Volume 3, Issue 1, January – 2018 International Journal of Innovative Science and Research Technology

ISSN No:-2456 –2165

A Review of A Latent Heat Storage Through PCMs with VCC System Integrations for Domestic Refrigerator

Varsha K. Tikudave
PG student: Department of Mechanical Engineering
RSCOE, Tathawade
Pune, India.

Jitendra A. Hole
Associate Professor: Department of Mechanical Engineering
RSCOE, Tathawade
Pune, India.

Abstract— Latent heat storage technique is an alternative technique to enhance the performance of heat exchangers in a domestic refrigerator. This study represents a comprehensive review of studies carried out up with their advantages and limitation. Researcher's comments on possible modifications in the present work to achieve improved performance are also reviewed. The key parameters those affect the performance of PCM and the key issues related to achieving a successful integration with the system are discussed here. The studies are limited to PCM application to hot wall type condenser only, the investigation of the PCM application on other type of condenser (naturally cooled, forced cooled) is subject to further scope of work. The PCM integration with conventional system is limited due to PCMs low thermal conductivity hence analyses on PCM with nano-particle additives are subject of future scope of work. Furthermore, the liquid suction heat exchanger with PCM can be another approach to achieve enhanced performance of refrigeration systems.

Keywords— Condenser; Evaporator; Latent heat storage; Liquid suction heat exchanger; PCMs.

I. INTRODUCTION

The 21st century's technology is different from earlier technology in technical up-gradation and type of energy consumption. The "energy crisis" in the world has inspired researchers to discover the alternate energy sources and to utilize the available energy in a better way. The one of the common type of energy equipment used in domestic appliances is refrigerator. IBEF presentation states that the India's refrigerator market is increased with a CAGR of 15.70% from 2010-14. Also in demand for durables like refrigerators are likely to witness a growing demand in the coming years in the rural markets as the government plans to invest significantly in rural electrification [1]. This presentation projects that the number of consumers is constantly increasing. The study shows that refrigerator consumes about 1/4th of the total energy consumption in a house. It also accounts to about 1/6th of the greenhouse gas emissions. Hence, performance enhancement of domestic refrigerator has given a prime consideration.

The energy consumption of refrigerators is affected by the efficiency of their components, ambient temperature, thermostat setting position, product loading, frequency of door openings, and refrigerant migration during the compressor off-cycle [2]. The performance enhancement of conventional system covers the wide research area since each part of system has its own technical complexity. So far, the techniques used to enhance the performance of the system are categorized as: 1) development of high efficiency compressor, which has a direct impact on the coefficient of performance (COP) of cooling system; 2) enhancement of the thermal insulation of refrigerators by thickening the insulation or use of other advanced thermal insulation techniques; and 3) enhancement of heat-transfer performance of the evaporator and the condenser.

The first category includes all the studies those focused on the compressor energy consumption and efficiency. In domestic refrigerator, conventionally used compressor (hermetically sealed reciprocating ON/OFF compressor) consumes 70-80% of the total energy consumption of a system. In addition, the losses resulting from refrigerant charge displacements e.g. due to off-cycle, migration and on-cycle redistribution, were estimated to be 11% (in capacity) and 9% (in energy efficiency) [2]. Hence the compressor modification is recommended in order to enhance the performance of compressor.

The alternatives available to achieve enhanced performance of system are variable speed compressors (VSC) or linear compressors. The advantages of the system with VSC include the capacity control (which matches the system capacity to the load) hence reduced losses of on-off cycling, lower starting current, lower noise generation and lower vibrations during operation. Nowadays, this technology has started replacing the conventional compressors in appliances like refrigerator and air conditioner. However, this technology is still too expensive [3]. Recently, linear compressors have received more attention for domestic refrigeration since they have significant advantages such as elimination of crank mechanism and direct drive of piston by a motor in linear compressors reduces frictional losses and enhances the performance of the system. However, their application in refrigeration systems had some technical difficulties. In summary, these promising alternatives raise some special difficulties preventing them from being widely and easily used. Therefore, cost-effective modification of systems with conventional compressors seems to be more desirable [4].

The second category includes the enhancement of the thermal insulation of system walls. The main load to the cabinet results from conduction through the cabinet walls and consequently by replacing the standard polyurethane foam insulation with vacuum insulated panels (VIPs) (highly resistant to heat, about 4 times more than a polyurethane foam), energy savings of up to 25% can be achieved [2]. However, the core material of VIPs is encapsulated in a barrier which needs to be thin with low conductivity and low gas permeability. These constraints as well as their reliability make them expensive, preventing their wide applications. Therefore, more cost effective methods of achieving high thermal insulation are required [4].

The last category includes the efforts for heat transfer enhancement of heat exchangers (condensers and evaporators) in refrigeration systems which can be further divided into four major groups [5]:

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

Phase change material (PCM) has received considerable attention for heat transfer enhancement due to their inherent advantages such as high latent heat of fusion per unit volume, small volume change on phase transformation and small vapor pressure at operating temperature, no degradation after a large number of freeze/melt cycle, non-flammable, non-toxic and cost effective [6]. 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 integrating to the evaporator or compartment [4].

II. PCM INTEGRATION IN REFRIGERATION SYSTEM

PCM can be integrated into a refrigerator system in following manner:

A. PCM at Evaporator (i.e. low temperature side)

The evaporator in a conventional refrigeration system works based on either free or forced convective heat transfer. In case of free convection heat transfer rate is low and it results in temperature stratification inside the compartment; while forced convection gives better temperature stability. The drawback of forced convection is, it consumes more power, spreads odor and loss of food weight due to high air circulation. One approach to overcome these drawbacks is the application of thermal energy storage (i.e. PCMs).

Azzouz applied PCM slab at the evaporator which resulted in heat transfer mechanism to take place by two types of heat transfer mechanism such as by conduction from evaporator to PCM and by free convection from PCM to air (Refer fig. 1) [7]. As a result of the application of energy storage (i.e. PCM slab), the compressor needs to work for a longer period of time to charge the energy storage (i.e. phase transformation of PCM from liquid to solid). Nevertheless, despite longer compressor ON time in each cycle to charge PCM, the global ON-time ratio decreases due to longer compressor off time. The main advantages of longer compressor off duration are lower overall energy consumption, better food quality, and preventing destructive effect of frequent compressor start/stop. In addition, the presence of PCM in a system resulted in cyclic fluctuations in food temperature much lower than conventional single temperature refrigeration cycle [8].

