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Hydraulic operating temperature control of a loop heat pipe

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ABSTRACT

In this work, a hydraulic operating temperature control of loop heat pipes (LHPs) was proposed to achieve a precise, stable, and theoretically predictable operating temperature control. To this end, a pressure controlled LHP was devised to control the saturated vapor temperature at the evaporator by applying hydraulic action on the compensation chamber with an immiscible control gas. In particular, by forming an isothermal region in the vapor transport line, it was attempted to control the temperature of the isothermal region, and the resulting operating temperature controllability was investigated in terms of stability, precision, and predictability. Theoretical basis and limitations of the proposed method were established based on the thermo-hydraulic operating principles of the LHPs, and experimental validation was performed using Dowtherm A as a working fluid and helium as the control gas. Test results showed that the devised pressure controlled LHP was able to control the isothermal region temperature within the stability of 25 mK, and the resolution of the temperature control was around 60 mK at 100 Pa change in the control gas pressure. Large scale operating temperature change was also possible, and a guide to achieve an effective operating temperature control was suggested. Details of the design and fabrication of the devised pressure controlled LHP was also provided.

1. Introduction

Loop heat pipes (LHPs) are highly promising passive two-phase heat transfer devices utilizing latent heat of a working fluid and high speed vapor flow for transferring large amount of heat very fast. The LHPs, due to their superior heat transfer capability and passive nature, have been extensively used as main thermal control devices for space-based equipment and are now extending their sphere down to earthbound applications [1,2]. However, despite this excellence in performance and variety of successful applications, the LHPs are generally known to have an intrinsic limitation on the precise operating temperature control due to their unique structural feature which is the integrated compensation chamber into the evaporator.

The active operating temperature control of the LHPs has been conceptually suggested since the early stage of the development, and the proposed method was to apply thermal action on the compensation chamber or on the liquid returning line [3–5]. This scheme of the operating temperature control was in principle to change the saturation state of the working fluid in the compensation chamber and accordingly the saturated vapor temperature at the evaporator. Based on this method, a few works investigated thermal responses of the LHPs to the active compensation chamber cooling and showed rough operating temperature decrease with active cooling of the compensation chamber [6,7]. However, due to the physical proximity of the compensation chamber to the evaporator, which resulted in complicated thermo-hydraulic phenomena in those components, a precise temperature control based on the thermal action on the compensation chamber was very hard to achieve [8].

Nevertheless, necessity for the precise operating temperature control of the LHPs has been raised again in consequence of a recently proposed loop heat pipe-based isothermal region generator (LHP-based IRG) [9]. The LHP-based IRG was originally proposed to meet a strict requirement of precision thermometry, which was a finite region of higher temperature uniformity (i.e., the isothermal region). Based on the high speed heat transfer ability of the LHPs, the devised LHP-based IRG showed a good promise for use in future precision thermometry. However, as the LHP-based IRG was solely relied on the heat load change to vary the operating temperature, the temperature control was slow, imprecise, and hard to predict. These traits were totally unacceptable for future use in the precision thermometry and raised a further requirement on a fast, precise, and predictable operating temperature control of the LHP-based IRG.

Interestingly, a key to solve this issue was found in the same work on the LHP-based IRG, and that was the operating

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Nomenclature

A_w	evaporating surface area of the wick/m^2
C.I.	condenser inlet
C.C.	compensation chamber
C.O.	condenser outlet
g	gravitational acceleration/m/s^2
h	maximum vertical height between the condenser and the vapor transport line/m
I.B.	bottom of the isothermal region
I.M.	middle of the isothermal region
I.T.	top of the isothermal region
K	permeability/m^2
L.I.	liquid inlet
L_w	thickness of the wick/m
P	pressure/Pa
$P_{C.}$	capillary pressure/Pa
$P_{control\ gas}$	control gas pressure at the pressure controller/Pa
$P_{NCG\ C.C.}$	partial pressure of the non-condensable gas at the compensation chamber/Pa
$P_{Sat.\ C.C.}$	partial pressure of the working fluid at the compensation chamber/Pa
$\dot{Q}_D$	dissipated heat load/W
r_{max}	maximum pore radius/m
R_s	specific gas constant/J/(kg K)
T	temperature/°C
$\overline{T}$	mean temperature/°C
V.O.	vapor outlet

