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Novel radial pulsating heat-pipe for high heat-flux thermal spreading

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ABSTRACT

As technology becomes increasingly miniaturized, extremely localized heat dissipation (so called hot-spots) leads to the challenge of how to keep these devices from overheating. Heat dissipation from advanced power and military electronics is expected to be on the order of 1 kW/cm^2, while conventional cooling techniques can only cool up to 10 W/cm^2 with forced air convection cooling and 500 W/cm^2 with advanced microchannel liquid cooling. In the present study, we propose and investigate a novel radial pulsating heat-pipe (RPHP), which is tailored for effective “spreading of heat” from a local high heat-flux heat source.

An experimental system for RPHP was constructed with a 110 mm diameter circular brass plate with 1 mm depth and 1 mm width primary channels. The primary channels are enclosed using a polycarbonate cover that is equipped with an internal working fluid charging port. The diameters of the boiling chamber (or evaporator section) and the condenser section were 10 mm and 60 mm, respectively. Thermocouples were installed to measure the temperatures of RPHP surface and the working fluid. The pressure of the fluid in the boiling chamber was measured using an absolute pressure transducer. The measured data was used to evaluate the thermal performance of the RPHP in terms of convective heat transfer coefficient and thermal resistance with respect to working fluid fill ratio and power input.

The study showed that the system was effective at spreading locally concentrated heat; in the study the heater temperature was dropped by 23 °C compared to that of pure heat conduction through the RPHP body in 30 W heater power case.

1. Introduction

Electronic component technology trends towards miniaturization, which leads to the generation of extremely high localized heat dissipation, termed hot-spot. According to the International Technology Roadmap for Semiconductors (ITRS), high performance chips are expected to dissipate an average heat-flux (local heat dissipation rate) as high as 120 W/cm^2, with the maximum junction temperature not exceeding 70 °C [1]. Wide bandgap semiconductor devices for advanced wireless communications and high power-density military applications [2,3], for example, consume only 5–10 W of power. Their microscale footprint ($\sim$100 μm^2), however, results in local power density of >1000 W/cm^2 [4,5]. Optoelectronic chips ($\geq$1 cm^2) incorporating directed-energy laser sources dissipates more than 500 W/cm^2 heat-fluxes as well [6]. Considering the heat removal capability of conventional cooling techniques, such as forced convection air cooling (<10 W/cm^2) and advanced microchannel liquid cooling (<500 W/cm^2) [5,7–9], to deal with localized heat dissipations, improved effective spreading of concentrated thermal energy over a large area is necessary.

A pulsating heat-pipe (PHP) (also known as oscillating heat-pipe) is a passive thermal transport device that has been recently developed [10] and investigated [11–13]. In PHPs, pulsating motions of bubble columns enable energy transport; therefore, the non-passive return of condensed liquid to boiling chamber is not required and an extremely simple wickless structure is facilitated. It is expected that the wickless pulsating mode of operation can address the geometric and operating issues (such as the effects of orientation, boiling, capillary, and entrainment limits) in conventional heat-pipe configurations. The PHP offers enhanced performance for long distance, high heat-load energy transport, which can benefit electronics cooling, heat exchangers, spacecraft thermal control systems and solar energy transport [14–16]. However, typical axially configured PHPs, while suitable for axial transport of thermal energy, cannot effectively accommodate local hot-spots of small areas. Thus, in this study, we propose and investigate the performance of a novel radial pulsating heat-pipe

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Nomenclature

A	area [m^2]
k	thermal conductivity [W/m K]
q	heat input [W]
R	thermal resistance [^{o}C/W]
R_e	electrical resistance [Ω]
t	thickness [m]
T	temperature [^{o}C]
U	overall heat transfer coefficient [W/m^2 K]
V	voltage [V]

Subscripts

b	boiling chamber
brass	brass
c	condenser section
f	fluid
h	heater
i	thermocouple location index
RPHP	radial pulsating heat pipe
s	surface
sp	spreading
tr	transport
w	water

(RPHP), which is tailored for effective “spreading of heat” from a local high heat-flux heat source.

