Experimental Analysis of Household Refrigerator Compatible with Phase Change Material, using R290/600a Blend as Refrigerant

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Abstract — *In developing countries like India there exists a widespread general problem of frequent power cuts, which gives rise to spoilage of perishable items such as medicine and food stuff due to lack of a passive cold retention system. Moreover, there exists the pressing need of the hour to incorporate eco-friendly practices from the grass root level, while at the same time conserving energy and increasing efficiency. In this paper the effects of phase change material (PCM) on performance of a household refrigerator with R290/R600 blend as refrigerant has been investigated experimentally. Theoretical analysis was carried out using Cool pack software. Experimental results 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 coefficient of performance (COP) 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. The experimental results with PCM also confirm that, average compressor running time is reduced about 5-30% as compared to without PCM, and the test results with PCM prove a noticeable reduction of the temperature fluctuation inside the cabinet.*

Keywords — *Household refrigerator, Phase change material, Compressor running time, Coefficient of performance.*

I. Introduction

Naturally, heat transfer occurs from the region of higher temperature to lower temperature without requiring any external devices. The reverse process that is from higher temperature to lower temperature cannot occur by itself. Its needed specially designed device called refrigerators. Refrigerator works on vapour compression refrigeration cycle. Vapour compression refrigeration system (Fig.1) is a system which is used to transfer heat from low temperature energy reservoir to the high temperature reservoir by the use of working fluid known as a refrigerant. Refrigeration, air conditioning and heat pump applications represent the sector which is the largest consumer of refrigerant chemicals, and electricity. The electricity usage by these devices in developed countries are about 10-20%. The economic impact of refrigeration technology is much more significant than generally believed. About 300 million tones or goods are continuously refrigerated. While the yearly electricity consumption may be huge. Refrigeration systems are directly or indirectly responsible for Global Warming problems which refer to the rise in temperature of Earth's atmosphere and ocean. Increasing the energy efficiency of refrigeration device is thus an important issue in terms of energy savings. Many countries have introduced labelling programs and minimum energy efficiency standards. Number of investigations have been carried out in the recent years to develop technical options for improving the energy performance of household refrigerators. They may be classified in three categories:

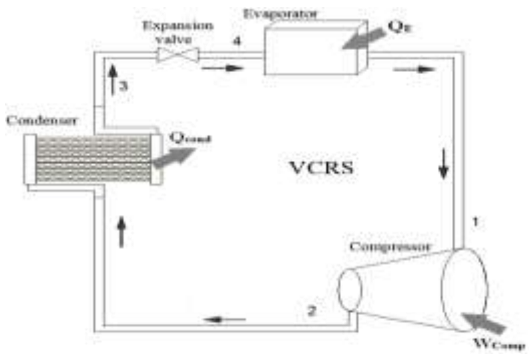

Fig 1: Vapour Compression Refrigeration System

1. Minimizing the heat losses by improving the cabinet and door insulation. For instance, a 25% average energy saving is noted by the VIP (Vacuum Insulation Panels) integration in the cabinet. The main reasons preventing the widespread use of this technology are related to less reliable over lifespan and high disposal and manufacturing costs.

2. Developing efficient compressor. In the conventional refrigerator technology hermetic reciprocating compressor are usually used which are designed to satisfy maximum load. These

reciprocating compressor are usually operates at partial load, resulting in an efficiency losses and increased cycling losses. Embraco developed variable capacity compressor for household refrigerator. This technology is efficient alternative to control the refrigerating capacity. The test result shows significant energy saving by replacing conventional compressor by VCC compressor Technology (Embraco, 2005). But this technology increases cost by 20%, therefore its used is limited.

3. Improving the efficiency of heat exchangers, and particularly of the evaporator which is a key component of refrigerator. Heat transfer through the evaporator requires a temperature difference between the air and the refrigerant: the higher the air side convective coefficient, the lower the temperature difference between the evaporator temperature and the air. For a given cabinet air temperature, this results in a higher evaporation temperature, and enhanced performance of the system.

