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Multi-artery heat-pipe spreader: monolayer-wick receding meniscus transitions and optimal performance

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ABSTRACT

For high heat flux and low thermal resistance, the multiple-artery heat-pipe spreader uses distributed high-permeability arteries (posts) for liquid supply and high-capillary pressure monolayer wick for liquid spreading and evaporation. Experiments indicate the receding meniscus transitions in monolayer play a role in sudden drop in thermal resistance prior to dryout. Using monolayer SEM images and the minimum surface energy principles, the meniscus dynamics up to dryout is analyzed, and the meniscus location, capillary pressure, effective thermal conductivity, and permeability are also predicted for heterogeneous, periodic sintered copper-particle (including bimodal particle size) unit cells. The liquid thickness is nonuniform within the heterogeneous unit cell, and with increase in the wick superheat local dryout occurs (meniscus snaps) in the loose-packed region influencing the wet-wick properties and the occurrence of the minimum thermal resistance. The monolayer wick continues to function under local dryout (away from post) until a receding dry front is formed followed by complete dryout. These predictions are in good agreement with experiments. The optimal wick thermal-hydraulic performance, i.e., dimensionless ratio of heat flux to thermal resistance (wick figure of merit Z_m) is sought through analysis. The uniform, sintered, close-packed 30–50 μm particles give the highest Z_m over a range of superheat in the wet regime, and 30 μm particles give a record low resistance near 2.5 μK/(W/m^2)

1. Introduction

Improvements in passive and active liquid supply in thermal management aims at increase in heat flux load and decrease thermal resistance. Specifically, capillary-driven liquid flow has been widely used to supply liquid (similar to heat pipe) without use of electric power. To enhance the heat transfer limit (critical heat flux), it is essential to decrease the liquid pressure loss, and various porous structures such as micropost arrays [1–3], columns (posts) [4], converging lateral arteries [5], and biporous wicks [6,7] have been used.

Multiple-artery heat-pipe spreader (MAHPS) is a heat pipe with large and spread vapor space and generally a smaller heated (evaporation) area compared to the condenser section with distributed liquid arteries [8]. In the MAHPS, Fig. 1, capillary-driven liquid flow begins in the condenser, through screen layer, then posts (liquid artery), and finally to the monolayer wicks. In screen-post-monolayer unit cell, the capillary pressure has a maximum value at the monolayer cell boundary, where the liquid thickness $\delta_{l,m}$ is minimum. While spreading over the monolayer wick, the liquid evaporates at the liquid surface (meniscus). For heat removal, the cooling water flows in the opposite side of condenser.

The thermal-hydraulics of MAHPS has been predicted by Min et al. [8] and Hwang et al. [4,5], using network model with its geometrical parameters. Min et al. [8] showed that overall thermal resistance in MAHPS increases with an increase in artery (post) diameter. They also compared performance with uniform wick and predicted the improved performance by MAHPS. In experiments by [4,5] using the screen-post and lateral artery for liquid supply, respectively, and monolayer wicks for capillarity, the slope of thermal resistance-superheat is positive as generally expected. However, for $q > 250$ W/cm^2, the resistance increases rapidly up to 320 W/cm^2 with decrease in superheat and for $q > 320$ W/cm^2, the thermal resistance recovers the general trend. This nonlinear resistance has been reported by [2,9–12] using copper powder wicks and by [6,9,11,13–16] using biporous wicks and media, but not observed in other wicks [3,17] with finger-like liquid supply [5]. This transition has been related to the onset of nucleate boiling [9,10,14,15], or meniscus transitions in heterogeneous monolayer wick [4,12], however, quantitative explanation has not been provided yet.