In Fig. 1, the conceptual diagram of RPHP as a heat spreader is illustrated. RPHP mainly consists of a boiling chamber, a condenser section, primary channels, secondary channels, and connecting bridges. Bubbles are generated from the boiling chamber heated by a strong hot-spot (~1 kW/cm^2). Due to the vapor expansion during phase change, the generated bubbles are driven out of the boiling chamber and pushed toward the perimeter of the heat-pipe through primary channels. A heat-sink affixed on the bottom of the heat spreader allows natural convection cooling to occur, the bubbles, therefore, are condensed into liquid while traveling the channels. The extended channels can augment the condensation of bubbles by increasing the fluid contact area for heat transfer. The successive and drastic volume changes during vaporization/condensation result in the pulsation and/or circulation of bubbles between the boiler chamber and the condenser section through the primary channels and the connecting bridges. The role of the connecting bridges is important, because a flow through a primary channel will be in opposite direction to the flow through the neighboring channel connected by the bridge; i.e., if the fluid in one primary channel is pushed towards the connecting bridge, then the fluid in the connected channel will flow toward the boiler chamber and vice versa, which forms closed-loop PHP flow structure. Therefore, the RPHP can be viewed as an assembly of multiple single closed-loop PHPs having the boiler chamber as a hub. Without connecting bridges, RPHP will be operated like an open-loop PHP, of which performance is generally lower and unstable [17,18] because open-loop bubble pulsations is not as strong when compared to closed-loop PHPs. Consequently, thermal energy absorbed from a hot-spot can be carried by generated bubbles, spread through the RPHP, and thereby the concentrated heat from the heater can be uniformly distributed all over the area of the RPHP and eventually rejected into the ambient medium through the attached heat-sink on the top surface. Since the area of the condenser section offered by the RPHP can be readily more than 100 times the hot-spot area (~1 cm^2), heat flux requirements from condenser section can be greatly reduced (<10 W/cm^2) to allow for an “air-cooled heat-sink” effect for heat rejection.

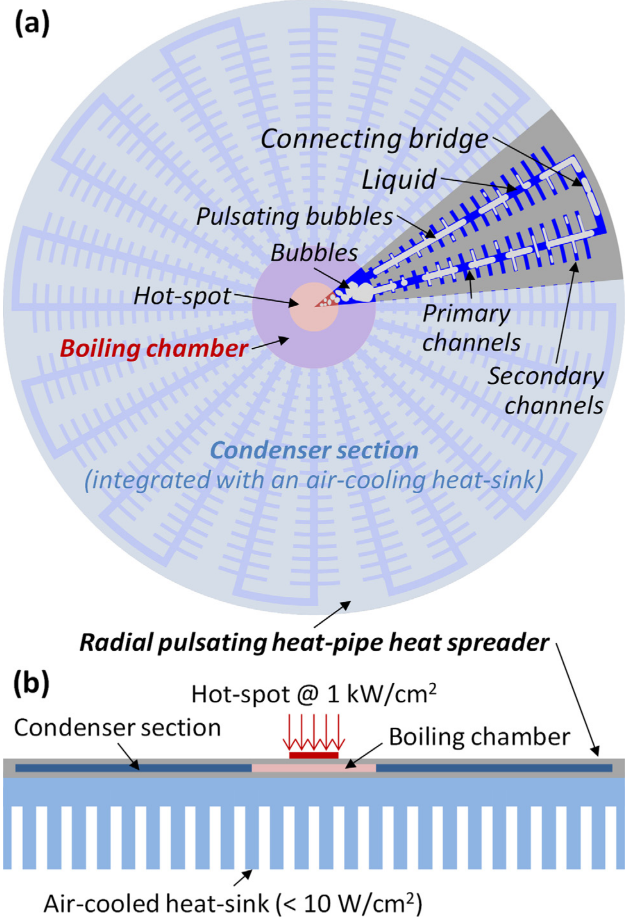

Fig. 1. Conceptual diagram of a radial pulsating heat- pipe (RPHP): (a) top view; (b) side view. The side view diagram is upside down; the heater is attached on the bottom surface of the RPHP, while the finned heat-sink on the top. The thickness of the heat spreader is less than 2 mm.

The proposed RPHP channel design mimics a blood circulation system; i.e., blood is pumped by a heart (boiling chamber), flows through arteries (primary channels) and delivers blood supply (thermal energy) to all over a body through capillaries (secondary channels). Secondary channels are very important for enhanced thermal energy distribution and thus efficiently deliver thermal energy down to a heat-sink. RPHP is a passive device, where the working fluid is driven by the repeating volume expansion and shrinkage during the phase change. As the fluid moves deeper into the condenser portion, the flow resistance through long and narrow primary and secondary channels can be very high and may nullify the motive of the heat spreader design. Also, the secondary channels need to extend all over the area of the RPHP to fully exploit the given surface area for heat transfer enhancement in the condenser section. A fractal tree-like microchannel net concept (Fig. 2), therefore, can be employed as a design for secondary channels in RPHP, which consist of subsequent branching (bifurcation) and folding to maximize the number of channels (heat transfer