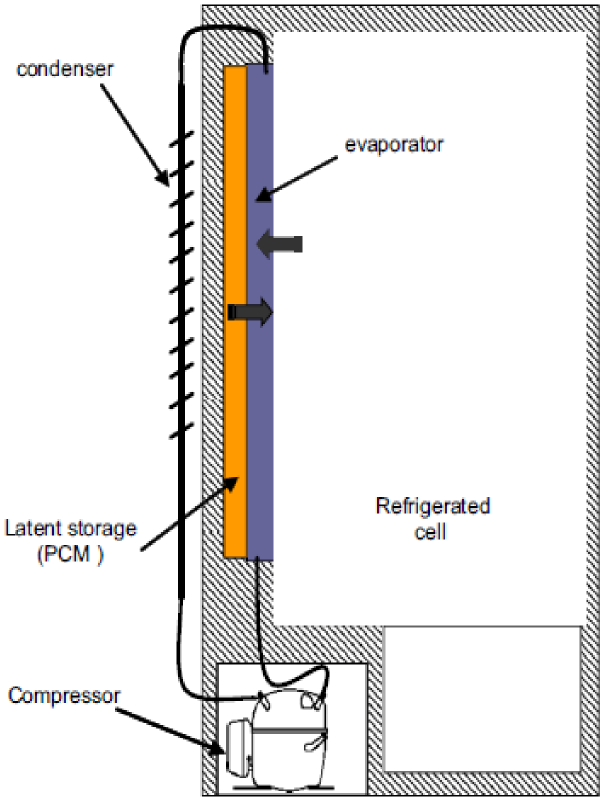

Fig. 1. Experimental setup with PCM at evaporator [7].

Visek has applied the PCM in direct contact with a naturally-cooled evaporator and he found it is more advantageous. The main reason is that PCM in the contact with refrigerator compartment (RC) evaporator increases evaporation temperature by improving evaporator heat transfer coefficient and stores excess cooling capacity in the latent heat of PCM [9]. Similar results were reported in cases where evaporator coils were immersed in PCM (Refer fig. 2). In such cases the refrigerant takes the chamber heat by conduction instead of free convection (case without PCM). For that reason the operating temperature of cooling coil drops by a few degrees to maintain the desired cabinet temperature. As a result the evaporator works at high temperature and pressure with PCM and the density of refrigerant vapor entering the compressor increases [5]. However, if the evaporator is immersed in a PCM with a phase change temperature higher than the compartment set-point temperature, a high thermal resistance is created around the evaporator which, in turn, brings more frequent compressor start/stop [4].

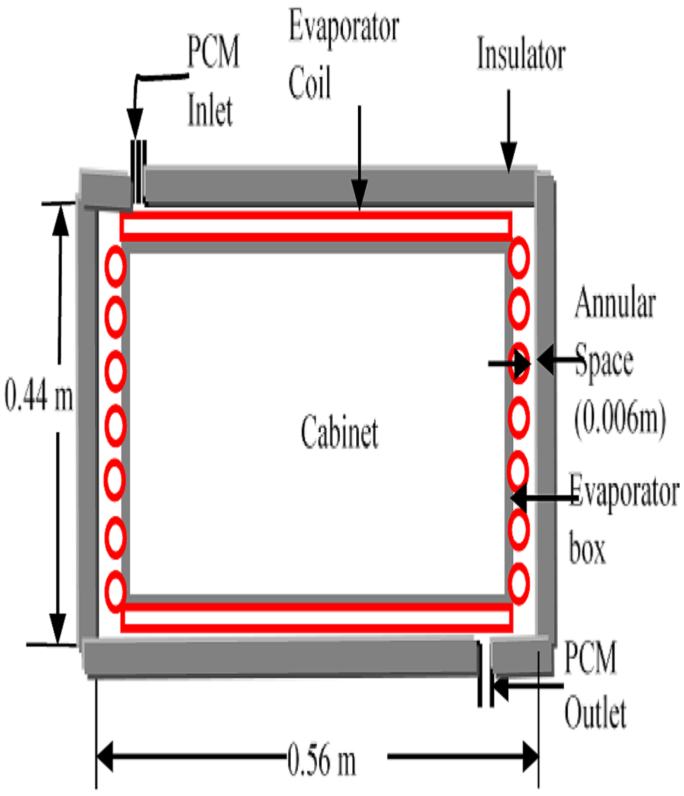

Fig. 2. Front View of the Evaporator Cabinet with PCM box [5].

The CFD simulations were used to identify the best performing (i.e. optimized for energy efficiency and more uniform temperature distribution) design options for a novel, household thermal storage refrigerator. The effect of PCM orientation, phase change temperature and compartment height on refrigerator temperatures were investigated through simulation. The results showed that a horizontal PCM configuration produces lower compartment temperatures than a vertical configuration due to maximum velocity value obtained in case of horizontal configuration. The simulations suggest that eutectic PCM must be employed in order to maintain a compartment temperature below . However, the refrigerator energetic autonomy (length of time that the compressor is off) can be maximized by employing a eutectic with a phase change temperature as close to as possible. Considering the results for all the simulations, Marques concluded that, combining horizontal and vertical eutectic PCMs in a full height compartment is a viable option. The required performance can also be obtained for the same volume (storage capacity) by dividing the compartment into two drawers and using a horizontal PCM in each drawer, with ice only [10].

a). Analysis of PCM at evaporator

- *Effect of PCM on compressor on-off cycling*

There are two types of losses caused by the on–off cycling. First, throughout the on cycle, the thermal load of the heat exchangers is higher than it would be for a constantly controlled system. This effect lowers the thermodynamic efficiency due to increased temperature lift. Second, there are losses due to refrigerant displacements following a compressor start and stop process [5]. These causes result in the energy losses 5–37%. Therefore, reduction of on–off compressor cycling is a crucial work for enhancing the performance of refrigeration system. The reduction of compressor on–off cycling ultimately reduces temperature fluctuation inside the storage cabinet and maintains an almost stable temperature resulting in better food quality [11, 12]. The application of PCM at evaporator acts as thermal inertia which absorbs the heat from surrounding; hence evaporator does not get directly exposed to the surroundings and this allows the evaporator to keep the lower temperature of compartment for longer duration. Hence it prolongs the compressor off time and reduces the compressor global ON-time ratio. Ultimately the compressor on-off cycling and losses due to this gets reduced.