In this study, we explain this transition (nonlinear pattern) through the heterogeneous structure of the monolayer, as revealed

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Nomenclature

A	area (m^2)
a	surface area to unit volume ratio (m^{-1})
C_J	constant for Leverett *J*-function
c_p	heat capacity (J/kg-K)
D, d	diameter (m)
f	friction factor
g	gravitational acceleration (m/s^2)
H	height (m)
Δh_{lg}	heat of evaporation (kJ/kg)
J	Leverett *J*-function
K	permeability (m^2)
k	thermal conductivity (W/m-K)
L	length, pitch, thickness (m)
M	mass (kg)
m	molecular weight (g/mol)
N_p	packing number
n_{sh}	number density of shute wire (wires/m)
n_{wa}	number density of warp wire (wires/m)
p	pressure (Pa)
Q	heat flow rate (W)
q	heat flux (W/m^2)
R	thermal resistance (K/W)
R_g	universal gas constant (J/mol-K)
Re	Reynolds number
r	radial location (m)
S	mean crimping factor
s	substrate, saturation in lg
T	temperature (K)
w	width (m)
Z_m	dimensionless figure of merit
z	Melros function
$\langle\rangle$	average

Greek symbols

α	tortuosity factor
Δ	difference, drop
δ_l	liquid thickness (m)
ϵ	porosity
μ	viscosity (Pa-s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ_c	contact angle (°)

Subscripts

ave	average packing
b	bulk
CHF	critical heat flux
Cu	copper
c	capillary, condenser, cooling, cross
cl	close-packed
c-v	capillary-viscous
e	effective, evaporator
g	gas
h	heated
i	index of node
k	kinetic limit
l	liquid
lg	liquid-gas phase change
lo	loose-packed
m	monolayer wicks
multi	multi-node
N	total number of nodes
o	baseline
p	post (artery)
po	pore
s	screen mesh, surface
sh	shute wire
t	thermal
u	fluid flow
up	upper layer
wa	warp wire
Z	Zuber
$\updownarrow$	across
$\leftrightarrow$	along

from SEM images, and define various regimes associated with it. We use minimum surface energy principle to track the receding monolayer meniscus and find the effective properties by solving numerically the liquid flow and heat transfer in monolayer unit cell. We then solve governing equations of the screen-post-monolayer unit cell using single- and multi-node network models. With the heterogeneous unit cell, the network models predict degrade of performance compared to the homogeneous unit cell. To improve the heat transfer limit caused by the spatial heterogeneity, we also seek and find the homogenous monolayer wick structure for optimal heat transfer performance: highest figure of merit and lowest thermal resistance.

2. Methods

2.1. Direct simulations of monolayer unit cell

The monolayer wick unit cell is defined, based on the SEM micrographs (Tescan MIRA3 FEG SEM) (Fig. 2(a,b)). There are sporadic multi-layer coatings and particle diameter variations as well as close- to loose-packed regions (Fig. 2(c)). The average porosity is estimated using image-processing software (Image J) and is $\langle\epsilon_m\rangle = 0.58$ with average diameter $\langle d_m\rangle = 50\ \mu m$ (Fig. 2(b)). As shown in Fig. 2(a,b), the multi-layered structure with particle size variation and sintering consolidation represents monolayer heterogeneous unit cell (varying local packing and porosity) [18]. The local porosity ranges from less than 0.5 to over 0.8 (Figs. 2(a, b)), and are considered to determine the heterogeneous unit cell in close- to loose-packed regions (Fig. 2(c)). The selection represents the observations on several SEM monographs and consequently explains the nonlinear thermal resistance in the experiment. The copper particles are slightly sintered and consolidated with each other since they have original spherical shape without shape distortion (Fig. 2(b, top)). However, particles are sintered more with the substrate and have truncated portion in the lower hemisphere (Fig. 2(b, bottom)). For improved water wettability, thermal oxidation is used and results in contact angle $\theta_c = 43 \pm 6^\circ$ [4,5]. The heterogeneous unit cell is shown in Fig. 2(c) and consists of square array of particles with a diameter $d_{m,o}$ in baseline with a portion having smaller particle with a diameter $d_{m,up}$ on top. The permeability is anisotropic and has the x and y-directional flows (Fig. 2(c)). Sintering consolidation is modeled with connecting cylinders of a diameter of $0.2d_{m,o}$, and the lower hemisphere of particles are truncated as sintered to the substrate with a depth of $0.1d_{m,o}$. The reduced, square periodic unit cell in average packing region has $l_x = l_y, = 1.49d_{m,o}$ with $\epsilon_{ave} = 0.58$