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Preliminary study on variable conductance loop thermosyphons

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ABSTRACT

Given that loop thermosyphons are widely used as simple and high-efficiency heat transfer devices, their passive heat transfer performance has attracted considerable research interest. The capability of loop thermosyphons for active heat transfer adjustment can potentially improve the precision and efficiency of heat and temperature management in many fields, but has not received much attention. A variable conductance loop thermosyphon (VCLT) is developed in this study. Heat transfer is precisely adjusted by actively regulating the internal flow resistance of the working fluid. The performance of VCLT under variable flow resistances is tested. The boundary conditions are set to those of a novel cool-storage refrigerator, wherein temperature control directly affects the freshness of stored food. VCLT behaviors under static and dynamic adjustment modes are also examined with the working fluid R134a. The maximum ratio of heat transfer adjustment is approximately 85%, when decreases the mass flow rate from 1.67 g/s to 0.21 g/s with increasing the equivalent thermal resistance from 0.0074 K/W to 0.54 K/W. Finally, the performance is verified with R404a, R407a and R410a. Results demonstrate that VCLT is an efficient and low-cost temperature adjustment device for refrigerators and other applications that require precise temperature control.

1. Introduction

Loop thermosyphons are common high-efficiency heat transfer devices that operate with the assistance of gravity. These devices possess excellent heat transfer enhancement, compactness, long life, and low cost [1]. Loop thermosyphons, or two-phase loop thermosyphons or separate heat pipes, are widely utilized in solar thermal collectors [2–7], base station cooling [8–11], miniature electronic component cooling [12,13], waste heat recovery [14,15], and light-water reactors [16–18]. They are also used to manage temperature in several new fields, with encouraging results. Chang and Huang suggested a sub-atmospheric loop thermosyphon to devise energy-saving cooling systems for shipping machineries. They tested the thermal performance of the loop thermosyphon under pitching and rolling conditions [19]. Yan et al. designed a seasonal cold storage system for sustainable building cooling. They utilized the loop thermosyphon to automatically charge cold energy from ambient air during winter. Their results showed that a system with a storage volume of 450 m^3 can provide approximately 1/3 of the total cooling demand of a building with a total area of 2000 m^2 [20]. Oliveira et al. investigated the in-flight cooling performance of a loop thermosyphon installed in an aircraft. They conducted tests at flight Mach numbers of approximately 0.78 and at altitudes that exceeded 40,000 ft. Their results showed that thermal performance of the loop thermosyphon is unaffected by roll angle, angular velocities (pitch, yaw, and roll rates), and aircraft accelerations [21]. Li et al. suggested that a loop thermosyphon filled with sodium–potassium alloy is a feasible cooling method for high-temperature stators of gas turbines. They tested the heatproof ability of the loop thermosyphon under 1230 °C. Their results showed that the loop thermosyphon successfully decreased the average wall temperature of the vanes to approximately 340 °C [22].

Given that traditional heat and temperature control processes waste considerable amounts of energy, experiments have been conducted to discover novel temperature and heat management methods [23–25]. In the meantime, an increasing number of applications simultaneously require efficient heat transfer and constant operating temperatures. For example, many precision instruments, particularly laser machineries, need efficient heat dissipation and precise working temperatures. The temperature precision requirements of electronic components increase with their performances. Input power is uncontrollable in solar energy utilization and loading power always varies in building energy conservation, thus requiring continuous and variable heat transfer. Therefore, the loop thermosyphon is an efficient and low-cost solution for heat transfer and thermal control problems.

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Nomenclature

C_p	specific heat capacity [J kg^{-1} K^{-1}]
f	flow resistance [N]
H	enthalpy [J/g]
h	heat transfer coefficient [W m^{-2} K^{-1}]
M	mass flow rate [g/s]
u	flow velocity [m s^{-1}]
NTU	number of transfer unit
P	pressure [MPa]
Q	heat transfer rate [W]
R	thermal resistance [K/W]
S	cross-sectional area [m^2]
T	temperature [°C]
V	volume flow rate [m^3 s^{-1}]
v	specific volume [m^3 kg^{-1}]

Greek letters

ε	effectiveness
ρ	density [kg m^{-3}]
ζ	resistance coefficient [kg m^{-1}]

Subscripts

c	condenser
e	evaporator
equ	equivalent
g	ethylene glycol solution
in	inlet
out	outlet
R	R134a working fluid
s	superheat
sat	saturation state
u	undercooling
w	water
work	working temperature

