Theoretical Analysis of Two Evaporator Configurations for a Conventional Refrigerator Coupled To a Phase Change Material

M Berdja¹, F Yahi¹, A Tétbirt¹, M Ouali¹, M A Djebiret¹, M Mokrane¹
¹ Unité de Développement des Equipements Solaires. UDES./ Centre de Développement des Energies Renouvelables. CDER. Bou-Ismail.42415.w.Tipaza. Algeria.
E-mail: berdjamohand@gmail.com / mohand.berdja@udes.dz

Abstract. In this paper, we present the study and development of prototypes of refrigeration systems that operate more efficiently and consume less electrical energy, and this based on the use of Phase change materials (PCM) as thermal energy storage (TES). These materials have the ability to store thermal energy on its latent heat form, which is produced during off-peak periods, and then release this thermal energy to the consumer during the desired period or during periods when electrical demand is high. The effect of phase change material on the energy performance of a conventional refrigerator has been highlighted for two different evaporator configurations; a flat evaporator and a ventilated finned evaporator. An analysis to select the adequate phase change material (PCM) as well as its arrangement to be integrated into the refrigerator, and the mechanism by which the PCM affects the refrigerator operating conditions according to the type of evaporator has also been discussed.

1. Introduction
The overall electricity consumption continues to increase from year to year, which encourages production companies to operate frequent load shedding so that the instantaneous and non-storable electricity production can meet consumer demand. This increase in overall consumption is mainly due to the increase in population, development of living standards and access to technologies, and also to the excessive and non-rational use of electrical equipment especially the refrigerating appliances. Therefore, It is more than necessary to design refrigerators systems that operate more efficiently (higher COP), with longer downtime and low energy consumption. The use of thermal storage with phase change materials (PCM) seems to be one of the least expensive solutions with no environmental impact [1-3].

A PCM is defined as any substance that has a significant latent heat that occurs at a certain temperature. This temperature is constant for pure and eutectic materials, and may represent a range of few degrees for mixtures and binary solutions [4]. Only the liquid-solid phase change to a practical interest in the field of thermal energy storage, even if the liquid-gas phase change may involve latent heat more important than that of the liquid-solid transformation. These materials have the advantage to offset the gap between the production of thermal energy (cold /heat) and the needs and to have a high energy density compared to a sensible storage. Nevertheless, PCM can present some disadvantages, such as low thermal conductivity and latent heat, supercooling phenomena, high price, corrosiveness and toxicity [5].
The use of PCMs as a thermal storage device concerns several fields of application. It is found mainly in the field of building, solar, and also in refrigeration and air conditioning. Regarding the application of PCMs in refrigeration, the PCM can be integrated in the refrigerator in different ways: In contact with refrigerator air [6], in contact with evaporator [7], in contact with condenser [8] and evaporator immersed in PCM [9].

In this study, two (2) configurations of domestic refrigerators are considered; one supplied with a flat evaporator and with a ventilated finned evaporator, in order to highlight the effect of the phase change material (PCM) on the refrigerator operating conditions and its thermal performance.

2. Effect of PCM on the refrigerator operating conditions

2.1. Flat plate evaporator

The presence of a PCM layer at the evaporator's surface (Figure 1.a) permits an extension of the compressor's downtime. The cold latent heat stored into PCM during the compressor's on cycle is released partly to the air, and partly to the evaporator's surface. The temperature of the thermostat bulb remains at a low temperature, allowing the compressor to be idle for a longer time. The PCM also improves heat transfer at the evaporator's surface, and permits an easier evaporation of the refrigerant and thus an improvement of the evaporator performance. This results in a slight increase of the evaporation temperature and the COP.

![Figure 1](image1.png)

**Figure 1.** (a) Flat plate evaporator coupled to PCM. (b) Finned ventilated evaporator coupled to PCM.

However, thicker layers of the PCM could allow for additional thermal resistance that reduces the heat transfer that occurs between the refrigerant and the air. Thus, a thicker layer of PCM would prolong the refrigerator's downtime without being able to maintain a low air temperature inside the refrigerator (figure 2). The search for the optimum thickness of the PCM is necessary to reduce the excessive rise in air temperature inside the refrigerator. This can be done by an optimization that leads to obtain the maximum value of the compressor downtime equivalent to the minimum value of the air temperature rise in the refrigerator.

