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Experimental investigation on a novel multi-branch heat pipe for multi-heat source electronics

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ABSTRACT

This paper proposes a novel multi-branch heat pipe (MBHP) that can be utilized for heat dissipation in multi-heat source electronics. The proposed heat pipe consists of three branches—two with an evaporator and one with a condenser—connected by vapor lines and liquid lines. A test system was implemented to study the filling ratio, the start-up characteristics, the power distribution characteristics, the dynamic characteristics and the thermal resistance of the heat pipe. The experimental results obtained indicate the following: 1) the optimal working fluid filling ratio of MBHP is between 75% and 100%; 2) the MBHP can start up steadily under tested heating load; 3) the ideal heat load of the MBHP (filling ratio 75%) was within a range of 30–160 W, in which the minimum total thermal resistance was 0.04 °C/W and the maximum temperatures of both evaporators were less than 110 °C under the limiting heating load of 160 W.

1. Introduction

Recently, as a result of steady increases in power and decreases in the volume of electronics, heat dissipation has become an increasingly critical problem that needs to be solved urgently [1]. A heat pipe is a two-phase-exchange heat transfer device with high thermal conductivity that has many advantages including fast heat transfer, good temperature uniformity, stable performance and long lifetime [2–4]. With continuous development of heat pipe technology, heat pipes have become increasingly diverse in terms of structure and shape. Examples of heat pipes include conventional thermosyphon [5], loop heat pipes [6], flat plate heat pipes [7] and pulsating heat pipes [8]. The high efficiency and superior flexibility of heat pipe technology make it an effective approach to solve the heat dissipation problem affecting electronics. It is widely used in areas such as space and aeronautics [9,10], solar energy control [11,12] and waste heat recovery [13].

At present, the vast majority of heat pipes are utilized in heat dissipation of single-heat sources, in which one heat source corresponds to one heat sink. Pastukhov et al. [14] designed the L- and S-shaped micro loop heat pipes predominantly used for heat dissipation of single-heat source high-power microelectronics, such as computer CPU or GPU. Wang [15] studied radiators embedded with multiple U- and L-shaped heat pipes utilized for heat dissipation of a desktop CPU with dimensions 30 mm × 30 mm, minimum thermal resistance values of 0.246 °C/W and 0.166 °C/W, respectively and fairly good conductivity. Lu et al. [16] conducted research on the performance of a high-power LED heat dissipation system that uses a loop heat pipe as the cooling device. It was demonstrated that the junction temperature was controlled below 100 °C under a heat load of 100 W, which guaranteed the performance stability of LED.

With the continuous improvements in miniaturization and integration, electronic devices now contain an increasing number of heat sources. For example, a computer could have multiple CPUs [17,18] and multiple high-power chips could package on the same PCB. For these multi-heat source systems, a heat dissipation scheme comprising multiple heat pipes is conventionally adopted. Ryan et al. [19] employed three heat pipes to implement one-on-one conductive heat dissipation for three chips on the same mainboard of a high-power electronics system, with the aim of guaranteeing that the temperature of chips with a sampling unit power of 230 W is controlled under 70 °C with an ambient temperature of 55 °C. Although this conventional heat dissipation scheme is simple and convenient, it has deficiencies such as large volume, low spatial utilization efficiency difficulty in meeting the requirement of miniaturization for highly integrated devices. Thus, flat plate heat pipes are being seriously considered to solve the problem of multiple heat sources because of advantages such as uniform heat flux and rapid heat transfer [20]. Using mathematical models, Tan et al. [21] analyzed the flow direction and pressure drop of the

