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Long-distance loop heat pipe for effective utilization of energy

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ABSTRACT

The purpose of this study is to develop a long-distance loop heat pipe (LHP). First, the mathematical model was developed to predict the operating characteristics of the LHP; the model is based on a one-dimensional steady-state flow. Second, three LHPs were fabricated with different distances for heat transport: 2 m, 4 m, and 10 m. The wick was made of a polytetrafluoroethylene porous material, the working fluid was ethanol, and the cooling method was natural convection. All three LHPs operated stably at heat loads up to 160 W. When the maximum heat load of 160 W was applied, the thermal resistances of the 2 m, 4 m, and 10 m LHPs were 0.073 K/W, 0.063 K/W, and 0.13 K/W, respectively. As the heat-transport distance increased, the temperature in the compensation chamber (CC) decreased and the temperature difference between the evaporator and CC increased. Finally, the computational results from the mathematical model were compared with the experimental data; there was a good agreement between the predicted and measured temperature distributions across the LHPs.

1. Introduction

Loop heat pipes (LHPs) are two-phase heat transfer devices that use the evaporation and condensation of a working fluid to transfer the heat and use the capillary forces developed in fine porous wicks to circulate the fluid [1,2]. The LHPs do not require electrical power because they have no moving mechanical parts. Compared with conventional heat pipes (HPs), which also use capillary forces to circulate the working fluid, the LHPs can transport heat over longer distances. In the conventional HPs, vapor flows through the center of the pipe from an evaporation area to a condensation area, while liquid flows through the wick, which is located in the inner surface of the entire pipe, from the condensation area back to the evaporation area. Therefore, if the distance needed for heat transport becomes longer, the length of the wick and the entire pipe also become longer. In contrast, in the LHPs, the wick is located only in the evaporator. Therefore, if the distance needed for the heat transport becomes longer, the length of the wick does not change. Because of this difference, the pressure loss at the wick in the LHPs can be kept lower than in the conventional HPs.

Instead of conventional HPs, the LHPs are being investigated for use as energy-saving cooling devices in electronic equipment, such as laptops [3–6]. Future applications for the LHPs could include smart houses, which will need effective ways to use the heat gained from the sun during daylight hours. Another future application could be in automobiles, which will need effective ways to use the exhaust heat from the engine and electronic equipment. In addition, utilization in applications such as snow melting during heavy snowfall and cooling of the data center can also be expected. To realize such effective methodologies, heat must be transported over distances from a few meters to about ten meters.

The wicks in the LHPs develop high capillary pressures that are used to operate against gravity and can also be used to increase the horizontal distance for heat transport. Maydanik [2] developed the LHP for long-distance heat transportation; however, the experimental conditions and detailed results were not presented in that study. In fact, very few studies have focused on the heat-transport distances of the LHPs, and even fewer have addressed the relationship between the heat-transport distances and the operating characteristics of the LHPs. Therefore, the purpose of this study is to develop LHPs that can transport heat over long distances.

Several steady-state mathematical models for predicting the operational characteristics of the LHPs have been published [7–11]. In particular, mathematical models have been developed for cylindrical evaporators [7,8], a flat evaporator [9], and other multiple evaporators and condensers [10]. However, these mathematical models did not place sufficient emphasis on the condensation in the vapor line. For heat transport over long distances, problems can be expected due to the heat losses from vapor and liquid lines to ambient air and due to the pressure losses in the single- and two-phase fluids in the vapor and liquid lines. Therefore, in this study [12–15], a mathematical model was developed that included the condensation in the vapor line; the model was also