Now-a-days power cuts are very common due to accidents, or could be due to implementation of demand side management schemes 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 temperatures within specified range inside refrigerator. Most frozen and chilled foods are very sensitive to temperature fluctuations. The used of Thermal Energy storage systems (TES) which is discussed in this paper belongs to the third category. TES will use phase change materials. Phase change material (PCM) melts within a narrow temperature range, and absorbs a large amount of energy while changing state, thus minimizing the rise in the refrigerator temperature. PCM with a suitable phase change temperature may be used to provide thermal capacity to maintain suitable cabinet temperature during power failure. In most of the refrigerators, heat transfer from the refrigerated area to evaporator is mainly by natural convection and radiation with a low air-side heat transfer coefficient. Adding a layer of phase change material on outer side of the evaporator is a cheap and efficient solution, which results in an enhancement of the global heat transfer at the evaporator due to the conduction inside the PCM.

A. Thermal Energy Storage

The most important desirable properties of any TES are high energy storage density and high power capacity. There are primarily two methods of Thermal energy storage: sensible and latent heat storage.

1) ***Sensible Heat Storage:*** In sensible heat storage (SHS), thermal energy is stored by elevating the temperature of a solid or liquid. SHS utilizes the change in temperature and heat capacity the material during the charging and discharging processes. The amount of stored heat depends on the specific heat of the medium, the temperature change and the quantity of storage material. This temperature change ($T=T_a - T_f$) depends on the application and it is limited by the heat source and by the storage system. The sensible heat stored in a material can be calculated as follows:

$$Q = mC_p(T_a - T_f) \quad (1)$$

Where Q is the stored sensible heat.

2) ***Latent Heat Storage:*** The latent heat storage (LHS) or phase change materials (PCM) absorb and release heat as it undergoes a phase change from solid to liquid or liquid to gas or reverse. The energy stored during the phase change process is called latent heat of fusion .The phase change takes place at constant temperature of the material. Figure.2 explain the mechanisms of heat absorption and release in LHS materials. From the figure.2 it is clearly understood that at the melting point, as the temperature of the PCM rises, gradually their chemical bonds break up as the material changes its phase from solid to liquid. The phase change is a heat absorbing (endothermic) process and as a result the PCM absorbs large quantity of heat without getting hotter, i.e. while storing heat, the temperature of the PCM remains almost constant until the melting process completed. It is another means of storing energy is by using phase change materials. The energy density could be increased by using PCM, having a phase change within the temperature range of the storage. The heat stored in a PCM can be calculated as follows,

$$Q = mC_{p,l}(T_a - T_o) + h_{fg} + C_{p,s}(T_o - T_f) \quad (2)$$

Where Q is the sensible and latent heat stored

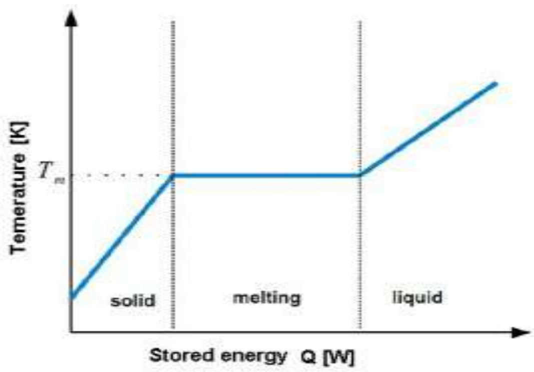

Fig 2: Phase change behavior of solid liquid latent heat storage system melting over a temperature range [1].

The use of phase change materials to accumulate thermal energy in domestic refrigerators is a new solution to improve the performance of these appliances. The cooling capacity stored in the PCM can be used to stabilize the temperature in the compartment, by reducing the effects of peak loads and cooling losses during periods when the door is open.