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Nomenclature

A	the wrapped area of the adiabatic cotton (m^2)
A_w	cross-sectional area of the wick (m^2)
D_w	inside diameter of the wick (m)
D	outer diameter of the copper tube (m)
g	gravitational acceleration (m/s^2)
h	gravity distance (m)
K	wick permeability (m^2)
k	thermal conductivity of the adiabatic cotton (W/(m K))
L	latent heat of vaporization (kJ/kg)
l_{eff}	effective length of the heat pipe (m)
l_s	length of the adiabatic section (m)
l_e	length of the evaporator (m)
l_c	length of the condenser (m)
n	totality of the time intervals
Q	total input power (W)
q	heat flux (W/m^2)
r	the capillary radius (m)
V_{powder}	volume of sintered copper powder (m^3)
V	volume of deionized water (m^3)
η	filling ratio
ε	the porosity of the wick
σ	surface tension (kg/s^2)
α	the contact angle
μ_l	dynamic viscosity of liquid (Ns/m^2)
$\dot{m}$	mass flow (kg)
ρ_l	density of liquid (kg/m^3)
Δp	capillary pressure of copper wick (N/m^2)
Δp_{tot}	total pressure drop (N/m^2)
Δp_l	liquid pressure drop (N/m^2)
Δp_v	vapor pressure drop (N/m^2)
Δp_{fl}	pressure drop due to friction (N/m^2)
Δp_g	pressure drop associated to gravity force (N/m^2)
ΔH	thickness of the adiabatic cotton (m)
ΔT_i	the temperature difference across the adiabatic cotton layer (°C)
ΔT	total temperature difference of heat pipe (°C)
$\Delta\tau$	time interval (s)
dT	temperature measurement error of K-type thermocouple (°C)
dW_{power}	output power error of the input power (W)
dT_{data}	resolution of the data acquisition card (°C)
dQ_{ac}	heat leakage of Wrapped adiabatic cotton (W)
T_{ave}	time-averaged temperature of each temperature measurement point (°C)
T_1	temperature of evaporator1 (°C)
T_2	temperature of evaporator2 (°C)
T_3	temperature of evaporator1 branch before merging into condenser branch (°C)
T_4	temperature of evaporator2 branch before merging into condenser branch (°C)
T_5	temperature of evaporator branches after merging into condenser branch (°C)
T_6	temperature of condenser section inlet (°C)
T_7	temperature of condenser branch end (°C)
T_8	ambient temperature (°C)
S	state
R_1	thermal resistance from heat source 1 to concourse of two branches (°C/W)
R_2	thermal resistance from heat source 2 to concourse of two branches (°C/W)
R_3	thermal resistance from concourse of two branches to condenser (°C/W)
R_{tot}	total thermal resistance of heat pipe (°C/W)
U_T	temperature measurement uncertainty
$W(L)$	power of heat source 1 (W)
$W(R)$	power of heat source 2 (W)

Subscripts

ac	adiabatic cotton
ave	average
c	condenser
e	evaporator
max	maximum
tot	total

working liquid in flat plate heat pipes under multiple heat sources. They found that the positional distribution of multiple heat sources on the plane of a flat plate heat pipe was optimized and thus optimal heat transfer performance was obtained. To solve the problem of multiple heat sources, the prerequisite of flat plate heat pipe is that all heat sources should be located on the same plane, making the method inappropriate for heat sources that are spatially scattered or have a staggered distribution. However, for complex positional distribution of heat sources, loop heat pipes may have adequate flexibility to handle the heat source positions problem. Bienert et al. [22] proposed and manufactured a type of loop heat pipe with multiple evaporators. It can start up successfully and solved the problem with different spatial locations and different power values of multiple heat sources. David et al. [23] proposed a multi-evaporator hybrid loop heat pipe and focused on the heat transfer performance of a four-evaporator loop heat pipe that can start normally and operate steadily under a heat load in the range 8–280 W, which is mainly used in spacecraft thermal management. Okutani et al. [24] made the research focuses on multiple-evaporator and multiple-condenser loop heat pipe (MLHP) with polytetrafluoroethylene porous media as wicks. They tested with heat loads to both evaporators to confirm the behavior of the MLHP and tested with heat load to one evaporator to confirm the heat transfer between the evaporators. And when the heat loads were applied to both evaporators, the heat pipe was stably operated up to 40 W/40 W. When the heat load was only applied to one evaporator, the heat pipe was stably operated up to 0 W/50 W. Habtour et al. [25] put forward the miniature multiple evaporator multiple condenser loop heat pipe. The dual-evaporator and dual-condenser was able to successfully transport the heating load from 5 W to 100 W. And the heat pipe demonstrated reliable, robust behavior with one or both evaporators powered, with nonuniform evaporator load, and as power was rapidly switched from one evaporator to another. Although suitable for multi-heat source heat dissipation, loop heat pipes also possess disadvantages such as complex structure, manufacturing difficulty and high cost. In conclusion, there is still no practical effective solution for heat dissipation of multiple heat sources.

Zhou et al. [26] manufactured an anti-gravity loop heat pipe which the outer diameter of copper tube is 8 mm and the overall size is 400 mm * 96.5 mm. The limiting heating load of this heat pipe is about 100 W, when the maximum temperature is lower than 105 °C and the minimum thermal resistance is 0.15 °C. Copper–water wicked heat pipe with a sintered-grooved composite wick, which the outer diameter of copper tube is 8 mm, is developed by Li et al. [27]. Their main study was the effects of vacuuming process parameters on the thermal performance. And the maximum heat transport capacity of the heat pipes could be main-