



Geometrical effects of wick structures on the maximum phase change capability



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ABSTRACT

Liquid-to-vapor phase change on porous wick structures has been proven efficient and capable of high density heat removal. This superior thermal performance is attributed to thin film evaporation on liquid–vapor interfaces, capillary enhanced liquid return mechanism, as well as rapid vapor ventilation. In this complicated physical process, wick geometrical parameters, such as wick thickness, particle diameter/gap size and heating area dimension, of the wick structures play critical roles in determining the maximum phase change capability. This article presents an analytical model to extract the wick geometrical effects on heat and mass transport limits, based on mono porous wick structures composed of cylindrical pillars. The model considers two extreme cases: (a) thin wick structure with large heating area; and, (b) thick wick structure with small heating area. Two dimensionless geometrical numbers are derived based on liquid and vapor phase flow resistances. For a thin wick structure with large heating area, wherein the liquid phase is dominant in flow resistance, the maximum heat flux is proportional to liquid phase geometrical number, defined as a product of the pillar diameter and the wick thickness divided by square of the heating area dimension. In contrast, phase change capability of a thick wick structure with small heating area is attributed to the vapor phase geometrical number, written as the ratio of the pillar diameter over the wick thickness. The analytical model is validated through experimental results by characterizing phase change performance of the silicon mono wick structures. A ratio between the heating area width and the wick thickness is presented to justify the broad applicability of the analytical model. The two analytic cases of thin wick structure with large heating area and thick wick structure with small heating area correspond to the ratios being >1.0 and <0.1 , respectively.

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1. Introduction

Liquid-to-vapor phase change heat transfer, in the form of evaporation and nucleate boiling, has been a topic of significant fundamental and applied research for several decades. Because of high latent heat of vaporization and high transportability of liquid and vapor flows, phase change has been implemented in many advanced heat transfer systems, such as heat pipes [1].

In a traditional heat pipe system, the wick cavities are saturated with the operating fluid. Phase change relies on evaporation on liquid–vapor interface menisci of the porous structure, as illustrated in Fig. 1(a). Compared with nucleate boiling, the interface phase change has a significantly high heat transfer coefficient, due to effective evaporation on the thin liquid film regions of the meniscus and a passive liquid supply mechanism [2,3]. However, the maximum heat fluxes of interface evaporation, one of the most

important measures of phase change performance for achieving high density heat removal, are reported to be only in the range of $20\text{--}80\text{ W/cm}^2$ on various wick structures [4,5], much less than nucleate boiling at $\sim 150\text{ W/cm}^2$ [6]. Beyond this heat flux limit, the increase of temperature differences across the wick structure triggers the onset of nucleate boiling [7]. Vapor generated from boiling may potentially be trapped inside the wick structure, forming a so-called vapor blanket that blocks the return of liquid to the heating area, eventually causing a dryout. Thus, nucleate boiling is avoided in a typical heat pipe design, thereby sacrificing its potential contribution to phase change [8].

To meet the ever increasing demand of high heat flux heat transfer technologies, a significant amount of research has focused on advanced wick structures. Nucleate boiling is strategically implemented in these wick structures as a part of phase change mechanism to enhance the phase change capabilities. Most of the initial research on the advanced wick structures focused on bi-porous wick structures, starting with a demonstration of high heat flux phase change [9], followed by a number of publications

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Nomenclature

d	particle diameter, m	σ	surface tension, N/m
f	dynamic function of vapor phase	ρ	density, kg/m ³
g	dynamic function of liquid phase	μ	dynamic viscosity, N s/m ²
h	heat transfer coefficient, W/m ² K	ϕ	porosity
h_{fg}	liquid latent heat, kJ/kg	φ	wick geometrical number of liquid phase
K	permeability, m ²	τ	τ wick geometrical number of vapor phase
k	thermal conductivity, W/m K	Δ	difference
L	wick dimension along flow direction, m		
l	width of heated wick area, m		
Me	dimensionless Merit number		
P	pressure, Pa	Subscripts	
\dot{q}	heat flux, W/m ²	<i>cap</i>	the maximum capillary
T	temperature, °C	<i>CK</i>	dimensionless Kozeny factor
t	thickness of wick structure, m	<i>eff</i>	effective
v	velocity, m/s	<i>h</i>	hydraulic
		<i>l</i>	liquid
		<i>max</i>	maximum
		<i>sat</i>	saturation
		<i>sup</i>	superheat
		<i>v</i>	vapor
		<i>wall</i>	substrate wall
Greek symbols			
α	liquid volume fraction		
β	dimensional ratio between heating area width and wick thickness		

