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Performance study on air-cooled household refrigerator with cold storage phase change materials

Zhongbao Liu [a,b,*], *Danfeng Zhao* [a], *Qinghua Wang* [c], *Yuanying Chi* [b], *Lingfei Zhang* [d]

[a] *The Department of Refrigeration and Cryogenics Engineering, The College of Environmental and Energy Engineering, Beijing University of Technology, 100 Pingleyuan Road, Chaoyang, Beijing 100124, China*

[b] *Beijing Advanced Innovation Center for Future Internet Technology, Beijing University of Technology, 100 Pingleyuan Road, Chaoyang, Beijing 100124, China*

[c] *School of Economics and Management, Beijing University of Technology, 100 Pingleyuan Road, Chaoyang, Beijing 100124, China*

[d] *Institute of Physics and Electronic Information Engineering of Qinghai Normal University, 3 Biyi Road, Xining 810007, China*

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ABSTRACT

The air-cooled frost-free refrigerator has become the main power consumer among household appliances. This study presents a new air-cooled household refrigerator that uses PCM in the fresh food and freezing chambers. Operational characteristics and performance test results are provided in the conditions of off-peak refrigeration with PCM and conventional refrigeration with/without PCM. Results show that refrigeration off-peak modes resulted in the peak temperature difference between M-packs and maximum temperature increase of M-packs in the freezing chamber. The energy consumption of the refrigerator is relatively increased. The energy consumption of the refrigerator prototype with PCM under the original control mode is reduced by 18.6% and the compressor ON-time ratio is reduced by 13.6% compared with the refrigerator prototype without PCM. Frost-free refrigerator with PCM under original control type exhibits advantages in terms of energy consumption and food quality.

Étude sur la performance d'un réfrigérateur domestique refroidi par air utilisant des matériaux à changement de phase pour l'entreposage frigorifique

Mots clés : Réfrigérateur domestique refroidi par air ; Matériaux à changement de phase ; Entreposage frigorifique ; Performance

* *Corresponding author.* The Department of Refrigeration and Cryogenics Engineering, The College of Environmental and Energy Engineering, Beijing University of Technology, 100 Pingleyuan Road, Chaoyang, Beijing 100124, China. Fax: +86 (0)10 67391613.
E-mail address: liuzhongbao@bjut.edu.cn (Z. Liu).
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Nomenclature

K	ON-time ratio of compressor
t_{qd}	ON-time of refrigerator compressor (h)
t_z	cycle time (h)
K_{with}	ON-time ratio for the case with PCM
$K_{without}$	ON-time ratio for the case without PCM
E_{with}	energy consumption for the case with PCM (kWh/24 h)
$E_{without}$	energy consumption for the case without PCM (kWh/24 h)
C_{with}	operation cost (electricity cost) for with PCM case
$R_{without}$	operation cost (electricity cost) for without PCM case

1. Introduction

Compressor and insulation modifications have been reported to be either costly or difficult to apply in household refrigerators for the purpose of enhancing the performance of refrigeration systems (Joybari et al., 2015; Kim et al., 2009; Marques et al., 2013). By contrast, PCM has received considerable attention for heat transfer enhancement because of the inherent advantages of these materials. PCM can be used in refrigerators for either heat or cold storage. The former requires the integration of PCM to the condenser side, whereas the latter is done through integration to an evaporator or compartment (Joybari et al., 2015).

The integration of PCM to the evaporator side of a refrigerator could prolong the compressor OFF-time because of the high latent heat (Subramaniam et al., 2010). This condition enables two new important options for refrigerators: the first option is off-peak refrigeration (i.e., 10 h refrigeration in off-peak time, 6 h refrigeration in peak time, and 8 h releasing cold to the chamber(s) in the power outage of the compressor in peak time) and the second is conventional refrigeration with PCM (i.e., no power outage) (Joybari et al., 2015).

In domestic refrigerators, the evaporator from the heat transfer point can be divided into free-convective and forced-convective heat-transfer evaporators. The former (also known as naturally cooled evaporator) has a low heat transfer rate and could result in temperature stratification inside the compartment, whereas the latter (also known as air-cooled evaporator) provides improved temperature stability. However, the main drawbacks of forced convective heat transfer include substantially high energy consumption, spread of odor, and food weight loss caused by high air circulation (Joybari et al., 2015; Maltini et al., 2004).

One approach to overcome these drawbacks is the application of thermal energy storage (i.e., PCMs). As a result of energy storage application, the compressor needs to work for a substantially long period to charge the energy storage. Nevertheless, despite the considerably long compressor ON-time in each cycle to charge the PCM, the global ON-time ratio decreases because of the significantly long compressor OFF-time. The main advantages of long compressor OFF duration include low overall energy consumption, improved food quality, and prevention of the destructive effects of frequent compressor start/stop. Furthermore, a uniform compartment temperature can be achieved with the presence of PCM (Joybari et al., 2015; Rahman et al., 2014; Wang et al., 2007).

A few studies reported that the direct contact of PCM with a naturally cooled evaporator is considerably advantageous (Rahman et al., 2014; Visek et al., 2014). Similar results were reported for cases where the evaporator coils were immersed in PCM. However, if the evaporator is immersed in PCM with the phase change temperature higher than the compartment setpoint temperature, then a high thermal resistance is created around the evaporator, thereby resulting in significantly frequent compressor start/stop (Berdja et al., 2012; Khan and Afroz, 2013). All studies can be categorized based on the analysis of various parameters, such as phase change temperature, PCM thickness, PCM geometry and orientation, and effects of thermal load. Proper phase change temperature selection is significant in refrigeration systems because such selection directly affects the performance of the system and 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 objective (Castell et al., 2012; Joybari et al., 2015; Li et al., 2013; Sharma et al., 2009; Wang et al., 2002). After the selection of the appropriate PCM with suitable thermal physical properties, the next issue to consider is the amount of PCM to use (Azzouz et al., 2008, 2009; Bastani et al., 2014; Joybari et al., 2015; Onyejekwe, 1989). PCM should be placed in a container the shape of which should be known a priori. The effect of container geometry was investigated based on thermal resistance comparison using identical volume and temperature difference for three different configurations (Onyejekwe, 1989).

The aforementioned research indicates that cold storage is one of the important factors that improve the performance of refrigerators. By contrast, PCMs can store energy whenever the system is functioning and release the stored energy in case of power outage. After two weeks with frequent power loss, PCMs were reported to provide promising results during power outage, thereby maintaining the quality of ice cream and frozen meat against ice recrystallization and drip loss, respectively (Gin and Farid, 2010). In another study that involved a 3 h power outage, the compartment air temperature was lower in an unloaded compartment with PCM compared with the loaded one without PCM. Evidently, the presence of PCM maintains a considerably low compartment air temperature caused by the high thermal storage (Farid and Cabeza, 2012). However, 3 h of power outage is significantly limited. Four different PCMs in two different refrigerator models were studied. The compressor on/off time was optimized, and improved energy efficiency was achieved. The use of only 0.95 kg of PCM resulted in 9.4% energy saving. Economic analyses have shown that using PCMs in household refrigerators is clearly a cost-effective method that saves energy and reduces harmful emissions (Yusufoglu et al., 2015). Thus far, for the air-cooled frost-free refrigerator, the research conducted on both off-peak refrigeration with PCM and conventional refrigeration with PCM is limited.

Utility companies typically charge customers different rates based on consumption time because electricity generation costs more during grid peak hours than during off-peak