Effect of phase change material on ON-OFF cycle of compressor of domestic refrigerator

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ABSTRACT— Efforts to increase energy efficiency of refrigerators shall directly reduce energy consumption. Incorporating phase change materials (PCM) is a new approach to improve the performance of refrigerators. This paper presents the study with experimental tests carried out to investigate the performance of a household refrigerator using phase change material (PCM).The PCM is located on outer bottom surface of evaporator in order to improve its efficiency and to provide storage capacity allowing several hours of refrigeration without power supply. The system has been tested with water and with Kcl, Nacl as PCM's. The analysis of the results shows a significant improvement of the performance compared to a conventional system.

Keywords— Energy efficiency, Phase change material, Experiment improvement ,energy consumption, household refrigerator, power supply.

I. INTRODUCTION

Nowadays, almost every household uses at least one refrigeration system for domestics food preservation or in the building's mechanical ventilation system to provide the required indoor thermal environment. In India for 165 liter, the specific energy consumption varies between 3.23 and 4.19 kwh/y/l for single door manual defrost unit (M. sidhharth bhatt (2001)). As per population of India for household applications a huge amount of energy consumption is required. Thus, even small performance enhancement of these appliances brings huge amount of energy saving. Generally, energy consumption of refrigerator depends upon its components efficiency, ambient temperature, thermal load, door openings, set-point temperature in its component(s), and refrigerant type(A.Marques,G.Davies,G.Maidment,J.Evans I (2014). Hence, performance enhancement of refrigeration systems covers a vast research area. Since each part of the system has its own technical complexity. Therefore, it is not easy to classify all those efforts in few categories. Nevertheless , most of the ideas applied to refrigeration systems lie in three major categories: development of energy-efficient compressors, enhancement of thermal insulation, and enhancement of heat transfer from heat exchangers, i.e. condenser and evaporator.

The first category includes all the studies focused on compressor energy consumption and efficiency.

The second category is about enhancing thermal insulation of system walls. Polyurethane boards are conventionally used to insulate refrigerated compartments.

The last category includes the efforts for heat transfer enhancement of heat exchangers(condensers and evaporators) in refrigeration systems which can be further divided in four major groups(M.I.H.Khan,H.M. Afroz ,(2013)):

- Addition of a liquid-to-suction line heat exchanger (also known as superheating coil),
- Application of loop pipe heat pipe evaporator,
- Application of micro-fins in condenser and evaporator , and
- Application of phase change materials.

It has been reported that the first two categories (compressor and insulation modification) are either costly or difficult to be applied. PCMs, on the other hand, have received considerable attention for heat transfer enhancement due to their inherent advantages. PCMs can be used in refrigerators for either heat or cold storage. The former requires integration of PCM to condenser side, while the latter is done by integration to evaporator. Since evaporator is the main source of cold in refrigerators, throughout this paper application of PCM at evaporator reflects all possible configurations for cold storage.

Due to the high latent heat, integration of PCM at evaporator side of a refrigerator could prolong the compressor OFF time. This enables two new important options for refrigerators; to work off-peak and to maintain the compartment cold for longer periods of time even during power outages or blackouts.

PCM application at evaporator

Several studies have focused on the performance analysis of refrigerator systems with PCM at evaporator. As a result of application of energy storage the compressor needs to work for a longer period of time to charge the energy storage. Nevertheless, despite longer compressor ON time in each cycle to charge PCM, the global ON time ratio decreases due to longer compressor OFF time. Main advantages of longer compressor OFF duration are lower overall energy consumption, better food quality, preventing destructive effect of frequent compressor start/stop.

1 Phase change temperature

Proper phase change temperature selection is of great importance in refrigeration systems since it directly affects not only the performance of the system but also the quality of the stored food. The main objective of domestic refrigeration systems is to preserve food; thus phase change temperature should be compatible with this main objective. The selection of the phase change temperature is an important design parameter for proper functioning of PCM and the melting point must fall within the thermostat temperature range of operation. In order to select the most beneficial melting/freezing point, it is worth nothing the effect of unsuitably selected high or low phase change temperature. Obviously ,high phase change temperature increases temperature in the compartment, decreasing stored food quality, while it increases COP of the system due to the lower power consumption (K.Azzouz 2008/892-901).conversely, too low phase change temperature decreases the corresponding compartment temperature. This is more important for fresh food compartment since its temperature should never fall below zero (to prevent freezing and food quality loss). Therefore. An admissible phase change temperature range exists between these two high and low extremes. Proper phase change temperature should be selected by means of a material with suitable thermo physical properties. Water has received considerable attention due to its unique characteristics. This is mainly due to its availability, large latent heat value and Sharpe phase change point (A.Marques 2014 /511-519). Nevertheless, a eutectic PCM with phase change temperature higher than water enhanced COP more than water due to the resulting higher evaporation temperature during phase change (M.I.H. Khan 2013/56-67)

