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Anti-Gravity Loop-shaped heat pipe with graded pore-size wick

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ABSTRACT

An Anti-Gravity Loop-Shaped Heat Pipe (AGLSHP) with a Continuous Graded Pore-Size Wick (CGPSW) was developed for the cooling of electronic devices at the anti-gravity orientation on the ground. At this orientation, heat is transferred toward the direction of the gravitational field. The AGLSHP consists of an evaporator, a condenser, a vapor line and a liquid line. The CGPSW is formed by sintered copper powders and it is filled inside the evaporator and the liquid line. The corresponding test system was developed to investigate the start-up characteristics and heat transfer performance of the AGLSHP at the anti-gravity orientation. The experimental result shows that, the AGLSHP has the capability to start-up reliably without any temperature overshoot or oscillation at the test heat loads. And the AGLSHP is able to keep the temperature of the evaporator below 105 °C and the overall thermal resistance below 0.24 °C/W at the heat load of 100 W. It is also found that the ideal heat load range of the AGLSHP at the anti-gravity orientation is from 30 W to 90 W. In this power range the overall thermal resistance stabilizes at about 0.15 °C/W, and the maximum temperature of the evaporator is lower than 84 °C at the heat load of 90 W.

1. Introduction

Loop Heat Pipes (LHPs) and Capillary Pump Loops (CPLs) are highly effective phase-change heat transfer devices developed for aerospace applications between 1960's and 1970's [1,2]. Both of these devices use the same basic principle and can be defined as capillary heat loops [1,3]. At present the main area of application of the LHP/CPL is space technology [2]; however, electronics and computers are quite a promising sphere of the LHP/CPL application on the ground [2,4,5]. In the terrestrial application, it is normal to have the heat source above the cold source. When a LHP/CPL is operating at this orientation, the evaporator is placed above the condenser and heat is transferred toward the direction of the gravitational field. This orientation is called the anti-gravity orientation. It is generally believed that the LHP/CPL has the capability to operate efficiently without any restrictions of orientation in the gravity field [1,2]. However, recent studies show that gravity does affect the thermal performance of the conventional LHP/CPL on the ground. When LHPs were tested with the evaporator above the condenser, phenomena such as the start-up difficulty [6], the higher temperature of evaporator with the lower loop heat transfer performance [7] and the considerable temperature oscillation in the vapor/liquid line [6,8] were observed. All of these phenomena could possibly limit the use of LHPs in terrestrial applications [9]. To improve the performance of the LHP/CPL in the gravity field, the dual-compensation chamber structure [10] and biporous wicks [11,12] have been developed.

To solve this problem, this paper presents an Anti-Gravity Loop-Shaped Heat Pipe (AGLSHP) with a Continuous Graded Pore-Size Wick (CGPSW). Similar loop-shaped heat pipes have been introduced before [13,14], while the graded pore-size wick is first adopted in our design. The distinctive wick structure, the CGPSW, consists of two sections with different capillary pore sizes, and these two sections are filled in the evaporator and the liquid line respectively. The corresponding test system of the AGLSHP was developed, and the start-up characteristics and heat transfer performance at heat loads below 100 W were investigated experimentally.

2. Description of the AGLSHP

2.1. Configuration of the AGLSHP and theory analysis

The schematic diagram and a photograph of the AGLSHP are shown in Fig. 1. The AGLSHP consists of four parts: the evaporator, the condenser, the vapor line and the liquid line. Compared with the conventional LHP/CPL, the AGLSHP has the following significant structural differences. First, the Continuous Graded Pore-Size Wick (CGPSW) consists of two sections which have different capillary pore sizes. Second, these two sections are filled in the evaporator and the entire liquid line respectively. Third, the evaporator does not have vapor grooves and a compensation chamber. All significant parameters of AGLSHP are listed in Table 1.

