



Design and optimization of well-ordered microporous copper structure for high heat flux cooling applications

Chi Zhang^a, James W. Palko^{a,b}, Michael T. Barako^{a,c}, Mehdi Asheghi^a, Kenneth E. Goodson^{a,*}

^a Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA

^b Department of Mechanical Engineering, University of California-Merced, Merced, CA 95340, USA

^c NG Next Basic Research Laboratory, Northrop Grumman Corporation, Redondo Beach, CA 90278, USA

ARTICLE INFO

Article history:

Received 19 January 2021

Revised 25 February 2021

Accepted 17 March 2021

Keywords:

Capillary-driven boiling

Inverse opals

Capillary limit

Boiling limit

Critical heat flux

Microporous copper

Self-assembly

ABSTRACT

Capillary-driven boiling enables promising passive cooling structures and devices, and the use of highly-ordered microporous media promises efficient heat transfer at low superheat. Here we leverage the structural regularity of copper inverse opals (IO) to develop capillary structures with unprecedented fidelity, enabling a detailed study of the impacts of architectural design variables on boiling critical heat flux (CHF) as well as liquid and vapor transport properties. Fabrication of IO using a template-assisted electrodeposition method allows fine control of the microstructure and bulk geometry, producing structures with varying pore diameters (3.2 - 10.2 μm), heated area lateral dimensions (0.2 - 5.5 mm^2), and structural thicknesses (10 - 40 μm). We demonstrate capillary fed copper IO structures capable of dissipating over 1 kW cm^{-2} in boiling with water as the working fluid. We identify two distinct transport regimes, namely, a capillary-limited regime where CHF increases as IO lateral dimension decreases, and a boiling-limited regime where further decrease in IO areal footprint does not significantly improve CHF. This yields an optimal length scale of porous media area and structural thickness that maximize the CHF of capillary-driven boiling due to hydrodynamic competition between capillary wicking of liquid replenishment and the viscous forces on vapor. This work makes progress both on the fundamentals of two-phase flow physics in porous media while providing fabrication and optimization details for practical capillary structures that will support the device design for applications ranging from energy conversion to electronics cooling.

© 2021 Published by Elsevier Ltd.

1. Introduction

Breakthroughs in heat transport are essential to the sustained development and efficiency of numerous energy conversion technologies as well as power electronics and data centers [1–3]. Boiling provides an efficient way of energy transport by leveraging the latent heat of working fluid during vaporization [4–7]. In particular, capillary-driven boiling in microstructured porous thin films (typically < 1 mm thickness) features compact form factors and pump-free liquid supply via capillary wicking, making it suitable for integration of systems with size and weight limitations [4,8]. Recent studies on boiling in various capillary structures have shown a significant increase in heat transfer coefficient upon boiling incipience, demonstrating superior heat dissipation capability (up to 1 kW cm^{-2}) at low superheats compared with other two-

phase heat transport schemes [9–12]. During capillary-driven boiling, the microporous wick structures with highly interconnected pores serve the dual purpose of supplying heat to extended phase-change interfaces while simultaneously transporting liquid-vapor two-phase flow through the pore space. The key characteristics of these porous films are low conductive resistance for heat distribution through the matrix, high capillary pressure for liquid pumping, and high fluid permeability for low pressure drop. The high density of microscale pores also provides a large number of potential nucleation sites and enormous interfacial area for boiling heat transport [7,13]. The heat transfer coefficient and efficiency of boiling heat exchange increases with increasing heat flux until a critical point (also known as the critical heat flux, or CHF), beyond which an abrupt temperature rise in the heated porous wick is observed, which can cause catastrophic burnout of the boiling structure. As such, much research has been focused on enhancing the CHF of capillary-driven boiling by investigating different microporous architectures, including sintered particles [10,14,15],

* Corresponding author.

E-mail address: goodson@stanford.edu (K.E. Goodson).

Nomenclature

A	area, m^2
d_n	neck diameter, m
d_p	pore diameter, m
h_{fg}	latent heat of vaporization, J kg^{-1}
I	heating current, A
K	fluid permeability, m^2
K_r	relative permeability, dimensionless
L	length of heated area, m
l	liquid wicking distance, m
p	pressure, Pa
q''	heat flux, W cm^{-2}
r	radius, m
T	temperature, K
t	time, s
U	velocity, m s^{-1}
V	voltage, V
v	specific volume, $\text{m}^3 \text{kg}^{-1}$
W	width of heated area, m

Greek symbols

δ	thickness, m
Δ	difference
θ	contact angle, $^\circ$
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}
μ	dynamic viscosity, Pa s

Abbreviations/subscripts

<i>boil</i>	boiling
<i>c or cap</i>	capillary
<i>CHF</i>	critical heat flux
<i>cri</i>	critical
<i>eff</i>	effective
<i>fg</i>	liquid-to-vapor
<i>IO</i>	inverse opal
<i>l or liq</i>	liquid
<i>opt</i>	optimal
<i>s</i>	saturation condition
<i>v</i>	vapor
<i>w</i>	wick

sintered screen meshes [7,16,17], micropillar arrays [9,18,19], and various hybrid wicks [20–23].

