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Copolymer-bound phase change materials for household refrigerating appliances: experimental investigation of power consumption, temperature distribution and demand side management potential

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ABSTRACT

This study presents the results of an experimental investigation of the influence of latent thermal heat storage elements on the power consumption as well as the temperature distribution of commercial household refrigerators. Two evaporator types and a standard wire-and-tube condenser are equipped with copolymer-bound phase change materials (PCM) and the performance is determined under standard conditions. The results show that refrigerating appliances equipped with PCM can be optimized through modifications of the control strategy to achieve different targets: (a) Power consumption can be significantly reduced by increasing the evaporator and decreasing the condenser temperature. (b) Temperature fluctuations in the refrigerator's fresh-food compartment during the cooling cycle can be reduced from 4 °C to 0.5 °C. (c) The cooling cycle duration can be tripled without compromising the fresh-food compartment conditions. The latter may help to meet the growing demand for balancing power consumption to stabilize the power grid, e.g. if the share of highly fluctuating, sustainable energy supply is large.

Les matériaux à changement de phase copolymères pour les appareils frigorifiques domestiques: étude expérimentale de la consommation d'énergie, de la distribution de température et du potentiel de gestion de la demande

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Nomenclature

h	specific enthalpy (kJ kg^{-1})
T	Temperature (K)
λ	thermal conductivity (W m^{-1} K^{-1})
ω	mass fraction (g g^{-1})

1. Introduction

Despite the fact that power consumption of a single household refrigerating appliance seems to be low, the energy saving potential of the entire fleet is significant due to its almost complete market penetration and its typical all-year runtime. On average, 13.4% of the power consumption of private households in the OECD member states is caused by cooling and freezing of food (IEA, 2003). In Germany, that share is 20%, which corresponds to about 7% of the overall national power consumption (Barthel et al., 2005). In recent years, the power consumption of household refrigerators and freezers was substantially reduced, where the major driver was the labelling of energy efficiency that became mandatory in many countries. Power efficiency has thus become a decisive criterion for consumers when purchasing new household equipment (Faberi et al., 2007).

Lower power consumption can be achieved by reducing the thermal load or by optimizing the refrigeration process. An option for the former is enhancing the isolation, e.g. by replacing polystyrene that was used up into the 1980s with polyurethane foam that is standard today, the thermal load was reduced by about 30%. A further significant reduction of the thermal load can be achieved through the extensive use of vacuum insulated panels (VIP), but their high costs are still an argument against their introduction in this price-sensitive segment (Philipp, 2002). One option for the latter is the use of speed-controlled compressors. Household refrigerators and freezers are usually operating intermittently through a simple on/off control. The application of speed-controlled compressors would enable for a transition to a sustained operation. This would decrease friction and throttling losses in the compressor, increase the evaporator temperature and decrease the condenser temperature, avoid shifting of the refrigerant due to pressure equilibration during standstill and result in a reduction of power consumption by up to 30% (Binneberg et al., 2002). However, also in this case, substantially higher costs impede the use of speed-controlled compressors in simple household refrigerators. Another possibility is to optimize heat transfer at the evaporator and condenser, because the maximum efficiency of refrigeration processes is determined by their temperatures. Increasing the evaporator temperature by 1 °C typically leads to a reduction of power consumption of 3–4%, decreasing the condenser temperature by 1 °C reduces power consumption by 2–3% (Dalkilic and Wongwises, 2010). In the most basic case, this can be achieved by larger evaporator and condenser surface areas. For example, surfaces that are enlarged by 50% reduce power consumption by about 10% and 6%, respectively (DKV, 1985). Ventilators also enhance convective heat transfer, however, their own power consumption must be taken into account (Roth, 2008). The latent heat storage elements studied in this work also optimize heat transfer.

Phase change materials (PCM) can absorb large amounts of heat at almost constant temperature and are thus particularly well suited for heat storage. By implementing PCM, temperature fluctuations were reduced successfully in a variety of applications, e.g. transport boxes for sensitive goods or heat sinks for electronic devices (Mehling and Cabeza, 2008). The integration of PCM in cooling devices has been a matter of scientific analysis for many years now. In 1989, Onyejekwe (1989) installed a simple latent heat accumulator based on a eutectic NaCl/H_2O mixture in a cooling device. Wang et al. (2007a, 2007b, 2007c) examined the influence of PCM at various locations in the cooling system, i.e. between the compressor and condenser, and were able to raise their prototype's efficiency by 6–8%. A direct connection of a PCM-layer to the evaporator of a household refrigerating appliance allowed Azzouz et al. (2008, 2009) to achieve a 10–15% increase of the coefficient of performance (COP) through a higher evaporator temperature and a considerable reduction of the on/off switch control frequency. Integrating PCM into the refrigerator compartment evaporator of a domestic refrigerator/freezer appliance, Visek et al. (2014) showed an increase in evaporation temperature by 2 °C that led to an improvement of approx. 6% in the energy consumption during the refrigeration cycle. In addition to the increase of energy efficiency via encapsulated PCM in an industrial device, Cheralathan et al. (2007) were able to prove the potential of charge shifting into cost-effective power night-rates. Through the integration of PCM panels into a household freezer, Gin and Farid (2010) found an improved storage quality due to the temperature stabilization and a lower power consumption during defrosting cycles and door openings (Gin et al., 2010). Oró et al. (2012a) found consistent results for commercial freezers and also evaluated the thermal response when subjected to refrigeration system failure (Oró et al., 2012b).

Refrigeration devices with latent heat storages are well suited for future Demand Side Management (DSM) concepts, because their compressor off-time can be considerably longer and also can be varied. DSM in general refers to the specific control of power use in order to meet a fluctuating power supply, which is crucial when the share of renewable energy is growing (Kohler et al., 2010). For example, Bagriyanik and Zehir (2012) demonstrated even for customary refrigerators that a large fraction of their power demand can be displaced in time, where this effect can be boosted significantly with the use of PCM.

The heat discharge to the environment via the condenser of most household refrigerating appliances is based on free convection and radiation, which results in a moderate heat flux. Their intermittent operational mode with a typical on/off relation of about 1:2 thus results in comparatively high condenser temperatures during compressor runtime. Lowering the temperature of the condenser during the runtime of the compressor and a partial shift of the heat discharge into the downtime of