However, loop thermosyphons operate in passive heat transfer states in existing applications. Many research works consider factors that affect the heat transfer capabilities of loop thermosyphons with only passive heat transfer [26–29]. For example, Samba et al. [12], Ling et al. [30], and Tong et al. [31] analyzed the effect of fill ratio on the heat transfer performance of loop thermosyphons. They reported that excessive or insufficient working fluid severely degrades the performance of loop thermosyphons by changing the structures of loop thermosyphons. Dube et al. [32] and He et al. [33] investigated the effect of non-condensable gas (NCG) on the steady-state operation of loop thermosyphons. They showed that NCG decreases the overall thermal conductance of loop thermosyphons, especially under low-temperature conditions. They also confirmed that NCG volume is significantly correlated with the steady-state operating temperature of the evaporator, and that installing a reservoir can minimize the adverse effects of NCG. Aung et al. [34] and Khodabandeh et al. [35,36] modified the diameters of vapor line and evaporator, respectively. They revealed that modifying the structures of individual loop thermosyphon components successfully enhances the overall heat transfer coefficient. These research works show that although the heat transfer capability or the conductance of a loop thermosyphon can be artificially adjusted, an accurate method has yet to be found.

A variable conductance loop thermosyphon (VCLT) is developed in this study. The internal flow resistance of the VCLT can be actively adjusted by a gate valve and the heat transfer rate changes correspondingly. This novel precise heat and temperature management device beneficially affects energy use by improving control precision and reducing energy consumption. The device is preliminarily designed to precisely control the temperature of fresh food in specially designed cool-storage refrigerators. The compressors of these refrigerators operate continuously for several hours to store cold energy in the phase change material (PCM) only in the top freezer. The temperature of the fresh food compartment is regulated by the VCLT. With the precise temperature management capability of VCLT, this novel cool-storage technology can be used

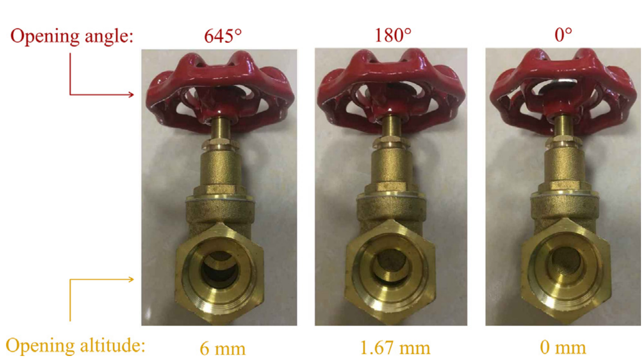

Fig. 1. Gate valve at different open positions.

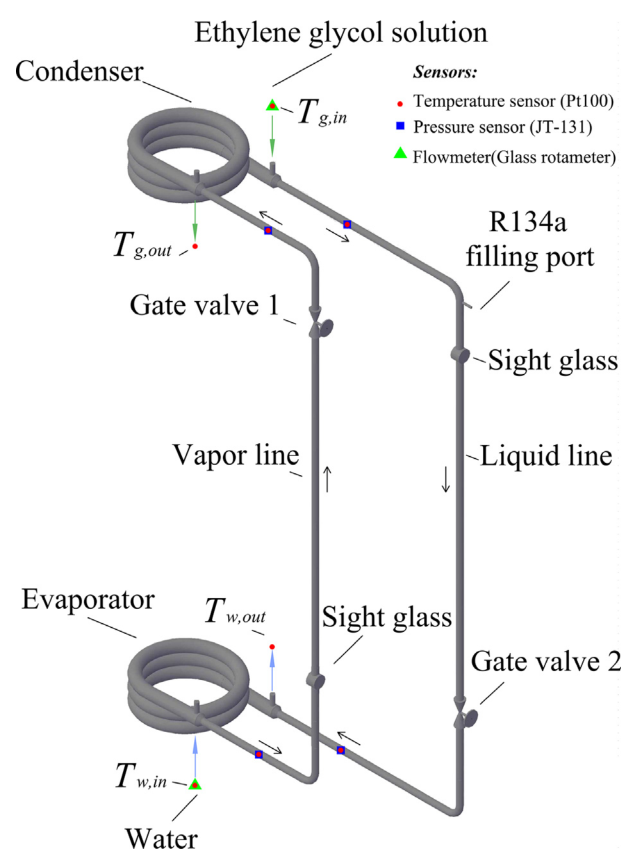

Fig. 2. Concrete structure and measurement points of VCLT.