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Multi-artery heat-pipe spreader: Lateral liquid supply

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ABSTRACT

We design and test a low thermal/hydraulic resistance, multi-artery heat-pipe spreader vapor chamber. Liquid (water) is supplied to a highly concentrated heat-source region through a monolayer evaporator wick and a set of lateral converging arteries, fabricated from sintered, spherical copper particles. The monolayer wick allows for a minimum evaporator resistance of 0.055 K/(W/cm^2), which is related to a critical transition where the receding meniscus approaches the particle neck. Similar behavior is also observed in a monolayer-wick evaporator, partially submerged in liquid bath. After this minimum, local dryout occurs and increases the resistance. However, a continuous liquid supply through the lateral arteries does not allow for total dryout in the test limit of 580 W/cm^2. These thermal/hydraulic behaviors are predicted using the local thermal equilibrium and nonequilibrium models.

1. Introduction

Limiting temperature of highly concentrated Joule-heating devices requires enhanced thermal management solutions. A common approach is to spread heat over a large area towards a sequential heat sink [1,2]. A vapor chamber acts as an idealized heat spreader with nearly isothermal and uniform heat spreading on evaporator wicks using liquid–vapor phase change. The dominant sources of its thermal resistance and heat removal limit are low thermal conductivity and large hydraulic resistance of the evaporator wick. Therefore, an optimal design of the evaporator wick is critical to the desired performance, e.g., evaporator resistance below 0.1 K/(W/cm^2) with critical heat flux (CHF) on the order of 100 W/cm^2.

A variety of approaches have been employed using uniform thickness wicks, e.g., screen [3], sintered metal powders [1,2], and microfabricated posts [4]. Since thin uniform wicks can only deliver a limited liquid supply due to large hydraulic resistance, their CHF is rather low. On the other hand, thick wicks create a rather large evaporator resistance because of a long conduction path. To reduce both resistances, nonuniform thickness wicks, i.e., a thin uniform wick incorporated with thick liquid arteries, have been designed.

This decreases a thermal resistance through the thin wick, while it enhances CHF through the thick wick. Columnar, multiple arteries (posts) design, providing well-distributed liquid supply to the thin monolayer, has enhanced the vapor chamber performance, e.g., q_{CHF} = 380 W/cm^2 and $A_h R_{k,e}$ = 0.05 K/(W/cm^2) [5]. However, due to the limited spread of the liquid around the posts, a sudden, total dryout occurs. To increase the dryout limit, new artery design is needed. Also, the thin evaporator wick controls the minimum thermal resistance assisted by the receding meniscus inside it [4–6]. However, the thermal/hydraulic features associated with the receding meniscus have not been carefully analyzed.

Here, to increase the dryout limit, a lateral converging multi-artery heat pipe spreader (LC-MAHPS) with a monolayer evaporator wick is designed, fabricated and tested. We also analyze its thermal/hydraulic behavior, explaining the observed minimum evaporator resistance with thermal equilibrium and nonequilibrium models which are applied to heat flow adjacent to the three-phase contact line.

2. Fabrications and experiments

2.1. LC-MAHPS

The lateral converging multi-artery wick is incorporated into a copper/water vapor chamber for experimental characterization.

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Nomenclature

A	area (m^2)
d	diameter (m)
K	permeability (m^2)
Δh_{lg}	enthalpy of vaporization (J/kg)
k	thermal conductivity (W/m-K)
L	length (m)
q	heat flux (W/m^2)
r	radius (m)
T	temperature (K)
<>	volume average

Greek symbols

ε	porosity
δ	thickness (m)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscript

a	artery
CHF	critical heat flux
c	capillary
e	evaporator
f	fluid
h	heater
k	conduction
l	liquid
LD	local dryout
lg	liquid–gas phase change
m	monolayer
p	post or particle
s	solid
w	wick

The vapor chamber had the following dimensions: 4.8 mm × 7.6 cm × 12.7 cm with a 1 cm^2 heat input region as shown in Figs. 1(a) and (b). A sintered monolayer of spherical copper powder particles, approximately 60 μm in diameter, is used to feed liquid to release highly concentrated heat in the evaporator, while providing low thermal resistance. Since its liquid permeation is low due to the low permeability, a secondary feed structure, i.e., liquid artery, is required to prevent local dryout. These converging arteries extend over the top of the monolayer to minimize hydraulic pressure drop, while maximizing the available evaporation area near the side surface of the arteries. The liquid arteries are sintered in-situ from spherical copper powders, approximately 100 μm in diameter. A thick, uniform wick is used outside (laterally) the evaporation region to deliver liquid to the arteries. Vapor space ensures that the vapor pressure drop is negligible.

