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The decoupling and synergy strategy to construct multiscales from nano to millimeter for heat pipe

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ABSTRACT

We decouple a heat pipe into capillary pressure, flow resistance, condensation heat transfer, and assign specific length scale to adapt each function. We verify the synergy of various length scales to activate various functions. The strategy guides multiscale design to realize an enhancement of capillary pressure, a well management of flow resistance and an ultra-thin liquid thickness on condenser surface. The porous wick consists of a particle sub-layer and 3D mastoid process array. The tips of mastoid process directly contact the condenser wall. Four vapor chambers are formed by sintering $d_m = 73.8$ μm without oxidation (#1), with oxidation (#2), $d_m = 556$ nm without oxidation (#3) and with oxidation (#4), respectively. Liquid suction and heat transfer experiments were performed. Four types of evaporator temperatures versus inclination angles were observed. Small difference is found between bottom and top heating modes. The multiscale wick influences the vapor–liquid phase distribution to cause the difference between side and other heating modes. The $d_m = 73.8$ μm particle sintering with nano-roughness successfully balance various conflicts among capillary pressure, vapor–liquid interface area, flow resistance and liquid removal from the condenser surface. Nano-roughness increases the vapor–liquid interface area to have 3–4 times of evaporation heat transfer coefficients compared with smooth particle surface. Nano-roughness increases the wettability to capture liquid from condenser, having ~18 times of condensation heat transfer coefficients to those without nano-roughness. The $d_m = 556$ nm particle sintering and nano-roughness are the poor match for heat pipes. This paper gives a clue to construct multiscale wicks for heat pipes and ensures better performance at varied gravity such as micro-gravity environment.

1. Introduction

Heat pipes have been widely used from the invention on 1950s. Various miniature heat pipes, such as micro heat pipes [1,2], loop heat pipes [3,4], pulsating heat pipes [5,6] and vapor chambers [7,8], have received great attention in recent 20 years. Besides, the fast developing space technologies need high performance heat pipes for electronics cooling, or for other applications, under varied gravity force levels [9]. A perfect heat pipe shall have the following characteristics: (1) heat pipe shall start up without apparent temperature excursion to avoid the start up burn-out; (2) heat pipe shall maintain high heat transfer coefficients during normal operation; (3) the operation of heat pipe shall be stable; (3) heat pipe shall have high critical heat fluxes to avoid dry-out.

Heat pipes are phase change devices with capillary force due to the wall wicking. However, gravity force still plays important role. Most of heat pipes are working as thermosiphon, that is, the condenser part is above the evaporator part. Heat pipes have poorer performance at horizontal position [10]. Under earth gravity, it is difficult to maintain good performance when the evaporator part is above the condenser part [11]. This is because liquid shall be recycled to evaporator by capillary force against gravity. The space technology needs heat pipes to be working under varied gravities. For example, on the moon, the gravity is only about 1/6 of that on the earth [12]. Heat pipes on board a space ship shall work under micro or zero gravities [13].

Heat pipe operation at varied gravities is dependent on vapor–liquid phase distribution inside. The widely used porous media with a single length scale is difficult to regulate the phase distribution under varied gravities. There are many conflicts if one relies on a single length scale for the wick structure. These conflicts are summarized as follows.

1.1. Conflict between capillary pressure and viscous force

A key challenge for implementing thin film evaporation is the ability to efficiently deliver liquid to the heater surface. Recent

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Nomenclature

A	surface area, m^2
A_{heater}	snake heater area, m^2
a	nanowires diameter, m
Bo	Bond number
b	minimum distance between two neighboring nanowires, m
D	vapor chamber diameter, m
d	particle diameter, m
d_1	smaller pore diameter, m
d_2	larger pore diameter, m
dE	surface energy difference between state A and state B, W
dK	work needed for the bubble traveling from state A to state B, W
dS_1	bubble traveling distance in smaller pore, m
dS_2	bubble traveling distance in larger pore, m
d_m	mean particle diameter, m
d_p	single length scale, m
g	gravity, m/s^2
H	nanowires height, m
h	heat transfer coefficient, W/m^2 K
L	characteristic length, m
l	capillary length, m
N	particle number
P_1	pressures in smaller pore, Pa
P_2	pressures in larger pore, Pa
Q	heating power, W
q	heat flux, W/m^2
R	thermal resistance, K/W
r	roughness factor
r_b	bottom part radius of vapor chamber, m
r_t	top part radius of vapor chamber, m
T	temperature, °C
T_θ	evaporator center temperature at θ

