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Micromembrane-enhanced capillary evaporation

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ABSTRACT

Micromembrane-enhanced evaporating surfaces were developed to enhance capillary evaporation heat transfer coefficient (*HTC*) and critical heat flux (*CHF*). Micromembranes made of sintered single-layer copper mesh screen were diffusion bonded on microchannels to effectively promote capillary pressure and reduce flow resistance. Compared with mono-porous evaporating surfaces such as microchannels and copper woven mesh laminates in the same thickness under the similar working conditions, *CHF* was substantially increased by 83% and 198%, respectively, because of the separation of the capillary pressure generation and fluid transport process that was enabled by the micromembrane. The major features such as "*M*"-shaped capillary evaporation heat transfer curves and the associated heat transfer regions were identified. Oscillating flows induced by the bubble growth and collapse as well as the capillary flows induced by the receding menisci were observed and believed to play imperative roles in enhancing the heat transfer by inducing advections and improving evaporation and nucleate boiling.

1. Introduction

Capillary evaporation [1] is one of the most efficient heat transfer modes and has been widely used in heat exchangers [2] and heat pipes [3–5]. Evaporators with high heat transfer coefficient (*HTC*) and critical heat flux (*CHF*) are highly desirable for compact heat exchangers for high heat flux applications [6,7]. Most of porous coatings used in enhancing capillary evaporation are usually mono-porous structures [8]. For example, sintered particles and powders were developed to substantially enhance thin film evaporation *HTC* [8,9]. The effects of porosity, wick thickness and other factors on the optimal design of the wicking structures were also examined [8,9]. Copper woven mesh laminates [10–13] were extensively studied to enhance the capillary evaporation *HTC* due to the augmented surface areas and increased capillary forces. However, the flow resistances in these microscale mono-porous structures remain high, resulting in low *CHF* due to the liquid supply crisis. Micro-grooves [14,15] or channels [16] were superior for liquid supply because of the attributed low flow resistance, but the capillary forces induced by the disjoining pressure differences in grooves [15] were still too low to reach high *CHF*. This brief review shows that both the microscale mono-porous structures (such as sintered meshes or particles/powders) and micro-grooves or channels cannot meet the needs of high heat flux applications. To solve this dilemma, various types of bi-porous surfaces were proposed and developed [5,17–21]. Semenic et al. [18,20] found that biporous surfaces of sintered powders performed better than the mono-porous copper wicks because the working fluid can be supplied to hot spots through micropores inside the clusters even though the voids were filled with vapor. Cao et al. [22] reported that when a mono-dispersed wick was replaced by a bi-dispersed wick with the same small pore diameter, both *HTC* and *CHF* were increased significantly. Cai et al. [6] studied the heat transfer performance on the carbon nanotube (*CNT*) based bi-porous structures, which consisted of *CNT* array separated by microchannels. The nanoscale pores in the *CNT* bi-porous structure provided ultrahigh capillary pressure and augmented surface areas, which significantly reduced the menisci radii and increased thin-film evaporation area and evaporation efficiency. Ćoso et al. [23] examined a type of bi-porous media consisting of microscale pin fins periodically separated by microchannels to simultaneously increase the heat dissipation capacity as well as the *HTC* of the evaporator wick. Some of the bi-porous wicks have also been integrated in heat pipes [19,24–26] to decrease the thermal resistance and increase working heat fluxes. Heat pipe performance was found to be greatly enhanced by applying modulated wick because of enhanced axial capillary liquid flows and additional evaporation surface area resulting from the cross-sectional area [5]. In these reported bi-porous structures, the main fluid passages were still through the micro or nanoscale mono-porous structures (such as microscale powders or *CNTs*). As a result, the overall liquid flow resistances still remain high.

On the other hand, the oscillating flow significantly increases *HTC* and *CHF* in closed mini/micro-channels as can be found in oscillating heat pipes [16,27]. However, the oscillating capillary

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Nomenclature

A	area of cross section, m^2
C_f	compress factor
d	diameter of copper mesh, m
D_h	hydrodynamic diameter, m
D_p	equivalent spherical diameter of porous media, m
f	friction factor
h	evaporation heat transfer coefficient, $W/(m^2\,k)$
k	thermal conductivity of copper, W/(m k)
L	the length along the macroscopic, m
L_0	pressure gradient in porous media microchannel length, m
M	mesh number
R_e	Reynolds number
S_v	surface area per unit volume of solid phase, m^2
T_5	temperature of the thermocouple 5, °C
q''	input heat flux, W/cm^2
Q	flow rate, m^3/s
v_s	superficial velocity, m/s
Δp	pressure drop, kp_a
ΔT	temperature difference between two thermocouples, C
Δx	distance between two thermocouples, m
$\Delta x'$	distance from T_{C5} to the evaporating surface, m

Greek symbols

β,γ	constant number
μ	fluid viscosity, kg/(s m)
ε	porosity
ρ	fluid density, kg/m^3

Subscripts

w	wall
sat	saturated

evaporation in unconfined or open microchannels was not reported.