2.2. Finned evaporator

For a finned evaporator type (Figure 1.b), the configuration of a heat exchanger should be selected in order to contain the quantity of PCM to be integrated into the refrigerator. In that case, the design of the PCM heat exchanger is required to ensure an optimal overall operation and a prolonged downtime of the refrigerator. The heat exchanger could take several configurations; plate, honeycomb or packed bed. The presence of fins on the evaporator does not allow placing the PCM on the surface of the evaporator in this type of configuration.
It would be necessary to have a melting time that is equivalent to the desired compressor shutdown time. The melting time is defined as the time for which the melting of the entire mass of the PCM in the heat exchanger takes part (Figure .3.a). The melting time, which is the most important parameter for the dimensioning of the heat exchanger containing the PCM, allows a rigorous control of the compressor’s operating time.

Figure 2. Air temperature profile. Case with vs without PCM.

The melting time is calculated from the following parameters:

- Thermal characteristics of PCM.
- PCM surface exchanger.
- Thermal balance through the walls of the refrigerator.
- Air velocity generated by the ventilator through the PCM heat exchanger.

However, a long shutdown requires a high amount of PCM. A large volume of PCM inside the refrigerator could limit the volume intended for the storage of foodstuffs. Beside disadvantage of the limitation of the volume due to the large the amount of PCM, melting time is also conditioned by two (2) constraints that must be minimized:

- Pressure drop at the PCM heat exchanger (Figure .3.b): a significant pressure drop through the PCM exchanger would require a sufficiently powerful fan (energy-consuming and expensive) to satisfy the air circulation inside the refrigerator, and overcoming the pressure drop. The pressure drop depends mainly on the configuration of the PCM heat exchanger (length, diameter and air velocity).
- Ventilation efficiency: the fan must be efficient energetically in its range of velocity. The minimum ventilation performance is dictated by the standard eco-design requirements for ventilation units.
It would be necessary to carry out an optimization of the dimensions of PCM heat exchanger in order to limit the pressure drop through the PCM heat exchanger and allow a more efficient operating condition of the ventilator. This permits to obtain an extended compressor downtime and a save in refrigerator energy consumption.

3. Selecting the phase change temperature of the PCM

3.1. Flat plate evaporator

The definition of the phase change temperature of the PCM to be integrated in a domestic refrigerator depends on the way it is placed inside the refrigerator. The PCM interacts thermally with its surrounding environment. In this case, the PCM is in direct contact with the evaporator, and tends towards thermal equilibrium by conduction with the surface of the evaporator. The temperature of the chosen PCM must in this case be between the maximum and minimum temperature of the surface of the evaporator (Figure 4), so that the PCM can solidify during the operating cycle of the compressor.

Figure 4. Evaporator temperature vs phase change temperature of PCM $T_{ev-min} < T_{pcm} < T_{ev-max}$. 

Figure 3. (a) PCM melting time profile. (b) Pressure drop through PCM heat exchanger.
3.2. Finned ventilated evaporator

In the case of a refrigerator equipped with a finned ventilated evaporator, the phase change temperature of the selected PCM should be between the maximum and minimum temperature of the air in the chamber. The PCM interacts thermally with its surrounding air, and tends towards thermal equilibrium by convection with air in the chamber. This is because the PCM is only in contact with the air, unlike the case of a plate evaporator where the PCM is in contact with the surface of the evaporator (Figure 5). The air temperature inside the refrigerator must be set to several set temperatures to find the proper temperature that would situate the phase change temperature between the maximum and minimum air temperature, and thus allow the phase change to occur.

