillary tube (Internal diameter 1 mm)
6) On/off control and self defrost
7) Refrigerant : 1,1,1,2-Tetrafluoroethane (R-134a)

Fig.1 Experimental test rig and setup

Temperatures at various locations (compressor, condenser, evaporator and cabinet) are measured with infrared

ISSN 2229-5518

thermometer. Two pressure transducers are used to measure the evaporation and condensation pressures at the inlet and outlet of the compressor. Temperature at compressor, condenser, evaporator, capillary tube, compartment, PCM, etc were measured. Measurements were carried out by means of infrared thermometer. PCM inclusion in the system affects the evaporation and condensation pressures. Since evaporation and condensation processes are examples of a phase change process, the pressure change in these components are negligible (unless refrigerant superheating or sub cooling takes place in the evaporator or condenser, respectively). Therefore, only two pressure transducers are normally used for measurement in these components. Pressure transducers are fitted at the low pressure and high pressure sides of the refrigerator and as shown in the figure 1.

A U Shaped box is fabricated and is fitted inside the evaporator cabin to contain the phase change material. It is fitted in such a way that it is fully in contact with the evaporator coils. The box is made of galvanized iron sheets with a thickness of 5mm [reference no].The fabricated model of the box are shown in figure 2.

Fig. 2 Fabricated PCM box fitted inside cabin

The experiments were carried out initially without PCM 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 400ml quantity at 0˚ C and the power consumption of compressor is evaluated.

Again for the recommended temperature mixture of water 90% and ethylene glycol 10 % by volume with total quantity of 400 ml melting time, freezing time, total power consumption in compressor for 24 hours are calculated. Also eutectic with the same composition as ethylene glycol is used as PCM. Then the results are compared and best recommended solution is evaluated.

4 Selection of PCM

A phase-change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units PCMs latent heat storage can be achieved through liquid–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 due to the large volumes or high pressures required to store the materials when in their gas phase [10].

The selection criterias are follows

1) Thermodynamic properties
2) Melting temperature should be in the desired operating temperature range
3) High latent heat of fusion per unit volume
4) High specific heat, high density and high thermal conductivity.
5) Safe and non-reactive

5 Results And Discussions

The experiment was conducted using different phase change materials in order to evaluate the performance enhancement of the household refrigerator. Temperature and pressure are two important parameters considered for the analysis.The data were analyzed according to the theory of refrigeration system and the result were tabulated. Since the objective of this work was to investigate the COP of the domestic refrigerator, therefore it's also closely related to refrigeration capacity and compressor power produced by the system.

The effects of employing different types of PCMs were discussed below. Various PCMs used are

1) Water (200ml and 400ml)
2) Ethylene glycol solution (200ml and 400ml)
3) Eutectic solution (200ml and 400ml)

The above stated three PCMs affect the system performance based on the difference in their melting point and heat carrying capacity. Water is having a phase change temperature of 0°C and both of ethylene glycol solution and eutectic solution possess below 0° C. The exact range value for ethylene glycol solution is -5°C and eutectic solution with -4°C. The following table shows the % increase in COP using different PCM's.

TABLE 2
PERCENTAGE IMPROVEMENT IN COP

Sl No			COP	% increase in COP
1	Without PCM		5.83	-
2	PCM	Water	6.3	7
3		Ethylene glycol mxture	6.52	11
4		Eutectic solution	6.96	19

Out of the three PCMs, Eutectic solution shows higher COP because of its lower phase change temperature. Eutectic solution starts to change its phase at -5°C while water at 0°C and ethylene glycol at -4°C. As a result Eutectic solutions stores more latent heat by phase change than water during the off mode of the compressor and transfer this heat to the refrigerant by faster conduction method during on period of compressor which eventually increases the evaporation temperature also the evaporation pressure of the evaporator.

