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Performance enhancement of a household refrigerator by addition of latent heat storage

K. Azzouz[a,*], D. Leducq[a], D. Gobin[b]

[a]Cemagref: Refrigerating Processes Unit, Parc de Tourvoie BP 44, 92163 Antony, France
[b]Univ Pierre et Marie Curie, CNRS, Lab FAST, F-91405 Orsay, France

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ABSTRACT

This paper studies the effect of adding a phase change material (PCM) slab on the outside face of a refrigerator evaporator. A dynamic model of the vapour compression cycle including the presence of the phase change material and its experimental validation is presented. The simulation results of the system with PCM show that the addition of thermal inertia globally enhances heat transfer from the evaporator and allows a higher evaporating temperature, which increases the energy efficiency of the system. The energy stored in the PCM is yielded to the refrigerator cell during the off cycle and allows for several hours of continuous operation without power supply.

Amélioration des performances d'un réfrigérateur domestique par usage d'un accumulateur à chaleur latente

Mots clés : Réfrigérateur domestique ; Évaporateur ; Revêtement ; Matériau ; Changement de phase ; Amélioration ; Performance

1. Introduction

For economical and environmental considerations, phase change materials (PCMs) are used in many applications (Zalba et al., 2003), such as food or pharmaceutical products preservation, storage devices in thermal conversion systems. In solar applications, these devices maybe integrated into building walls in order to increase the thermal inertia of buildings (Darkwa and O'Callaghan, 2006) or to reduce heating, ventilation and air conditioning costs.

Increase of thermal inertia related to the thermal energy storage with PCM and its influence on the energy efficiency of refrigerating systems are a matter of many investigations. An interesting study on the thermal behaviour of a latent heat cold storage unit for a refrigerated compartment of a truck was presented by Simard and Lacroix (2003). A

* *Corresponding author*. Tel.: +33 140966507; fax: +33 140966249.
E-mail address: kamel.azzouz@cemagref.fr (K. Azzouz).
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Nomenclature

a	thermal diffusivity of PCM
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
e	thickness (m)
h	specific enthalpy ($J\,kg^{-1}$)
K	average heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
L_f	latent heat ($J\,kg^{-1}$)
M	mass (kg)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
N	motor rotation speed (rpm)
$\dot{Q}$	thermal load (W)
S	area (m^2)
s	interface solid–liquid position (m)
V	volume (m^3)
t	time (s)
T	temperature (K)
x	vapour quality (–)
$\bar{x}$	average refrigerant quality (–)

Greek symbols

$\bar{\gamma}$	average void fraction (–)
η	efficiency (–)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
τ_{diff}	characteristic conduction time (s)

Subscripts

a	air
c	condenser, condensation
co	condenser outlet
c-out	compressor out
ci	condenser inlet
cr	evaporator refrigerant
cw	condenser wall
do	door opening
e	evaporator, evaporation
ei	evaporator inlet
eo	evaporator outlet
er	evaporator refrigerant
ew	evaporator wall
ext	external
heat	heaters
is	isentropic
l	liquid
max	maximum
pcm	phase change material
ref	refrigerator
s	solid
v	vapour, volumetric

Dimensionless numbers

$Ste = C_p(T_{ew} - T_{pcm})/L_f$ Stefan number

mathematical model of parallel plates filled with a phase change material that absorbs heat from the flow of warm moist air was developed and validated. In this study, effects of the design and the operating conditions on the performance of the system are discussed only for the melting process and the interaction with the refrigeration system is not studied. An experimental analysis and a statistical analysis were performed by Zalba et al. (2004) to examine phenomena involved in a free-cooling system in which cold from outside air is stored in a phase change material during the night and used during the day for air conditioning. Results indicated that the effect with significant influence in the solidification process was the thickness of the PCM. For the melting process, the air temperature had higher influence than the thickness of the PCM. Maltini et al. (2004) performed an experimental study of a household refrigerator using a sodium chloride–water mixture as cooling storage system. It was observed that the PCM behaved as a temperature damper and minimized the temperature fluctuations, leading to a better preservation of food. Cerri (2003) has simulated a domestic refrigerator including cold storage. This model, based on differential equations, was used to determine appropriate operating conditions in order to achieve a minimum electrical power. In this study, the coefficient of performance is improved by 12% using PCM. Nevertheless, it must be observed that Cerri (2003) used a low quantity of PCM in this study. Lovatt et al. (1998) have built a numerical model for predicting the transient behaviour of an ice-bank coupled with a refrigeration system; in this model authors assume that the refrigerant is in single-phase only and the PCM is in contact with the refrigerant. Wang et al. (2007) have developed a dynamic mathematical model for coupling a refrigeration system and a PCM heat exchanger positioned between the condenser and the thermal expansion valve (TEV). This model is able to predict the refrigerant states and dynamic coefficient of performance. However, none of the investigation was carried out to examine the effects of the PCM heat exchanger on the refrigeration system performance.

An advantage of the increase of thermal inertia is also to reduce the frequency of start/stop for cooling devices controlled by intermittent run as refrigerator or freezers, allowing to reduce the efficiency losses already identified in earlier works (Bjork and Palm, 2006; Rubas and Bullard, 1995; Coulter and Bullard, 1997) and due to the refrigerant displacements within the cooling system that affects the overall performance.

Most of the investigations cited above were focused on the heat transfer in the latent heat storage system. There are only few studies that have been reported in the literature on the behaviour of a refrigerator coupled with a phase change material as a slab applied on the entire area of the evaporator. The purpose of this paper is to propose a model for the dynamic behaviour of a refrigerator using a PCM storage system and to perform a parametric study in order to analyze the consequences of the operating conditions on the energy efficiency.

2. Mathematical model

In this section, we describe the assumptions and the set of equations used for modelling the problem. The system is constituted of three different elements: the phase change unit, the vapour compression device and the refrigerated cell (Fig. 1). We will successively describe the governing equations for these elements.