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Nomenclature

A_s	cross-section area, m^2
c_p	specific heat at constant pressure, J/kg K
D	diameter, m
f	Darcy's friction coefficient
G_{A-B}	thermal conductance between A and B per unit length, W/m K
h	heat transfer coefficient, W/m^2 K
K	permeability, m^2
k	thermal conductivity, W/m K
L	length, m
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
Q_{A-B}	heat transfer from A to B, W
Q_{load}	heat load, W
R_{LHP}	thermal resistance from evaporator to condenser, K/W
r	radius, m
Re	Reynolds number
T	temperature, °C
u	velocity, m/s
Greek	
λ	latent heat, J/kg
ε	porosity
θ	contact angle, °
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m^2
τ_w	wall shear stress, Pa
Subscripts	
amb	ambience
bay	bayonet tube
cap	capillary limit
cc	compensation chamber
con	condenser
ec	evaporator case
eV	evaporator
g	groove
hb	heater block
I	inner
ll	liquid line
O	outer
p	pipe
pore	pore of wick
sub	subcooled
sat	saturation
vl	vapor line
wi	wick
2f	two-phase

used to clarify the relationships between pressure losses and the distance for heat transport.

In this study, three LHPs were fabricated; to clarify the relationships between heat-transport distances and operating characteristics, each LHP had a different one-way distance from evaporator to condenser: 2 m, 4 m, and 10 m. Ethanol was selected as the working fluid. The wick was made of a polytetrafluoroethylene (PTFE) porous material. Previously, copper, titanium, and nickel have been used as the wick materials [16–18]; however, in consideration of future use in consumer products, a plastic porous wick was selected because it is easier to machine and can be less expensive than metal wicks [19]. An additional advantage of the plastic wick is that it can reduce conductive heat leak from the evaporator to the CC because of its low thermal conductivity, which results in a lower loop-operating temperature. The drawback of the plastic wick is that when a high heat flux is applied, large thermal resistance is generated between the evaporator casing and the wick causing the degradation of the thermal performance.

This paper focuses on heat-transport distances, which are the lengths of the vapor and liquid lines in the LHPs. First, the steady-state mathematical model is described; this model enables the calculation of the temperature and pressure in each part of an LHP. Second, experiments using the three LHPs are described. Finally, the experimental and computational results are compared.

2. Numerical model

The schematic of an LHP is shown in Fig. 1. The LHP is composed of an evaporator, vapor line, condenser, liquid line, and a compensation chamber (CC). A wick is enclosed in the evaporator. A core and grooves are machined in the wick. As heat is applied to the evaporator, liquid is evaporated and menisci form at the liquid/vapor interface in the wick. The vapor flows from the evaporator through the vapor line to the condenser. The vapor condenses in the condenser and the condensate flows through the liquid line back to the evaporator. Condensation occurs only in the vapor line and the condenser, while the fluid in the liquid line is always liquid.

Our mathematical model is based on one-dimensional steady-state incompressible flow. The physical properties of the working fluid are defined as the functions of the saturation temperature. In the model, the heat losses through the thermal insulation in the evaporator, vapor line, liquid line, and the CC are taken into account using the experimentally measured values for the thermal conductance from the pipe surfaces to the ambient atmosphere.

2.1. Transport lines and condenser

The vapor line, liquid line, and the condenser are connected by piping. The working fluid in the lines is in either one of the three states: single-phase vapor, single-phase liquid, or two-phase vapor–liquid. For single-phase flow, the conservation of energy and momentum discretized at element i can be written as follows:

$$\dot{m}c_p\frac{dT_i}{dz} = G_{i-amb}(T_i - T_{amb}) + \pi D_I \tau_{wi} u_i \quad \text{and} \tag{1}$$

$$\frac{dP_i}{dz} = -\frac{\pi D_I}{A_p}\tau_{wi}, \tag{2}$$

with

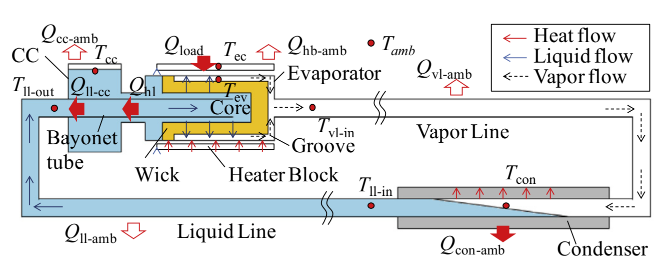

Fig. 1. Schematic of an LHP.