Also the average compressor on time per cycle is significantly reduced for the system with PCM with respect to without PCM and this ultimately reduce the energy consumption of the system. Among the selectedPCMs, the percentage of compressor running time for Eutectic and ethylene glycol is higher than water at zero load condition

Based on the results, the addition of PCM prolongs the compressor OFF time and enhances the COP of the system. Based on the rsults, 5–19% enhancement of COP can be achieved by the application of PCM inside the evaporator cabinet. The amount of enhancement strongly depends on the ambient temperature and type of PCM used. PCM at the evaporator increases evaporation temperature (prevents evaporation temperature drop during phase change) which in turn increases compressor inlet temperature. Thus, the performance enhancement of a system equipped by PCM at evaporator side is somewhat limited by the high condensation temperature. A PCM-equipped refrigerator has smaller ON-time ratio as well as higher COP. These two results are significantly important for performance enhancement of the system. Moreover, due to its high thermal inertia, the rate of temperature change in compartment is lower and better food quality is guaranteed by presence of PCM. This feature not only helps the regular performance of the system, but also is greatly helpful for defrost. Thermal storage by PCM at evaporator keeps compartment cold for longer periods of time. In case of a power failure, the thermal storage compensates the heat gain through the compartment walls.

Moreover, PCM adds the thermal capacity of the compartment, which is of great importance if the refrigerator door is opened during power outage. Since door opening from hot ambient air flow into the compartment, an ordinary refrigerator, even with the maximum possible insulation, cannot go back to a colder temperature after the air exchange. However, when PCM is used at evaporator it absorbs heat from compartment air, allowing lower air temperature. This is an important feature in case of rolling blackouts since the refrigerator can perform in such a scenario.

Graph below shows the variation of evaporator temperature without and with the additions of several phase change materials like water, ethylene glycol mixture and eutectic solution.

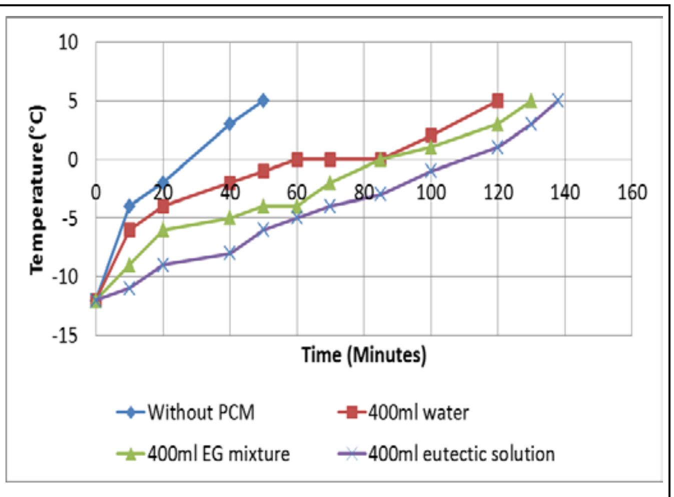

Fig. 3 Variation of evaporator temperature with time

Figure 3 shows the effect of PCM on average air temperature inside the cabin at no load condition which shows the average temperature fluctuation for a specific time is significantly reduced for the system with PCM in respect to without PCM. The compressor on-off mode is activated by the thermostat which is located in the evaporator compartment .In case of Base system (ie, without PCM), during compressor off mode the cabinet temperature rises quickly due to the heat inlet by the door opening and intake heat from the surroundings due to ambient conditions. As a result the thermostat triggers the compressor in on mode quickly.

On the other hand when PCM is used, this excessive heat is absorbed by PCM due to its phase change nature (solid to liquid) which does not allow the compartment temperature to rise quickly. A low enough temperature near to the desired point inside the cabinet is maintained during the whole melting period of PCM and the compressor is not triggered in on mode quickly by the thermostat. As a result a prolonged off mode of compressor is obtained. This longer off mode of compressor ultimately reduces the number of on-off cycle significantly which ultimately reduces temperature fluctuation inside the evaporator cabinet for a certain period of time.