![Figure 5](image-url)

**Figure 5.** Air and PCM temperature ($T_{\text{consign}}=-1^\circ \text{C}$). $T_{\text{air-min}} < T_{\text{PCM}} < T_{\text{air-max}}$

Manipulating the set point temperature of the thermostat makes may modify the air temperature range of the refrigerator (minimum-maximum temperature). This temperature range could shift with respect to the value of the phase change temperature of the PCM. The problem does not arise for a flat evaporator, because the difference between the maximum and minimum temperature of the surface of the evaporator is very large (around 20°C) and the manipulation of the thermostat does not allow a significant shift with respect to the phase change temperature of the PCM. On the other hand, for a finned ventilated evaporator, the difference between the maximum and the minimum temperature of the air is generally very small (2 to 4°C), and this interval shifts greatly with the manipulation of the thermostat, generating a shift with respect to the phase change temperature of the PCM (Figure 6.a and Figure 6.b).
Figure 6. Air and PCM temperature. (a) $T_{\text{consigne}}=-3.5^\circ\text{C}$. $T_{\text{PCM}}>(T_{\text{air-max}}, T_{\text{air-min}})$. (b) $T_{\text{consigne}}=+1^\circ\text{C}$. $T_{\text{PCM}}>(T_{\text{air-max}}, T_{\text{air-min}})$

4. Conclusion
An energy analysis of refrigerator using a phase change material (PCM) as a cold thermal storage device has been conducted for two (2) types of evaporators commonly used in conventional refrigeration; a flat evaporator and a ventilated finned evaporator. The analysis to select the adequate phase change material (PCM) as well as its arrangement to be integrated into the refrigerator showed that for a flat plate evaporator, the PCM is in contact with air and evaporator surface. The PCM phase change temperature should be selected to be close to the refrigerant phase change temperature. However, for a ventilated finned evaporator, the PCM is only in contact with the room air, and the PCM temperature should be selected to be between the maximum and minimum air temperature inside the refrigerator. The mechanism by which the PCM affects the refrigerator operating conditions differs according to the type of evaporator. For a flat evaporator without forced ventilation, the PCM improves heat transfer at the evaporator which increases the evaporator performance and extends the compressor downtime. However, beyond a certain thickness, the PCM can act as thermal insulation to the heat transfer that occurs between refrigerant and air, and increase the air temperature inside refrigerator. Finding an optimal thickness of the PCM slab is necessary for this kind of application, which is defined by a maximum of extension of the compressor downtime that corresponds to the minimum of the air temperature rise inside the refrigerator. For a ventilated finned evaporator, the PCM does not affect directly the performance of the refrigerator, but allows a more precise control of the compressor downtime. In fact, the compressor downtime is equivalent to the PCM melting time, which depends mainly on the mass of PCM contained into the heat exchanger, and the quality of the heat transfer through, but limited by an elevated pressure drop and low ventilation efficiency. An optimization of the dimensions of the heat exchanger is necessary to limit the pressure drop, to allow the reduction of the ventilation energy consumption and the extension of the compressor downtime.

5. References
[1] Desmons, J. Aide mémoire génie climatique, 2010, 2ème édition DUNOD.
[2] Chidambaram LA, Ramana AS, Kamaraj G and Velraj R. 2011, Review of solar cooling methods and thermal storage options. Renewable and Sustainable Energy Reviews, 15, 3220-3228.
[3] Laidi, M, Hanini S, Abbad B, Berdja M and Ouali M, 2012, The study and performance of a modified ENIEM conventional refrigerator to serve as a photovoltaic powered one under Algerian climate conditions, Journal of Renewable and Sustainable Energy 4, 053112.
[4] Farid M M, Khudhair A M, Razack S A and Al-Hallaj S, 2004, *A review on phase change energy storage: materials and applications*, Energy Conversion and Management 45, 1597–1615.

[5] Zalba B, Marin J, Cabeza L F and Mehling H, 2003, *Review on thermal energy storage with phase change: materials, heat transfer analysis and applications*, Applied Thermal Engineering 23, 251–283.

[6] Oro E, Miro L, Farid M M and Cabeza L F, 2012, *Improving thermal performance of freezers using phase change materials*, International Journal of Refrigeration 35, 984–991.

[7] Azzouz K, Leducq D and Gobin D, 2008, *Performance enhancement of a household refrigerator by addition of latent heat storage*, International Journal of Refrigeration 31, 892–901.

[8] Wang F, Maidment G, Missenden J and Tozer R, 2007, *The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation*, Applied Thermal Engineering 27, 2893–2901.

[9] Berdja M, Abbad B, Laidi M, Yahi F and Ouali M, 2012, *Numerical Simulation Of A Phase Change Material (PCM) In A Domestic Refrigerator Powered By Photovoltaic Energy*, ICHMT Digital Library Online.