- *Effect of PCM on heat gain to the compartment*

B. Gin has investigated the effectiveness of PCM panels placed against the internal walls of a freezer to maintain stable temperatures in the presence of heat loads such as heat gain through door openings, defrosting, and loss of electrical power. This study showed that the application of PCM into a freezer has beneficial effects in minimizing temperature variations inside the freezer. Energy consumption tests have shown that heat loads resulting from door openings and defrost cycles increase the energy consumption of the freezer by 11–17% and 15–21% respectively. The inclusion of PCM into the freezer have decreased the energy consumption during a defrost cycle by 8%, and by 7% during door opening operation in this system [13]. Furthermore, in the event of power loss, PCM helps to reduce the rate of temperature increase of the freezer contents as compared to without PCM [11].

In summary, several studies have focused on the performance analysis of refrigeration systems with PCM at evaporator based on parameters such as the phase change temperature, PCM thickness, its geometry and orientation, and also the effect of thermal load. In the following sections 3, the impact of each parameter is discussed separately. A detailed analysis of the pros and cons of using PCM at evaporator is presented in table 1 and 2.

Ref.	Advantages	Comment
[5]	Higher refrigerant density at compressor inlet	Higher refrigeration capacity
[5]	Higher COP	Better cooling performance of the system
[7]	Longer compressor off time	PCM acts as thermal inertia; hence prolongs compressor off time Shows economic benefit due to lower energy consumption Positive environmental impacts
[7]	More stable condition against thermal load variations	Better system performance Lower sensitivity against ambient temperature changes
[7]	Shorter compressor global ON-time ratio	Less compressor work Lower energy consumption Lower noise generation
[11]	Assistance in case of power loss	Acting as an emergency backup Keeping stored food cold for longer periods with no power supply More useful during tight power supplies due to rolling blackouts
[8,13]	Lower compartment temperature fluctuations	Lower compressor ON/OFF frequency Positive effect on compressor lifetime Uniform temperature distribution inside cabinet Better food quality
[13]	Helpfulness for the damping temperature increase due to defrost and frequent door openings	Addition of thermal storage (PCM) absorbs added extra heat due to defrost heater and frequent door openings Slower compartment temperature raises during defrost
[14]	More controlled temperature at the compressor inlet	Possibility of lower superheat Better system performance
[15]	Beneficial for end-users, national economies and for the global environment	Lower compressor ON-time ratio Lower energy consumption Positive environmental impact

Table 1. Advantages of Pcm Application At Evaporator

Ref.	**Disadvantages**	**Comment**
[7,15]	Longer compressor ON time during a cycle	• Possibility of destructive effect on compressor due to long operation
[14]	Higher condensation temperature	• Negative effects on system performance • Higher heat transfer from condenser to compartment • Requirement of condenser modification or utilization of condenser fan • Provision at condenser to lower the condensation temperature is required

Table 2. Disadvantages of PCM Application At Evaporator

B. PCM at Condenser (i.e. high temperature side)

A condenser is a heat exchanger responsible for rejecting heat of compression from a refrigeration system to the environment. The more condenser heat removal from the refrigeration cycle is the better. The aim of using PCM at condenser is to achieve lower temperatures in a condenser. Unlike wide investigation of PCM at the evaporator or inside compartment, its application at condenser did not receive much attention. The reason might be some undesirable outcomes of such configuration.

The application of PCM at condenser resulted in the heat dissipation of the novel refrigerator continuous during a complete cycle (including a successive on-time and off-time period), different from the intermittent heat dissipation of the ordinary setup. Thus, the overall heat-transfer performances of the condensers could be significantly improved, which resulted in a lower condensation temperature, a higher evaporation temperature and a much larger sub-cooling degree at the condenser outlet. Experiments demonstrated that the novel refrigerator could increase the energy efficiency by about 12% with only a slight increase of the cost. The heat loss of the novel refrigerator through the cabinet was less compared to that of the ordinary refrigerator during the on-time. However, the heat leakage of the novel refrigerator was more serious during the off-time. Consequently, the total cycle time and the ratio of on-time to the total cycle time of the novel refrigerator were shortened, resulting in more frequent starts of the compressor but lower energy consumption [16]. This negatively affects compressor performance in long-term usage.

W. Cheng developed a dynamic model of a novel household refrigerator (refer fig. 3) with shape-stabilized phase change material (SSPCM) and by simulation, the coefficient of performance has increased about 19% by a continuous heat transfer of condenser due to the latent heat storage of SSPCM, however the energy saving is 12% and offset about 7% of the heat leakage increase because of the SSPCM inside the insulation layer. The effects of ambient temperature, freezer temperature and phase change in temperature on the energy saving were analyzed to provide a theoretical basis for the optimal design of the refrigerator with SSPCM. It was found that when ambient temperature increased or freezer set-point decreased, COP decreased and energy consumption increased. It was also reported that when the phase change temperature increased, the amount of energy consumption showed a minimum value at 49°C which was close to the phase change temperature of the SSPCM. This result confirms the importance of proper PCM melting point selection [17].

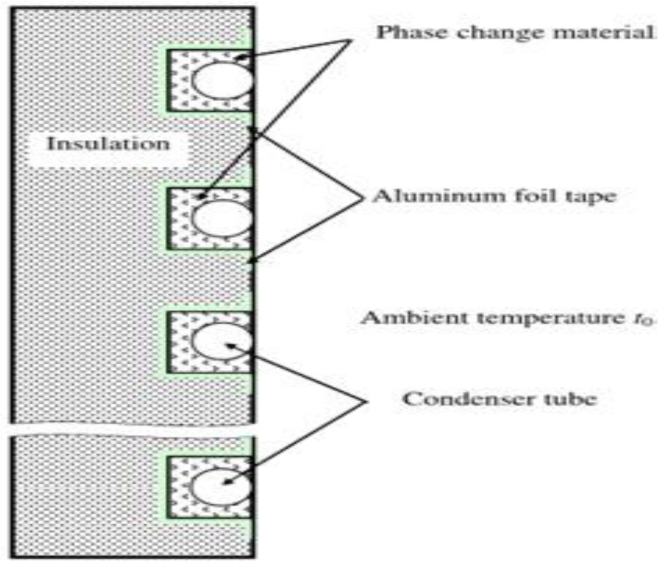

Fig. 3. Shape Stabilized PCM (SSPCM) heat storage at condenser [17].

Finally, a novel refrigerator with heat-storage condensers and an ordinary refrigerator with conventional hot-wall condensers are optimized by the method for multi-objectives of minimizing total cost and energy consumption per 24 h. Under the condition of same total cost, energy saving of optimized novel refrigerator compared with optimized ordinary refrigerator is from 20% to 26% (i.e. novel system can save 20-26% energy of that of conventional one) [18].

a). Analysis of PCM at condenser

The table 3 and 4 summarizes the advantages and disadvantages of PCM at condenser respectively.