reporting its systematic design, fabrication, experiments and modeling [10–12]. The novel bi-porous wick structures contain micro pores in two different scales, or called large and small pores. The large pores provide low viscous flow and vapor ventilation paths when nucleate boiling occurs, while the small pores enhance thin film evaporation and provide high capillarity to return the operating fluid. The unique configuration of the bi-wick structure allows nucleate boiling to occur in the large-scale pores, and rapidly vent the vapor to avoid the local dryout. As a result, the maximum heat fluxes on the bi-porous wick structure can be a few times higher than nucleate boiling [13]. In addition to the bi-porous wick structures, recent studies have shown that mono porous wick structures are also capable of high heat flux phase change. On sintered copper wick structures, heat fluxes over 500 W/cm² were demonstrated on a 25 mm² heating area [14]. The mono wick structures designed for high heat flux phase change adopt large particles/pores so that the transverse liquid flow (in the wick plane) and the axial vapor flow (perpendicular to the wick plane) can co-exist within the same wick cavities, as illustrated in Fig. 1(b). The new flow configuration alters the traditional heat and mass transport mechanism

from two different aspects: (a) At high heat flux, liquid phase recedes into the wick cavity while vapor phase advances into wick structures, creating more surface area for interfacial evaporation. The heat conduction distance from the hot substrate to the vapor–liquid interface is therefore reduced, which significantly increases the heat transfer coefficient. (b) Vapor bubbles or jets occupying the wick cavities reduce the passage volume used for liquid transport. The presence of vapor within the wick structure reduces wick permeability and increases liquid flow resistance.

In physics, maximum phase change capability essentially reflects a mass transport limit or the capability of liquid delivery to wet the heated porous structure. The maximum heat flux on the wick structures is strongly dependent on their geometric parameters, such as wick porosity, thickness, particle diameter and size of the heated wick area. For example, in previous studies, dimension variations of the heated wick area resulted in an order magnitude change in the maximum heat flux [15,16]. In another case, while reducing the wick particle size to nanoscale, the dense carbon nanotube mono wick dramatically lowers structural permeability by two orders of magnitude and suppresses growth of nucleate bubbles. As a result, both vapor ventilation and liquid supply are blocked, leading to the early occurrence of dryout [17].

In this article we establish an analytical model to link the wick geometrical effects to the maximum phase change capability. Mono porous wick structures with isotropic in-plane wick properties are used to develop the analytical model and its experimental validation. On these bases, new dimensionless geometrical numbers are presented, which provide a clear view of the heat and mass transfer physics in the wick structure.

2. Heat and mass transfer analysis

To extract the geometrical contributions from the complicated physics of phase change, we developed an analytical model, based on heat and mass transfer equilibria in the wick structure. As shown in Fig. 2, a heated mono wick structure, composed of perpendicular cylindrical pillars, has a length of l and thickness of t . In an ideal condition of mass transport, liquid is fed into the wick structure from one side. Vapor vents in a perpendicular direction to ambient at the constant pressure. To support the maximum phase change heat flux capability, flow pressure drops between the

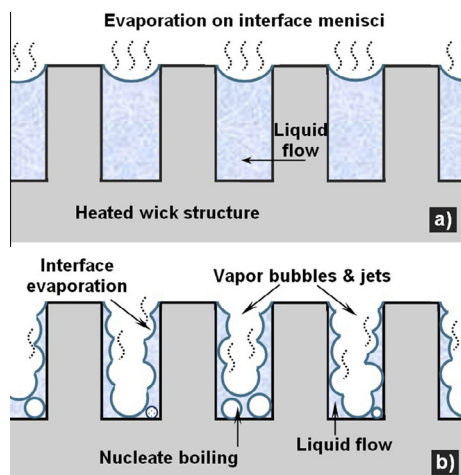


Fig. 1. Schematic diagram of phase change in mono porous wick structure: (a) traditional evaporation on interface menisci, (b) boiling enhanced evaporation in mono porous wick structure.

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