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A Review on use of Phase Change Materials as Thermal Energy Storage in Domestic Refrigeration System

Shamuvel Shinder[1], Krishnakant Pawar[2], Sanket Mahajan[3], Bhushan Tambe[4]
[1,2,3,4]*Student, Department of Mechanical Engineering, PCET's NMIET, Pune, India*

***Abstract*: Various refrigeration systems are widely used in India on domestic as well as commercial scale. Several researches have been done to improve the performance of refrigeration systems and quality of food by application of various methods. Recently, the use of phase change materials (PCM) as thermal energy storage has proved to be an effective way to store heat energy due to their capability of gaining and loosing large amount of latent heat for changing phase. This review paper studies different experimental approaches comprising application of phase change material in domestic refrigerator. A number of studies have focused on the application of PCM at evaporator for cold storage. On the other hand, not much has been done on the condenser side and fresh food storage compartment. Advantages and disadvantages of integrating PCM in both evaporator and condenser sides have been studied and future potential applications of PCMs have been discussed.**

***Keywords*: Evaporator, Phase Change Temperature (PCT), condenser, Thermal Load.**

1. Introduction

In India according to the survey carried out by STATISTA [1] the refrigerator market is excelling at very fast rate as shown in table 1. Thus we can conclude from this stat that market of domestic refrigerator is rapidly increasing and so is its energy consumption. Generally, energy consumption of a refrigerator depends upon its components efficiency, ambient temperature, thermal load, door openings, set-point temperature in its compartment(s), and refrigerant type [3]. So efforts are being made to enhance its performance. These efforts are mainly distributed in three categories i.e. development of energy-efficient compressors, enhancement of Thermal insulation and enhancement of heat transfer at heat exchangers i.e. condenser and evaporator.

In domestic refrigerators, hermetically sealed reciprocating ON/OFF compressors are conventionally used because of their high reliability and efficiency with less cost and noise. These compressors are major consumers of electricity. Thus, compressor modification is strongly recommended to enhance the performance of refrigerators. Some alternatives with lower energy consumption are available for conventional ON/OFF compressors, e.g. variable speed compressors and linear compressors. In variable speed compressors, motor speed continuously changes based on the load and driving efficiency. Advantages of variable speed compressors include continuous control, lower noise generation, lower vibration, lower starting current, and better COP compared to the conventional ON/OFF systems. However, still this technology is too expensive. Another way of improving performance of refrigeration system is enhancing thermal insulation. Polyurethane layer is used for insulation. It is clear that the higher the thermal resistance of insulation in a refrigeration system, the longer the compartment remains cold. It is possible to further reduce heat loss from the walls of a refrigeration system by means of vacuum insulation panels (VIPs). VIP is highly resistant against the heat transfer, about 4 times more than a polyurethane board of equal thickness [5]. But as they are expensive, their application is restricted. Therefore, more cost effective methods of achieving high thermal insulation are required. It has been reported that the first two categories (compressor and insulation modification) are either costly or difficult to be applied. There's another way to improve refrigerator performance i.e. enhancement of heat exchangers (condenser and evaporator) using thermal energy storages like phase change material. 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 or compartment.

Table 1
Market size

Year	Market size in 100 crore
2009	46.2
2013	84
2014	91
2015	98
2016	105
2019	252

2. PCM application at evaporator

The evaporator in domestic refrigerator is based on either free or forced convective heat transfer. Application of a Thermal Energy Storage (TES) near evaporator coils has proved to improve the thermal stability of refrigerator systems in various situations. As a result of application of energy storage the compressor needs to work for a longer period of time to charge the energy storage. Despite longer compressor ON time in each cycle to charge PCM, the global ON-OFF time ratio decreases due to longer compressor OFF time [6]. Longer compressor off period results in lower overall energy consumption, better food quality and avoiding critical effect of frequent compressor start/stop.

Some studies suggested that direct contact of phase change material with naturally cooled evaporator is very advantageous as it enhances heat transfer from evaporator and store excess cooling capacity of system in PCM. This results in higher temperature and pressure during phase change period of PCM. Thus, refrigerant density as well as cooling capacity increases [6].

This increases the COP of system. Also, during power outages and frequent door openings, moist and warm air enters the cabinet increasing the thermal load. In such cases, PCM can dampen this effect and maintain the cabinet temperature for better food quality. Furthermore, the PCM showed promising performance when the set-point temperature of the compartment was close to its phase change temperature but for lower set-point temperatures it did not damp temperature significantly. It was also found that the larger the surface of the PCM panels, the lower the compartment temperature variation [2].

A. Advantages

- Higher COP.
- Low compressor ON-OFF ratio.
- Effective in maintenance of food temperature and quality up to certain levels in Power Outage and frequent door opening conditions.
- Provides cooling effect during compressor OFF period.

B. Disadvantages

- Higher condensation temperature.
- Longer Compressor On period.
- Increased cost and space utilized.

3. PCM application at condenser

A condenser is a device used to condense a substance from its gaseous to its liquid state, by cooling it. In so doing, the latent heat is given up by the substance and transferred to the surrounding environment. The aim of application of PCM at condenser is to achieve low temperature at condenser. Using PCM at condenser can extend condenser's heat rejection process to compressor OFF time so as to enhance condenser heat transfer and achieve lower condensation temperature [3]. According to a study conducted, when PCM is located in between Compressor and condenser it acts as an extra condenser [6]. In this case, COP was enhanced due to the lower temperature and pressure in condenser. Whereas when PCM was placed between condenser and expansion valve lower phase change temperature resulted in higher COP [4].