2 PCM thickness

After selection of a proper PCM with suitable thermo physical properties, the question is the amount of PCM to be used. Based on a very simple calculation, the minimum volume of PCM in order to meet required energy can be calculated (D.C.Onyejekwe 1989/11-18). If a compartment only contains PCM, the amount of energy (E) stored in PCM neglecting its sensible heat variation is: to measure evaporator pressure

$E=\rho v\lambda$---(1)

Where ρ and λ are the density and the latent heat of fusion of PCM, respectively. The compartment inevitably has heat gain from the ambient as:

$Q=(UA)_{cold}(T_{amb} - T_{cold})$-----------------------------(2)

Where the indices amb and cold represent the ambient and cold compartment, respectively and UA is the overall thermal conductance. In order to marginally meet the required load, the amount of energy stored in the PCM should meet the amount of energy passing through compartment walls during compressor OFF time(t_{OFF}); thus, minimum volume for PCM is (D.C.Onyejekwe 1989/11-18)

$V_{min}=\frac{tOFF\,[(UA)cold(Tamb-Tcold)]}{\rho\lambda}$----------------------------(3)

Therefore amount of PCM should be more than what was calculated from Eq.(3) PCM should not be thicker than a certain amount since otherwise not all the thickness has the chance to undergo phase change(K.Azzouz.2009/1634-1644). In such a case, PCM is partially melted/frozen which reduces its effectiveness. Besides thicker PCM is more expensive and also requires longer compressor work for cold storage; thus PCM thickness should be selected based on the load. However, whenever increasing the PCM thickness still kept all the PCM participating in phase change process, its effect was greatest on reducing the ON time ratio as a consequence of longer compressor OFF-time (K.Azzouz 2008/892-201). In other words, when the amount of PCM was increased, the system had to work longer in order to charge higher amounts of PCM; however the ON-time ratio was reduced since the duration of compressor OFF period was much longer. Based on numerical modeling, it was reported that increasing PCM thickness from 2 to 5mm (2.5 times higher) prolonged both compressor ON and OFF periods for about 2.5 times longer (A.Marques 2014/511-519). Therfore, the compressor needs to work longer continuously to charge higher amounts of PCM. Since too long compressor ON time is not desirable, there is a limit to increase the amount of PCM. Thus, the total amount of PCM has an admissible range. It is important to point out that ON-time ratio of a refrigerator with PCM is predominantly determined by thermal load (K.Azzouz 2009/1634-1644). A framework for designing the optimum thickness of PCM has been developed.

3 Ambient temperature

Ambient temperature affects both the performance of refrigeration system and the usefullness of PCM. Generally , higher ambient temperature results in lower system COP due to the higher compartment air temperature (K.Azzouz 2005/15-17) and higher condensation temperature and pressure (M.I.H. Khan 2013/56-67). Earlier studies reported that by increasing the thermal load, system COP decreased even in presence of a PCM. The reason is that the increase in thermal load results in more partially melted PCM which in turn decreases the system COP (K.Azzouz 2009/1634-1644). High thermal load directly affects both charging and discharging duration of the PCM as it shortens melting time while it prolongs freezing time since the compressor has to both overcome the thermal load and charge the PCM (A.Marques 2014 /511-519). In addition. Very low ambient temperature also has anegative effect on the PCM performance. The reason is that when the refrigerator is working in low thermal load, compartment temperature drops faster (due to the low heat gain through the walls) and reaches sooner to the set-point temperature; hence, the

PCM does not have enough time to be fully solidified before compressor stops. Moreover, the temperature in fresh food compartment might drop below zero. It was found that a melting temperature even for a low ambient temperature of 15^0C (K.azzouz 2008/892-201). In addition to purely considering the effect of ambient temperature, some studies investigated the effect of continuous thermal load by placing a heater inside the compartment. It was found that higher heat generation in a compartment shortens compressor OFF period and the system has to work longer in order to keep the refrigerated compartment cold; thus, COP decreases (K.Azzouz 2009/1634-1644).

