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Operating characteristics of a loop heat pipe-based isothermal region generator

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ABSTRACT

An isothermal region of a finite size is an important requirement for precision metrology and its related industries. In this work, a loop heat pipe (LHP)-based isothermal region generator was devised in which a high speed vapor flow region of the LHP was utilized to achieve the isothermal region. To this end, a stainless steel LHP employing water as a working fluid was designed and fabricated. In particular, an annular type vapor flow region was configured in the vapor transport line to accommodate the isothermal region with dimensions of 50 mm × 360 mm (diameter × height). Temperature uniformity testing demonstrated that the maximum temperature difference and the effective thermal conductivity of the isothermal region at the maximum heat load were 0.56 °C and 311 000 W/(m K), respectively. The temperature uniformity improved with increasing mass flow rate and showed a dependence on the speed of the working fluid. The steady state operating temperature of the isothermal region ranged from 47.1 °C to 64.0 °C with temperature hysteresis at low heat loads. Details of the design and operating characteristics of the LHP-based isothermal region generator are provided and discussed.

1. Introduction

Loop heat pipes (LHPs) are one of the most promising passive two-phase heat transfer devices, and due to their superior heat transfer capability and operational reliability, they have been used successfully in various fields from space to terrestrial applications [1,2]. In particular, as LHPs can overcome the boiling and entrainment limits and extend the capillary limit of conventional heat pipes significantly, they are now being considered as the improved version of heat pipes and are replacing them especially in areas where the thermal control of high heat flux devices is required [3,4].

Besides this conventional use of the LHPs, there is another possible application where a high speed heat transfer capability is required. In precision thermometry, where fixed-point temperatures are realized or thermometers are calibrated by comparison, the most important requirement is a attainment of an isothermal environment over a finite space [5]. In this regard, various types of high speed heat transfer devices, such as thermosyphons and heat pipes, have been used, and they are generally named isothermal furnace liners (IFLs). Among these, heat pipe IFLs have been of particular interest. Heat pipe IFLs are essentially annular type heat pipes, where the cylindrical inner space serves as an isothermal region, and by extending the wick structure over the inner surface of the isothermal region, it is possible to attain outstanding temperature uniformity over a few tens of centimeters [6,7]. Due to these characteristics, heat pipe IFLs are now used in almost all precision high temperature furnaces and are finding their applications in precision thermometer calibration by comparison and thermocouple inhomogeneity evaluation. [8–10].

Despite these outstanding features and the widespread use of heat pipe IFLs, they have some weaknesses due to the intrinsic limitations of the heat pipes, which include possible operation failure due to the heat transfer limits of the heat pipes and the influence of the magnetic field generated by the heater wound onto the external surface of the heat pipe. Since these problems limit the reliable use of the heat pipe as an IFL and increase measurement uncertainty, an alternative heat transfer device that guarantees reliable operation in a wide range of heat loads and has a spatially separated isothermal region from the heating elements is necessary. LHPs, as already noted, are highly efficient two-phase heat transfer devices, extending their heat transfer capability beyond that of conventional heat pipes, and allow more structural flexibility. Thus, when implemented successfully as an IFL, an LHP can improve the measurement uncertainty in precision thermometry significantly.

In this work, a water-stainless steel LHP was devised specifically for use as an isothermal region generator. In particular, to produce a region of highly uniform temperature, the vapor transport line of the LHP, where high speed vapor flow exists, was used to attain the isothermal region. Fig. 1 shows the schematic of the

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Nomenclature

$A_{I.R.}$	cross-sectional area of the isothermal region
A_w	evaporating surface area of the wick
C.I.	condenser inlet
C.C.	compensation chamber
C.O.	condenser outlet
$\Delta T_{I.R.}$	maximum temperature difference of the isothermal region
c_p	liquid specific heat
g	gravitational acceleration
h	maximum vertical height between the condenser and the vapor transport line
h_{fg}	latent heat
I.B.	bottom of the isothermal region
I.M.	middle of the isothermal region
I.T.	top of the isothermal region
K	permeability
k_{eff}	effective thermal conductivity
L.I.	liquid inlet
$L_{I.R.}$	length of the isothermal region
L_w	thickness of the wick
$\dot{m}$	mass flow rate
$P_{C.C.}$	compensation chamber pressure
$\dot{Q}_D$	dissipated heat load
$\dot{Q}_{HL}$	heat leak
R_{th}	thermal resistance
r_{max}	maximum pore radius
T	temperature
$T_{C.C.}$	average temperature of the compensation chamber
U	expanded uncertainty
V.O.	vapor outlet

