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Research Paper

Performance evaluation of controllable separate heat pipes

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HIGHLIGHTS

- A controllable separate heat pipe (CSHP) is designed and tested.
- The start–stop performance of CSHP is investigated and confirmed.
- CSHP starts up quickly in approximately 15 seconds.
- The quickest stopping time of CSHP approximates to 80 seconds.

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ABSTRACT

A controllable separate heat pipe (CSHP) combined with cool storage can be an efficient and low-cost solution to release the necessary cool power and to improve the precision in the temperature control of cool-storage refrigerators powered by solar energy or electricity with time-of-use price policy. However, the precise temperature control performance of separate heat pipes under active control depends on system design and thus should be confirmed. In this study, a CSHP was developed and an active control method was achieved by interrupting its two-phase natural circulation flow. A one-dimensional steady-state model was used to calculate the critical fill ratio, heat transfer rate, and average working temperature of CSHP. A series of experiments was conducted to analyze the start–stop and heat transfer performances of CSHP at various R134a fill ratios and heat sink temperatures. Under different test conditions, the optimum working points were obtained through fitting. The most suitable control mode was determined and the start–stop performance of CSHP was examined in detail. CSHP starts up quickly in approximately 15 seconds and the quickest stopping time of CSHP approximates to 80 seconds. Therefore, the performance of CSHP under active control can be applied to cool-storage refrigerators.

1. Introduction

For energy-saving and environmental considerations, phase-change materials (PCMs) are widely used in many applications. For instance, cool-storage refrigerators provide attractive advantages and promising prospects, especially in the following two fields.

The first field includes photovoltaic (PV) refrigerators. For small cooling capacities in remote areas, a solar PV vapor compression refrigerator is the most viable solar-powered refrigerator [1–3]. In early PV refrigerators, storage batteries are used commonly for long-term operation because of unstable solar energy [4]. Batteries entail huge investments and cause considerable energy wastage in the charge–discharge process. In 2000, Foster and Bergeron designed a battery-free direct drive PV refrigerator and used a water–glycol mixture as a PCM to store cold energy [5]. The cool-storage system stores cold energy on a sunny day and keeps products cold at night without power input. In 2004, Pedersen et al. investigated a solar PV refrigerator without batteries. Pedersen et al. found that the specific cooling capacity of ice is 62% higher than that of lead batteries on the basis of weight [6]. These PV cool-storage refrigerators provide significant advantages in terms of cost and efficiency; thus, solar refrigeration has been highly accepted and distributed.

The second field involves the performance improvement of domestic refrigerators. Power resources have been put to waste and the time-of-use (TOU) price policy has been implemented worldwide because of the significant difference between peak and valley power demand [7]. PCMs have been applied to store cold energy in the valley electric time [8]. As a major energy-consuming home appliance, a cool-storage refrigerator has been considered as promising materials to stabilize electric grids and to reduce electricity bills [9]. This home appliance can also prolong the storage time of fresh food in the event of a power outage. Cool-storage refrigerators are more efficient than traditional direct cooling refrigerators [10].

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As a compressor stops working, cool-storage refrigerators cannot precisely control the temperature of fresh food, especially when fresh food compartments are opened frequently. This disadvantage is caused primarily by natural convection between PCM and air in fresh food compartments. In traditional direct cooling refrigerators, the temperature of fresh food compartments is controlled by the start–stop mechanism of compressors. Compressors without frequency conversion functions routinely run for more than 20 minutes within a start–stop cycle to maintain a sufficiently high COP, which directly restricts temperature control performance [11].

A cool-storage system combined with a separate heat pipe can be an efficient and low-cost solution to control the temperature of fresh food in a traditional or cool-storage refrigerator precisely. Fig. 1 shows a simplified sample configuration of the novel cool-storage refrigerator. The freezer is located above the fresh food compartment so that the separate heat pipe operates with the assistance of gravity, and the evaporator is located only in the freezer. The compressor of this novel cool-storage refrigerator can operate continuously for hours to store cold energy and the self-acting heat transfer of the separate heat pipe interrupts frequently to control the temperature of the fresh food compartment. Thus, the precision in temperature control and the efficiency of refrigerating systems or PV systems are improved significantly.

Separate heat pipes, which are also named as two-phase thermosyphon loops, wickless gravity-assisted heat pipes, or single-turned pulsating heat pipes, are promising in cool-storage refrigerator applications because of the following characteristics. These pipes can operate passively with the natural circulation of a working fluid, and no additional energy input is needed. These pipes do not comprise moving parts; as such, they are considered simple and reliable. The cost of a separate heat pipe system is low because inexpensive refrigerants, such as water, methanol, and R134a, and common materials, such as copper and aluminum, can be employed. The structure of separate heat pipes can also be changed reasonably to adapt to different applications.

