Energy Conversion and Management 132 (2017) 180–188

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Analysis of energy saving performance for household refrigerator with thermal storage of condenser and evaporator

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ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form 13 November 2016
Accepted 14 November 2016

Keywords:
Household refrigerators
Cold storage evaporator
Heat storage condenser
Dual energy storage
Energy saving
Dynamic simulation

ABSTRACT

The heat transfer performances of evaporators and condensers significantly affect the efficiency of household refrigerators. For enhancing heat transfer of the condensers and evaporators, a novel dual energy storage (DES) refrigerator with both heat storage condenser (HSC) and cold storage evaporator (CSE) is proposed. The performance comparison of three kinds of energy storage refrigerators: HSC refrigerator, CSE refrigerator and DES refrigerator is analyzed by establishing dynamic simulation models. According to the simulation results, the DES refrigerator combines the advantage of HSC refrigerator and CSE refrigerator, it has more balanced operational cycle and higher evaporation pressure and temperature. The DES refrigerator shows a best energy saving performance among the three energy storage refrigerators with largest off-time to on-time ratio of 4.3 and the electrical consumption saving can reach 32%, which is greater than the sum (28%) of the other two kinds of energy storage refrigerators.

1. Introduction

As one of the most common household appliances, refrigerators are largely produced in China. Over 80 million [1] refrigerators are produced every year. Based on statistical data, it is estimated that there are more than 300 million refrigerators in China and they responsible for 40–50% of the residential electricity demand approximately. Therefore, even a small performance enhancement of refrigerators could bring huge amounts of energy saving. The study of energy-saving technology of household refrigerators has important significance for alleviating scarce energy sources and reducing greenhouse gas emission.

Manufacturers and related research institutions are exploring a variety of methods to improve energy performance of refrigerators without increasing (or a small increasing) refrigerators' production cost [2,3]. The performance of refrigerators can be enhanced by improving the efficiency of the compressor [4], optimizing the match and control of the system by adopting advanced circulation [5], or improving the heat insulation effect [6]. Besides, the heat transfer performances of evaporators and condensers significantly affect the efficiency of household refrigerators, thus an optimization of them can largely enhance the refrigerator performance [7]. Many of these methods and technologies have been relatively maturely developed, but there are some bottleneck problems to further improve those methods or technologies at present. Therefore, getting a better refrigerator performance requires multiple approaches.

Because the intermittent work mode of most refrigerators, the heat transfer of evaporators and condensers are intermittent, which affects the heat transfer performance of the evaporator and condenser largely. Other refrigerators equipped with variable speed compressors (VSC) can work continuously under normal conditions. In VSC refrigerator, motor speed compressors changes based on the load and driving efficiency [8]. The VSC refrigerator has advantages include continuous control, lower noise generation, lower vibration, lower starting current, and better COP compared to the conventional ON/OFF systems [9]. However, still this technology has not been widely used in market because it is too expensive and not cost-effective [10]. Therefore, another appropriate way to get a novel refrigerator is equipping evaporator or condenser with phase change materials (PCMs). Because of its large latent heat and outstanding ability to absorb and release heat, PCMs are getting the favor of many researchers and been widely used as energy storage materials in many applications [11].

In household refrigerators, PCMs can be used as either heat or cold storage. Some researchers used PCMs to construct HSC and did some experiments under ISO standard test conditions [12].

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http://dx.doi.org/10.1016/j.enconman.2016.11.029
0196-8904/

Nomenclature

ρ	density (kg m^{-3})	am	ambient
c	specific heat capacity (J kg^{-1} K^{-1})	et	evaporator tube
T	temperature (K)	ct	condenser tube
t	time (s)	air	indoor air
k	thermal conductivity (W m^{-1} K^{-1})	ins	insulation
S_i	coordinate direction of the X or Y (m)	ref	refrigerant
U	average heat transfer coefficient (W m^{-2} K^{-1})	i	inside
Q	heat transfer rete (W)	o	outside
h	specific enthalpy (J kg^{-1})	in	inlet
m	mass flow rate (kg s^{-1})	out	outlet
M	mass (kg)	e	evaporator
A	aero (m^2)	c	condenser
PCM	phase change material	SH	superheat region
COP	coefficient of performance	TP	two-phase region
		SC	subcooling region

Subscripts

sspcm	shape stabilized PCM

Experiment results show that HSC can achieve continuous heat transfer, and the condensation temperature of the novel refrigerator is decreased obviously. Compared with the ordinary refrigerator, the HSC refrigerator has higher COP [13], shorter compressor global ON-time ratio, faster stable condition of refrigerator system, and lower condensation temperature [14]. However, there are some disadvantages, such as more frequent compressor ON/OFF and higher heat gain from condenser to compartment during OFF time [15].

