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AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF PHASE CHANGE MATERIAL ON COEFFICIENT OF PERFORMANCE (COP) OF A HOUSEHOLD REFRIGERATOR.

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Abstract- Experimental investigation of the performance improvement of a household refrigerator using phase change material (PCM) has been carried out. 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 three different PCMs (Water, Eutectic solution-1, and Eutectic solution-2 of melting point 0°C, - 5°C, and -10°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 21-34% COP improvement of the refrigeration cycle has been observed with PCM in respect to without PCM. With the increase of the quantity of PCM (from 3.00 liter to 4.25 liter) COP increases about 6%. The COP improvement of the system with PCM in comparison without PCM follows the sequence as Eutectic-2 > Eutectic-1 > Water.

Keywords: Phase change material (PCM), House hold refrigerator, Energy consumption, COP, Compressor

1. INTRODUCTION

Global warming is the most alarming environmental disorder of today's world. Refrigeration & air conditioning systems are directly and indirectly responsible of that global warming problem as their use in household, commercial and transportation sector is increasing rapidly. Undoubtedly, household refrigerators are the most widely used appliances of today's world and they are consuming huge portion of the total world energy. For an example, in France there are 1.7 refrigerators per household AFF[1] which consume about 26% of the residential electricity demand and they are estimated to be responsible for 17% of the overall green house gas emission in the country Etude[2]. Today, 80 million refrigerators are produced each year worldwide, among which the Asia-Pacific Economic Cooperation (APEC) produces about 45 million Cogan [3]. In this situation improving the energy efficiency of house hold refrigerator is thus an important issue in terms of energy savings and global warming reduction. 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-

(i) Developing high-efficiency compressors
(ii) Improving the efficiency of heat exchangers by enhancing the heat transfer
(iii) Improving the cabinet and door insulation to reduce heat losses

Among the above 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-

(i) Installing Liquid-suction heat exchangers in condenser
(ii) Designing loop heat pipe based evaporator
(iii) Using micro fin tubes for both condenser and evaporator, etc

Using **phase change material (PCM)** (as discussed in this paper) 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 [4] has simulated a domestic refrigerator including cold storage. This model, based on differential equations, was used to determine appropriate operating conditions in order to achieve a minimum electrical power. In this study, the coefficient of performance is improved by 12% using PCM. Nevertheless, it must be observed that Cerri used a low quantity of PCM in his study. Maltini [5] performed an experimental study of a household refrigerator using a sodium chloride–water mixture as cooling storage system. It was observed that the PCM behaved as a temperature damper and minimized the temperature fluctuations, leading to a better preservation of food. Wang [6] have developed a dynamic mathematical model for coupling a refrigeration system and a PCM heat exchanger, Positioned between the condenser and the thermal expansion valve (TEV). This model is able to predict the refrigerant states and dynamic coefficient of performance. However, none of the investigation was carried out to examine the effects of the PCM heat exchanger on the refrigeration system performance. Azzouz [7] developed a dynamic model of the vapor compression cycle including the presence of the phase change material and showed its experimental validation. The simulation results of the system with PCM show that the addition of thermal inertia globally enhances heat transfer from the evaporator and allows a higher evaporating temperature, which increases the energy efficiency of the system. The energy stored in the PCM is yielded to the refrigerator cell during the off cycle and allows for several hours of continuous operation without power supply. Azzouz [8] design and developed a model of an improved refrigerator using phase change material as a cold storage. A simplified dynamic model on differential equation is developed for predicting the energy impact due to the addition of the PCM. The numerical result yields a 72% increase in the COP and a 25% decrease in the global working time of the compressor. Azzouz [9] experimentally investigated the performance of a household refrigerator by using phase change material. The experimental results indicate that the response of the refrigerator to the addition of PCM and its efficiency are strongly dependent on the thermal load. The integration of latent heat storage allows 5-9h of continuous operation without electrical supply (to be compared to 1-3h without PCM) and a 10–30% increase of the coefficient of performance, depending on the thermal load. Concerning that the purpose of the present work is set to remove the problem of third material between the PCM and cooling coil by installing the evaporator coil into the PCM box so that the evaporator coil directly contacts with the PCM material as immersed condition. As a result higher conduction heat transfer is expected to obtain.