Experimental and theoretical studies on separate heat pipes have been conducted since the 1980s [12]. Chen et al. analyzed the temperature distributions, flow oscillations, overheat phenomenon, and heat transfer coefficient of a double-looped separate heat pipe. Overheat occurs when the liquid charge level is <35% [13]. Garrity et al. focused on instability observed in a separate heat pipe. Static instabilities are observed in large heat fluxes and are influenced by the height of condensers and by stochastic variations in the flow rate [14]. Franco et al. investigated the heat and mass transfer performances of a small separate heat pipe. The mass flow rate is determined in two different ways to overcome experimental errors and is strongly influenced by the operating pressure and filling ratio [15]. Haider et al. suggested a natural circulation model of a separate heat pipe. Simulations have shown a void fraction variation of 4.0 percent in the evaporator and 2.3 percent in the condenser of the tested entire heat flux range [16].

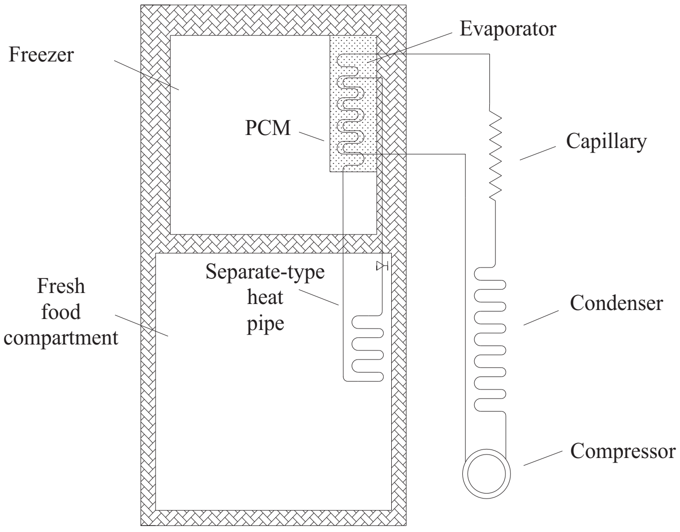

Fig. 1. A simplified sample configuration of the novel cool-storage refrigerator.

Separate heat pipes have been used in various practical applications. Khodabandeh suggested a separate heat pipe to cool radio base stations. A heat load of 80 W from a simulated component of less than 1 cm^2 can be dissipated [17]. Samba et al. developed a separate heat pipe for cooling telecommunication equipment. The power of telecommunication equipment is increased from 250 to 600 W [18]. Liu et al. investigated a waste heat recovery facility by using a separate heat pipe. Parametric studies have revealed that an increase in the diameter of hydraulics can significantly increase the upper critical values of the initial filling ratio and can slightly extend the lower boundary [19]. Esen et al. investigated a separate heat pipe solar water heater and obtained a 58.96% maximum daily collection efficiency of R410A as a working fluid [20]. Zhu et al. analyzed the application of a separate heat pipe in air-conditioning. In its operation, the average COP is 11.8, and this value is much higher than that of split air-conditioners [21]. Lee et al. proposed the use of separate heat pipes for thermoelectric refrigeration. A heat transfer rate of up to 5400 W/°Cm^2 can be obtained [22]. Ling et al. conducted primary performance calculation and investigated a new separate heat pipe refrigerator and a heat pump; Ling et al. found that the use of these devices is feasible [23]. These experimental results have confirmed that separate heat pipes work well under different conditions and that they can be applied to cool-storage refrigerators. Two passive operating modes of separate heat pipes have been widely explored: (1) at imposed temperature, such as solar applications, or (2) at imposed heat flux, such as electronic equipment cooling [24]. However, a relevant ability of separate heat pipe has been neglected; in particular, a precise temperature control capability under active control should be considered.

Precise temperature control is of great importance, and a cool-storage refrigerator combined with separate heat pipe is a new technology. The performance of the precise temperature control of separate heat pipes under active control has yet to be reported within a known range. In this study, a controllable separate heat pipe (CSHP) was developed and the active control method was achieved by artificially interrupting its two-phase natural circulation flow. The performance of CSHP under active control was initially investigated. The factors relevant to its future applications in cool-storage refrigerators were also determined. A one-dimensional steady-state model was used to calculate the critical fill ratio, heat transfer capability, and average working temperature of CSHP. Tests were performed to determine various R134a fill ratios and heat sink temperatures. The heat transfer performance, control mode, and start–stop performance of CSHP were also examined under different experimental conditions. The rapid restarting performance of an incompletely stopped CSHP was also evaluated.

2. Experimental setup

2.1. Operating principle of CSHP

The thermodynamic cycle of CSHP is introduced in Fig. 2. The two-phase natural circulation flow in CSHP can be depicted as follows. First, the liquid working fluid absorbs heat and evaporates in the evaporator. Then, the vapor working fluid flows to the condenser through the vapor line. The working fluid changes from the vapor phase to the liquid phase in the condenser and flows back