Ref.	Advantages	Comment
[16]	Continuous heat rejection from condenser, even during compressor off period	Higher overall condenser heat transfer efficiency Higher sub-cooling Lower condensation temperature Higher evaporation temperature
[16]	Short duration to attain a stable condition of the refrigeration system	Better food quality Shorter compressor work
[16]	Lower condensation temperature and pressure	Higher COP Faster stable condition Higher sub-cooling
[16,17]	Smaller starting compressor power due to higher refrigerant temperature in condenser	Lower energy consumption Longer compressor lifetime
[16,1	Higher sub-cooling degree	Higher cooling capacity

7]		
[16,17]	Lower heat gain from condenser to compartment during ON time	Lower temperature change inside compartment Better food quality Shorter compressor work
[16,17]	Shorter compressor global ON-time ratio	Shorter compressor work in a cycle Lower energy consumption Lower noise generation
[18]	Lower energy consumption	Economic benefits for users Helpfulness for the grid Positive environmental impacts
[17]	Higher COP	Better cooling performance of the system

Table 3.Advantages Of Pcm Application At Condenser

Ref.	**Disadvantages**	**Comment**
[16]	More frequent compressor ON/OFF	• Destructive effect on compressor lifetime • More frequent noise generation • Possibility of heat accumulation in PCM since it might not have enough time to reject the stored heat between compressor off and on intervals
[16]	More refrigerant displacement Losses	• Compressor start/stop results in losses • The more frequent the compressor start/stop, the more the losses
[16,17]	Higher heat gain from condenser to compartment during off time	• Negative effect on food quality • More frequent compressor work

Table 4. Disadvantages of Pcm Application At Condenser

In summary, very few studies have focused on the PCM application at the condenser. These studies have analyzed novel system with conventional system to present the COP enhancement and energy saving potential of novel system. Researchers have analyzed the effect of the PCM application on the hot wall type condenser; the analysis of other types of condenser (such as naturally cooled, forced cooled) is subject to further scope of work.

C. Pcm In Between Components

PCM can be applied in following manner:

- In between compressor and condenser (PCMA) (to act as desuperheater)
- In between condenser and expansion valve (PCMB) (to act as subcooler)
- In between evaporator and compressor (PCMC) (to act as suction line heat exchanger)

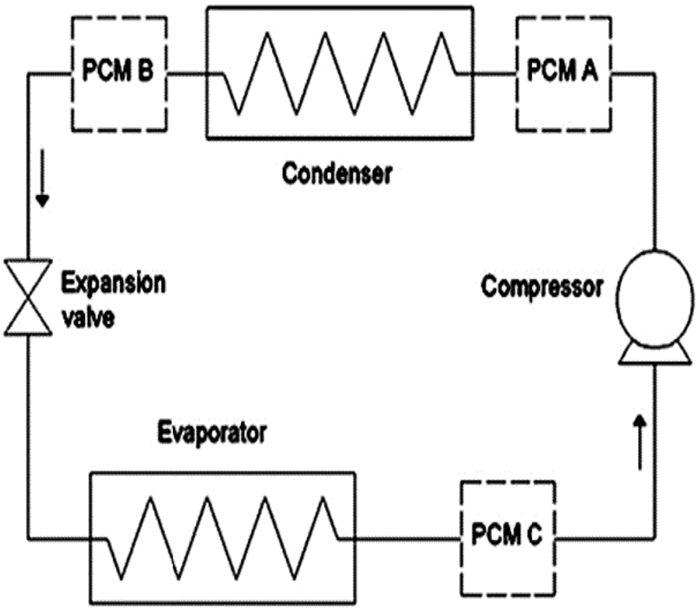

Fig. 4. Considered PCM locations in the system investigated by Wang et al. [14].

The experiments were conducted using different PCMs at different locations of a refrigeration plant as shown in Fig.4. The PCMs were separately placed between the compressor and condenser (PCMA), between the condenser and expansion valve (PCMB), and between the evaporator and compressor (PCMC) [19].

In PCMA position, the PCM was acting as an extra condenser (i.e. was acting as desuperheater) and resulted in lower temperature and pressure in the condenser. In PCMB position, the PCM was acting as sub-cooler and it is sub-cooled the outlet of the condenser; hence COP of system enhanced due to sub-cooling effect. It is observed; the lower phase change temperature of PCM resulted in a higher degree of sub-cooling and higher COP [14]. The reason was due to the fact that the lower the phase change temperature of PCM, the higher the sub-cooling. The higher ambient temperature deteriorates the COP but it is observed that PCMB has less reduction in COP due to high temperature difference between refrigerant and ambient during phase change. In PCMC position, the PCM heat exchanger has lowered superheat and enhanced COP as well, but the pressure drop in suction line due to the PCM heat exchanger was higher and it affected the COP enhancement potential of PCMC. Nevertheless, PCMC has showed stabilized temperature in the system.

The studies have used different PCMs in three different positions and it was also reported that the performance of the system was sensitive to amount of refrigerant. Therefore, it prevents the proper comparison between the results. Generally, PCMB resulted in the highest COP while PCMC provided stabilized temperature of the refrigerant at the inlet of the compressor; hence this showed higher system stability [14]. Table 5 shows each location's advantages and % increase in system COP. It also presents a limitation at each location. Further on; the system was also dynamically modeled [20].

In dynamic model, the system parameters were sensitive to its initial conditions and this model presented some weakness in predicting the superheat and sub-cooling. This is due to the lumped parameters assumption. The main drawback of the model is, all the parameters calculated were the average parameters rather than the spatial distributed parameters [20]. Wang concluded that the optimum size and structure of the PCM heat exchanger will depend upon the application. The large relative size of the PCM heat exchanger makes PCM recharging longer and more difficult. With PCMC the additional suction line pressure drop that needs to be minimized and the optimum structure of this is the subject of further work. In particular, it may be possible to integrate the PCM directly with the suction piping and insulation [14].