Other researchers focused on the integration of PCMs to evaporator side. According to the simulation and experiment results, compared with the ordinary refrigerator, the CSE refrigerator also has higher COP and shorter compressor global ON-time ratio [16]. Besides, it has longer compressor OFF time which makes the compressor ON/OFF frequency of refrigerator lower [17]. However, the refrigerator with CSE has higher condensation temperature and a long compressor ON time during a cycle at the meantime [18].

Obviously, evaporator side PCM integration has some advantages which can cover disadvantages of condenser side PCM and vice versa. It seems that simultaneous application of PCMs at condenser and evaporator could be more advantageous [19]. Therefore, based on the achievements about the energy storage refrigerators which have been published by our previous work [14,15], both HSC and CSE are applied to the refrigerator for enhancing the heat transfer of condenser and evaporator, respectively. Besides, two kinds of SSPCM (shape-stabilized phase change material) [20] were adopted for constructing the HSC and CSE of the refrigerator. The SSPCM was prepared in our laboratory with the following advantages: (1) low cost of the SSPCM. The mass of the SSPCM in each refrigerator is about 1.5 kg with the cost of about 2 dollars, (2) no corrosion, no liquid leakage during phase change process, so the packaging difficult of the conventional PCM is solved and the additional packaging cost of the refrigerator is reduced, (3) suitable phase change temperature to the condenser and evaporator and (4) high thermal conductivity, which may enhance the heat transfer during heat storage process. Finally, a novel SSPCM dual energy storage (DES) refrigerator is proposed and the dynamic simulation model of the refrigerator is established. The energy saving effect of three kinds of energy storage refrigerators with HSC, CSE and DES are analyzed and compared with the ordinary refrigerator.

2. Numerical model analysis

In order to establish dynamic simulation models of the three refrigerators, the numerical models of refrigerator' each components should been established firstly. Then each component model coupled with each other to establish the final overall model. On the basis of our previous study, the numerical models of the HSC, general evaporator, compressor, capillary and refrigerator compartment model had been established. Therefore, the numerical model of CSE is introduced in detail, and the model of HSC and entire refrigerator system algorithm process are described briefly in this paper.

2.1. CSE model

As shown in Fig. 1. For CSE, when the compressor is on, part of the cooling capacity passes to the phase change materials and is stored as the latent heat. During this process, a part of the PCMs change from liquid state to solid state. On the contrary, when the compressor is off, a portion of PCMs will change from solid state to liquid state and the cooling capacity stored in the materials is released to the indoor air. Thus the heat dissipation of the energy storage refrigerators is continuous during a complete cycle and the overall heat transfer performances can be significantly improved.

Because the SSPCM can be assumed in a "single solid phase" [21,22], its shape changes little in the phase change process, so heat conduction is assumed as the only transfer mode during the heat storage process. The assumptions of evaporator tube in this paper are: (1) separated-phase lumped-parameter dynamic mod-

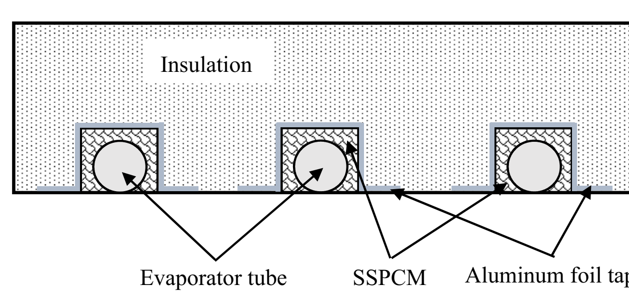

Fig. 1. Schematic representation of the cold storage evaporators with PCM.