4 Evaporation temperature

PCM integration and evaporation temperature have mutual effects. Due to the high latent heat of a PCM giving it a high thermal capacity, it keeps evaporation temperature higher during phase change which is essentially controlled by its phase change temperature (K.azzouz 2008/892-201). Besides, higher evaporation temperature means higher evaporation pressure as compared to a refrigerator without PCM (M.I.H. Khan 2013/56-67) whichresults in higher COP. Lower evaporating temperature on the other hand, requires longer PCM freezing time which is not only due to the heat transfer from PCM but also because of lower COP (A.Marques 2014 /511-519). It is worth nothing that compartment set-point temperature affects PCM performance.

5 Door opening

When the door of a refrigeration system is opened a sudden thermal load is introduced due to air exchange to compartment.
Thus the system has to for work longer time to remove the excessive heat and, as a result, its energy consumption increases. PCM can damp such a thermal load by adding to the thermal inertia of the compartment (K.Azzouz 2008/892-201).

6 Defrost

The heat generated during defrost is another source of thermal load to the compartment. The effect of PCM on defrost of a freezer was investegated (B.gin 2010/2698-2706). First, energy consumption of the base case system without PCM was compared to the one with PCM-equipped system (both without defrost) which showed a slight energy consumption difference. Comparing the same cases including a 30 min defrost showed that PCM could save 7% of energy consumption. Even with a high latent heat capacity, PCM was fully melted after defrost due to the high power consumption of the heater. The effect of combined door opening and defrost for an unloaded compartment was also investigatd. The results showed that PCM is more benefical during defrost since it is the sole source of cold, while during door opening the compressor might be ON and its cooling power is much more than PCM.

7Power outage

In order to quantify the usefulness of PCM during power outage, a factor called “period factor” was introduced (E.oro 2013/102-109).

Period factor=$\frac{(refri\ period\ with\ pcm)}{(refri\ period\ without\ pcm)}$

The period factor greater than one means that PCM can help the system to remain cold longer.

8 Reduction of peak hour consumption

PCM can store cold during off-peak hours and release it to the compartment during peak hours; hence, eliminating the compressor work. Potential cost saving s of 30-54% was reported by applying PCM solely at evaporator (B.Gin 2010/2698-2706). Thus PCM equipped refrigerator not only helps the grid and prevents environmental impacts of higher greenhouse gas emission, but also gives economic advantages for customer as well.

Thermal storage in refrigeration systems can also help the penetration of renewable energy resources such as solar energy. Plenty of renewable energy is available during day time and thermal storage can be useful for this case based on proper use of control strategy. In an attempt to implement this idea, PCM was used in a domestic freezer whose control strategy was changed to adapt to grid supply availability. It was found that refrigeration systems could change their energy consumption pattern to have higher consistency with renewable source availability.

It is worth mentioning that due to the longer OFF period of refrigeration systems with PCM and lower energy consumption,PCM-equipped refrigerators can be a promising option to be used in net zero energy building. Their long OFF time can compensate for intermittency of renewable energy sources.

Experimental set-up

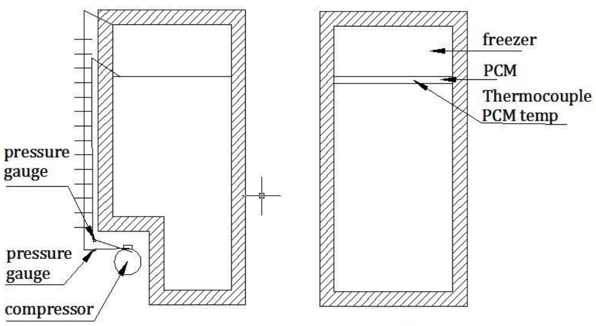


Fig. 1. Experimental Set-up

The original experimental device is a single door refrigerator with the following characteristics:

- Storage capacity 165 liters
- Evaporator: free convection roll bond
- Condenser: free convection, steel and wire tube
- Hermetic reciprocating compressor: (THK1340YCF)
- Refrigerant: R-134a