Name	Location	Advantage	Limitation	COP change
PCMA	Between compressor and condenser	Act as extra condenser Decreasing condenser pressure and temperature	More frequent compressor start/stop	6%
PCMB	Between condenser and expansion valve	Increasing sub-cooling	More frequent compressor start/stop Lower temperature stabilization achieved	8%
PCMC	Between evaporator and compressor	Temperature stabilization achieved Decreasing superheat	Increased pressure drop	0%

Table 5. Advantages And Limitations Based On Pcm Location [14, 19]

The study on the advantages and limitation of PCM at each location shows that; the limitation of PCMB (i.e. lower temperature stabilization) can be covered with PCMC. This means that, the combination of PCMB with PCMC can achieve the stabilized temperature and hence lower compressor on-off cycling. However, further work is necessary to optimize the form of this heat exchanger to minimize pressure drop and maximize heat transfer. There is further scope for improvement by making changes in heat exchangers (to improve U value), cycle system (to improve Freezer PCM melt / freeze) and to optimize capillary and the gas quantity of refrigerant for the new PCM based system. Mass flow rate measurements for all new developed cycles would help a much more thorough engineering analysis of the new refrigeration systems [8].

D. PCM panels/packs Inside Compartments of Refrigerator

E. Oro investigated the effect of PCM integration inside the refrigerator compartment. The aim of work was to evaluate the thermal response of low temperature chambers incorporating phase change materials (PCM) having a low freezing temperature when subjected to refrigeration system failure. This was to simulate food transportation in non-refrigerated trucks or vans. Two commercial PCMs with different melting temperature were tested (Climsel C-18 with melting temperature as -18℃ , latent heat of 306 kJ/kg value and Cristopia E-21 with melting temperature -21.3℃ , latent heat of 233 kJ/kg value). The results showed that when there was no refrigeration, both the air and the frozen product temperatures remained at lower values for much longer time when PCM was employed [21].

In order to quantify this benefit, a relationship between the period that the system without PCM is below a certain temperature (period ref) and the period that the unit with PCM is under the same temperature (period PCM) is defined as:

$$\text{Period Factor}(PF) = \frac{\text{Period ref}}{\text{Period PCM}} \qquad (1)$$

Therefore, when the period factor is one there is no enhancement in terms of air temperature. During experimentation, in terms of both air and frozen product temperature, the PF was always higher than one; i.e. the addition of PCM can help the system to remain cold longer and enhances the storage efficiency of the low temperature storage unit or transportation unit [21].

III. SUMMARY OF STUDIES CONDUCTED ON PCM INTEGRATIONS WITH VCC SYSTEM

Table 6 summarizes the thermo-physical properties of PCM and the details of its application. These details are comparable to have an idea about the changes in type of PCM and its properties based on application. These details are comparable to have an idea about the changes in type of PCM and its properties based on application.

Ref.	PCM	Melting Point (°C)	Latent Heat (kJ/kg)	Details of PCM application (PCM location)
PCM at evaporator				
[7]	Water	0	333	5mm thick slab at the back of evaporator
	Eutectic	-3	280	
[11,13]	19.5% Ammonium Chloride (NH_4Cl) salt in water	-15.4	282	PCM panels against wall of refrigerator
[2]	Distilled water	0	333	5mm thick PCM slab
[22]	A4 PlusICE	4	200	U-type tubes PCM heat exchanger around evaporator section
[5]	Distilled water	0	333	PCM in direct contact with the evaporator coil and cabinet box
	10% (NaCl) + 90% Water	-5	289	
[15]	Binary aqueous mixture	-2.5	228	PCM slab at the evaporator
		-4.4	251	
		-3.6	201	
[23]	18% NaCl +5% SAP + 0.03% diatomite	-18.98	120.6	PCM trays at the bottom of drawer and PCM slab on the top drawer
[24]	Ethylene glycol ($C_2H_6O_2$)	-12	181	PCM panels placed against wall of the cabin
[25]	Water	0	333	U-shaped PCM box placed around the evaporator cabin
	Ethylene glycol	-4	181	
	Eutectic solution	-5	-	
PCM at condenser				
[16]	SSPCM (Paraffin + Extended graphite + HDPE)	50.3	103.3	Shape stabilized PCM (SSPCM) at the condenser
[26]	Water	0	333	Macro-encapsulated PCM at the Condenser
	Paraffin	34	251	
	Copolymer bound PCM	34	182	
PCM in between components				
[14,19]	Eutectic solution E 21	21	150	PCMA, PCMB
	Eutectics	8	140	PCMC
[8]	Propylene glycol ($C_3H_8O_2$)	20	146	PCMB
[27]	n-octadecane	30.5	244	PCMB
PCM panels/packs inside compartments of refrigerator				
[21]	ClimSel C-18	-18	306	Encapsulated PCM placed inside refrigeration compartment
	Cristopia E-21	-21.3	233	

Table 6 Summary of Studies Conducted on Pcm Integration With Refrigerator

IV. PARAMETERS AFFECTING THE PERFORMANCE OF PHASE CHANGE MATERIAL

A. Pcm Properties

a). Effect of type of PCM

The choice of the PCM highly depends on the type of application (hot side/cold side), cabinet sets point temperature [21], PCM properties (LH value, HC value, ability to maintain required temperature in the cabinet) [28] and expected thermal load of the refrigerator [5, 7]. For example, the cool storage capacity of the system is slightly smaller with a eutectic aqueous solution than with water as a PCM, but the advantage of the eutectic solution is the ability to maintain the air in the refrigerated cell at proper temperature values recommended for the refrigerator [28]. In addition, water has high LH value hence it is best candidate to work against high thermal loads.

b). Effect of Phase change temperature

Ideally, the phase change temperature of PCM must fall within the operating temperature range of the system. High phase change temperature increases temperature in the compartment, decreases stored food quality, while it increases COP of the system due to the lower power consumption. On the other hand, lower the phase change temperature results in lower compartment temperature and hence better food quality can be achieved. However, this is more important for the fresh food compartment for 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. These effects are presented in fig. 5.

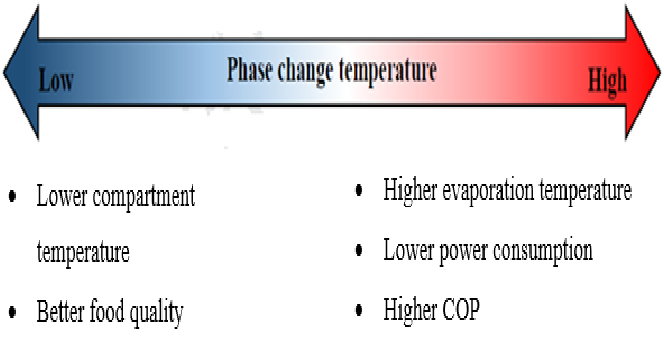

Fig. 5. Advantages of high/low phase change temperature on system performance [4].

c). Effect of PCM quantity and PCM thickness

The amount of PCM strongly affects the performance of the refrigeration system. It is reported that the increase in the significant amount of PCM (approximately 40%) resulted in just 6% increase in the system COP [5]. However, whenever increasing, the PCM thickness still kept all the PCM participating in the phase change process, its effect was greatest on reducing the global ON- time ratio as a consequence of longer compressor on time but prolonged compressor off time [7]. On the other hand the application of thicker PCM is more expensive and also initially requires higher compressor work for making the PCM as solid; thus, PCM thickness should be selected based on the thermal load [4].