II. LITERATURE REVIEW

K. Azzouz et al (2009) studied the effect of adding a phase change material (PCM) slab on the outside face of a refrigerator evaporator. The simulation results of the system with PCM show that the addition of PCM enhances heat transfer from the evaporator and elevate the evaporating temperature, which increases the energy efficiency of the system. The thermal energy stored in the PCM is give back to the refrigerator cell during the off cycle and allows continuous operation for several hours without power supply.

K. Azzouz et al (2008) carried out experimental tests to investigate the performance of a household refrigerator using a phase change material (PCM). On the back side of the evaporator the PCM is located in order to improve its efficiency. Water and eutectic mixture (freezing point -30C) are used as PCMs. The analysis of the results shows a significant improvement of the performance compared to a conventional system.

A.C. Marques et al. (2014) investigated the design and operation of a thermal storage refrigerator. Firstly the analysis of compressor is carried out which shows larger compressor gives higher efficiency but more start/stop events, which reduces overall efficiency. The high cooling capacity output of larger compressor is stored in a phase change material (PCM), reducing the number of on/off cycles. Numerical modeling and experimental validation is carried out using a prototype thermal storage refrigerator with PCM. The results showed that the addition of a 5 mm PCM slab into the refrigerator allowed for 3 to 5 hours of continuous operation without a power supply. The numerical model was found to be in good agreement with the experimental results, with the error between the simulation and tests below 5% for most experiments.

A.C. Marques et al. (2013) carried out numerical simulations using the computational fluid dynamics (CFD) software ANSYS Fluent were undertaken to characterize the airflow and temperature distribution in a natural convection thermal energy storage refrigerator. Scenarios investigated included the PCM orientation, PCM temperature and compartment Designs .The simulated model indicated that combining vertical and horizontal PCMs in a full height compartment or dividing the same compartment into two drawers with a horizontal PCM configuration setup for each drawer are feasible design options for the household thermal storage refrigerator.

Sattar. M. A. et al (2007) carried investigation of domestic refrigerator using pure hydrocarbons and blends of hydrocarbons as refrigerants. In this research, a domestic refrigerator designed to work with R-134a was used as a test unit to find the possibility of using hydrocarbons and their blends as refrigerants. Pure butane, isobutene and mixture of propane, butane and isobutene were used as refrigerants. The results show that the compressor consumed 3% and 2% less energy than that of R-134a at 28°C ambient temperature when butane and iso-butane was used as refrigerants respectively. The COP and energy consumption of hydrocarbons and their blends shows that hydrocarbon can be used as refrigerant in the domestic refrigerator.

Oro. E, et al (2012) studied the thermal performance of freezers using phase change materials. A commercial PCM was selected with a melting temperature of 18 °C, which is contained in 10 mm thick stainless steel panels placed at different locations in the freezer. During 3 hours of electrical power failure, the use of PCM maintained the freezer temperature 4 to 6 °C lower and that of the frozen products remains at acceptable levels for much longer time. With frequent door openings the benefit of the PCM is evident when the temperature of the cabinet is near the melting temperature of the PCM.

Rezaur Rahman et al (2013), investigated the performance of domestic refrigerator improvement with application of PCM with the evaporator in a domestic refrigerator. The analysis of the experiment shows the considerable improvement in COP of a conventional refrigeration system. Here the PCM used in a chamber built manually and which surrounds the Evaporator chamber of a conventional refrigerator. Majority of heat transfers by conduction mode from load given to refrigerator cabinet to evaporator and evaporator to PCM. So heat transfer rate of evaporator refrigerant increases considerably which improves the COP of the refrigeration system by approximately 18-26%.

Tulapurkar et al (2010) explains the method and design of a novel Dual evaporator based domestic refrigerator with Phase Change materials (PCM). The usage of PCM as a Thermal energy storage will help to improve the COP (Coefficient of performance) of new refrigeration cycle by introducing a new sub cooling routine. This enhancement by sub cooling can be done for both single evaporator refrigeration system as well as dual evaporator system for a refrigerator / freezer combination. Because of prolonging of the compressor off time by using the latent heat of energy of the PCM we can have better food quality due to lower hysteresis cycles of on/off for a given period of operation.

