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Research Paper

Study on a loop heat pipe for a long-distance heat transport under anti-gravity condition

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HIGHLIGHTS

- 10 m-class long-distance loop heat pipe was developed based on calculation model.
- Several tests were conducted under horizontal and anti-gravity conditions.
- The gravity effect on the heat transport efficiency was evaluated.
- Easier generation of vapor blanket as the increase of gravity effect was indicated.
- It revealed the possibility for use of loop heat pipe in the terrestrial field.

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ABSTRACT

This paper reports the test results and evaluation of gravity effects on long-distance loop heat pipe (LLHP) with 10 m distances for heat transport. First, the LLHP was designed based on the one-dimensional steady-state model, fabricated and tested. Test results showed the LLHP could transport heat up to 340 W for 10 m and the thermal resistance between the evaporator and the condenser was 0.12 K/W under horizontal condition. Next, the LLHP was tested in top-heat mode. The maximum heat transports were 310, 270, 220 W and the thermal resistances were 0.15, 0.17, 0.22 K/W under 30, 60, 100 cm anti-gravity condition respectively. The heat transfer efficiency of the LLHP was discussed in detail. The evaluation results showed 71.4% of the 340 W heat load was dissipated at the condenser under the horizontal condition. On the other hand, 62.8, 61.8, 57.1% of the maximum heat load was dissipated at the condenser under 30, 60, 100 cm anti-gravity condition respectively. The calculation model was in good agreement with the experimental results by considering the existence of a vapor pocket between the evaporator case and the vapor-liquid interface. This analysis indicated the vapor blanket generates easily and becomes thicker as anti-gravity effect increases.

1. Introduction

Loop heat pipe (LHP) is an efficient two-phase heat transfer device that utilizes the evaporation and condensation of a working fluid, and uses the capillary force developed in a fine porous wick for circulation [1–3]. It has been developed and applied in the field of space engineering, however, it is being investigated for use in the terrestrial field [4]. This is because of the current demand for energy saving and the LHP's advantages such as no utility power requirement, capability of transferring heat over long distance and anti-gravity orientation. Electronics and computers are quite a promising sphere of LHP application [5,6]. In the future, LHP could be applied in the field of smart houses, automobiles, snow melting [7]. Applying LHP to these fields, transferring heat over long distance and anti-gravity direction could be required. Considering LHP can be utilized in the smart houses, LHP could be applied to use the heat gained from the sun during daylight for floor heating, water heating, and heat storage tank.

In author's previous study, a long-distance loop heat pipe (LLHP) that has one-way heat transport distance of 10 m had been designed and fabricated based on a one-dimensional steady-state flow system [7]. The experimental results showed the fabricated long-distance loop heat pipe could transport heat up to 160 W and the thermal resistance between the heat absorbing part and the heat radiating part was 0.13 K/W. However, the LHP performance was not enough, that is, for the practical utilization, higher heat transport and lower thermal resistance, and the operation under anti-gravity condition could be necessary, also, the heat transfer efficiency needs to be evaluated.

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Nomenclature

A	surface area (m^2)
A_0	heat dissipation area of no fin part (m^2)
CR	contact thermal resistance between pipe and insulator (K/W)
D	diameter (m)
h	heat transfer coefficient (W/m^2 K)
h_{ev}	heat transfer coefficient from the evaporator to the vapor-liquid interface of the wick (W/m^2 K)
HD	height difference between the evaporator and the condenser (cm)
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q_{amb}	heat loss from the evaporator (W)
Q_{ev}	heat of vaporization (W)
Q_{gr}	superheat of groove (W)
Q_{hl}, Q'_{hl}	heat leak from the evaporator to the CC (W)
Q_{load}	heat load (W)
Ql	heat loss (W)
r	radius (m)
R	thermal resistance from the evaporator to the condenser (K/W)
R_{fin}	thermal resistance between the pipe and the fin (K/W)
S	cross-sectional area (m^2)
T, T'	temperature (K)

Greek

λ	latent heat (J/kg)
φ	porosity (–)
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ	contact angle (°)
η	fin efficiency (–)

Abbreviations

amb	ambient
a_b	from a to b
ca	case
cap	capillary limit
cc	CC
con	condenser
ec	evaporator case
eff	effective
ev	evaporator
f	fluid
gr	groove
i	inner
ins	insulator
ll	liquid line
l	l-th thermocouples
nuc	nucleate boiling
o	outer
s	solid
sat	saturation
sup	superheating
v	vapor
vl	vapor line
wi	wick

When it comes to previous studies of the gravity effect on LHP, Riehl [8] and Chuang [9] experimentally showed anti-gravity effect results in the increase of LHP's operating temperature. Ku [2] and Mo et al. [10] theoretically explained the increase of operating temperature from the point of increase of pressure drop between the evaporator and the compensation chamber (CC) due to gravity. Furthermore, Chuang [9] reported anti-gravity effect was crucial at low heat loads, because at low heat load, gravity effect plays an important role in the total pressure drop compared with the frictional pressure drop. However, anti-gravity effect could have further effects on LHP's operation and as a results, operating temperature could be further increased. Tang et al. [11] developed anti-gravity loop-shaped heat pipe (AGLSHP) that has a continuous graded pore-size wick in the evaporator and the liquid line. The AGLSHP was able to transport 100 W under 40 cm anti-gravity condition, however, it would be difficult to transport heat over long distance because of the high pressure drop of the wick in the liquid line.

This paper reports the development of the 10 m-class long-distance loop heat pipe based on the one-dimensional steady-state model. Tests were conducted under horizontal and 30, 60, 100 cm anti-gravity conditions. Anti-gravity effect on the operating temperature and the heat transport efficiency was evaluated based on the temperature data of the test results and calculation model. Total pressure drop was evaluated from the computational results.

2. Numerical modeling of loop heat pipe

One-dimensional steady-state numerical model was constructed to design and evaluate the LLHP performance. Fig. 1 shows the configuration of LHP. LHP consists of cylindrical evaporator, vapor/liquid line, condenser and CC. A cylindrical wick is enclosed in the evaporator and a core and grooves are machined in the wick.

In this model, some assumptions are made: (1) the wick is fully saturated with liquid. (2) There is an axisymmetric flow in all the parts of the LHP. (3) The temperature of the CC's case is equal to the working fluid in it. (4) Heat leak from the evaporator case to the vapor line is disregarded.

2.1. Evaporator and wick model

The energy balance in the evaporator can be expressed by Eq. (1).

$$Q_{load} = Q_{ev} + Q_{gr} + Q_{hl} + Q_{amb} \tag{1}$$

Q_{ev} is written by Eqs. (2) and (3).

$$Q_{ev} = h_{ev} A_{ev} (T_{ec} - T_{ev}) \tag{2}$$

$$Q_{ev} = \dot{m}\lambda \tag{3}$$

where h_{ev} is estimated from the comparison of steady-state temperature between the experimental and the calculation results, as it substantially depends on the contact condition between the evaporator and the wick and the position of the vapor-liquid interface. Q_{gr} is computed by the heat transfer coefficient of the forced convection of the vapor through the groove. Q_{hl} consists of the heat leak through the wick (Q_{ev_wi}) and the evaporator case (Q_{ec_ca}) and is expressed by Eq. (4).

$$Q_{hl} = Q_{ev\_wi} + Q_{ec\_ca} \tag{4}$$

Q_{ev_wi} and Q_{ec_ca} are calculated by Eqs. (5) and (6) respectively.