ISSN 1996-3343

Asian Journal of Applied Sciences

http://knowledgiascientific.com

Knowledgia SCIENTIFIC
A Place to Publish Outstanding Research

Asian Journal of Applied Sciences 6 (2): 56-67, 2013
ISSN 1996-3343 / DOI: 10.3923/ajaps.2013.56.67

Effect of Phase Change Material on Performance of a Household Refrigerator

Md. Imran Hossen Khan and Hasan M.M. Afroz
Department of Mechanical Engineering, Dhaka University of Engineering and Technology (DUET), Gazipur1700, Bangladesh

Corresponding Author: Md. Imran Hossen Khan, Department of Mechanical Engineering, Dhaka University of Engineering and Technology (DUET), Gazipur1700, Bangladesh

ABSTRACT

Experimental investigation of the performance improvement of a household refrigerator using Phase Change Material (PCM) has been carried out. The PCM is a latent heat thermal energy storage system which could be a new option of performance improvement of a household refrigerator by enhancing heat transfer of the evaporator. The PCM is located behind the five sides of the evaporator cabinet in which the evaporator coil is immersed. The refrigeration system has been tested with two different PCMs (Water and Eutectic solution of melting point 0 and - 5°C, respectively) at different thermal loads. Experimental results show that the Coefficient of Performance (COP) of the refrigeration cycle with PCM is considerably higher than that of without PCM. Depending on the types of PCM and thermal load, around 20-27% COP improvement of the refrigeration cycle has been observed with PCM in respect to without PCM. With the increase of the quantity of PCM (0.003-0.00425 m^3) COP increases about 6%. Between two different PCMs the COP improvement for Eutectic solution is higher than Water. The experimental results with PCM confirm that, depending on the thermal load and the types of PCM average compressor running time per cycle is reduced significantly and it is found about 2-36% as compared to without PCM.

Key words: Phase change material, household refrigerator, energy consumption, COP, compressor

INTRODUCTION

Refrigeration and air conditioning systems are directly and indirectly responsible of present energy crisis problem as their use in household, commercial and transportation sector is increasing rapidly. Household refrigerators are the most widely used appliances of present world and its consuming massive portion of the total world energy. Liu *et al.* (2004) investigated the energy consumption of refrigerator-freezers and he found about 15-20% of energy has been consumed by a refrigerator. Mahlia *et al.* (2003) examined that about 26% of Malaysian energy has been consumed by refrigerator-freezer. In developed countries, refrigerator production and application have come to saturation and they are growing up rapidly: total production rose 30% in 2000 (Billiard, 2005). In this situation improving the energy efficiency of house hold refrigerator is an important issue in terms of energy savings. Scientists, engineers and researchers in the field of refrigeration and air conditioning are now involving themselves to develop different technical options for improving the energy efficiency of household refrigerators. Followings are the well known technical options in this regard:

- Improve the efficiency of compressors
- Developed an effective heat exchangers by attractive the heat transfer
- Developed a good insulation for the cabinet and door insulation to decrease heat losses

Among the above mentioned technical options, improving the efficiency of heat exchangers (Condenser and Evaporator) has got intense scrutiny. Many researchers are involved in improving the heat transfer performance of this heat exchanger in many different ways like:

- A Liquid-suction heat exchangers is incorporated in condenser
- Designing loop heat pipe based evaporator
- Using micro fin tubes for both condenser and evaporator, etc.

Using Phase Change Material (PCM) as a latent heat thermal energy storage system could be a new option of performance improvement of a household refrigerator by enhancing heat transfer of the evaporator.

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. 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. 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. However, none of the investigation was carried out to examine the effects of the PCM heat exchanger on the refrigeration system performance. Azzouz *et al*. (2005) a mathematical model has been established of the vapor 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. The PCM stored the energy is yielded to the refrigerator cell during the off cycle and allows for a number of hours of continuous operation without power supply. 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 72% COP has been improved and a 25% decrease in the global working time of the compressor. 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. Concerning that this study is devoted to obtain clear concept and more experimental data of performance improvement of a house hold refrigerator by using different PCMs of different quantities.

EXPERIMENTAL METHODOLOGY

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 and data acquisition system. Figure 1 and 2 show the details of the location of the PCM box with the evaporator cabinet. The PCM box is made up by Galvanized Iron (GI) sheet have 1 mm thickness which is 0.56 m width, 0.44 m height and 0.47 m depth. The evaporator cabinet box of outer volume 0.04 m^3 with cooling coil (Fig. 1a) is inserted into the empty PCM box of internal volume 0.11 m^3 (Fig. 1b). The thickness of the annular space between PCM box and evaporator cabinet box is 0.006 m. The open face of the annular space is sealed by a third sheet

