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Theoretical study on a frost-free household refrigerator-freezer

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ABSTRACT

This study deals with a frost-free household refrigerator-freezer, in which frosting can be retarded by dehumidifying the air before it enters the evaporator of the refrigerator-freezer via a desiccant-coated heat exchanger. Because the desiccant can be regenerated via the condensation heat of the refrigerant (which is exhausted into ambient air in conventional household refrigerator-freezers), the proposed system can achieve high energy efficiency. Calculations show that the coefficient of performance of this system (*COP*) is within the range 1.5–2.5 at an ambient temperature of 15–35 °C. Moreover, it is found that the relative humidity of the refrigerator air (RH_{RA}) and the temperature of freezer air (T_{FA}) have a significant effect on *COP*: *COP* decreases by about 13% when RH_{RA} varies from 0.4 to 0.8 and by 10% when T_{FA} runs from –18 to –23 °C.

Étude théorique d'un réfrigérateur-congélateur domestique exempt de givre

Mots clés : Givre ; Réfrigérateur ; Congélateur ; Déshydratant

1. Introduction

Domestic refrigerator-freezers are among the most energy-hungry household appliances, due to their near continuous operation. In Japan, they contribute approximately 14.2% of the average household electricity use (JANRE, 2015). It has been estimated worldwide that there is one household refrigerator for every six people on Earth, which corresponds to approximately 6% of the total electrical energy produced (Negrao and Hermes, 2011). Accordingly, improving their energy efficiency is crucial. Certain options can increase the energy efficiency of these appliances, including improvements in cabinets (e.g. optimized insulation (Yoon et al., 2013)), improvements in refrigeration systems (i.e. dual-evaporator refrigeration circuits (Ding et al., 2004; Matej et al., 2014; Yoon et al., 2011)), high efficiency compressors (Kim et al., 2011; Mustafa et al., 2014) and other hardware (such as improved heat exchangers (Lee et al., 2010; Rahman and Jacobi, 2015)), the use of phase-change materials (Azzouz et al., 2008; Gin et al., 2010), advanced defrosting

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Nomenclature

AD	adsorption
C_w	moisture content of desiccant [kg·moisture (kg·dry desiccant)$^{-1}$]
COP	coefficient of performance [–]
DE	desorption
DP	dew point of air [°C]
DCHE	desiccant-coated heat exchanger
F. Compartment	freezer compartment
i	enthalpy [kJ kg^{-1}]
m	mass flow rate [kg s^{-1}]
m_{vap}	moisture transfer rate [kg·vapor s^{-1}]
ΔM_{vap}	amount of moisture removal [kg]
P	pressure [Pa]
q	heat load [kW]
Q	amount of heat [kJ]
RH	relative humidity [–]
R. Compartment	refrigerator compartment
SHF	sensible heat factor [–]
T	temperature [°C]
w	electric power of compressor [kW]
W	electric power consumption of compressor [kJ]
X	humidity ratio [kg·vapor (kg·dry air)$^{-1}$]
Greek symbols	
η_T	thermal effectiveness
η_X	humidity effectiveness
η_{com}	isentropic efficiency
τ	time [s]
Subscripts	
ad	adsorption process
d	desiccant
de	desorption process
in	inlet
out	outlet
r	refrigerant

mechanisms (Hitachi EL. Co, 2015; Kim and Lee, 2015; Mitsubishi EL. Co, 2015; Xiao et al., 2009). This paper focuses on the frosting problems in household refrigerator-freezers.

Frost formation is a common phenomenon observed in household refrigerator-freezers. The accumulation of frost on the evaporator surface increases the thermal resistance and the air side pressure drops, which causes a higher electrical power input to the compressor. Modern household refrigerator-freezers have an automatic mechanism to remove frost before it noticeably degrades their performance. Electrical resistance heaters are usually applied to periodically melt the frost. The efficiency of a defrost heater, defined as the ratio of total energy input to the energy required to melt the frost, was measured at 15–30% (Niederer, 1986; Pradeep et al., 2010), while the electrical power consumption of the refrigerator-freezer was found to increase by about 18% due to the automatic defrosting (Knabben et al., 2011; Pradeep et al., 2010). Therefore, although needed, the defrosting system increases the energy consumption of these appliances. Furthermore, during defrosting, the compressor and fan remain off and part of the heat provided by the electrical heater is transferred to the refrigerated compartments. It was observed that the air temperature of the cabinet caused by the defrosting process rose from −1.57 to 6.8 °C for the refrigerator compartment (R. Compartment) and −23.1 to 11.8 °C for the freezer compartment (F. Compartment) (Zakrzewski et al., 2011). This temperature fluctuation affects the food quality, and the compressor also has to run for longer to compensate for this extra thermal load after the defrosting process. Implementing phase-change material (PCM) based thermal storage in refrigerators and freezers is a method commonly proposed to improve energy efficiency, reduce temperature fluctuations and improve resistance to electricity blackouts (Matej et al., 2014).

The defrosted water runs through a tube and is collected in a tray, which is often located close to the compressor or condenser and finally evaporates from the tray due to the heat of the compressor or condenser. This system works satisfactorily in countries where the ambient air has low relative humidity and the amount of defrosted water is also low. However, under hot and humid ambient conditions, more defrosted water is generated, but the evaporation speed is slower, which may lead to water overflowing from the tray (Xie and Bansal, 2000).

Desiccants are well known as efficient means of air dehumidification. Some researchers have proposed a method to prevent air-source heat pumps from frosting, i.e. in which air is dehumidified by a solid adsorbent before entering the evaporator (Kondepudi et al., 1995; Wang and Liu, 2005; Wang et al., 2014; Zhang et al., 2012). The energy consumption for the desiccant regeneration process limits the improvement in energy efficiency of those proposed systems.

We found almost no reports about preventing frost with desiccant in household refrigerator-freezers. In this study, the idea of using desiccant to prevent the frosting of an air source heat pump is applied to develop a frost-free household refrigerator-freezer. Furthermore, the desiccant can be regenerated using the condensation heat of the refrigerant that would otherwise be simply ejected into the ambient air in conventional household refrigerator-freezers. Accordingly, this system could not only retard the evaporator frosting, but also achieve high energy efficiency by regenerating the desiccant with the system's exhaust heat.

2. System description

A schematic diagram of the frost-free household refrigerator-freezer is shown in Fig. 1, with the process illustrated on a pressure (P)–enthalpy (i) diagram of refrigerant and a psychometric chart in Figs. 2 and 3. The system consists of a compressor (1), an air-cooled heat exchanger (2), an expansion valve (3), a desiccant-coated heat exchanger (4), a