Despite intensive efforts in the past decade, the structure-property relations of microporous wick architectural design variables to capillary-driven boiling CHF are still challenging. During boiling, capillary suction in the porous wick laterally replenishes the working fluid, while vapor escaping from the wick in a vertical direction across the wick thickness, as shown in Fig. 1. Both efficient liquid wicking and rapid vapor venting are key to preventing wick dryout at elevated heat fluxes [15–17,19]. For capillary-driven boiling in porous wicks where liquid is only supplied via a capillary feed, the maximum heat flux is reached when liquid viscous pressure losses exceed the wick capillary pressures, resulting in liquid starvation [16,19]. The ability to deliver liquid via capillary pumping establishes the capillary limit of CHF. Recent studies on increasing boiling CHF have developed both experimental methods and numerical simulations to analyze the absolute (intrinsic) fluid permeability [18,24–27] and capillary wicking performance [20,28–32] of various porous wicks. These studies, although informative, have mostly been limited to single-phase liquid trans-

port, and did not include the effect of vaporization and the subsequent two-phase flow in the porous wicks. The occupation of vapor within the interconnected pores can block permeable pathways for liquid replenishment, reducing the effective liquid permeability to be much less than the single-phase value due to partial saturation of vapor phase. The difficulty in determining the liquid transport limit in a two-phase flow regime prevents a precise evaluation of the capillary limit based on wick geometries [11,15]. On the other hand, boiling crisis can also be reached if the vapor flow resistance retards extraction and leads to vapor blanketing adjacent to the heated wick surface, which defines the boiling limit of CHF. While several prior studies [5,10,12,15] have hypothesized that vapor clearance controls the ultimate limit of heat flux in wick structures with short liquid wicking distances, there has been relatively little work to elucidate the effective vapor permeability hindered by partial blockage of pores by the liquid. Hence the relative importance of vapor escape compared with liquid supply has not been clearly delineated. Systematic investigations with varying liquid transport distances and wick thicknesses are required to identify the transition between capillary limit and boiling limit of CHF. Further, a quantitative relation that links the effect of architectural design variables on such transitions would benefit wick optimization for enhancing boiling heat transfer performances.

Copper inverse opal (IO) structures have demonstrated the potential of heat dissipation over 1 kW cm^{-2} using a capillary liquid feed [12]. The uniform pore diameters and regular pore arrangement of IO structures promote spatially uniform vaporization throughout the wick, and make it feasible to evaluate two-phase flow transport resistances leading to CHF for model development. In addition, the fabrication of IO using a template-assisted electrodeposition method enables the ability to tailor the wick lateral dimension and thickness for a parametric study. In this work, we investigate capillary-driven boiling CHF in well-ordered copper IO wicks while varying liquid wicking lengths and wick thicknesses. We experimentally realize a transition from the capillary limit of CHF to the boiling limit as the liquid wicking length of IO wicks is reduced, and the effect of wick thickness is investigated for CHF optimization. We use this data to develop a semi-analytical model to predict the critical heat fluxes by analyzing both liquid and vapor transport within the porous media. Liquid and vapor relative permeabilities (defined as the ratio of effective permeability to the absolute permeability) are incorporated in the CHF model to account for reduction in transport capability due to two-phase flow in the porous structure. With this experimental platform and supported by thermofluidic modeling, we elucidate the optimal length scale at which microporous structures can be effective when operating via capillary action in boiling.

2. Experimental methods

2.1. Inverse opal capillary structure fabrication

Inverse opal capillary wicks are synthesized using a derivative of the template-assisted copper electrodeposition protocol developed in previous works [12,33]. This electrochemical process leverages closely packed polystyrene colloidal crystals for templating the growth of copper (see Supplementary Information Section I for the fabrication process flow). The sacrificial opal template is formed on glass substrates by self-assembly of monodispersed colloidal polystyrene spheres. We use three different polymer sphere diameters to synthesize IO wicks with averaged spherical pore diameters (i.e. d_p) of $3.2 \mu\text{m}$, $5.4 \mu\text{m}$, and $10.2 \mu\text{m}$. The colloidal crystallization of polystyrene particles is driven by a combination of particle sedimentation [34,35] and a convective self-assembly mechanism [36]. As the aqueous solvent evaporates to the am-

