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Improving performance of household refrigerators by incorporating phase change materials

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ABSTRACT

Efforts to increase energy efficiency of refrigerators shall directly reduce energy consumption in residential buildings. Incorporating phase change materials (PCM) is a new approach to improve the performance of refrigerators. In this study, we have tested four different PCMs in two different refrigerator models. Compressor on/off time was optimized and better energy efficiency was achieved. Increasing condenser surface area by 20% enhanced the PCM effect. The use of only 0.95 kg of PCM has resulted in a 9.4% energy saving. Economic analyses show that using PCMs in household refrigerators is clearly a cost effective method that saves energy and reduces harmful emissions.

Amélioration de la performance des réfrigérateurs domestiques par incorporation de matériaux à changement de phase

Mots clés : Réfrigérateur domestique ; Matériau à changement de phase ; Efficacité énergétique ; Bénéfices environnementaux

1. Introduction

Buildings – with their share of 35% – are currently leaders in energy consumption. Looking at existing consumption trends, the energy demanded by buildings shall increase from 117 EJ in 2010, to 173 EJ by the year 2050. This – in turn – means that global direct CO_2 emissions from all buildings will be 25% higher than today in 2050 and possibly reach 3.5 GT. Domestic appliances and other electronics consumed nearly 2500 TWh of electricity in 2010 with an increase of 43% over the last decade. This figure corresponds to about half of the total electricity consumption of homes. Ownership of large appliances seems to have reached saturation in many countries; there still is considerable potential for demand growth in other regions of the world (IEA, 2013). The omnipresent

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Nomenclature

CD	Closed-door algorithm
COP	Coefficient of Performance
OD	Open-door algorithm
P	Energy consumption, kWh(24 h)$^{-1}$
PCM	Phase Change Material
T	Temperature, K
t	time, s
V	Volume, m^3

Subscripts

1	without PCM
2	with PCM
aa	Ambient
cond	Condenser
comp	Compressor
corr	Corrected
eva	Evaporator
i	Compartment
meas	Measured

refrigerator is the number one appliance that is in almost all households around the world today. Many countries are trying to introduce consumer awareness programs, standards, and new labels to reduce energy consumption by homes. The "Energy star" program of the U.S. has reduced 277 million tonnes of greenhouse gases in 2013 alone, providing over $10 billion USD in energy savings (www.energystar.gov). In Europe, energy efficiency labels from A+++ to G are being used in appliances (Council Directive 92/75/EEC of 22 September 1992). Recently, with a new and ambitious attempt for further increasing energy savings in appliances more stringent energy consumption levels that requires manufacture of products with A+ or above are mandated (Commission Delegated Regulation (EU) No 1060/2010 of 28 September 2010.). Such programs and the alarming growth in energy consumption are mandating appliance manufacturers to find new solutions and to make more efficient products.

Making changes in refrigeration systems, cabinets, and/or other components can increase energy performance of the refrigerators. Among these anticipated changes are: using variable speed/capacity compressors, placing larger heat exchangers, better permanent magnet fan systems, on-demand defrost systems, hollow insulation panels, thicker insulations, better seals, magnets, and gasketing, and new types of refrigerants (Bansal et al., 2011). Energy efficiency that can be achieved – by individual or multiple changes – is approximated to be in the range of 5%–45%. Efficient machines need to be affordable by end-users; yet, providing these significant improvements is a prominent challenge for appliance manufacturers.

Using phase change materials (PCMs) to increase energy efficiencies of refrigerators has gained interest in the past decade. Recently, Oro et al. (2012) presented a review of PCM candidates for cold storage applications. For sub-zero applications, aqueous salt solutions are the main PCMs. Formulating their thermal properties accurately and dealing with supercooling, corrosion and thermal stability problems are challenges that need to be overcome with salt solutions (Oro et al., 2013; Yilmaz and Paksoy, 2012; Yilmaz et al., 2013). Using a proper combination of PCM and packaging can result in significant benefits without needing major design changes in their refrigeration systems or enclosures. Among these benefits are longer autonomy of the refrigerator, more homogeneous temperature distribution in the refrigerator, optimization of runtime of the compressor, keeping the cabin temperature at the desired level in case of power failure and increase in COP.

Within the refrigeration cycle, PCM can be added either on the evaporator side or on the condenser side. In the numerical study by Azzouz et al. (2008) using a thick slab of PCM behind the evaporator has increased COP by 25%. In further experimental work, Azzouz et al. (2009) added a PCM slab with thicknesses of 5 or 10 mm on the evaporator side. They tested water and a eutectic mixture with −3 °C melting point for the PCM. The 10 mm slab was only partially frozen in the process and showed almost the same effect as the 5 mm slab. The eutectic as PCM was found to be more advantageous due to its ability to maintain lower temperature in the refrigerator. Their studies indicate that the COP can be improved in the range of 10–30% depending and thermal load and choice of PCM. For higher thermal loads, due to the partial melting of the PCM, the COP enhancement was less.

On the condenser side of the refrigeration cycle, PCM was used to store the waste heat given off from the condenser (Cheng et al., 2011). In this study, 0.5 kg of shape-stabilized PCM – consisting of paraffin, high-density polyethylene, and expanded graphite – was wrapped around the condenser tubes. The phase temperature range of the PCM used was 25 °C–60 °C. The condensation temperature and heat dissipation loads were lowered, this led to higher evaporation temperatures as well as 12% energy savings.

Adding PCM in the enclosures helps maintain a homogeneous temperature distribution. Heat is gained from door openings and/or from thermal loads in the refrigerator. This leads to a reduction of usable cabinet volume, and more energy consumption to re-freeze the PCM packages. On the other hand, more homogeneous temperature maintained by PCMs leads to reduction of the on time of the compressor. This compensates for the extra energy used for re-freezing of PCM and also saves additional energy. In the experimental work by Azzouz et al. (2009) off duration of the compressor was increased from 5 to 9 h with 5 mm of PCM slab. Gin et al. (2010) placed PCM panels on the internal walls of a freezer to show that energy consumption during defrosting and door openings can be lowered. The use of PCM in the cabins will also be useful in the case of power failures by keeping cabin temperatures at desired levels for longer durations. In a study by Marques et al. (2014), integrating 1 kg of distilled water as PCM in a 5 mm thick rectangular slab into the refrigerator allowed keeping the temperature at the desired level for 3–5 h depending on the thermal load.

Marques et al. (2010) also investigated the effects PCM-use on compressor performance numerically. Results of their study show that larger displacement compressors that allow PCMs to store excess cooling capacity are more efficient. In addition, PCM freezes faster with larger compressors. Using