According to Onyejekwe, the minimum volume of PCM to meet the required energy can be calculated by the following equation: [29]

$$E = \rho v h \tag{2}$$

Where, E is the total energy stored in the PCM, ρ and h are the density and latent heat of vaporization of PCM respectively and v is the volume of PCM. The total heat gain by the compartment from the ambient (Q) can be estimated from the following equation:

$$Q = (UA)_{cold}(T_{amb} - T_{cold}) \tag{3}$$

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:

$$v_{min} = \frac{t_{OFF}[(UA)_{cold}(T_{amb}-T_{cold})]}{\rho h} \tag{4}$$

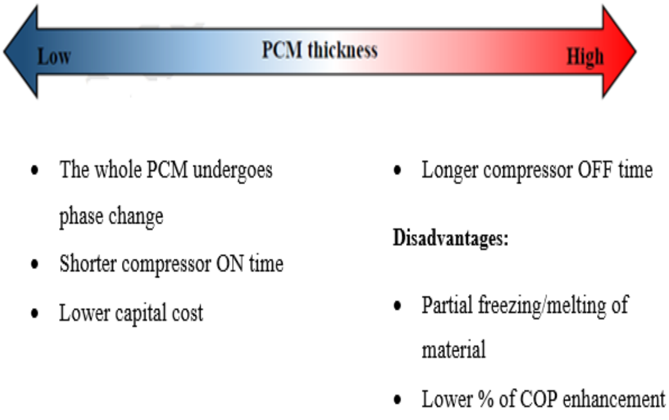

Fig. 6. Advantages and disadvantages of high/low PCM thickness on system performance [4, 27].

d). Effect of PCM position

To effectively integrate a PCM heat exchanger in a refrigerator compartment, it is necessary to apply PCM at the evaporator, walls and racks of the compartment which helps to rapidly stabilize and homogenize the temperature. This increases the off time of the compressor and thereby minimizes the energy consumption of the refrigerator [22].

The integration of PCM with a refrigerator system is a tough task. The application of PCM at evaporator or condenser or in between components or inside the cabinet has shown the different performance. The advantages and the limitations for each location are presented in the above section. Therefore, it can be argued that there are no specific guidelines on the effective PCM position. Hence, rigorous studies are needed for investigating the proper position of PCM that will enhance higher energy efficiency and better food quality.

e). Effect of PCM orientation and percentage of PCM coverage

The horizontal PCM configuration produces lower compartment temperatures than a vertical configuration. Hence the full height compartment coverage with combination of horizontal and vertical orientation is a good option. [10]. In addition to type of PCM orientation, the percentage of PCM coverage also affects the performance of the PCM. Elarem et al. have studied the four different percentage PCM coverage cases (Case-1:10%, Case-2:50%, Case-3:75%, Case-4:90%) as shown in fig. 7 [22]. It is observed that, to reach the reduction of the compartment temperature, Case-1 took much time (600 s) compared to Case-2, Case- 3 and Case-4 which took 195 s, 90 s and 80 s, respectively. A comparison of the three novel cases (Case-2, Case-3 and Case-4) with the basic configuration (Case-1) indicated 67.5%, 85% and 86.66% reduction in duration, respectively. Therefore, Case-4 offers better heat transfer performance, to reach the stabilization temperature inside the compartment which in turn reduces the energy consumption. However, there is a limit beyond which increasing PCM coverage in the racks more that 75% does not lead to any significant reduction in time to achieve the uniform temperature [22].

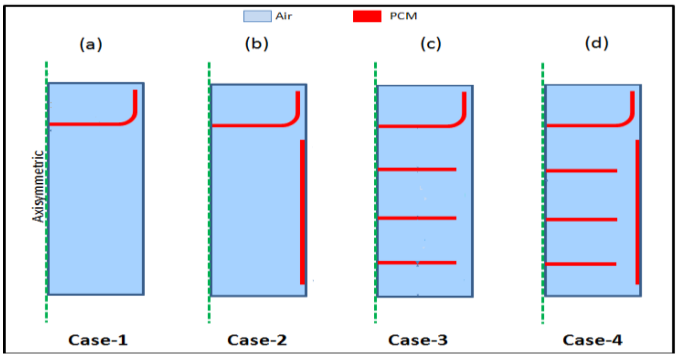

Fig.7. various cases of the refrigerator compartment with variable percentage of PCM coverage used for simulation study by Elarem [22].

In summary, the combination of horizontal and vertical orientation of PCM with 75% coverage on refrigerator compartment can achieve the stabilization temperature inside the compartment in shortest time.

B. Operational Conditions

a). Effect of Evaporation Temperature and Pressure

Improving the efficiency of heat exchangers, particularly of the evaporator is the most emphasized areas in the performance improvement of a household refrigerator. Azzouz observed that the incorporation of PCM has increased significant evaporation temperature due to the high latent heat of fusion of PCM, which gets released during phase transformation [7]. This kept higher evaporation temperature and pressure. However, higher evaporation temperature of a system with PCM resulted in higher COP [30]. On the other hand, the lower evaporating temperature needs longer time to freeze PCM because of the heat transfer from PCM as well as due to lower COP [16].

b). Effect Of Thermal Load

The response of the refrigerator to the addition of PCM and its efficiency are strongly dependent on the thermal load [7]. The heat gain of the refrigerator cabinet has a crucial effect on the amount of PCM melting/freezing during compressor on/off period. When the PCM is completely frozen and melted, the energy efficiency of the refrigerator can be increased. For further improvement of energy efficiency, the amount and the location of the PCM on the evaporator must be optimized in accordance with the heat gain of the refrigerator at a standard ambient temperature [15].

In addition, the heat loads resulting from frequent door openings and defrost cycles increase the energy consumption [13]. It is well established that the performance of refrigeration system decreases while increasing the thermal load. On the other hand, application of PCM in a refrigeration system can improve the system performance. A 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 [16].