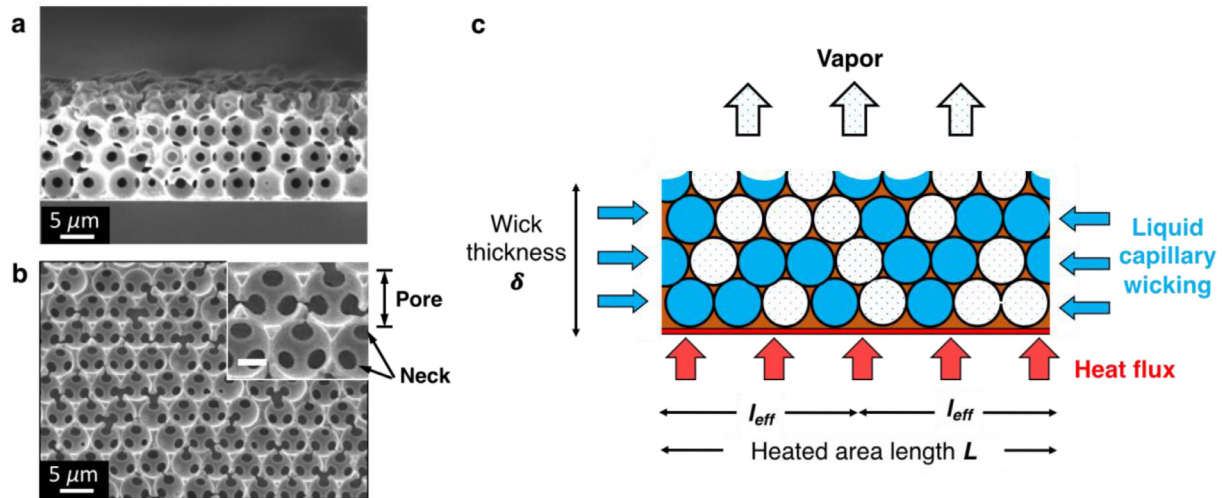


Fig. 1. (a) Cross-sectional and (b) top view scanning electron microscopy (SEM) images of the well-ordered inverse opal capillary structure. The spherical pores are connected together via the circular necks to form fluid permeable pathways. The scale bar in the inset SEM image is 2 μm. (c) Schematic of liquid and vapor two-phase flow inside the confined cavities of copper inverse opal during capillary-driven boiling. Lateral liquid delivery over the heated area is driven by capillary pressures of the porous structure during boiling. The hydraulic resistances of liquid and vapor transport depend on architectural design variables of the porous medium. The length L of heated areal footprint determines the liquid wicking length l_{eff} under capillary pressures, and the porous wick thickness δ decides the vapor transport distance.

bient (temperature 22°C, relative humidity 30%), the liquid film becomes thinner and the colloidal spheres are pulled toward the substrate. Toward the last stage of water evaporation, a meniscus forms in the center of the well and grows radially toward the edge due to the concave shape of the aqueous layer. As the meniscus shifts, colloidal particles further assemble into closely packed templates under immersion capillary forces [37,38]. Opal template sintering is implemented to form bonded area between neighboring polymer spheres, which later causes an increase in interpore neck sizes (Fig. 1b) of the resulting copper structures. These circular necks bridge adjacent spherical pores forming fluid permeable pathways in the IO wicks [12,25]. Copper is electrodeposited at a constant current onto the gold seed layer and up through the void volume of the sintered template from an aqueous electrolyte solution (0.6M copper sulfate and 5mM sulfuric acid). A three-electrode configuration is utilized with a copper counter electrode and Ag/AgCl as reference electrode. Tailoring of IO wick thicknesses is enabled by varying electrodeposition durations. Dissolving the polystyrene template in tetrahydrofuran solvent after copper deposition exposes the spherical pores in orderly arrangements. A more detailed description of opal template self-assembly and copper IO synthesis can be found in Supplementary Information Section I through Section III.

The uniform pores of IO wicks are interconnected via fluid permeable necks, which are determined by the bonded area of sacrificial polystyrene spheres resulted from template sintering. These narrow windows between neighboring pores act as flow restrictions along the fluid pathways, thus the wick permeability in relation to fluidic transport performances is strongly dependent on neck diameter d_n [25]. To evaluate the permeability of IO wicks, we analyze the neck sizes from scanning electron microscopy (SEM) images of IO structures. For IO samples of different pore diameters, representative SEM images and neck diameter distributions under various template sintering conditions are summarized in Fig. 2. Owing to its well-ordered pore arrangements, the absolute (single-phase) fluid permeability K of IO structures can be predicted using computational fluid dynamics (CFD) simulations based on pore and neck diameters, as detailed in Supplementary Information Section IV. Numerical simulations of absolute permeability of IO structures have shown agreement with experimental results within $\pm 30\%$ [12,32,39].

2.2. Capillary-driven boiling in inverse opal wicks

A thin titanium/gold seed layer of 5/50 nm thickness is deposited using electron beam evaporation onto a glass substrate, which later serves as the cathode for copper electrodeposition. The seed layer is patterned using shadow masks to define a bridge area with different widths W and lengths L connecting two contact pads (Fig. 3a). By varying the seed layer patterns, we produce active IO wicks of widths of 2.0 mm and 4.0 mm, and lengths ranging from 100 μm to 1100 μm (summarized in Table 1) for a systematic study.