The objective of this study is to develop a new type of micromembrane-enhanced evaporating surfaces that are capable of both generating high capillary pressure and managing flow resistances. The effects on capillary evaporation were systematically examined. These effects include the separation of liquid supply and capillarity generation as well as the induced oscillating flows in unconfined micromembrane-enhanced evaporating surfaces.

2. Design of micromembrane-enhanced capillary evaporating surfaces

During the capillary evaporation, the counter interactions of flow resistance and capillary force determine the overall liquid supply and thus, the *CHF*. Fine copper woven meshes with microscale pores can generate high capillary pressure, but the associated flow resistance through the in-plane direction was significantly high. Microgrooves [14,15] or channels [16] were superior for liquid supply because of the low flow resistance, but with limited capillarity [15]. The combination of the advantages of single layer meshes and microchannels could lead to a new type of capillary evaporating surfaces with high capillary pressure and low flow resistance, which would consequently result in much higher *CHF* than each individual (Fig. 1(a)). The membrane with microscale pores was developed to generate high capillary pressure and augment heat transfer area. Smooth microchannels were designed as the primary fluid passages to reduce flow resistance. Moreover, the micromembranes would greatly enhance thin film evaporation because of the augmented area and high resistance to surface flooding using capillarity.

A theoretical model was developed to verify the design. Due to the unavailability of two-phase models for single layer mesh screens, the single-phase flow resistances through microchannels and single layer mesh (in-plane direction) were estimated. A modified Ergun equation for the porous media [28] was employed in this study to estimate the flow resistance through sintered woven meshes

$$\frac{\Delta p}{L} = \beta\frac{\mu(1-\varepsilon)^2 v_s}{D_p^2\varepsilon^3} + \gamma\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho v_s^2}{D_p} \quad (1)$$

where, Δp is pressure drop; L is the length along the macroscopic pressure gradient in porous media; v_s is the average velocity estimated from $v_s = Q/A$ (Q is flow rate through a cross-sectional area A); μ is the absolute viscosity of fluids; ε is the volumetric porosity; D_p is the equivalent spherical diameter of porous media; and ρ is the fluid density. Here, the β and γ vary with different porous media [13] and were modified for the one layer woven screen meshes as $\beta = 15940$ and $\gamma = 12$ according to this experimental study using the method in Ref. [11]. The equivalent diameter of particles for a mesh is defined as, $D_p = 6/S_v$ [13], where, S_v is defined as the surface

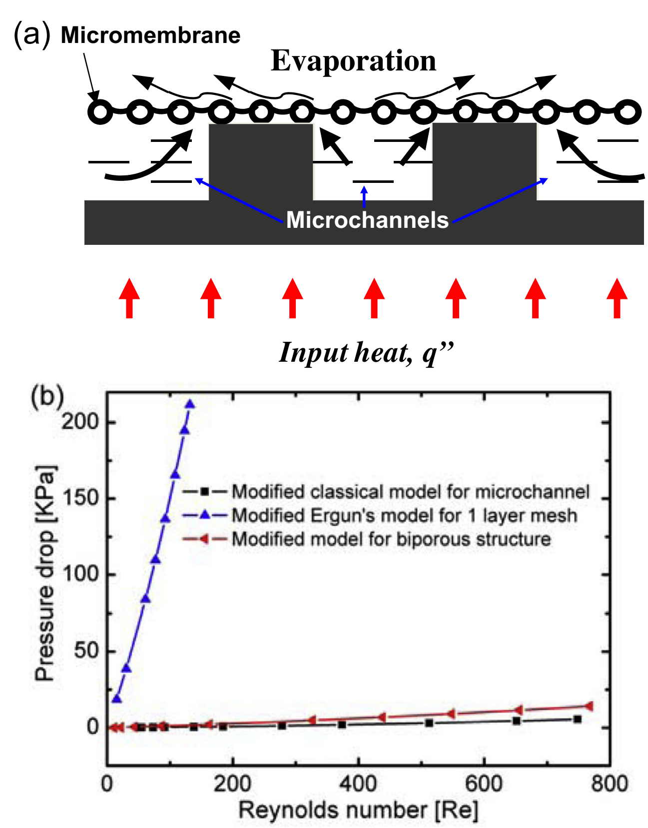

Fig. 1. (a) Design of micromembrane-enhanced evaporating surfaces. (b) Comparisons of flow resistances between meshes, microchannels and the micromembrane-enhanced evaporating surfaces.