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2. EXPERIMENTAL SET-UP

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. Fig.1 shows 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 1mm thickness, which is 0.56m width, 0.44m height and 0.47m depth. The evaporator cabinet box of outer volume 0.04m^3 with cooling coil [Fig. 1(a)] is inserted into the empty PCM box of internal volume 0.11m^3 [Fig. 1(b)]. The thickness of the annular space between PCM box and evaporator cabinet box is 0.006m. The open face of the annular space is sealed by a third sheet 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. This modified PCM based refrigerator has a single evaporator cabinet with a single door. The followings are the major technical specifications of the refrigerator.

1. Cabinet : Internal volume, 0.03 m^3
2. 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 m and 0.0772 m respectively, Material of the coil/tube: Copper tube
3. 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
4. Hermetic reciprocating compressor HITACHI FL 1052-SK, 13 FL 220-240V, 50Hz
5. Expansion device: Capillary tube (Internal diameter 1.00 mm)
6. On/off control and self defrost
7. 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. 2. 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^{0}C) thermometer (begman 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. 2. 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 minutes).

Table 1 Estimated uncertainties of measurement

Measured Parameter	Measuring Device	Uncertainty
Temperature	Thermocouples	± 2.78 %
Pressure	Pressure Transducer	± 0.01bar
Pressure	Pressure Gauge	±0.03kg/cm^2

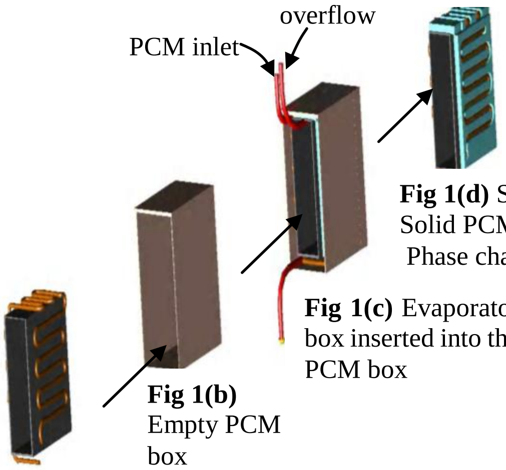


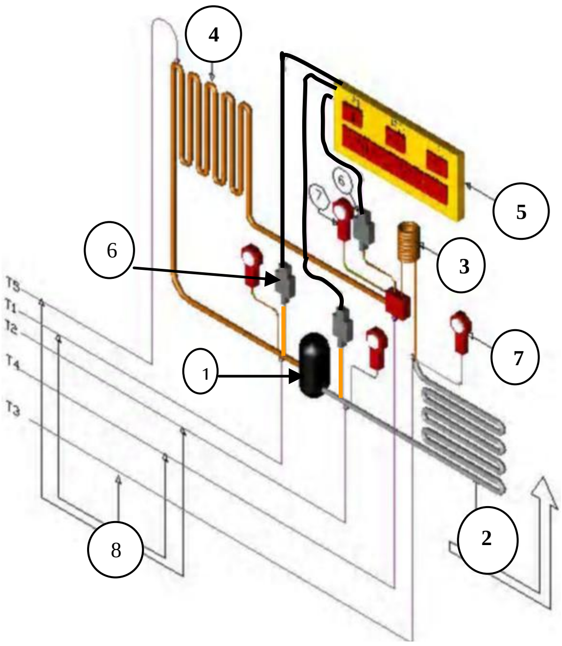
Fig 1(d) Shape of Solid PCM after Phase change

Fig 1(c) Evaporator box inserted into the PCM box

Fig 1(b) Empty PCM box

Fig.1 (a) Evaporator cabinet with coil

Fig. 1 The arrangement of the PCM based evaporator



(1) Compressor
(2) Condenser Coil
(3) Capillary Tube
(4) Evaporator Coil
(5) Pressure and Temperature display unit
(6) Pressure Transducer
(7) Pressure Gauge
(8) Thermocouples

Fig. 2 Location of pressure transducer, pressure gauge and thermocouple

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

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

PCMs	**M_T (^{0}C)**	**Latent heat of fusion (kJ/kg)**
Distilled Water (H_2O)	0	333
Eutectic Solutions -1 (90% H_2O + 10% NaCl), (%wt.)	-5	289
Eutectic Solutions -2 (80% H_2O + 20% KCl), (%wt.)	-10	284

3 EXPERIMENTAL CONDITIONS

Experiments were carried out under four different thermal loads with three different PCMs of different quantities.