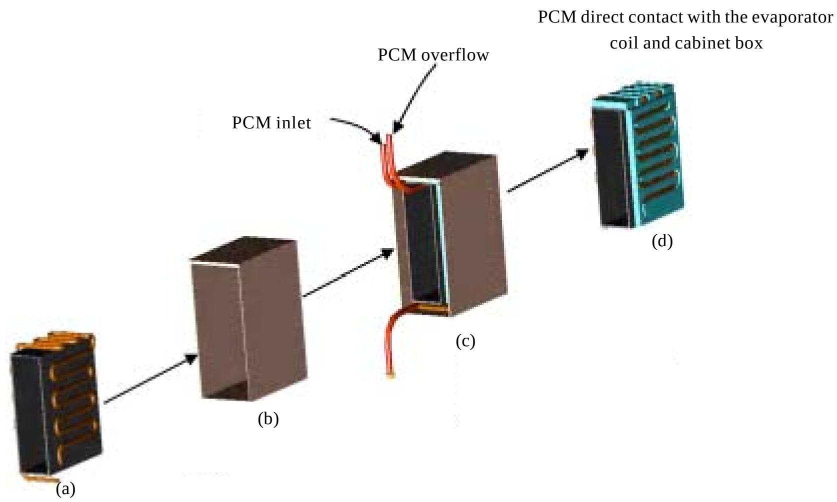

Fig. 1(a-d): Arrangement of the PCM based evaporator, (a) Evaporator cabinet with coil (b) Empty PCM box (c) Evaporator box Inserted into the PCM box and (d) Shape of solid PCM phase change (liquid to solid)