The system at different thermal load can also be affected by different types of PCM. The refrigeration system with PCM argued that when the thermal load was small, eutectic PCM (with phase change temperature of -5℃) had a shorter compressor on time, while, for higher loads, water was a better candidate [30] because of its higher latent heat of fusion as compared to eutectic. Therefore, optimization of PCM effect at different thermal loads is important for further improvement.

c). Effect of Ambient Temperature

Ambient temperature affects both the performance of a refrigeration system and the usefulness of PCM. Generally, the higher the ambient temperature, the lower the COP of systems due to the higher compartment air temperature and higher condensation temperature and pressure. Earlier studies reported that by increasing the thermal load, system COP decreased even in the 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 [28].

In addition, very low ambient temperature also has a negative effect on the PCM performance. The reason is that when the refrigerator is working in a 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 of -3°C for PCM prevents subzero fresh food compartment temperature even for a low ambient temperature of 15°C [7]. Fig. 8 represents the negative effects of ambient temperature on system performance.

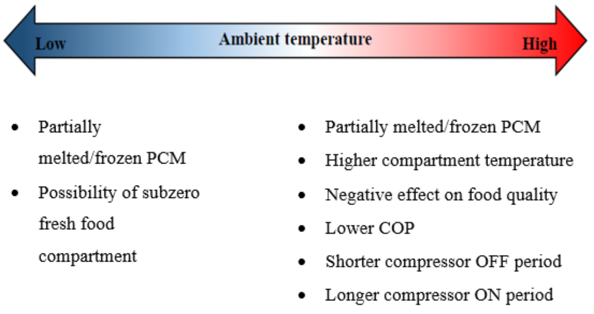

Fig. 8. Negative effects of high and low ambient temperatures on the system performance [4].

C. Other Parameters

a). Effect of condenser surface area

Increasing the condenser surface area with refrigerator by 20% enhanced the effect of PCM. It is recommended to redesign the heat transfer area of evaporator and/or condenser to enhance the energy saving potential of PCM use in refrigerators [5].

b). Heat exchanger geometrical properties

- *Effect of Heat Exchanger Tube Diameter and Length*

It is found that increasing the tube diameter and length of heat exchanger has a considerable effect on decreasing refrigerant temperature. This is due to increase in the heat transfer area has allowed the most heat transfer between refrigerant and PCM and ultimately it resulted in an increase in COP [27].

V. LIMITATION AND CHALLENGES OF APPLICATION OF PCM IN REFRIGERATION SYSTEM

A. Limitation of Application of PCM in Refrigeration System

A refrigeration system with PCM can improve the system performance. However, the attachment of PCM with the refrigeration system has some limitations. The main criteria that have limited the use of PCM in different refrigeration systems are the selection of PCM container material, the number of cycles it can withstand without any degradation, cycling stability and corrosion effect of PCM. There were many problems found while using PCM. For example, most of the salt hydrate PCM does not freeze immediately leading to cooling below the melting temperature; however, starts crystallization after a temperature well below the melting temperature (i.e. sub-cooling effect). If nucleation does not occur at all, then the latent heat cannot be released and the material stores sensible heat only [29].

Moreover, poor stability of the material properties and corrosion between the PCM and its container ultimately reduces the PCM long-term stability. PCM container must have anticorrosive properties, high thermal conductivity, as well as most reliability. The selection of PCM container material is one of the challenging tasks. Copper and carbon steel must be avoided due to their high corrosion rate, presence of precipitates and pH changes. Aluminum has high thermal conductivity but it shows pitting action on its surface those can change the material properties of a container. Therefore, stainless steel (SS) can be recommended for PCM container for corrosive PCMs as it has good corrosion resistance [29].

B. Challenges of Application of PCM in Refrigeration System

Certainly, PCM enhances the heat transfer rate through changing its phase from solid to liquid or vice versa. Therefore, successful application of PCM in the household refrigerator would be the energy-efficient next generation refrigerator.

However, there are many challenges to incorporate PCM in a refrigeration system. For example, choice of PCM thickness is very crucial for designing PCM based refrigerators. Low thickness of PCM reduces the COP while high thickness (amount of PCM) works as an extra thermal load, therefore reduces the compressor efficiency. The thickness of PCM mainly depends on the cooling capacity and the size of the refrigerator or the freezer [4, 27]. No study showed the optimum thickness of PCM for a household refrigerator.

Furthermore, the selection of PCM container is another challenge. Most of the PCMs have a corrosive property that damages the PCM container. As mentioned earlier, SS has been recommended to make a PCM container for using the corrosive PCM. However, SS has poor thermal conductivity which ultimately decreases the heat transfer rate between PCM and heat exchanger. Therefore, to investigate the optimum PCM thickness and perfect PCM container is the ultimate challenge of incorporating PCM in a conventional refrigeration system [29].

VI. CONCLUSION

A comprehensive review of the PCM application in domestic refrigeration system was carried out and presented in table 6. The results showed the latent heat storage technique is promising one. The most of studies were focused on the application of PCM on the low temperature side (i.e. evaporator). The application of PCM on the high temperature side (i.e. condenser) showed less promising results due to undesirable effects on the system. In summary, the limitations of studies are:

- The studies are limited both in number and types of PCM (approximately 20); therefore more investigation on different types of PCM is required.
- The study of the PCM application at high temperature side (i.e. condenser) is limited to hot wall type condenser only. This is resulting in more frequent compressor ON/OFF and more refrigerant displacement losses. Hence the investigation of the other types of condensers (naturally cooled, forced cooled) is required to explain the usefulness of PCM at the condenser.

- The comparative study on the advantages and disadvantages of PCM at evaporator and condenser shows that, the desirable effects of PCM at evaporator can cover the some undesirable effects of PCM at the condenser. Hence it seems to be the simultaneous application of PCM at evaporator and condenser can be most advantageous.
- The study on the advantages and disadvantages of PCM application in between components shows that, the combination of sub-cooler (PCMB) and suction line HX (PCMC) can be most advantageous. With consideration of this, it seems to be use of liquid suction heat exchanger (LSHX) with PCM can be another approach to achieve the enhanced performance of refrigeration systems.
- The PCM integration with conventional system is limited due to limiting properties of PCM such as low thermal conductivity; hence analyses on PCM with nano-particle additives are subject of future work.

VII. ACKNOWLEDGEMENT

We would like to acknowledge the support provided by institute RSCOE, Pune.

REFERENCES

[1]. [1] IBEF presentation, Indian Consumer Durables Industry Analysis, https://www.ibef.org/industry/consumer-durables-presentation (accessed 27 September 2017, 9 November 2017).