We experimentally characterize capillary-driven boiling in IO porous wicks using deionized (DI) water as the working fluid. Water is driven across the active IO area from two adjacent liquid reservoirs via capillary pressures of the porous wick (see Fig. 3b and c). To reduce the risk of flooding, we utilize highly permeable cellulose wicks to supply water to the laser-ablated reservoirs from a water pool whose liquid level is maintained ~ 2 mm below the wick level. The gravitational pressure loss is less than 2% of the capillary pressure generated by the microporous IO wicks, hence its influence on liquid feeding is neglected. As liquid is laterally replenished from both sides of the capillary wick, the effective liquid wicking length l_{eff} of each IO sample is defined as half of the bridge area length (i.e. $l_{eff} = 0.5L$). The passive liquid transport setup allows for self-regulation of working fluid wicking responded to heating, as the porous wick only syphons the required amount of liquid for phase change processes.

The patterned bridge area of IO structure serves as both a heater and a resistance temperature detector (RTD) [11,12,40,41]. Prior to measurements, resistance thermometry is performed on IO samples and calibrated against T-type thermocouples (see Supplementary Information Section V). During the boiling experiments, a heating current I_{IO} is applied to the sample incrementally using a direct current (DC) power supply (BK Precision 1693), and the voltage across the IO active region V_{IO} is measured using a voltmeter (Keithley 2182A) with a four-probe configuration. The heating current is evaluated by simultaneously measuring the voltage across a current sensing resistor, which is in series with the IO sample. We calculate the heat fluxes by dividing the actual heating power ($I_{IO} \times V_{IO}$) with the active area of the wick ($W \times L$). The corresponding wick temperature T_w at a given power input is determined by the wick electrical resistance. Parasitic heat losses