Greek symbols

μ	viscosity/(N s)/m^2
Λ	latent heat/J/kg
ρ	density/kg/m^3
σ	surface tension/N/m or stability

Subscripts

C.C.	compensation chamber
Evap.	evaporator
l	liquid-phase working fluid
Sat.	saturation state

temperature hysteresis due to the non-condensable gas accumulation in the compensation chamber [9]. The non-condensable gas (NCG) in the LHPs has been generally known to be collected in the compensation chamber where the pressure is lowest and also known to increase the compensation chamber pressure. This increase in the compensation chamber pressure would lead to the increase in the saturation temperature of the evaporator due to the thermo-hydraulic link between those components [10–13]. The LHP-based IRG showed similar behavior, and resulted in the operating temperature increase due to the accumulated NCG in the compensation chamber. This behavior of the LHP-based IRG suggested another way of operating temperature control, which was to apply a hydraulic action on the compensation chamber.

The hydraulic means of the temperature control has already been used in traditional thermometry using the well-known gas pressure controlled heat pipes, where a separate pressure controller and an immiscible control gas (i.e., an NCG) are used to control the internal pressure of the heat pipes. However, due to the intrinsic vulnerability of the heat pipes to the non-condensable gas, the gas pressure controlled heat pipes are normally used for temperature stability enhancement, not for the active operating temperature control [14,15]. Differently from this limitation of the heat pipes, the LHPs are tolerant to the generated or injected NCG because of the existence of the large compensation chamber which can contain the NCG. Due to this characteristic, the LHP was expected to be a suitable device for the hydraulic means of the operating temperature control.

In this work, a pressure controlled LHP was devised to achieve the operating temperature control by applying hydraulic action on the compensation chamber. In particular, employing the structure of the LHP-based IRG, the main focus of this work was to investigate the controllability of the isothermal region temperature in terms of the stability, precision, and predictability. Fig. 1 shows the schematic of the devised pressure controlled LHP having an isothermal region in the vapor transport line. As shown in the figure, the pressure controlled LHP was designed to operate with a separate pressure controller and an immiscible control gas to control the compensation chamber pressure. Dowtherm A was chosen as the working fluid for higher operating temperature, and helium was used as the control gas due to its light weight compared to the working fluid. Development of a theoretical model based on thermo-hydraulic analysis of the proposed method was performed, and corresponding experimental validation was provided. Details of the design and fabrication of the devised pressure controlled LHP were also provided.

2. Theoretical analysis

2.1. Concept of the hydraulic operating temperature control

Fig. 2 shows the thermodynamic operation curve (P–T diagram) of a conventional loop heat pipe (red curve). As shown in the figure, the driving force of the working fluid flow from the evaporator to the compensation chamber is the saturation pressure difference between those components ($\Delta P_{Sat.}$), and this pressure difference is generated from the saturation temperature difference between them ($\Delta T_{Sat.}$) at a given heat leak. Therefore, the operating temperature of an LHP is determined at which the saturation pressure difference balances the pressure loss through the working fluid flow from the evaporator to the compensation chamber ($\Delta P_{loss\ 1}$).

The basic idea of the hydraulic operating temperature control of the LHPs was based on the assumption that the saturated vapor temperature at the evaporator could be changed by the compensation chamber pressure change. Unlike the conventional heat

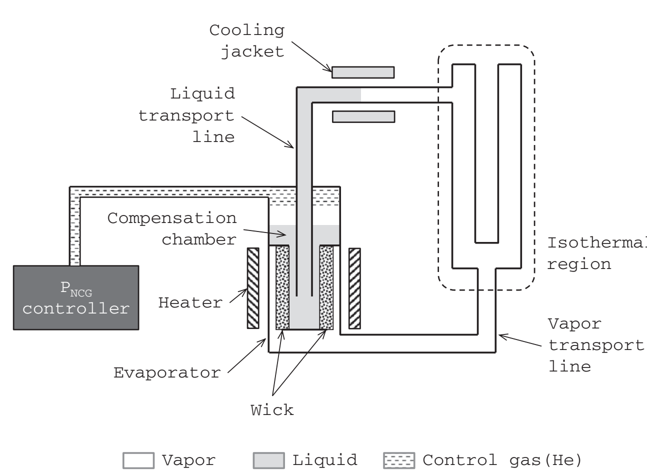

Fig. 1. Schematic of the pressure controlled LHP.