The PCM slab is located on the bottom portion of the evaporator as shown in fig.1.It must be noted that it is easily accessible. The thermocouple used to measure ambient, freezer ,PCM temperatures. Pressure gauges are mounted at inlet and outlet of compressor to measure evaporator pressure. A timer is used to measure time of on and off time of compressor

1 Experimental and calculation procedure

Basically ON-time of compressor at constant thermal load conditions is measured by timer without PCM and with PCM.
COP can be calculated as

$$COP=\frac{\emptyset ev}{wcomp}$$

$$\emptyset eva = k.s.(Text - Tair) + Qheat$$

Where $\emptyset_{eva}$ is heat extracted, w_{comp} is compressor work, k is thermal conductivity ,s specific heat Q_{heat} is thermal load by electric heaters.

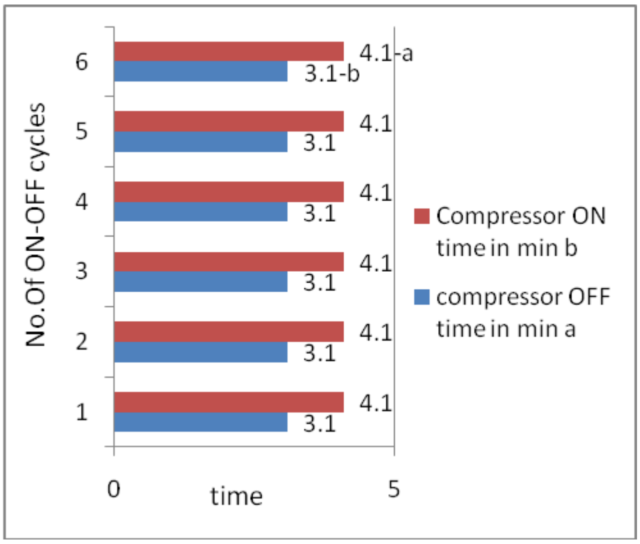
Table:1 Thermo physical properties of PCM (ENB-5921)

Material	Comp^n(wt.%)	Melting point(^{0}C)	Latent heat(KJ/Kg)
H_2o		0	333
$NaCl/H_2o$	90	-5	289
$NaCl/H_2o$	22.4	-21.2	222
KCl/H_2o	19.5	-10.7	283

Experiment without PCM

In the first step, refrigeration system is tested without PCM at constant thermal load and fixed set-point and the result is plotted as below

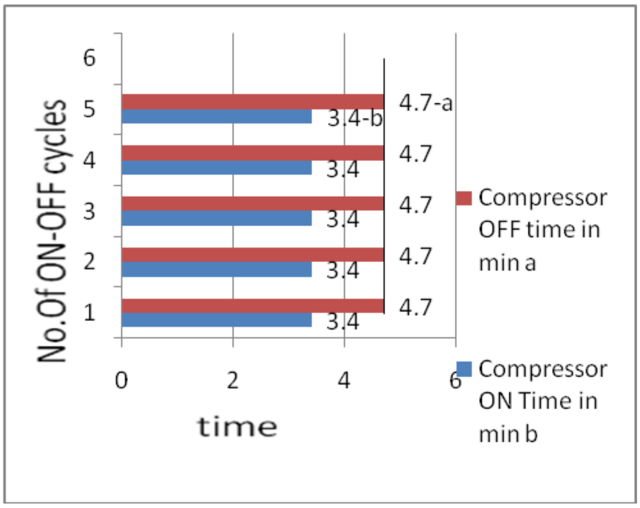
Chart:1 Compressor ON-OFF cycle without PCM



Experiment with water as PCM

In next step water is used as PCM and ON-OFF cycle is plotted as below with same conditions.

Chart: 2 Compressor ON-OFF cycles with water as PCM 5mm thick



II. CONCLUSION

The experimental study of household refrigerator equipped with a latent heat storage unit on bottom face of evaporator shows an enhancement of the system performance and energy saving of refrigeration system.

1) Percentage increase in OFF Period of compressor due to water as PCM is 12.767%

Still effect of PCM materials in table 1 with 5,10,20mm thicknesses has to evaluate. Also effect on COP and gross energy savings has to be calculated.

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