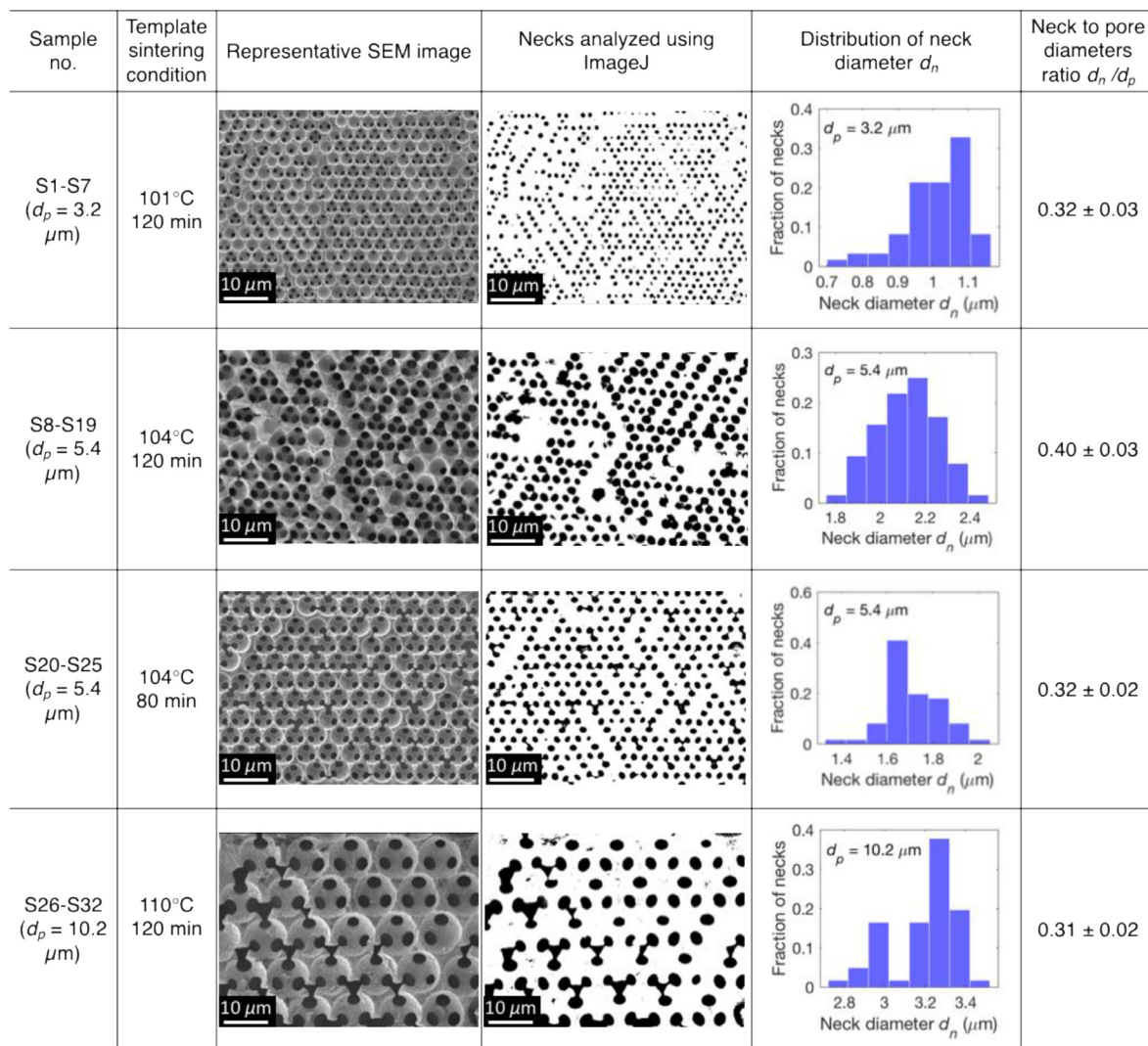


Fig. 2. Summary of statistical analysis of neck diameter distribution of copper IO samples having pore diameters of 3.2 μm , 5.4 μm , and 10.2 μm . Neck diameters (d_n) of copper IO samples with different pore diameters (d_p) and template sintering conditions (i.e., temperature and duration) are analyzed using SEM images. Examples of SEM images analyzed in ImageJ to determine the necks are shown. Histograms of neck diameter distribution are obtained by statistically sampling over 200 necks from SEM images and the neck to pore diameter ratios are applied to computational fluid dynamic (CFD) simulations to calculate IO permeabilities.

(e.g. conduction through the glass substrate) are characterized by quantifying the power dissipated by dry IO samples as a function of temperature without liquid feed to support boiling (see Supplementary Information Section VIII). Identical experimental setup to that of boiling heat transfer measurements is utilized with no liquid supply to the active IO area. This parasitic heat loss is deducted from the heating power in all heat fluxes reported in this study. Fig. S10 shows typical temporal results for an IO sample. The heating power is increased in a stepwise manner, and each power input is maintained to reach steady state, where the measured wick temperature changes at a rate less than $\pm 0.2^\circ\text{C}/\text{min}$ for 1 min. When the power input exceeds the maximum heat flux that can be sustained by the porous wick, a sudden temperature spike of the temporal data is observed (see Fig. S10). The last recorded steady-state heat flux is assumed to be the CHF of capillary-driven boiling in the IO sample. More details about electrical measurement and uncertainty analysis can be found in Supplementary Information Section IX.

Fig. 4a shows the representative boiling curves of IO wicks with pore diameters of 3.2 μm , 5.4 μm , and 10.2 μm . The boiling curves show a similar shape for IO structures of different pore diameters. At low heat fluxes ($< 100 \text{ W cm}^{-2}$), no bubble nucleation is

observed, and the heat transfer mechanism is primarily thin-film evaporation from the free liquid menisci formed at the top of the wick. Upon boiling initiation of the capillary wick, the slope of the heat transfer curve increases rapidly due to increased liquid-vapor interfaces resulted from bubble generation. This causes a significant reduction in wick thermal resistances in the boiling regime compared to the thin-film evaporation regime. As heat flux is increased, we visually observe bubble nucleation, departure, and violent liquid ejection from the wick, as shown in Fig. 4b. Upon boiling incipience, bubbles nucleate simultaneously over the active IO bridge area, and collapse when they grow beyond the wick height. At low to moderate heat fluxes, nucleating bubbles grow and coalesce to larger sizes ($\sim 200 \mu\text{m}$) before collapsing on top of the wick. At high heat fluxes, intensive liquid ejection is observed above the wick and clear bubble boundaries are difficult to obtain as bubble generation frequencies increase significantly. The bubble diameters at all heat flux levels are much smaller than what have been observed for extensive pool boiling experiments (millimeter scale) [42–45], which is likely due to confinement of the thin liquid layer in a capillary-driven boiling configuration [41]. In pool boiling where bubbles depart from the heated surface under buoyancy forces in the stagnant liquid pool, the bubble departure

Table 1
List of IO samples used for systematic characterization.

Sample no.	Pore diameter d_p (μm)	Neck to pore diameter ratio d_n/d_p	Heated area width W (mm)	Heated area length L (μm)	Liquid wicking length l_{eff} (μm)	Wick thickness δ (μm)
S1	3.2	0.32	2.0	151	75.5	10.6
S2	3.2	0.32	2.0	238	119	11.3
S3	3.2	0.32	2.0	344	172	10.9
S4	3.2	0.32	4.0	545	272.5	11.4
S5	3.2	0.32	2.0	329	164.5	10.8
S6	3.2	0.32	2.0	314	157	8.3
S7	3.2	0.32	2.0	325	162.5	15.1
S8	5.4	0.40	4.0	465	232.5	16.1
S9	5.4	0.40	4.0	560	280	15.9
S10	5.4	0.40	4.0	748	374	16.5
S11	5.4	0.40	4.0	592	296	20.7
S12	5.4	0.40	4.0	636	318	21.3
S13	5.4	0.40	2.0	117	58.5	24.5
S14	5.4	0.40	2.0	168	84	24.2
S15	5.4	0.40	2.0	268	134	24.2
S16	5.4	0.40	4.0	820	410	24.4
S17	5.4	0.40	2.0	150	75	27.9
S18	5.4	0.40	2.0	174	87	28.4
S19	5.4	0.40	4.0	1106	553	28.6
S20	5.4	0.32	2.0	274	137	9.2
S21	5.4	0.32	2.0	275	137.5	14.4
S22	5.4	0.32	2.0	283	141.5	19.4
S23	5.4	0.32	2.0	284	142	22.1
S24	5.4	0.32	2.0	281	140.5	26.2
S25	5.4	0.32	2.0	290	145	29.6
S26	10.2	0.31	2.0	209	104.5	35.2
S27	10.2	0.31	2.0	350	175	35.5
S28	10.2	0.31	4.0	572	286	33.8
S29	10.2	0.31	4.0	817	408.5	32.1
S30	10.2	0.31	2.0	292	146	32.8
S31	10.2	0.31	2.0	282	141	22.6
S32	10.2	0.31	2.0	301	150.5	41.5