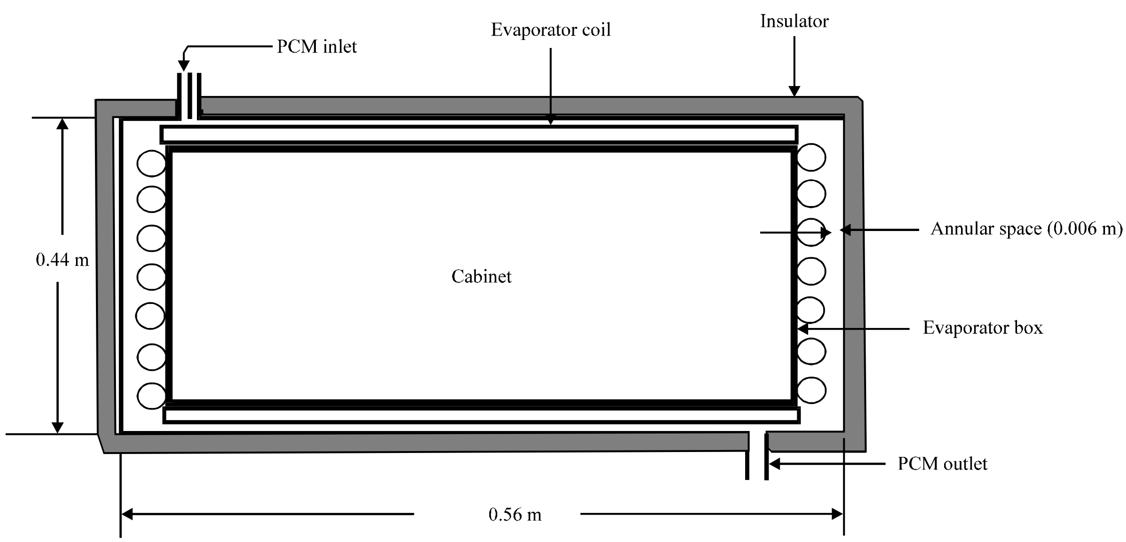

Fig. 2: Front View of the evaporator cabinet with PCM box

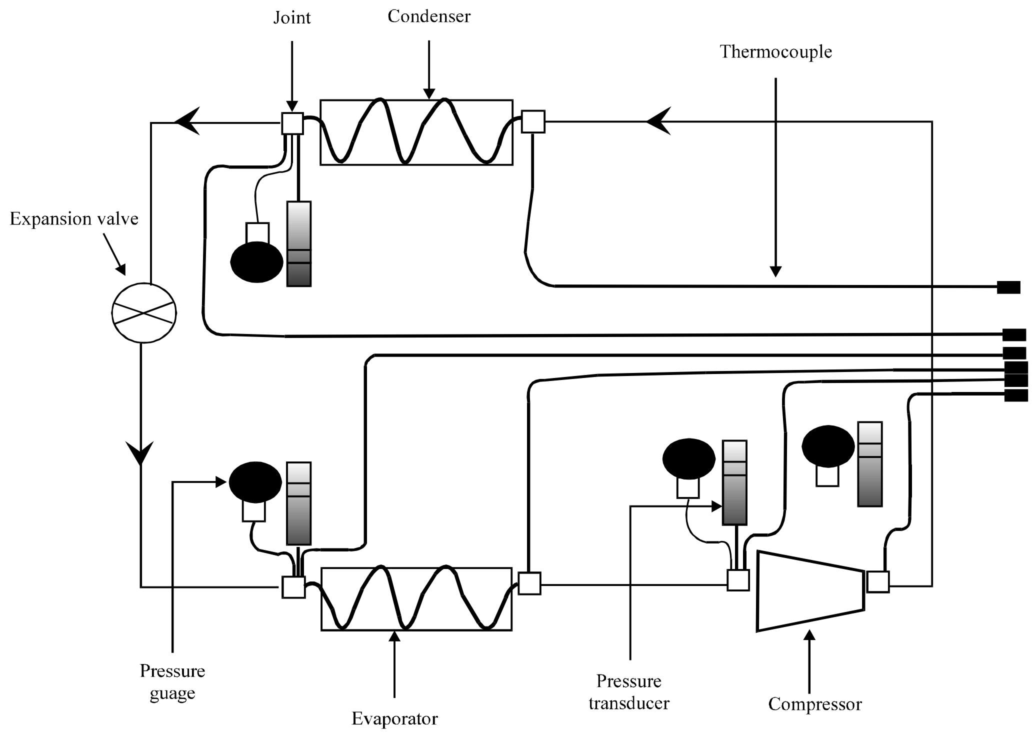

Fig. 3: Location of pressure transducer, pressure gauge and thermocouple

metal. Two copper tubes are attached with the top of the annular space for PCM supply in the box and to maintain the overflow. Another tube is attached in the bottom of the annular space to discharge the PCM if necessary. Figure 3 shows details circuitry of the setup. The modified PCM based refrigerator has a single evaporator cabinet with a single door. The followings are the major technical specifications of the refrigerator:

- **Cabinet:** Internal volume, 0.03 m^3
- **Evaporator:** Mode of heat transfer-free convection, Linear length of the coil/tube: 12.2 m, Internal and external diameter of the tube: 0.0762 and 0.0772 m, respectively, Material of the coil/tube: Copper tube
- **Condenser:** Mode of heat transfer-Free convection, Linear length of the coil/Tube: 5.8 m, Internal and external diameter of the tube: 0.003 and 0.004 m respectively, Material of the Coil/tube: Steel and wire tube
- **Compressor:** Hermetic reciprocating compressor, HITACHI FL 1052-SK, 13 FL 220-240 V, 50 Hz
- **Expansion device:** Capillary tube (Internal diameter 1 mm)
- On/off control and self defrost
- **Refrigerant:** 1,1,1,2-Tetrafluoroethane (R-134a)

Temperatures at various locations (compressor, condenser, evaporator and cabinet) are measured with K-type (copper-constantan) thermocouples having 0.0005 m diameter as shown in Fig. 3. Three thermocouples are also positioned at the bottom, middle and the top of the PCM in the left face of the cabinet to measure the temperatures of PCM. The uncertainty of the temperature measurements by the thermocouples is estimated to be ±2.78% with respect to a high precision (0.002°C) thermometer (beg man thermometer) which can be found in the Table 1. Two pressure transducers are used to measure the evaporation and condensation pressures at the inlet and outlet of the compressor. Another pressure transducer is placed at the inlet of the evaporator to measure the pressure drop in the evaporator section. Four pressure gauges are used to cross check the pressure measurements of the pressure transducer and the deviations have been found within ±0.03 kg cm^{-2}. The location of all of the pressure transducers and pressure gauges are shown in Fig. 3. A heater is used in the cabinet to do experiments at different thermal loads. The heater is located at the bottom of the cabinet box which is linked with a variable voltage transformer (variac) to control the supply voltage for required thermal load variation into the cabinet. A K-type thermocouple is used for the measurement of the air temperature within the cabinet which is located at the center of the cabinet space. A thermostat is used to drive the compressor cycling; the thermocouple of the thermostat is located at the centre of the cabinet. The experimental set-up is equipped with a data acquisition system linked to a personal computer which allows a high sampling rate and the monitoring of all the measurements made by means of the thermocouples. The experiments have been carried out in a room where the temperature and humidity are maintained constant with the aid of air conditioner. All the data have been collected from the data acquisition system after ensuring the steady state condition of the refrigerator. To obtain the steady state condition the system is allowed to run for several minutes (about 70 min).

Two types of PCMs are used in this experiment. Table 2 shows their melting temperature and latent heat of fusion.

Experimental conditions: Experiments were carried out under four different thermal loads with two different PCMs of different quantities. Table 3 shows the details of the experimental conditions.

