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Multi-artery heat pipe spreader: Experiment

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ABSTRACT

We constructed a low thermal resistance, multi-artery heat pipe spreader vapor chamber by designing a thin (monolayer) evaporator wick and distributed permeable columnar arteries supplying liquid (water) to highly concentrated heat source region. The condenser wick is layered copper screens in intimate contact with the columnar arteries. The vapor chamber is sealed and externally surface-convection cooled on the condenser side. For the evaporator wick and arteries, sintered, surface etched-oxidized copper particles are used to enhance wettability.

The measured evaporator thermal resistance is less than 0.05 K/(W/cm^2) using a 1 cm^2 heat source, and the critical heat flux is about 380 W/cm^2. This is in good agreement with thermal–hydraulic network models prediction, 389 W/cm^2. The resistance is dominated by the small effective thermal conductivity of the evaporator wick and by the small conduction path through the receding meniscus within it. This resistance decreases nonlinearly with the heat flux, due to a decrease in the radius of the receding meniscus.

1. Introduction

Heat pipes are widely used in the thermal management of high-performance electronic devices, as they offer simple, reliable and passive cooling solutions. However, conventional heat pipe performance deteriorates under high heat flux with concentrated heating, and its cylindrical geometry mismatches planar interface of semiconductor devices and packages. So, thin, planar heat pipes have been examined, mostly micro-fabricated silicon or metallic wick structures capable of heat fluxes below 200 W/cm^2 [1–3]. However, many new semiconductor devices (e.g., dense array power amplifiers for microwave and radio-frequency applications, power-conditioning and switching devices for electrical propulsion applications) dissipate heat fluxes greater than 250 W/cm^2 over areas of the order of 1 cm^2. This high flux heat removal is limited by the large thermal resistance of the liquid-filled evaporator wick (small effective thermal conductivity), unless it is made very thin. Thus, the optimal design requires an evaporator wick with strategic, distributed liquid supply, effective vapor removal, and a short conduction path.

Biporous wicks [4,5] and multi-artery wick [6,7] allow for such strategic liquid supply and vapor escape through high permeable wicks and a large evaporation area. Similarly, small thermal–hydraulic resistance has been used in the modulated-wick heat pipe [8] and in pool boiling [9] to enhance the critical heat flux (CHF). These enhancements are mainly limited by the fabrication challenges in the modulation pitch and the height-to-base aspect ratio, but fabrication advances continue to be made [10].

Here, we describe fabrication and testing of a multi-artery heat pipe spreader (MAHPS), and extend the analysis [6] to include our experimental observation of a receding meniscus inside the thin evaporator wick. This meniscus recession makes for an extremely low evaporator thermal resistance (which is many times larger in the uniform artery vapor chamber [11]) in the pre-CHF regime.

2. MAHPS construction

The multi-artery heat pipe spreader (MAHPS) is a vapor chamber using posts as liquid artery, as shown in Fig. 1. Heat and liquid/vapor flow paths, from heat source to the external heat sink, along with the evaporator, arteries, and condenser, are also shown. MAHPS has a thin evaporator wick and multilayer screen condenser wicks connected by the capillary arteries. The capillary arteries deliver liquid from the condenser to the evaporator wick due to smaller meniscus radius at the evaporation sites. Water is used as working fluid for high capillary pumping pressure (surface tension) and large heat of evaporation. Phase change occurs at the liquid–vapor interface on the evaporator and condenser wicks, and the generated vapor spreads and moves toward the condenser, where it is uniformly condensed over a large area. The condensed liquid returns towards the evaporator through the capillary suction.

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Nomenclature

A	(cross-section) area (m^2)	δ	thickness (m)
D	diameter (m)	μ	viscosity (Pa-s)
d	(column) diameter (m)	ρ	density (kg/m^3)
F	constant	σ	surface tension (N/m)
g	gravitational acceleration (m^2)		
K	permeability (m^2)	*Subscripts*	
k	thermal conductivity (W/m-K)	a	apparent
L	length (m)	c	capillary, column, condenser
p	pressure (Pa)	e	evaporator
Q	heat flow rate (W)	eff	effective
q	heat flux (W/m^2)	f	fluid
R	resistance (K/W)	p	particle or pore
T	temperature (K)	lg	liquid–gas phase change, or saturation
		s	surface or solid
Greek symbols		w	wick
ϵ	porosity		