Greek symbols

μ	viscosity
ρ	density
σ	surface tension

Subscripts

C.C	compensation chamber
C.I	condenser inlet
C.O	condenser outlet
l	liquid-phase working fluid
L.I	liquid inlet
V.O	vapor outlet
WF	working fluid

devised LHP-based isothermal region generator. The thermal performance in general and in terms of the temperature uniformity was investigated thoroughly, and the operating characteristics are discussed. Details of the design and fabrication of the devised LHP-based isothermal region generator are also provided.

2. Design and fabrication of the LHP-based isothermal region generator

2.1. Isothermal region

The isothermal region was a key component of the LHP-based isothermal region generator, and was responsible for the generation of the uniform temperature region. In this work, to attain the concept of the isothermal region generator based on the LHP, the vapor transport line, in which high speed superheated vapor flows, was configured to accommodate the isothermal region. Fig. 2 shows the dimensions and the section view of the isothermal region designed in this work.

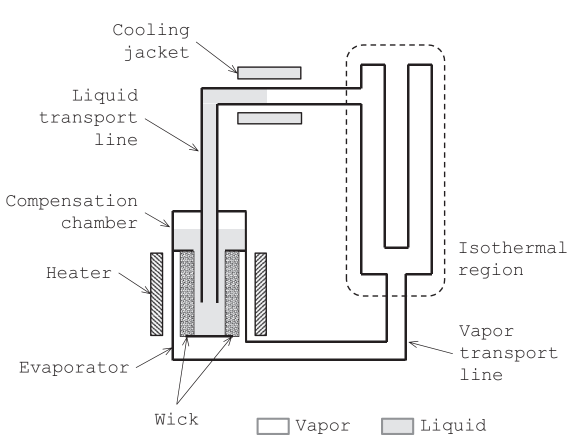

Fig. 1. Schematic of the LHP-based isothermal region generator. The isothermal region was configured to utilize the high speed vapor flow of the vapor transport line of the LHP.

As shown in Fig. 2, the vapor transport line was designed to have an annular vapor flow region, the inside of which the isothermal region was located. The isothermal region was intended to accommodate a fixed-point cell of the International Temperature Scale of 1990, which comprises a pure metal sample in a cylindrical graphite crucible with an outer quartz envelope [11]. In this work, the isothermal region was intended to accommodate an indium fixed-point cell with an outer diameter of 50 mm and a vertical height of 450 mm. Thus, the isothermal region was designed to have a cylindrical space with a diameter of 52 mm and a vertical height of 455 mm. The vapor entering the vapor entrance was directed to flow through the 5 mm-wide annular space to the vapor exit. In this case, as the vapor exit was located at a fixed position on the circumferential plane, there was a possibility of biased vapor flow toward the vapor exit. To resolve this problem, a vapor flow barrier, which blocked half the vapor flow space, was placed directly below the vapor exit.

2.2. Wick

The wick of the LHPs plays an important role in producing the saturation pressure difference between the evaporator and the compensation chamber and in generating the capillary pressure difference on the evaporating surface of the wick. For the wick to produce those forces properly, the material, physical dimensions, and the maximum pore size of the wick should be determined properly. In this work, a cylindrical stainless steel sintered filter with dimensions of 50 mm × 114 mm × 3 mm (outer diameter × height × thickness) was used as a wick structure. An impermeable flange and an impermeable end cap were laser welded at the opening and at the opposite side of the wick. These parts were intended for better installation of the wick and complete separation of the phases across the wick, respectively. Fig. 3 shows the external shape and dimensions of the wick assembly.

To determine the maximum pore size of the wick, a pressure balance equation based on the capillary limit was used [12]. In this