Table 1: Estimated uncertainties of measurement

Measured parameter	Measuring device	Uncertainty
Temperature	Thermocouples	±2.78%
Pressure	Pressure transducer	±0.01 bar
Pressure	Pressure gauge	±0.03 kg cm^{-2}

Table 2: List of phase change material (PCM) used in this experiment

PCMs	Melting temperature (MT) (0 C)	Latent heat of fusion (kJ kg^{-1})
Distilled water (H_2O)	0	333
Eutectic solution (90% H_2O+10% NaCl), (%wt)	-5	289

Table 3: Experimental conditions

Types of PCM	Quantity of PCM (m^3)	Test time (min)	Thermal load (Watt)	Ambient Temp. (°C)	Cabinet setting Temp. (°C)
Without PCM	-	121	0, 5, 10 , 20	22.8-23.8	-5
Water	0.003, 0.00425	121	0, 5, 10 , 20	22.8-23.8	-5
Eutectic sol.	0.003, 0.00425	121	0, 5, 10 , 20	22.8-23.8	-5

EXPERIMENTAL RESULTS AND DISCUSSION

The effects of different PCMs of different quantities at different thermal loads on the performance parameter of house hold refrigerator are given below:

Effect of PCM on coefficient of performance (COP)

Figure 4 and 5 show the effects of different PCMs on COP improvement at different thermal loads. The followings are the significant findings:

- Depending on the PCM and thermal load around 20-27% COP improvement has been achieved by the PCM in respect to without PCM
- With the increase of the quantity of PCM (0.003-0.00425 m^3) COP increases about 6%

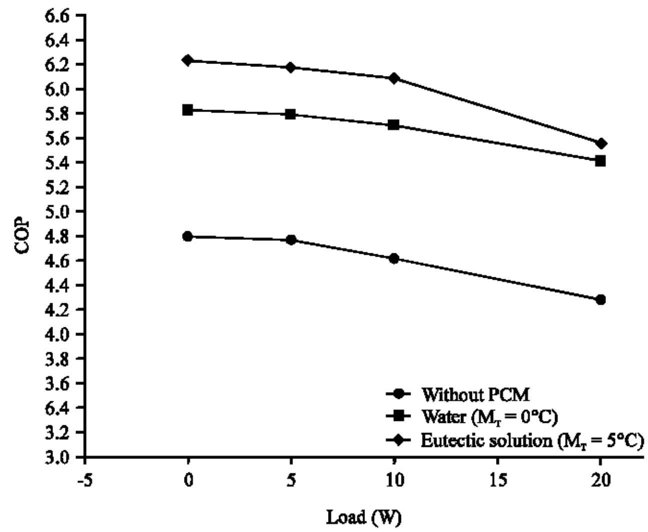

Fig. 4: Effect of PCM on COP at different thermal load (Q = 0.00425 m^3)

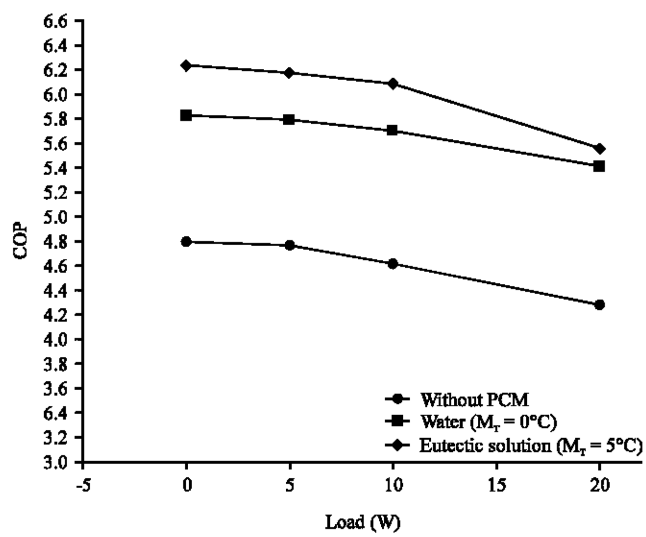

Fig. 5: Effect of PCM on COP at different thermal load (Q = 0.003 m^3)

- Among the two PCMs, the COP improvement with Eutectic-1 is higher than water
- In both the cases of without PCM and with PCM the COP is higher at low thermal load while it decreases with the increase of thermal load

The COP of a refrigeration cycle is defined by the Eq. 1:

$$\text{COP} = \frac{\text{Cooling effect}}{\text{Compressor work}} = \frac{h_1 - h_4}{h_2 - h_1} \tag{1}$$

where, h_1, h_2, h_4 is the enthalpy (kJ/kg) of compressor suction, compressor discharge and evaporator inlet, respectively. The enthalpy values at the corresponding pressure and temperature are calculated by using “REFPROP vs.8.0 (Lemmon *et al.* 2007)”.

Figure 6 shows the refrigeration cycle change with PCM in comparison to without PCM on the p-h diagram.