Table 3 Experimental conditions

Types of PCM	Quantity of PCM (liter)	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	3.00, 4.25	121	0, 5, 10 , 20	22.8-23.8	-5
Eutectic-1	3.00, 4.25	121	0, 5, 10 , 20	22.8-23.8	-5
Eutectic-2	3.00, 4.25	121	0, 5, 10 , 20	22.8-23.8	-5

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Experiments were carried out under four different thermal loads with three different PCMs of different quantities. In this chapter the effects of different PCMs of different quantities at different thermal loads on the performance parameter of house hold refrigerator are discussed.

4.1 EFFECT OF PCM ON COEFFICIENT OF PERFORMANCE (COP)

Figs. 4 & 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 21-34% COP improvement has been achieved by the PCM in respect to without PCM.
- With the increase of the quantity of PCM (from 3.00 liter to 4.25 liter) COP increases about 6%.
- Among the three PCM , the COP improvement with PCM in comparison with no PCM maintain the sequence as Eutectic-2 > Eutectic-1 > 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.

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

$$COP = \frac{\text{Re } frigerating\ effect}{Compressor\ workdone}$$

$$= \frac{h_1 - h_4}{h_2 - h_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Equation (1) has been used to calculate COP of the present analysis. The enthalpy values at the corresponding pressure and temperature are calculated by using "REFPROP vs.8.0 [Lemon et al. 2007]"

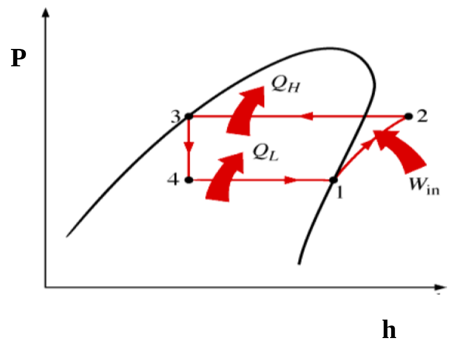


Fig. 3 P-h diagram of a refrigeration cycle

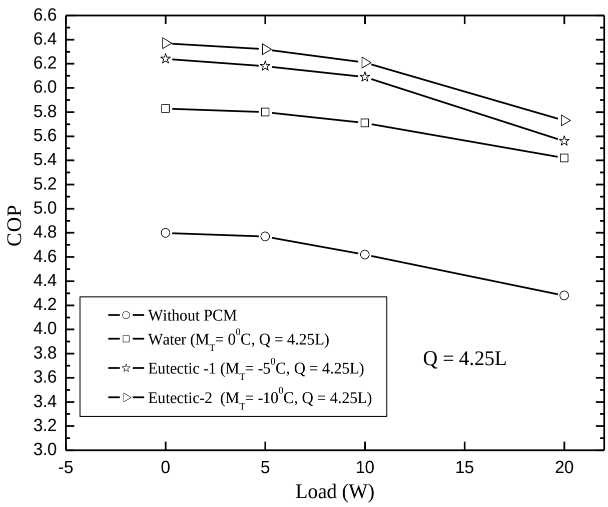


Fig. 4 The effect of PCM on COP at different thermal load (Q = 4.25L)

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 temperature. As a result the evaporator works at high temperature and pressure with PCM as shown in the Figs. 6 & 7. From Fig. 6 it can be observed that the increase of evaporation pressure for Eutectic-1 is 0.146 bar, Eutectic-2 is 0.171 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. 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.