Greek symbols

α	contact angle between liquid and solid surface, °
α_w	contact angle between liquid and microstructure, °
β	non-dimensional parameters, $\beta = b/a$
Δ	distance away from the heater, m
δ	liquid layer thickness, m
δ_s	liquid layer thickness within the porous stacks, m
ε	deviation degree factor
θ	inclination angles
ρ	density, kg/m^3
σ	surface tension force, N/m
ξ	non-dimensional parameters, $\xi = H/a$

Subscript

c	condenser
c, c	condenser center
ave	average
e	evaporator
e, c	evaporator center
$e, 1 \sim e, 8$	location on evaporator wall
$c, 1 \sim c, 8$	location on condenser wall
g	gas
i	ith particle
l	liquid
$loss$	heat loss
s	solid
w	wall
v	vapor

efforts have investigated super-hydrophilic micro/nano structured surfaces, such as micro-pillar arrays, sintered copper powders, and carbon nanotubes, to transport liquid *via* capillarity [14–16]. However, capillary pressure and viscous resistance are coupled with each other. By reducing the characteristic structure size, the capillary pressure increases, but liquid transport is inhibited due to the significant viscous resistance associated with the small spacing.

1.2. Conflict between capillary pressure and vapor venting

Considering boiling/evaporation in a wick structure with a single length scale d_p, capillary pressure is increased if d_p decreases. Meanwhile, the volume will be expanded by ~100–1000 times if liquid is changed to vapor. The smaller pore size definitely blocks the vapor venting and hinders the liquid toward the heater surface to induce critical heat flux (CHF) [17,18]. Alternatively, larger pores are helpful for vapor venting but are not useful to generate sufficient capillary pressure for liquid supply [19,20]. The two and three dimensional (2D/3D) modulated porous wicks [21,22], and the biporous wicks [23,24], are able to overcome the conflict between capillary pressure and vapor release. Ji et al. [25] found that the 3D modulated porous wicks significantly increase critical heat fluxes, which are 3.7 times of that on plain smooth surface. Semenic and Catton [26] used a wick consisting of large clusters of small copper particles and suggested that small pores serve to transport liquid to the boiling sections by capillary suction, while large pores between the clusters facilitate vapor transport away from the wick thus enhancing the overall heat transfer performance. Ćoso et al. [27] showed both enhancements of boiling/evaporation heat transfer coefficients and critical heat fluxes by using biporous wick with the silicon fabrication technique.

1.3. Balance between heat transfer coefficients and critical heat fluxes

For an efficient boiling/evaporation surface, one shall balance heat transfer coefficients and critical heat fluxes. Recently, micro/-nano structured surfaces have been investigated widely [28,29]. The textured surfaces strongly influence the surface wettability. A hydrophobic surface maintains high evaporation heat transfer coefficients due to thin liquid film on the surface, but the operation range of heat fluxes is narrowed due to weak ability to suck liquid toward the heater surface [30]. On the contrary, a hydrophilic surface expands the heat flux operation range but heat transfer coefficients are not large. The problem is how to construct a surface that not only maintains high heat transfer coefficients but also has high critical heat fluxes?

1.4. Coupling of the evaporator and condenser

The vapor–liquid two-phases are recycled between evaporator and condenser. Heat pipe performance is relied on the coupling between evaporator and condenser. For a heat spreader, liquids on the condenser surface should be removed successfully to maintain better condenser performance. The evaporator shall receive liquid from the condenser surface. For a conventional vapor chamber, the condensed liquid travels a distance of D and returns to the evaporator, where D is the vapor chamber diameter. This increases the liquid film thickness to deteriorate the condenser performance