During the compressor running time the refrigerant takes the chamber heat by free convection in case of without PCM which is slower heat transfer process in respect to conduction process. For that reason the operating temperature of the cooling coil drops very low to maintain the desired cabinet temperature. But with PCM most of the heat in the cabinet is stored in the PCM during compressor off time and this heat is extracted by the refrigerant through conduction during compressor running time. Since 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

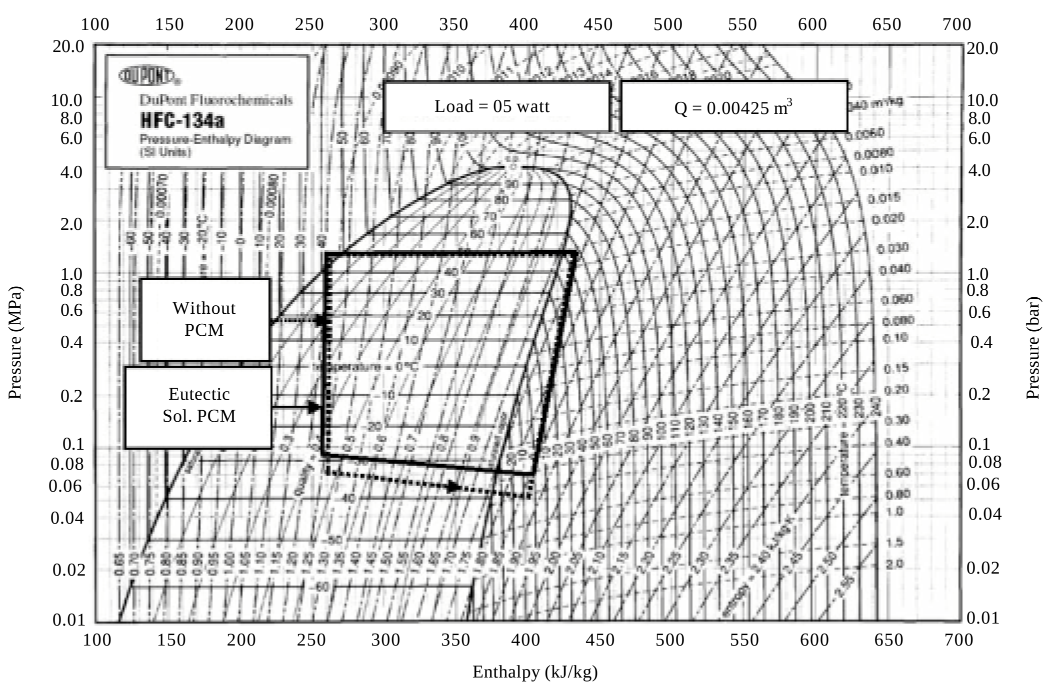

Fig. 6: Pressure enthalpy (p-h) diagram of R-134a refrigerant with and without PCM

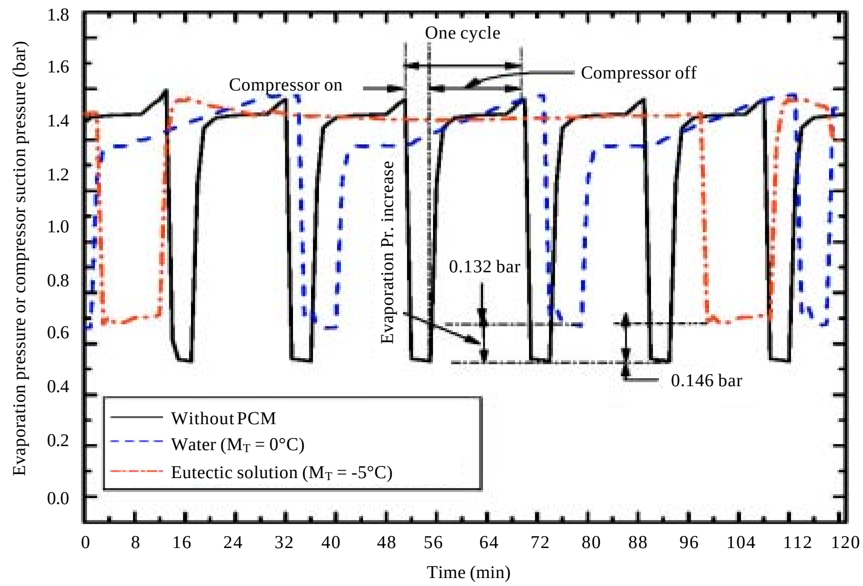

Fig. 7: Effect of PCM on evaporating pressure of the system. Load ($Q = 0.00425\ m^3$)