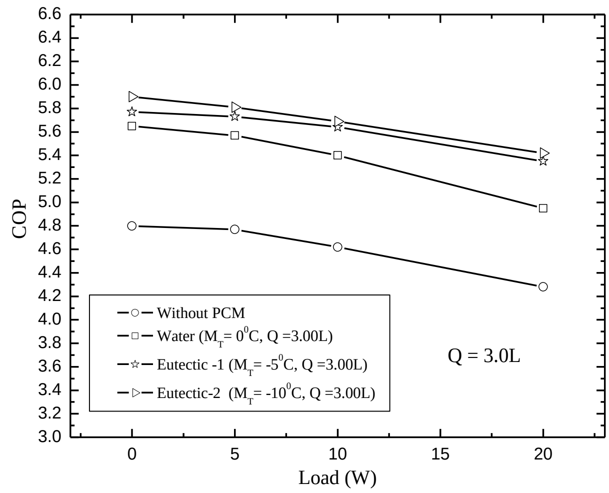


Fig. 5 The effect of PCM on COP at different thermal load (Q = 3.00L)

Fig. 4 shows the effects of 4.25liter of PCM on the COP of the system and Fig. 5 shows the same with 3.0 liter of PCM. From the comparison of these figures it can be observed that the COP with 4.25 liter of PCM is higher than that with 3.00 liter of PCM, which is simply for the higher total latent heat transfer of higher quantity of PCM.

Among the three PCMs, Eutectic-2 shows higher COP because of its lower phase change temperature. Eutectic-2 starts to change its phase at -10^0C while Eutectic-1 is at -5^0C and water at 0^0C. As a result Eutectic-2 stores more latent heat by phase change than other two 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 and pressure of the evaporator as shown in the Figs. 6 & 7.

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.

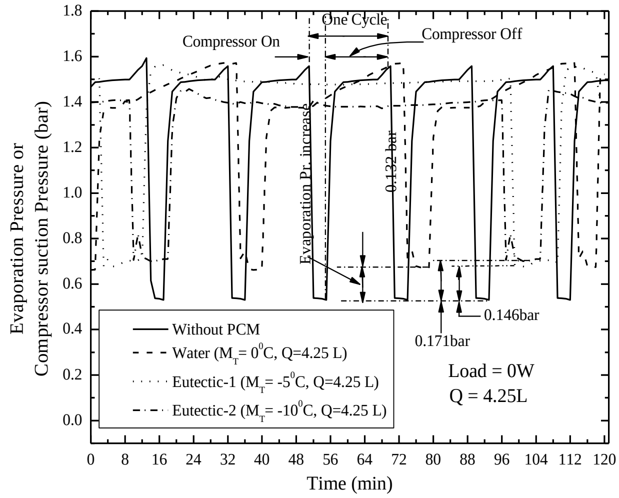


Fig. 6 The effect of PCM on evaporating pressure of the system

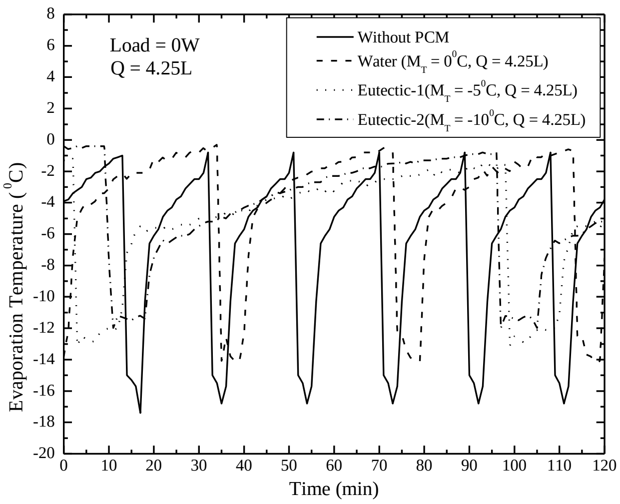


Fig. 7 The effect of PCM on evaporating temperature of the system

5. CONCLUSIONS

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 21-34% COP improvement has been achieved by the PCM in respect to without PCM. With the increase of the quantity of PCM (from 3.00 liter to 4.25 liter) COP increases about 6%. The COP improvement with PCM in comparison with no PCM maintain the sequence as Eutectic-2 > Eutectic-1 > 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.

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7. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(^{0}C)
P	Pressure	(bar)
COP	Coefficient of performance	
PCM	Phase change material	
h	Enthalpy	(KJ/kg)
M_T	Melting temperature	(^{0}C)
Q	Quantity of PCM	(Liter)