Figure 4 explains the variation in COP of refrigerator using different PCM's

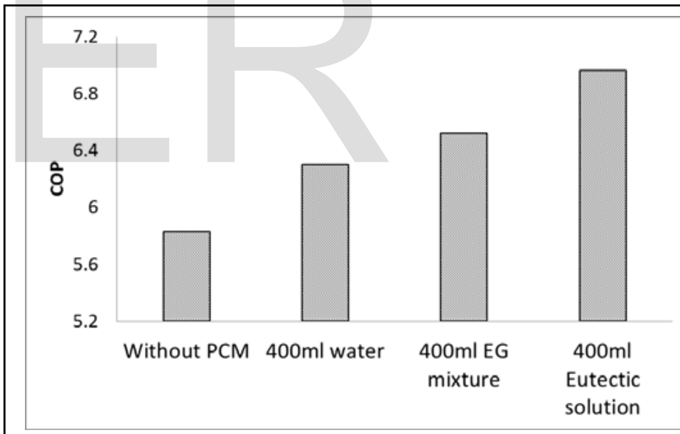

Fig. 4 Variation of COP using different PCMs

The phase change material incorperated system gives 5–19% increase in the coefficient of performance and a significant decrease in the number of starts and stops of the compressor and consequently of the temperature fluctuations inside the refrigerated cell. Experimental tests with water and both PCM's with a melting temperature of -4˚C and -5˚C have confirmed these results. The autonomy of the device allowing safe food preservation without electrical supply ranges between 2 and 3 h, zero thermal load , with a only 5 mm thick slab.

6 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 using three different phase change materials of different quantities. Depending on the PCM around 19% COP improvement has been achieved by the PCM respect to without PCM. With the increase of the quantity of PCM, COP increases about 6%. The maximum COP improvement is 19% for eutectic solution followed by ethylene glycol and water. The recommended temperature of evaporator or storage depends on the type of the food products or any other storage material. This melting point should be slightly below the recommended temperature in evaporator or storage.

The integration of 400 ml phase change materials inside the evaporator cabin maintains the desired temperature of 5˚C for 40 minutes, 70 minutes, 90 minutes for water, ethylene glycol mixture and eutectic solution respectively without electrical supply. It has been found that the addition of the phase change material results in an enhanced conduction heat transfer from the evaporator to the PCM in addition to the natural convective heat transfer to the air. The experiments results suggested that a eutectic solution would need to be employed to maintain the compartment temperature within the required range for domestic refrigerators.

These results show that PCM could be utilized to limit temperature rises during loss of electrical power, which may occur due to an accidental power loss or done purposely to achieve electrical load shifting. Since the conduction heat transfer process is faster than the free convection process the cooling coil temperature does not require dropping very low to maintain desired cabinet temperature. As a result the evaporator works at high temperature and pressure with PCM.

References

[1] Cerri. G, "Identification of Domestic Refrigerator Models including Cold Storage", proceedings of the 20th international congress of refrigeration, 2003, Washington, USA

[2] Maltini et al, "Design and performances of a constant temperature compartment for domestic refrigerator", proceedings of the 9th international congress on engineering and food, 2004, Montpellier, France

[3] Belen Zalba et al, "Free cooling of builings with phase change materials", *International Journal of Refrigeration*, 2004, pp. 839–849

[4] Azzouz K, D. Leduq, J. Guilpart and D. Gobin, "Improving the energy efficiency of a vapor compression system using a phase change material", proceedings of the 2nd conferece on phase change material and slurry, 2005, Yverdon-les-Bains, Switzerland

[5] Wang et al," The novel use of phase change materials in refrigeration plant part2: dynamic simulation model for the combined system", Applied Therm. Eng.27, 2007, pp. 2902-2910.

[6] Azzouz K., Leducq D., Gobin, D., "Performance enhancement of a household refrigerator by addition of latent heat storage", *International Journal of Refrigeration*, 2008, vol. 31(5), pp. 892–901.

[7] Azzouz K, D. Leduq and D. Gobin, "Enhancing the performance of houdehold refrigerators with latent heat storage: An experimental investigation", *Int. J. Refrigeration*, 2009, pp. 1634-1644

[8] C. Marques b, G. Davies a, G. Maidment a, J. Evans a, I. Wood "The use of phase change materials in domestic refrigerator applications", *Refrigeration and air conditioning*, 2013, vol. 3 issue 9

[9] Xiao X, Zhang P, Li M., "Effective thermal conductivity of open-cell metal foams impregnated with pure paraffin for latent heat storage", *Int J Thermal Science*, 2014, vol. 81, pp. 94–105

[10] Atul sharma, V.V. Tyagi et al,"Review on thermal storage with phase change materials and applications", *Renewable and Sustainable Energy Reviews*, 2009, vol-13, pp. 318-345

[11] Xie, J., Qu, X.H., Shi, J.Y., Sun, D.W., "Effects of design parameters on flow and temperature field of a cold store by CFD simulation", *J. Food Eng*., vol-77, pp. 355-363

[12] Cheng W.L, Mei B.J et al, "A novel household refrigerator with shapestabilized PCM heat storage condensers: An experimental investigation", *J. Energy*, 2011, pp. 5797-804