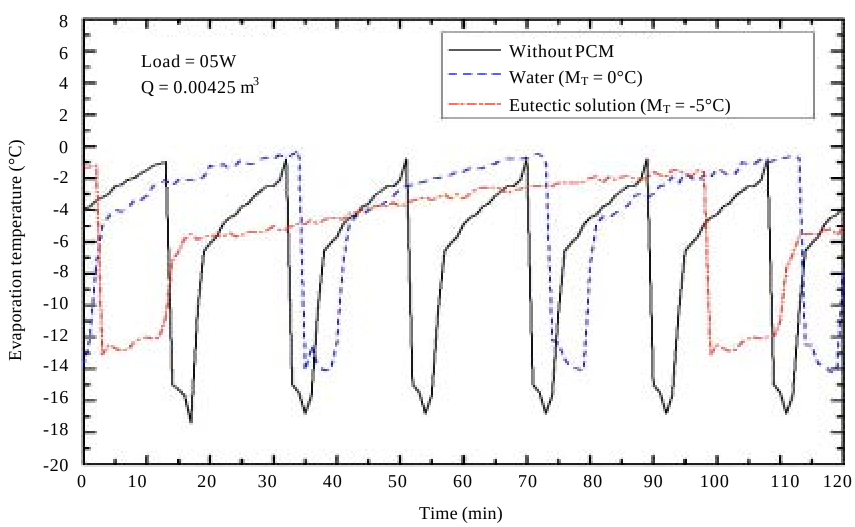

Fig. 8: Effect of PCM on evaporating temperature of the system (Load = 05 W, $Q = 0.00425\ m^3$)

temperature. As a result the evaporator works at high temperature and pressure with PCM as shown in the Fig. 7-10. From Fig. 7 it can be observed that the increase of evaporation pressure for Eutectic solution is 0.146 bar and for water is 0.132 bar with respect to without PCM.

Moreover, due to high operating pressure and temperature of the evaporator the density of the refrigerant vapor increases, as a result the mass flow extracted from the evaporator by the fixed volumetric rate compressor is higher than without PCM. Table 4 shows the refrigerant thermo-physical properties in the evaporator during different test runs. In all the cases the results show that the density of the refrigerant vapor entering the compressor is higher than without PCM and, as a consequence, a higher refrigerating capacity is obtained.

Table 4: Average values of the thermo physical properties of refrigerant for different run

	Load	Evaporation pressure (P_{ev}) (bar)			Evaporation temperature (T_{ev}) (°C)			Vapor density (ρ) (kg m^{-3})		
Run	(W)	Without PCM	Water	Eutectic solution	Without PCM	Water	Eutectic solution	Without PCM	Water	Eutectic solution
1	00	0.574	0.684	0.690	-7.5	-0.5	-0.2	2.69	3.13	3.16
2	05	0.593	0.688	0.711	-7.3	-0.4	-0.1	2.78	3.15	3.26
3	10	0.606	0.708	0.740	-3.3	0.6	1.0	2.80	3.23	3.38
4	20	0.623	0.726	0.782	-2.7	0.9	1.8	2.87	3.31	3.56

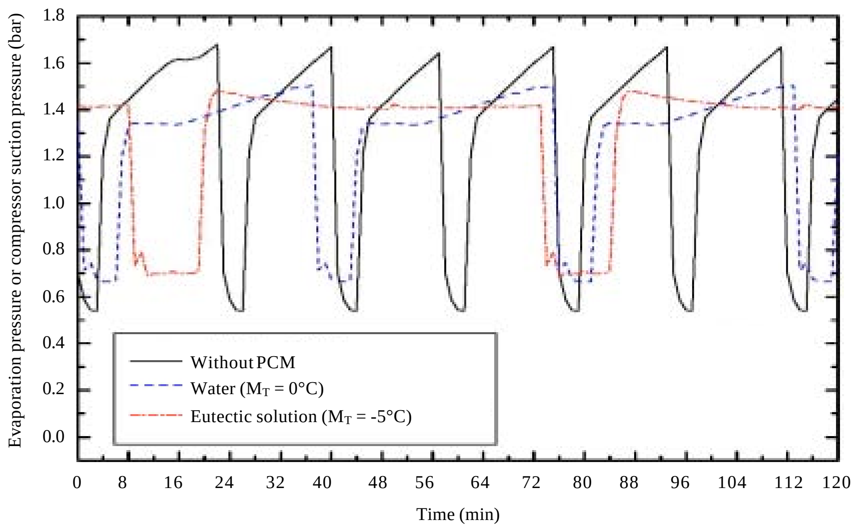

Fig. 9: Effect of PCM on evaporating pressure of the system (Load = 05 W, Q = 0.00425 m^3)