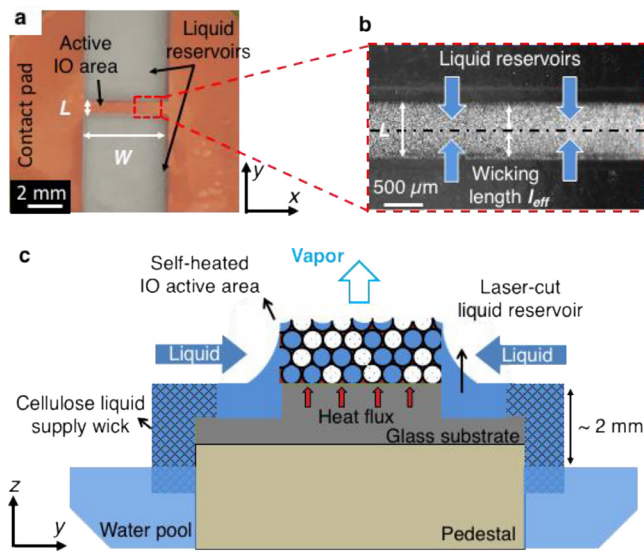


Fig. 3. Boiling in copper IO wicks via capillary wicking of liquid. (a and b) Top view of patterned IO active area showing IO bridge width W , bridge length L , and maximum liquid wicking length l_{eff} . Liquid reservoirs are patterned on both sides of the IO active area via laser ablation of the glass substrate to deliver liquid to wick edges. (c) Schematic (no-to-scale) of the side view showing lateral liquid transport via capillary wicking and vapor venting in a perpendicular direction across the wick thickness. Heat fluxes are supplied by volumetric Joule heating of the active IO bridge.

diameters are comparable to the capillary length [46], which is approximately 2.5 mm given water properties at a saturation temperature of 100°C. Whereas in capillary-driven boiling, the porous wick thickness (tens of micrometers) provides an upper bound for liquid layer thickness, and such thin liquid film prevents bubbles

from growing to be of millimeter-scale sizes before collapsing at the wick surface. The wick superheat ($\Delta T = T_w - T_s$) at maximum heat dissipation of IO wicks varies by less than 1K for a fixed pore diameter, but increases from ~ 9 K to ~ 18 K as the pore diameter of IO wicks reduces from 10.2 μm to 3.2 μm , suggesting a possible confinement of nucleating vapor bubbles to sizes similar to those of the spherical pores themselves [11]. Similar increases in wick superheat as pore diameter decreases have also been observed in pool boiling experiments with IO structures having pore diameters ranging from 0.6 μm to 5 μm [42,47].

3. Modeling of critical heat flux of capillary-driven boiling

Capillary-driven boiling in porous wicks features lateral liquid delivery driven by capillary pressures while vapor vents in a perpendicular direction across the wick thickness. To predict critical heat fluxes of capillary-driven boiling, both liquid and vapor transport within the porous wicks should be considered. As the porous matrix imposes drag forces on both liquid and vapor flows, the maximum phase change capability reflects either the liquid supply without dry out (the capillary limit), or the ability of liquid rewetting the heated surface facilitated by vapor extraction from the wick (the boiling limit).

The capillary limit of CHF is determined by balancing the capillary pressure available from the porous structure as determined by the pore diameter with the flow resistance imposed by the porous matrix. The maximum viscous pressure drop of lateral liquid wicking Δp_{liq} at a given heat input q'' depends on working fluid supply configuration (i.e. the effective wicking length l_{eff}) and wick thickness δ as [11]

$$\Delta p_{liq} = \frac{\mu_l}{2K_l K} \frac{q''}{h_{fg} \rho_l \delta} l_{eff}^2 \quad (1)$$

