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Novel design and performance enhancement of domestic refrigerators with thermal storage

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HIGHLIGHTS

- The design/operation of a household thermal storage refrigerator was investigated.
- Demonstrated that single speed compressor efficiency increases with displacement.
- The additional cooling capacity of larger compressors can be accumulated in a PCM.
- Integration of a PCM into the refrigerator allows for an extended off-cycle period.
- Combination of large compressors and PCMs enhances overall refrigerator efficiency.

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ABSTRACT

This paper investigates the design and operation of a thermal storage refrigerator. Firstly, compressor performance at a range of typical refrigerator operating conditions was analysed. The model results suggest that larger compressors are more efficient when running, with isentropic efficiency increasing by 50% as the displacement increased from 4 to 8 cm^3. The impact of compressor performance on the overall refrigerator efficiency was estimated and the results indicated that an energy reduction of 19.5% can be obtained by replacing a conventionally sized, 4 cm^3 compressor by a larger 8 cm^3 model. However, using a larger compressor will normally lead to more start/stop events, which reduces overall efficiency. A method is proposed for exploiting the superior performance of large compressors by accumulating their high cooling capacity output in a phase change material (PCM), reducing the number of on/off cycles. Numerical modelling and experimental validation were undertaken using a prototype thermal storage refrigerator, incorporating a PCM, to estimate the PCM charge and discharge rate and the corresponding refrigerator on and off cycle durations at different ambient conditions. The results showed that the integration of a 5 mm PCM slab into the refrigerator allowed for 3–5 h of continuous operation without a power supply. The numerical model was found to be in good agreement with the experimental results, with the error between the simulation and tests below 5% for most experiments.

1. Introduction

A growing global environmental awareness and the rising costs of energy are driving the demand for the development of sustainable cooling technologies. It is estimated that refrigeration and air-conditioning are responsible for 15% of the global electricity consumption [1]. There are approximately 1 billion domestic refrigerators in use worldwide [2], and although their direct GHG emissions have been greatly reduced by the introduction of hydrocarbon refrigerants, their indirect emissions remain very high due to the electricity input needed for operation of the refrigerator. Most governments have implemented minimum energy performance standards for household refrigerators and energy labelling programs to regulate the market and drive the search for innovative solutions, to further improve the efficiency of these appliances.

The energy consumption of refrigerators is affected by the efficiency of their components, ambient temperature, product loading, number of door openings, thermostat setting position and refrigerant migration during the compressor off-cycle. The main load to

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air Conditioning Engineers; COP, coefficient of performance; GHG, greenhouse gases; PCM, phase change material; SLHE, suction line heat exchanger; VIP, vacuum insulated panel; VCS, variable speed compressor.

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Nomenclature

A	surface area (m^2)
A_L	area of layer (m^2)
B	PCM thickness (m)
cp	specific heat (J kg^{-1} K^{-1})
Δt	time step (s)
ΔT	temperature difference (K)
Δy	layer thickness (m)
H	enthalpy change (J)
k	thermal conductivity (W m^{-1} K^{-1})
L_f	liquid fraction
m_L	mass of layer (kg)
$Q_{evaporator}$	cooling capacity (W)
Q_{fridge}	refrigerator heat gain (W)
s	solid–liquid interface
T	temperature (K)
t	time (s)
U	global heat transfer coefficient (W m^{-2} K^{-1})
y	distance through PCM from bottom surface (m)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
λ	latent heat of fusion (J kg^{-1})
ρ	density (kg m^{-3})

Subscripts

liq	liquid
mel	melting point
N	node point at north of point P
P	point P
S	node point at south of point P
sol	solid