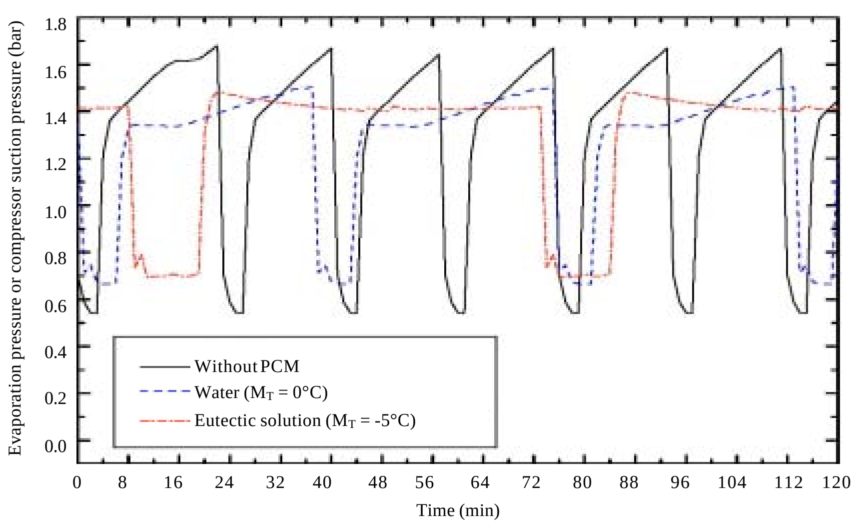

Fig. 10: Effect of PCM on evaporating temperature of the system (Load = 05 W, Q = 0.00425 m^3)

Figure 4 shows the effects of 0.00425 m^3 of PCM on the COP of the system and Fig. 5 shows the same with 0.003 m^3 of PCM. From the comparison of these figures it can be observed that the COP with 0.00425 m^3 of PCM is higher than that with 0.003 m^3 of PCM which is simply for the higher total latent heat transfer of higher quantity of PCM.

Between the two 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. 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 ultimately increases the evaporation temperature also the evaporation pressure of the evaporator as shown in the Fig. 7-10.

In both the cases of without PCM and with PCM, COP decreases with the increase of thermal load; this is because of higher operating temperature and pressure of condenser. This higher operating temperature and pressure decreases the sub cooling effect of the condenser. As a result refrigeration capacity is decreased. Moreover, higher operating pressure of the condenser mean higher compressor work done which reduces the COP of the system.

Cerri (2003) has simulated a domestic refrigerator including cold storage and he found about 12% increase with PCM as compared to without PCM. Azzouz *et al.* (2009) investigated the performance of a household refrigerator by using PCM and he found depending on the thermal load about 10-30% more COP improvement has been observed with PCM as compared to without PCM. From the present research it is clearly observed that depending on the PCM and thermal load around 20-27% COP improvement has been achieved by the PCM in respect to without PCM which is almost similar to the findings of Azzouz *et al.* (2009) that show good agreement.

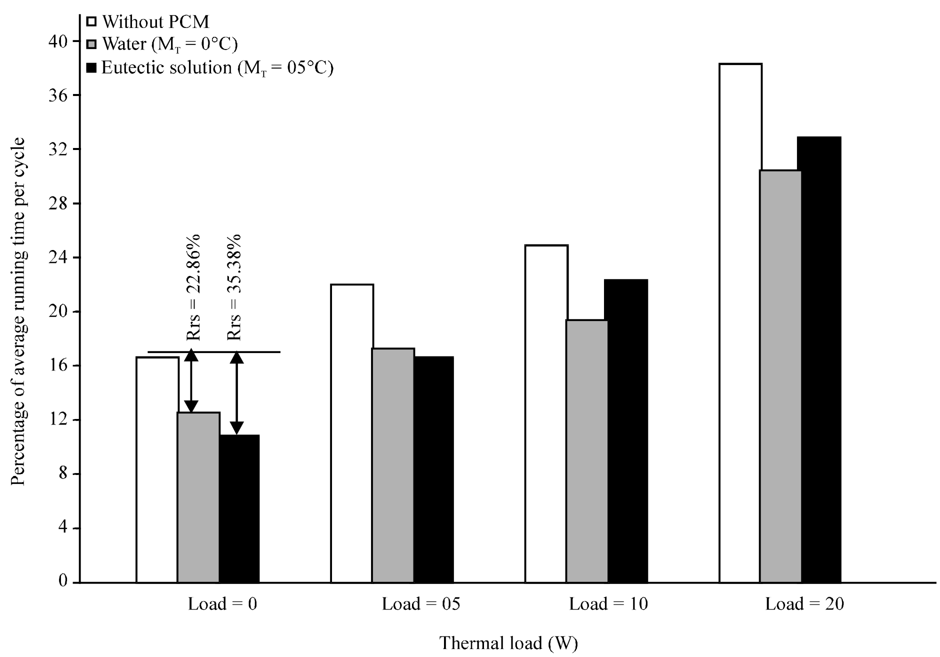

Fig. 11: Effect of PCM on compressor running time at different thermal loads (Q = 0.00425 m^3), Rrs = Relative running time savings

Effect of PCM on compressor running time at different thermal load: Figure 11 shows percentage of average compressor running time per cycle at different thermal loads. The followings are the significant findings:

- Average compressor running time per cycle is significantly reduced for the system with PCM in respect to without PCM which ultimately reduce the energy consumption for the system with PCM
- Depending on the thermal load and the types of PCM the reduction of average compressor running time per cycle is found about 2-36% as compared to without PCM
- Among the two PCMs, the percentage of compressor running time for Eutectic-1 is higher than Water at low load condition. In case of high load opposite result has been observed

At lower thermal load (0-5 W) the relative compressor running time savings for Eutectic-1 is better as compared to another PCMs, this is because of their higher melting point (-5°C) which enhanced higher heat transfer rate and ultimately prolonged the off cycle of the compressor as compared to on cycle. As a result percentage of running time reduced. In case of water at zero load it is does not participate any phase change process because of its lower melting temperature (0°C) which ultimately reduces off cycle as compared to on cycle, as a result increase the percentage of running time.