III. OBJECTIVE OF THE STUDY

The main objective of this project work is to study and to develop a new Thermal Energy storage (TES) system using Ethylene Glycol as PCM and R290/R600a blend as alternative refrigerant for domestic refrigerator.

1. To develop vapour compression refrigeration system with R290/R600a (60/40 by weight %) blend as an alternative refrigerant
2. To carry out the experimentation with PCM & without PCM
3. To investigate the feasibility of PCM in domestic refrigerator to maintain passive cooling inside cabin
4. To validate Coolpack simulation results with experimental results
5. To observe temperature informality in cabin with PCM

IV. METHODOLOGY OF THE STUDY

The experiment was carried out conventionally by taking all of data manually. A conventional household refrigerator of 165 liter capacity is used with some modification. The PCM slab is located on the back side of the evaporator. It must be noted that a consequence of this modification is that both faces of the evaporator are used in this configuration.. The experimental set up involves a refrigerator, a pressure gauge, a thermocouple, a phase change material box. The modified PCM based refrigerator with a single door and has a single evaporator cabinet. The followings are the major technical specifications of the refrigerator.

1. Cabinet: Internal volume, 0.165 m^3
2. Evaporator: Plate type Evaporator, Mode of heat transfer - natural convection, Surface Area: 0.2392 m^2, Material of the Evaporator: Aluminum.
3. Condenser: Mode of heat transfer - natural convection, linear length of the tube: 9.56 m, Internal and external diameter of the tube: 0.0033 and 0.0048 m respectively, Material of the tube/wire: steel.
4. Compressor: Hermetic reciprocating compressor, TECUMSEH THK 1335 MUCF, 230V, 50Hz.
5. Expansion device: Capillary tube (Inner diameter 1 mm), Length 11m.
6. Refrigerant: R290/R600a blend (60/40 by weight %) 60 gm.

Temperatures at various locations (compressor, condenser, evaporator, and cabinet) are measured with K-type (chomel-alumel) thermocouples having 0.0015 m diameter as shown in. The uncertainty of the temperature measurements by the thermocouples is estimated to be ± 1o C. Two pressure gauges are used to measure the evaporation and condensation pressures at the inlet and outlet of the compressor. A heater is used in the cabinet to perform experiments at different thermal loads. The heater is located at the center bottom of the cabinet box, which is connected with a variable voltage transformer (variac) to regulate the supply voltage for required thermal load variation into the cabinet. Temperature of cabinet is measured by K-type thermocouple which is located at the center of the cabinet. Thermostat is used to control the temperature of the cabinet. The knob of thermostat is located at the center of the cabinet. The steady state condition is obtained by allowing the system to run for several minutes. Experiments were carried out under various thermal loads like 0, 20 and 30 watt with ethylene glycol as PCM.

V. RESULTS AND DISCUSSION

A. *Effect on Coefficient of performance (COP)*

The performance of refrigerator is determined in terms of coefficient of performance (COP), it is the ratio of refrigeration capacity to the electrical power supplied to the compressor. It is noticed that the COP values are higher for setup with PCM. The improvement in the coefficient of performance ranges in between 5 - 20% depending upon thermal load, external temperature, and phase change material nature. COP increases due to a higher evaporation temperature.

$$\text{COP} = \frac{\text{Refrigerating effect}}{\text{Elecrical power supplied}} = \frac{h_1 - h_4}{h_2 - h_1}$$

Fig 3: Refrigerator used in the Experimentation

B. *Effect of the reduction of the compressor on/off cycling*

The major losses related to the compressor on/off are due to the refrigerant migration. The efficiency losses due to refrigerant migration are noted 5 to 30%. Bjork et al (2006) found that refrigerant migration losses are 11 % of the cooling capacity. Fig shows compressor outlet temperature verses time for different PCMs. The figure shows that number of compressor on/off cycle within certain periods of time for different PCMs and without PCMs. From the figure it is noted that compressor on/off cycle with PCM is 3 - 7 times lower than that of without PCM configuration. The number of on/off cycle depends on the types of PCM and the quantity of PCM.