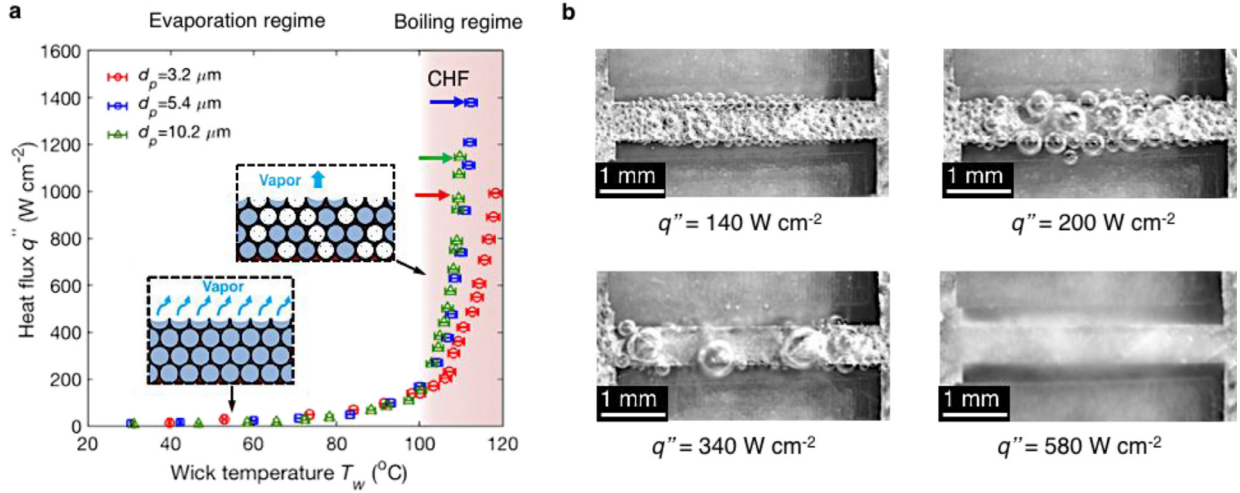


Fig. 4. (a) Representative boiling curves of IO wicks having pore diameters of 3.2 μm , 5.4 μm , and 10.2 μm . The arrows show the CHF for each curve. The uncertainty bars in the heat flux measurement are smaller than the symbol size and generally less than $\pm 2\%$. (b) Series of images showing boiling over active IO area at varying heat fluxes as viewed from the top. The IO sample (S11) has a heated area of 2.4 mm^2 (4.0 $\text{mm} \times 0.6 \text{ mm}$) and pore diameter of 5.4 μm .

Where μ_l and ρ_l are liquid dynamic viscosity and density, respectively, h_{fg} is latent heat of vaporization, K is absolute permeability of IO wick, and K_{rl} is relative permeability of liquid phase accounting for partial saturation of vapor in the wick. As vapor bubbles nucleate and grow inside the capillary wicks upon boiling incipience, the effective fluid permeability for liquid transport is reduced to $K_{rl} \cdot K$, where K_{rl} is a dimensionless fitting parameter less than unity. The available capillary pressure of the porous structure Δp_c is decided by [2,46]

$$\Delta p_c = \frac{2\sigma}{r_{eff}} = \frac{4\sigma \cos\theta}{d_p} \quad (2)$$

Where σ is surface tension, r_{eff} is effective pore radius of the wick ($r_{eff} = d_p/(2\cos\theta)$), d_p is pore diameter, and θ is contact angle. We solve for the capillary-limited dryout heat flux by balancing Δp_{liq} with Δp_c , and arrive at the capillary limit of CHF as

$$q''_{cap,CHF} = \frac{8\sigma K_{rl} K h_{fg} \rho_l \delta \cos\theta}{\mu_l d_p l_{eff}^2} \quad (3)$$

While reducing effective wicking length of working fluid can alleviate fluid supply limitation in capillary-driven boiling as suggested by Eq. (3), vapor blanketing during vigorous boiling can impede continuous liquid replenishing, leading to the boiling limit of CHF. Vapor upward movement across the wick thickness is subject to the viscous forces imposed by the porous wick. The pressure drop to vent vapor from wick bottom to the ambient Δp_v is given by

$$\Delta p_v = \frac{\mu_v \delta}{K_{rv} K} U_v \quad (4)$$

Where μ_v is vapor dynamic viscosity, δ is IO wick thickness, U_v is vapor velocity, $K_{rv} \cdot K$ is effective vapor permeability, and K_{rv} is relative permeability of vapor phase considering partial saturation of liquid. The vapor velocity U_v is related to the applied heat flux q'' based on continuity and energy balance as

$$U_v = \frac{q''}{h_{fg} \rho_v} \quad (5)$$

where ρ_v is vapor density, and h_{fg} is latent heat of vaporization.