Superscripts

i	iteration

the cabinet results from conduction through the cabinet walls and consequently by replacing the standard polyurethane foam insulation with vacuum insulated panels (VIPs), energy savings of up to 25% can be achieved [3]. Door openings also introduce heat gains into the refrigerator compartment due to heat transfer to interior surfaces and air exchange with the exterior ambient air. The energy consumption of a refrigerator-freezer with door openings (one opening every 40 min for the freezer and one every 12 min for the refrigerator over a 10 h period) was found to increase by 10% compared to the same product without door openings [4]. The significant influence of thermostat setting position has been demonstrated experimentally and suggests that a 1 °C reduction in the freezer temperature can result in a 7.8% increase in energy consumption [5]. In addition, the losses resulting from refrigerant charge displacements e.g. due to off-cycle migration and on-cycle redistribution, were estimated to be 11% (in capacity) and 9% (in energy efficiency) [6]. However, the energy loss due to refrigerant charge displacement can be prevented by fitting a liquid line solenoid valve to stop refrigerant migration from the condenser to the evaporator during the compressor off-cycle.

The compressor is responsible for more than 80% of the total energy consumed by the refrigerator. Energy savings of up to 40% are possible by replacing a standard single speed compressor by a variable speed compressor (VSC), which adjusts the refrigeration capacity in relation to the load [7]. Both VIPs and VSCs are very promising technologies, however they are also very expensive, which limits their application to premium appliances only.

Phase change materials (PCMs) are substances with high latent heat content that freeze and melt at a nearly constant temperature, accumulating or releasing large amounts of energy during the process. The application of PCMs in domestic refrigerators is a novel solution with the potential to improve the appliance efficiency. The cooling energy stored in the PCM can be used to cool the compartment, increasing the refrigerator energetic autonomy, while the power supply is switched off. This approach was taken by Azzouz et al. [8], who tested a domestic refrigerator with 5×10^{-3} and 10×10^{-3} m (i.e. 5 and 10 mm) ice slabs in contact with the evaporator surface. Their results showed that the time for which the refrigerator could be operated without power supply increased by up to 5 and 9 h respectively, depending on the thermal load. It was observed however, that only 60% of the 10 mm slab was frozen when the compressor switched off during the tests, probably due to the low thermal conductivity of the PCM, and/or the low cooling capacity of the 5×10^{-6} m^3 (i.e. 5 cm^3) swept volume compressor employed.

In the next section of the current paper, it is demonstrated that for current single speed compressors efficiency increases with the compressor size. The impact of compressor selection on conventional refrigerators' energy consumption and running time is also demonstrated. However, high efficiency is only achieved when the compressor is running, and frequent on/off cycling of the compressor will reduce the overall efficiency. An effective way to exploit the higher performance of large compressors is to accumulate their excess cooling capacity in a PCM, thereby extending the length of the on and off cycle periods and minimizing the number of cycles per unit time.

The remainder of the paper describes a numerical and experimental investigation of the heat release and storage rate of encapsulated ice, which was used as the thermal energy storage material (i.e. PCM) in the refrigerator. The mathematical model used to predict the heat transfer during the phase change is based on the enthalpy method [9], with the governing equations discretized on a fixed grid using the finite difference method. The influence of PCM thickness (2, 3, 4 and 5 mm slabs) and ambient temperature (20 °C, 25 °C, 30 °C) and evaporating temperature (−15 °C and −10 °C) have been investigated numerically. The numerical model was validated experimentally at two ambient conditions using a test rig specifically designed for that purpose. The test rig consisted on a prototype refrigerator, fitted with a 5 mm PCM slab, which was cooled by an external coolant system.

2. Compressor size and efficiency

In the design of energy efficient domestic refrigerators it is important both to incorporate novel, energy efficient solutions, e.g. PCMs, and to combine them in the most efficient way with other components. This section considers the performance for different sizes of single speed compressors, which is a key component influencing refrigerator efficiency.

Compressor manufacturer datasheets provide information on compressor performance under ASHRAE conditions [10], i.e. a condensing temperature of 54.4 °C, and ambient, liquid and suction gas temperatures of 32.2 °C. These operating conditions are quite different from those obtained when the compressor is part of a domestic refrigeration system. Therefore, compressor performance under ASHRAE conditions may not reflect how well compressors will perform under more realistic conditions e.g. at ambient