[2]. [2] A.C. Marques, G.F. Davies, G.G. Maidment, J.A. Evans, I.D. Wood, “Novel design and performance enhancement of domestic refrigerators with thermal storage”, Applied Thermal Engineering 63, pp. 511-519, 2014.

[3]. [3] Cooling India, http://www.coolingindia.in/blog/post/id/9958/benefits-of-using-inverter-compressors (accessed 7 November 2017).

[4]. [4] Mahmood Mastani Joybari Fariborz Haghighat Jeff, “Heat and cold storage using phase change materials in domestic refrigeration systems: The state-of-the-art review”, Energy and buildings, in press.

[5]. [5] Md. Khan and Hasan M.M. Afroz, “Effect of phase change material on performance of household refrigerator”, Asian Journal of Applied Sciences 6 (2), pp. 56-67, 2013.

[6]. [6] E. Oro, A. de Gracia, A. Castell, M.M. Farid, L.F. Cabeza, “Review on phase change materials (PCMs) for cold thermal energy storage applications”, Applied Energy 99, pp. 513–533, 2012.

[7]. [7] K. Azzouz, D. Leducq, D. Gobin, “Performance enhancement of a household refrigerator by addition of latent heat storage”, International journal of Refrigeration 31, pp. 892-901, 2008.

[8]. [8] C. Tulapurkar, P. R. Subramaniam, G. Thagamani, Ramasamy Thiyagarajan, “Phase change materials for domestic refrigerators to improve food quality and prolong compressor off time”, International Refrigeration and Air Conditioning Conference, Purdue University, 2010.

[9]. [9] M. Visek, Cesare Maria Joppolo, Luca Molinaroli, Andrea Olivani, “Advanced Sequential Dual Evaporator Domestic Refrigerator/Freezer: System Energy Optimization”, International Journal of Refrigeration, in press.

[10]. [10] A.C. Marques, G.F. Davies, J.A. Evans, G.G. Maidment, I.D. Wood, “Theoretical modeling and experimental investigation of a thermal energy storage refrigerator”, Energy 55, pp. 457-465, 2013.

[11]. [11] B.Gin and Mohammed M. Farid, “The use of PCM panels to improve storage condition of frozen food”, Journal of food engineering 100, pp. 372-376, 2010.

[12]. [12] Md. Imran H. Khan and Hasan M.M. Afroz, “Diminution of temperature fluctuation inside the cabin of a household refrigerator using phase change material”, International Journal of Recent Advances in Mechanical Engineering (IJMECH) Vol.3, No.1, February 2014.

[13]. [13] B. Gin, M.M. Farid, P.K. Bansal, “Effect of door opening and defrost cycle on a freezer with phase change panels”, Energy conservation and management 51, pp. 2698-2706, 2010.

[14]. [14] Fuqiao Wang, G. Maidment, John Missenden, Robert Tozer, “The novel use of phase change materials in refrigeration plant. Part 3: PCM for control and energy savings”, Applied Thermal Engineering 27, pp. 2911–2918, 2007.

[15]. [15] Y. Yusufoglu, T. Apaydin, S. Yilmaz, H.O. Paksoy, “Improving performance of household refrigerators by incorporating phase change materials”, International Journal of Refrigeration, in press.

[16]. [16] W. Cheng, Bao-Jun Mei, Yi-Ning Liu, Yong-Hua Huang, Xu-Dong Yuan, “A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condensers: An experimental investigation”, Energy 36, pp. 5797-5804, 2011.

[17]. [17] W. Cheng and Xu-Dong Yuan, “Numerical analysis of a novel household refrigerator with shape-stabilized PCM (phase change material) heat storage condensers”, Energy 59, pp. 265-276, 2013.

[18]. [18] X. Yuan and W. Cheng, “Multi-objective optimization of household refrigerator with novel heat-storage condensers by Genetic algorithm”, Energy Conversion and Management 84, pp. 550–561, 2014.

[19]. [19] Fuqiao Wang, G. Maidment, John Missenden, Robert Tozer, “The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation”, Applied Thermal Engineering 27, pp. 2893-2901, 2007.

[20]. [20] Fuqiao Wang, G. Maidment, John Missenden, Robert Tozer, “The novel use of phase change materials in refrigeration plant. Part 2: Dynamic simulation model for the combined system”, Applied Thermal Engineering 27, pp. 2902–2910, 2007.

[21]. [21] E. Oro, Laia Miro, Mohammed M. Farid, Luisa F. Cabeza, “Thermal analysis of a low temperature storage unit using phase change materials without refrigeration system”, International Journal of Refrigeration 35, pp. 1709-14, 2012.

[22]. [22] R. Elarem, S. Mellouli, E. Abhilash, A. Jemni, “Performance analysis of a household refrigerator integrating a PCM heat exchanger”, Applied Thermal Engineering, in press.

[23]. [23] Z. Liu, Danfeng Zhao, Qinghua Wang, Yuanying Chi, Lingfei Zhang, “Performance study on air-cooled household refrigerator with cold storage phase change materials”, International Journal of Refrigeration 79, pp. 130-142, 2017.
[24]. [24] M. Ahamed, J.Kannakumar, P.Mallikarjuna reddy, “Design and fabrication of cold storage plant using phase change material (PCM)”, International Journal of Innovative Research in Science, Engineering and Technology Vol. 2, issue 9, September, 2013.
[25]. [25] D. Boban, Jijo George, Akhil Geo Biju, Binu chacko, Easwaran Nampoothiry K, “Performance enhancement of a domestic refrigerator using phase change materials”, International Journal of Scientific & Engineering Research, Volume 7, issue 4, April-2016.
[26]. [26] G. Sonnenrein, A. Elsner, E. Baumhögger, A. Morbach, K. Fieback, J. Vrabec, “Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and tube condensers”, Thermodynamics and Energy Technology, University of Paderborn, Germany.
[27]. [27] S. Bakhshipour, M.S. Valipour, Y. Pahamli, “Parametric analysis of domestic refrigerators using PCM heat exchanger”, International Journal of Refrigeration, in press.
[28]. [28] K. Azzouz, D. Leducq, D. Gobin, “Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation”, International journal of Refrigeration 32, pp. 1634-44, 2009.
[29]. [29] Md. Imran H. Khan, “Conventional Refrigeration Systems Using Phase Change Material: A Review”, International Journal of Air-Conditioning and Refrigeration, Vol. 24, No. 3, 2016.
[30]. [30] Gang Li, Yunho Hwang, Reinhard Radermacher, Ho-Hwan Chun, “Review of cold storage materials for subzero applications”, Energy 51, pp. 1-17, 2013.