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Heat and cold storage using phase change materials in domestic refrigeration systems: The state-of-the-art review

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ABSTRACT

Domestic refrigerators are among the most widely used household appliances and a great portion of energy is used by these systems. Reduction of temperature fluctuation and enhancement of system performance is the main reason of using phase change materials (PCMs) in refrigeration systems. Different approaches have been used to improve the thermal performance of these systems by integration of PCM. 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. Despite large number of studies, a comprehensive literature review specifically focusing on the application of PCM in domestic refrigerators is missing. This paper presents a review of the experimental efforts as well as modeling approaches to study the application of PCMs in domestic refrigerators. Moreover, advantages and disadvantages of each type of storage are presented and, the future and potential promising applications of PCMs in domestic refrigerators are discussed.

1. Introduction

Nowadays, almost every household uses at least one refrigeration system for domestic food preservation or in the building's mechanical ventilation system to provide the required indoor thermal environment. Based on statistical data, in 2008, there were an average 1.27 and 0.54 refrigerators and freezers per household in Canada, respectively [1]. Besides, in 2011, there were a total number of 13,320,615 households in Canada [2]. This indicates a minimum of about 24 million household refrigerators and freezers are currently in use in Canada, which confirms that a huge amount of energy consumption is required for their operation. Thus, even small performance enhancement of these appliances brings huge amounts of energy saving. 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]. 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 [4].

The first category includes all the studies focused on compressor energy consumption and efficiency. In domestic refrigerators, the requirements for a suitable compressor are cost-effectiveness, low noise generation, high efficiency, high reliability and easy manufacturing process; thus, hermetically sealed reciprocating ON/OFF compressors are conventionally used [5]. The reason of significance is that more than 80% of the total energy consumption by a refrigerator is devoted to its compressor [6]. Furthermore, based on exergy analysis and using experimental data, it was found that the highest exergy destruction of a domestic refrigerator occurred in its compressor [7]. In order to reduce exergy destruction in a compressor, its energy consumption should be reduced [8]. 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 [9]. 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 [10]. However, still this technology is too expensive and is not cost-effective to be widely used in market [6]. Recently, linear compressors have received more

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Nomenclature

COP	coefficient of performance (–)
E	energy (J)
Q	heat transfer rate (W)
T	temperature (K)
t	time (s)
UA	thermal conductance ($\mathrm{W\,K^{-1}}$)
V	volume ($\mathrm{m^3}$)

Subscripts

amb	ambient
cold	fresh/frozen food compartment

Greek symbols

λ	latent heat of fusion ($\mathrm{J\,kg^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)

attention for domestic refrigeration since they have significant advantages compared to the conventional reciprocating compressors. Elimination of crank mechanism and direct drive of piston by motor in linear compressors reduce frictional losses and enhance the performance of the system [11]. However, their application in refrigeration systems had some technical difficulties [12]. 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.

The second category is about enhancing thermal insulation of system walls. Polyurethane boards are conventionally used to insulate refrigerated compartments. Since the conductive heat transfer coefficient of polyurethane boards is almost high, even the optimum thickness has great heat loss. 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 [13]. The core material of VIPs is encapsulated in a barrier which needs to be thin with low conductivity and low gas permeability [14]. These constraints as well as their reliability make them expensive, preventing their wide applications [6]. Therefore, more cost-effective methods of achieving high thermal insulation are required.

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 [15]:

- addition of a liquid-to-suction line heat exchanger (also known as superheating coil),
- application of loop 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 or compartment. Since evaporator is the main source of cold in refrigerators, throughout this paper, application of PCM at evaporator reflects all possible configuration for cold storage (including compartment).

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, especially tight power supplies due to rolling blackouts.

Table 1 shows some of the studies focusing on PCM application in domestic refrigeration systems. The main purpose of this paper is to cover these studies including the investigations into heat and cold storage. This paper not only reports the effect of PCM integration, but also tries to identify the effective parameters, which affect the performance of PCM. Therefore, the outcomes of both experimental and simulation work on this subject are reported and the potential for the application of PCMs is discussed.

2. PCM application at evaporator

In domestic refrigerators, the evaporator works based on either free or forced convective heat transfer. The former (also known as naturally-cooled evaporator) has low heat transfer rate and could result in temperature stratification inside the compartment, while the latter gives better temperature stability. However, its main drawbacks are higher energy consumption, the spread of odor, and the food weight loss due to high air circulation [18]. One approach to overcome these drawbacks is the application of thermal energy storage (i.e. PCMs). Several studies (see Table 1) have focused on the performance analysis of refrigeration 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, and preventing destructive effect of frequent compressor start/stop. Furthermore, PCM can be helpful in case of power outages or blackouts since it affects both product and air temperatures and their rate of increase during power loss [27]. In addition, more uniform compartment temperature can be achieved by PCM presence [25]. A detailed analysis of pros and cons of using PCM at evaporator will be presented in Section 2.5.

Some studies reported that the direct contact of PCM with a naturally-cooled evaporator is more advantageous. The main reason is that it enhances heat transfer from the evaporator and also it can store excess cooling capacity of the system in the PCM [40]. Besides, this configuration results in higher evaporator temperature and pressure during phase change period of PCM [39]. Thus, refrigerant density is higher and, as a result, cooling capacity increases. Similar results were reported for cases where evaporator coils were immersed in PCM. In such cases, faster heat transfer is achieved which is due to the faster nature of conduction/convection in PCMs than natural convection of air. Therefore, due to the high thermal inertia of a PCM, the refrigerant pressure and temperature do not fall as much as the case with no PCM which in turn gives higher refrigerant mass flow rate [15]. 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 [29].

A summary of studies, which investigated effective parameters for PCM inclusion at evaporator side, is tabulated in Table 2. Basically, all studies can be categorized based on analyzing parameters such as the phase change temperature, PCM thickness, its geometry and orientation, and also the effect of thermal load. In the following