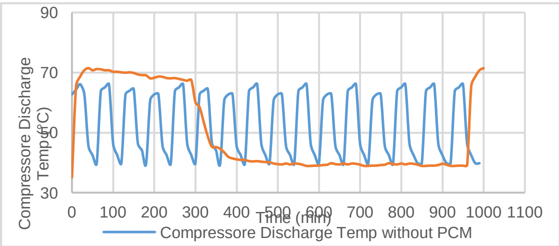

Fig 4: The effect of PCM on compressor on-off cycling

C. *Effect on Temperature fluctuation*

Fig.5 shows the effect of PCM on average air temperature inside the cabinet of the refrigerator at no load condition. As seen from the figure the minimum temperature of ethylene glycol goes up to -8^{o}, up to this point the cabinet and ethylene glycol temperature goes decreasing gradually. From figure it is noted that the average air temperature fluctuation inside the cabin for a specific time is significantly reduced for a system with PCM in respect to without PCM. Ethylene glycol provides uniform cabin temperature. The use of PCM gave benefits to food quality.

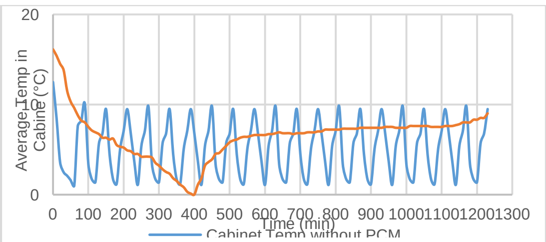

Fig 5: The effect of PCM on average air temperature inside the cabin.

D. *Effect of PCM on compressor working time*

The addition of PCM has an impact on cycle time of the system. In Fig.6 the on-cycle of the refrigerator with PCM is five times longer and the off-cycle is ten times longer than system without PCM. From the figure it is noted that the addition of PCM significantly reduced the average compressor running time per cycle with ultimately reduces the energy consumption.

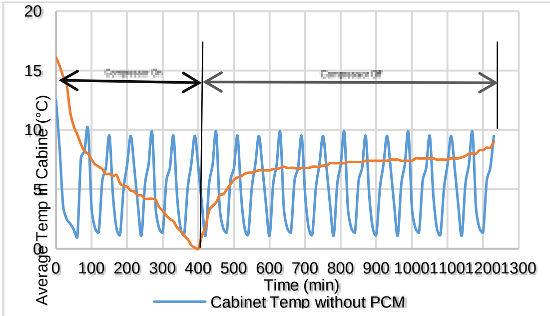

Fig 6: The Effect of PCM on Compressor Working time

VI. CONCLUSIONS

The experiment test were conducted to inspect the effect of phase change material (PCM) on the performance of domestic refrigerator. Ethylene glycol were used as PCM. The 5 to 20% improvement in the coefficient of performance is noted depending upon thermal load. The number of compressor on/off cycle with PCM is reduced significantly as compare to without PCM. Reduction of compressor on/off cycle enhances the efficiency by minimizing the system losses associated with refrigerant migration which are about 9-11% and increases the life of refrigerator system as compared to conventional refrigerator system. The fluctuation of the cabinet temperature with PCM configuration is decreases, which ultimately improves the food quality. The average compressor running time per cycle is significantly reduced as compared to without PCM.

NOMENCLATURE

COP	Coefficient of Performance
$C_{p,l}$	Specific Heat of Liquid
$C_{p,s}$	Specific Heat of Solid
h_{fg}	Latent heat of fusion
LHS	Latent Heat Storage
PCM	Phase Changing Material
SHS	Sensible Heat Storage
TES	Thermal Energy Storage
T_f	Freezing Temperature
T_a	Ambient Temperature
T_o	Phase Change Temperature
h	Enthalpy

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