At higher thermal load this phenomena is completely changed, where water shows better performance than other PCMs. At high thermal load of the cabinet some heat is extracted by solid water PCM during the compressor on mode and participate in phase change partially before reaching the thermostat setting temperature (-5°C). As a result, due to higher latent heat of vaporization of water, it shows better performance as compared to another two PCMs.

Azzouz *et al.* (2008) design and developed a model of an improved refrigerator using PCM and found that decrease the compressor running time about 25% with PCM as compared to without PCM. From the present research it is clearly observed that depending on the PCM and thermal load decrease the compressor running time about 2-36% has been achieved by the PCM in respect to without PCM which is almost similar to the findings of Azzouz *et al.* (2008) that show good agreement.

CONCLUSION

Experimental tests have been carried out to investigate the performance improvement of a household refrigerator using three different phase change materials of different quantities at different thermal loads. Depending on the PCM and thermal load around 20-27% COP improvement has been achieved by the PCM in respect to without PCM. With the increase of the quantity of PCM (0.003-0.00425 m^3) COP increases about 6%. The COP improvement with PCM in comparison with no PCM maintain the sequence as Eutectic solution>Water. In case of without PCM and with PCM, the COP is higher at low thermal load while it decreases with the increase of thermal load. Depending on the thermal load and the types of PCM average compressor running time per cycle is reduced significantly and it is found about 2-36% as compared to without PCM.

NOMENCLATURE

COP	=	Coefficient of performance
h	=	Enthalpy (KJ/kg)
L	=	Load (Watt)
M_T	=	Melting temperature (°C)
PCM	=	Phase change material
P_{ev}	=	Evaporation pressure (bar)
Q	=	Quantity of PCM (m^3)
R	=	Refrigerant
Temp.	=	Temperature (°C)
T_{ev}	=	Evaporation temperature (°C)
ρ	=	Density (kg/m^3)
Subscript		
ev	=	Evaporator

REFERENCES

Azzouz, K., D. Leducq, J. Guilpart and D. Gobin, 2005. Improving the energy efficiency of a vapor compression system using a phase change material. Proceedings of the 2nd Conference on Phase Change Material and Slurry, June 15-17, 2005, Yverdon-les-Bains, Switzerland.

Azzouz, K., D. Leducq and D. Gobin, 2008. Performance enhancement of a household refrigerator by addition of latent heat storage. Int. J. Refrigeration, 31: 892-901.

Azzouz, K., D. Leducq and D. Gobin, 2009. Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation. Int. J. Refrigeration, 32: 1634-1644.

Billiard, F., 2005. Refrigerating equipment, energy efficiency and refrigerants. Bull. Int. Inst. Refrig., 85: 12-25.

Cerri, G., 2003. Identification of domestic refrigerator models including cool storage. Proceedings of the 20th International Congress of Refrigeration, August 17-22, 2003, Washington, DC., USA.

Lemmon, E.W., M.L. Huber and M.O. McLinden, 2007. NIST reference fluid thermodynamic and transport properties-REFPROP: Version 8.0, user's guide. NIST Standard Reference Database 23. http://www.nist.gov/srd/upload/REFPROP8.PDF.

Liu, D.Y., W.R. Chang and J.Y. Lin, 2004. Performance comparison with effect of door opening on variable and fixed frequency refrigerators-freezers. Applied Therm. Eng., 24: 2281-2292.

Mahlia, T.M.I., H.H. Masjuki, R. Saidur, I.A.Choudhury and A.R. NoorLeha, 2003. Projected electricity savings from implementing minimum energy efficiency standard for household refrigerators in Malaysia. Energy, 28: 751-754.

Maltini, E., G. Cortella, M. Stecchini, M. Deltorre, P. Pittia, M. Spaziani, G. Mansutti, 2004. Design and performances of a constant temperature compartment for domestic refrigerator. Proceedings of the 9th International Congress on Engineering and Food, March 7-11, 2004, Montpellier, France.

Wang, F., G. Maidment, J. Missenden and R. Tozer, 2007. The novel use of phase change materials in refrigeration plant. Part 2: Dynamic simulation model for the combined system. Applied Therm. Eng., 27: 2902-2910.