The reason was due to the fact that the lower the phase changes temperature, the higher the Subcooling. On the other hand the heat rejection time is longer. Generally, higher ambient temperature deteriorates the COP but it was found that when PCM was used, the magnitude of COP reduction was lower since the PCM created higher temperature difference between the refrigerant and the ambient during phase change.

A. Advantages

- Higher COP.
- Shorter compressor global ON time ratio.
- Continuous heat rejection from condenser even during compressor OFF time.
- Lower condensation pressure and temperature.

B. Disadvantages

- More frequent compressor ON/OFF which result in destructive effect on lifetime of compressor.
- Higher heat gain from condenser to compartment during OFF time.
- More refrigerant displacement losses.

4. PCM Selection

Selection of Phase Change Materials (PCM) is based on factors such as its phase change temperature and thermal load which also decides the quantity of PCM needed for providing significant effect. These factors are explained in brief as follows:

A. Phase change temperature (PCT)

It is the temperature at which the material changes its phase by accepting or releasing large amount of latent heat. Selection a material with proper PCT is of great importance in preserving the quality of food. When placed inside the refrigerator compartment it is essential to choose the PCM with the PCT within the thermostat temperature range (the range which decides the compressor ON/OFF). The performance of PCM changes as high/low PCT is selected within the thermostat range [6]. High PCT decreases the food quality while increasing its evaporation temperature during phase change which increases the overall COP of the system. On the other hand, low PCT maintain the compartment temperature low for better food quality but extends the phase change and increases the compressor ON time. So, a PCM with a phase change temperature in between both the high/low extremes needs to be chosen for getting the benefits of both and diminishing their disadvantages. It is worth noting that the position and type of encapsulation of PCM also affects its performance. For proper heat transfer between the PCM and evaporator, PCM should surround the evaporator coil and the material of PCM containing slab/container should have high Thermal conductivity.

B. Thermal load

It is the heat load on the system which is generated by the food present in the compartment and heat transfer from ambient to the system during the door openings, defrosting and the power outage. It is dependent on the following factors:

1) Amount of food present

The temperature and quantity of Food decides the heat load it generates on the system. This heat flow rate (qfood) can be calculated by knowing their specific heat capacities (Cp). Thus the load can be calculated by following formula:-

$$q_{food} = \left(\frac{m \cdot c_p \cdot \Delta T}{\Delta t}\right)_{food}$$

2) Ambient temperature

Higher the ambient temperature, greater is the ambient to system heat transfer which decreases the COP of the refrigeration system. Studies have shown decreased COP even in the presence of PCM. High thermal load also directly affects the charging and discharging of PCM. The melting time of PCM decreases while the freezing time increases. Also, sometimes during compressor OFF state due to high thermal load the compartment temperature increases rapidly up to the thermostat set temperature before the PCM gets completely discharged (i.e. melted). This decreases the efficiency of the PCM. Similarly, a too low ambient temperature can decrease the compartment temperature rapidly before the PCM gets completely charged (i.e. frozen). Possibly, it can also decrease the fresh food compartment temperature which is not ideal. The heat flow rate from ambient (qAir) can be calculated with experimentation by formula:

$$q_{Air} = \left(\frac{\rho \cdot v \cdot \Delta T \cdot c_p}{\Delta t}\right)_{Air}$$

3) Amount of PCM

The PCM slab thickness depends on the volume of PCM used. The heat transfer at PCM during phase change process is given as:

$$q_{PCM} = \left(\frac{\rho \cdot v \cdot Q_L}{\Delta t}\right)_{PCM}$$

where QL is Latent Heat of Fusion

Therefore, the minimum volume (V) of PCM used to overcome the heat transfer by thermal Load due to food and Ambient air is given as follows:

$$q_{PCM} = q_{food} + q_{Air}$$

$$\left(\frac{\rho \cdot v \cdot Q_L}{\Delta t}\right)_{PCM} = q_{food} + q_{Air}$$

$$V_{PCM} = \frac{\Delta t_{PCM} \cdot (q_{food} + q_{Air})}{(\rho \cdot Q_L)_{PCM}} \quad (1)$$

The amount of PCM should be greater than the calculated amount from equation 1. But PCM slab should not be thicker than certain amount or it will result in partial melting. Whereas, it will also result in prolonged compressor ON time.

5. Conclusion

- In summary we can conclude from the above studies that, PCM can act as efficient thermal energy storage to enhance the heat transfer in refrigerators.
- Most of the studies were focused on application of PCM in evaporator side which yielded better result in terms of quality of food, prolonged compressor off time, increase in evaporator temperature and pressure, maintaining cabinet temperature, etc. though it has showed increase in condenser temperature.
- Recently some studies on application of PCM on condenser side has also showed promising results like subcooling of condenser refrigerant and improved ratio of compressor ON-OFF period, though it leads to frequent compressor starts.
- Least researched area was fresh food compartment which has huge scope for further research.
- So, implementation of PCM in evaporator side nullifies all the losses generated by use of PCM at condenser and vice versa.
- So, it will prove to be beneficial to use PCM simultaneously at both sides i.e. condenser and evaporator.

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