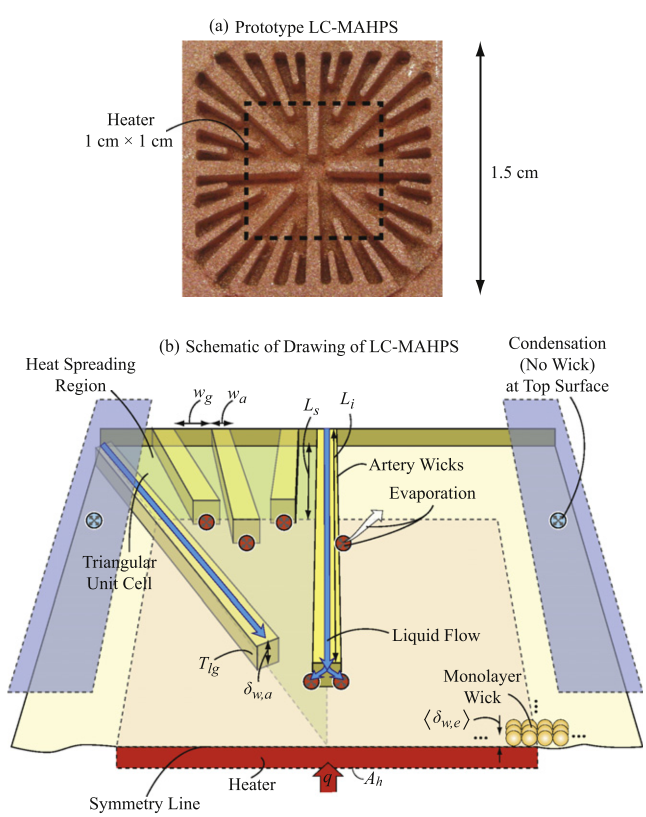

Fig. 1. (a) An image of a prototype LC-MAHPS. (b) A schematic of LC-MAHPS showing the thin evaporator monolayer wick and a set of lateral-converging liquid arteries. Phase change, heat, liquid and vapor flow paths, and key dimensions are illustrated. Condensation (no wick) at the side edges of top surface is also shown.

This liquid-artery pitch design has been successful in enhancing critical heat flux by controlling the hydrodynamics stability of the liquid–vapor interface in pool boiling (liquid submerged wick) [7–9], and by creating distinct liquid supply (artery) and evaporator (monolayer) wicks [5,10,11]. Here we propose lateral liquid wick arteries to increase a dryout limit, while maintaining low thermal resistance through the monolayer wick.

The thermal/hydraulic characteristics of the vapor chamber are tested in a gravity neutral orientation as shown in Fig. 2. Condensers are placed on both edges of the top surface without wick. No condenser wick is needed as condensate pools at the bottom of the vapor chamber and then returns to the evaporator via the LC feed structure (thick uniform wick). For a general description of the test apparatus and testing methods are given in our previous work [5]. New to this test apparatus is the use of two separate liquid cooled heat sinks placed on the edges of the vapor chamber instead of one single heat sink spanning the whole surface opposite the evaporator. This approach was chosen to represent cold rail applications but the impact on the evaporator resistance has been shown insignificant. The vapor temperature is set to T = 90 to 95 °C during the test at the atmospheric pressure, while controlling the input heat flux by q = ±25 to 50 W/cm^2. The thermal/hydraulic characteristics of the vapor chamber are also sensitive to the liquid charge. Decreasing the charge reduces the thermal resistance, due to the smaller, effective liquid-filled wick thickness. However, it also results in a lower critical heat flux. Here, we use a 3 g liquid fill for a fully-flooded evaporator and artery wicks.

2.2. Monolayer evaporator wick: Meniscus recess

The thermal/hydraulic characteristics of the monolayer wick are also tested partially submerged in a liquid bath. The wick is comprised of Cu spheres, having a nominal diameter of approximately 60 μm with a standard deviation of ±4.5 μm, and average distance among the particles is 63 μm, as measured by an SEM image analysis as shown in Fig. 3(a). The spheres are sintered onto a 3 cm × 3 cm × 500 μm Cu substrate for 1 h at 960 °C. A 5 mm × 5 mm Au thin-film heater on a 100 μm Si wafer is soldered onto the back of the sample using a 100 μm layer of solder (thermal conductivity $k_s \sim 64$ W/m-K). To measure the heater tempera-