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Nomenclature

A_{ew}	Cross-sectional area of the wick in evaporator, m^2
A_{lw}	Cross-sectional area of the wick in liquid line, m^2
d	Diameter of the copper powder particle, m
d_{ew}	Diameter of the copper powder particle of the wick in evaporator, m
h	Anti-gravity distance, m
ID	Inner diameter, mm
IR	Infrared
K	Wick permeability, m^2
K_{ew}	Permeability of the wick in evaporator, m^2
K_{lw}	Permeability of the wick in liquid line, m^2
k_s	Rate of sintering shrinkage
L	Latent heat of vaporization, kJ/kg
$l_{e-\mathrm{eff}}$	Effective length of the evaporator, m
$l_{l-\mathrm{eff}}$	Effective length of the liquid line, m
$\dot{m}$	Mass flow, kg
M_{cp}	Mass of the copper powders used in each sintering process, g
OD	Outer diameter, mm
ΔP_{cap}	Capillary pressure, N/m^2
$\Delta P_{\mathrm{cap,max}}$	Maximum capillary pressure, N/m^2
ΔP_g	Pressure drop associated to the gravity force, N/m^2
ΔP_l	Liquid pressure drop, N/m^2
ΔP_{lew}	Liquid pressure drop within the wick in evaporator, N/m^2
ΔP_{llw}	Liquid pressure drop within the wick in liquid line, N/m^2
ΔP_{tot}	Total pressure drop, N/m^2
ΔP_v	Vapor pressure drop, N/m^2
Q	Heat load, W
$Q_{\mathrm{ca,max}}$	Maximum heat load at capillary limit, W
R_l	Nominal thermal resistance, °C/W
r_e	Effective capillary radius, m
R_{ov}	Overall thermal resistance, °C/W
T_0	Temperature at the evaporator's inlet, °C
T_1	Temperature at the evaporator's outlet, °C
T_2	Temperature on the wall of vapor line, °C
T_3	Temperature on the wall of vapor line, °C
T_4	Temperature at the condenser's inlet, °C
T_5	Temperature at the condenser's outlet, °C
T_6	Temperature on the wall of liquid line, °C
T_7	Temperature on the wall of liquid line, °C
ΔT_1	Temperature difference between the evaporator's outlet and condenser's inlet, °C
ΔT_2	Average temperature difference between the evaporator and condenser, °C
ΔT_3	Temperature difference between the outlet and inlet of the evaporator, °C
ΔT_4	Temperature difference between the inlet and outlet of the condenser, °C
V	Volume of the wick in each sintering process, m^2
ε	Fractional voidage
μ_l	Dynamic viscosity of liquid, Ns/m^2
ρ_{cp}	Loose packed density of the copper powders, g/cm^3
ρ_l	Density of liquid, kg/m^3
σ_l	Surface tension, kg/s^2

Subscripts

ca	Capillary limit
cap	Capillary pressure
eff	Effective
ew	Wick in the evaporator
g	gravity
l	liquid
lw	Wick in the liquid line
v	Vapor

In a conventional LHP/CPL, there is a porous wick structure only in the evaporator. When it is operating at the anti-gravity orientation, if big vapor bubble enters the liquid line and blocks it, the wick is not in contact with the working fluid and the evaporator would dry out. If the wick is not saturated with the working fluid before start-up, the LHP/CPL would not start-up successfully. To prevent this, the liquid line of the AGLSHP is filled with the wick connecting the wick in the evaporator and the condenser chamber respectively. The soaked wick in the liquid line will not permit the passage of vapor, and because of this, it stabilizes the vapor–liquid phase-change interfaces in the evaporator and condenser. The wick in the evaporator has smaller capillary pore size than the wick in the liquid line which has big capillary pore size. These two sections form the Continuous Graded Pore-Size Wick (CGPSW). The CGPSW is processed by sintered copper powders. Powders with different particle sizes are used to form these two sections. The parameters of the wick are listed in Table 1. This two-section design is based on the concept that, the fine wick in the evaporator provides enough capillary pressure and the wick in liquid line has a large cross-sectional area and big pore sizes to minimize hydraulic resistance. This concept has been proposed and proved efficient in the conventional heat pipe [15,16].

The upper section of the CGPSW fits tightly to the inner wall of the evaporator, inside which is the vapor cavity Fig. 2 shows the internal configuration of the evaporator. The size of the wick powder particle is less than 75 microns. This section provides the capillary pressure to maintain the operation of the AGLSHP. The maximum capillary pressure must be greater than the total pressure drop in the loop represented by the relation:

$$\Delta P_{\mathrm{cap,max}} \geq \Delta P_{\mathrm{tot}} = \Delta P_v + \Delta P_l + \Delta P_g \tag{1}$$

where $\Delta P_{\mathrm{cap,max}}$, ΔP_v, ΔP_l and ΔP_g are the maximum capillary pressure, the vapor pressure drop, the liquid pressure drop and the pressure drop associated to gravity force. $\Delta P_{\mathrm{cap,max}}$ can be calculated using the Young–Laplace equation:

$$\Delta P_{\mathrm{cap,max}} = \frac{2\sigma_l}{r_e} \tag{2}$$

where σ_l is the surface tension and r_e is the effective capillary radius, in this case calculated using the equation:

$$r_c = 0.205 d_{\mathrm{ew}} \tag{3}$$

In the CGPSW, ΔP_l consist of two parts: ΔP_{lew} and ΔP_{llw}, which are liquid pressure drops within the two sections of the CGPSW respectively.

$$\Delta P_l = \Delta P_{\mathrm{lew}} + \Delta P_{\mathrm{llw}} \tag{4}$$

ΔP_{lew} and ΔP_{llw} can be calculated using a form of Darcy's law:

$$\Delta P_{\mathrm{lew}} = \frac{\mu_l l_{e-\mathrm{eff}} \dot{m}}{\rho_l K_{\mathrm{ew}} A_{\mathrm{ew}}} \tag{5}$$

$$\Delta P_{\mathrm{llw}} = \frac{\mu_l l_{l-\mathrm{eff}} \dot{m}}{\rho_l K_{\mathrm{lw}} A_{\mathrm{lw}}} \tag{6}$$