Evaporator and artery wicks are fabricated by sintered copper powders, and then surface etched-oxidized for improved wetting. Small particles $d_{p,e} = 60\ \mu m$ are used in the evaporator for a low thermal resistance, whereas large particles, $d_{p,c} = 150\ \mu m$ are used in the posts for large permeability. The evaporator wick extends beyond the heater area, up to approximately 8 cm^2 [6]. No wick is used outside this area, so all liquid delivery is through the permeable arteries to the evaporator wick. An array of 12 arteries is used, and their diameter is optimized including the fabrication constraints [6]. The condenser wick is fabricated by two layers of 145 × 145 mesh copper screen, covering an entire area (Fig. 1). In addition, another two-layered strips of the same mesh screen in 1.9 cm width are used along the central line (rather than whole layers) to minimize the total amount of screen being used without hydraulically limiting the performance. The vapor chamber is made of two copper plates (CDA-101), welded after wick fabrication to form a sealed vapor space. The heater size is $1 \times 1\ cm^2$, and the condenser size is $12 \times 7\ cm^2$. Dominant heat transfers through the evaporator wick with small heat spreading, and this leads to evaporation mostly at the base of the arteries [6].

3. Experiment

3.1. Heat flow and wick superheat measurement

MAHPS is tested in a set up shown in Fig. 2, with Joule heating provided through a copper block with embedded four cartridges capable of up to 1 kW (controlled by a Variac). Heat then flows through a 1 cm^2 rectangular pedestal extending from MAHPS. Two thermocouples in the pedestal are used to determine the heat flow rate q with the Fourier law, and the evaporator surface temperature (beneath the evaporator wick, T_s) by extrapolation. The vapor (saturation) temperature T_{lg} is measured with a thermocouple spaced in the vapor space, and assuming thermal equilibrium. The wick superheat is $T_s - T_{lg}$.

MAHPS is insulated using Kaowool™ insulation. However, there are heat losses from the heater and heater–pedestal interface, causing measurement uncertainties both in the heat flow and wick superheat. An uncertainty analysis is performed by considering the precision uncertainty of the DAQ system (assumed negligible by averaging every 10 samples), the uncertainty in the thermocouples,

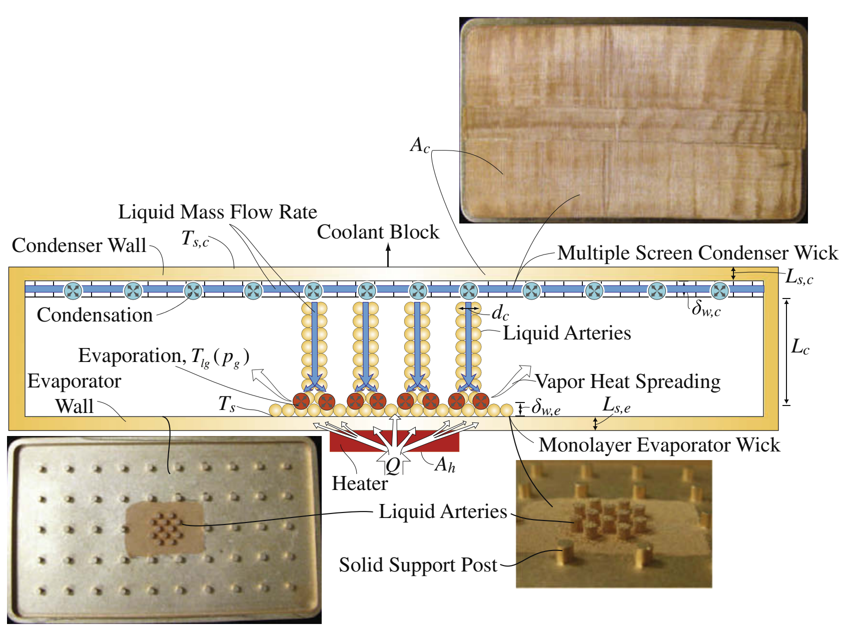

Fig. 1. A schematic of MAHPS. The thin evaporator wick, liquid arteries, multiple screen layer condenser wick (including central strips), are shown. Phase change, heat, liquid and vapor flow paths, and key dimensions are also illustrated. Images of monolayer evaporator wick, liquid artery posts, and screen condenser wick are also shown.