The vapor pressure drop Δp_v should be compensated by an elevation in vapor saturation pressure Δp_s at wick superheat $\Delta T = T_w - T_s$, which can be estimated using the Clausius-Clayperon equation

[48,49]

$$\frac{\Delta p_s}{\Delta T} = \frac{h_{fg}}{T_s \Delta v} = \frac{h_{fg} \rho_l \rho_v}{T_s (\rho_l - \rho_v)} \quad (6)$$

Where T_w is wick temperature, T_s is saturation temperature, Δv is specific volume difference between the vapor and liquid phase, and ρ_l and ρ_v are liquid and vapor densities, respectively. By balancing Δp_v with Δp_s , we arrive at the boiling limit of CHF accounting for vapor transport limitation within the wick as

$$q''_{boil,CHF} = \frac{K_{rv} K h_{fg}^2 \rho_l \rho_v^2 \Delta T}{\mu_v T_s (\rho_l - \rho_v) \delta} \quad (7)$$

4. Results and discussion

4.1. The effect of liquid wicking length on CHF of capillary-driven boiling

Eq. (3) shows that the capillary-limited critical heat flux varies inversely with l_{eff}^2 , suggesting that as the liquid wicking distance is decreased, the maximum heat flux of capillary-driven boiling should increase due to a reduction in liquid transport resistance. This enhancement in CHF, however, stops at short wicking lengths where vapor transport becomes dominant (hence the boiling limit). To validate the prediction, we perform experiments on IO wicks with similar wick thickness δ but different wicking length l_{eff} (IO samples S1-S5, S13-S16, S26-S30, as in Table 1). Fig. 5 shows experimental CHF of IO wicks with d_p of 3.2 μm , 5.4 μm , and 10.2 μm , and δ roughly of 11 μm (S1-S5), 24 μm (S13-S16), and 34 μm (S26-S30), respectively. Liquid and vapor relative permeabilities, K_{rl} and K_{rv} , are determined to be 0.15 and 0.11, respectively, by best fit of experimental data (see Supplementary Information Section VII), suggesting substantial decrease in flow mobility of one phase due to the presence of the other. Our experimental results show a transition from the capillary limit to boiling limit of CHF as l_{eff} decreases. In the capillary limit regime, decreasing the wicking length reduces the liquid viscous loss and enhances the CHF of capillary-driven boiling from $\sim 100 \text{ W cm}^{-2}$ to $\sim 1000 \text{ W cm}^{-2}$. This enhancement trend is expected to continue until the boiling limit becomes comparable to the capillary limit, where the boiling performance is no longer limited by liquid capillary wicking, but by vapor transport exiting the wick. Further decreasing l_{eff} of IO wicks in the boiling limit regime does not show a significant benefit in CHF in Fig. 5, as predicted by Eq. (7).

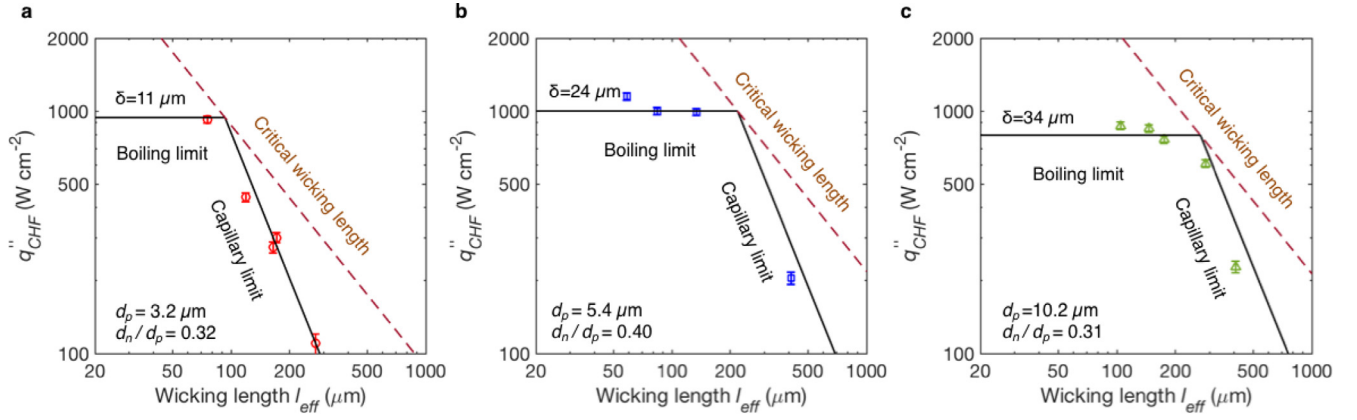


Fig. 5. Effect of liquid wicking length on the critical heat flux of capillary-driven boiling from IO samples having (a) $d_p = 3.2 \mu\text{m}$, $\delta \approx 11 \mu\text{m}$, (b) $d_p = 5.4 \mu\text{m}$, $\delta \approx 24 \mu\text{m}$, and (c) $d_p = 10.2 \mu\text{m}$, $\delta \approx 34 \mu\text{m}$. The semi-analytical model is shown by the black solid lines, which compares reasonably well with our experiments by fitting liquid and vapor relative permeabilities $K_{rl} = 0.15$ and $K_{rv} = 0.11$, respectively. The boiling CHF decreases after the liquid wicking length increases beyond a critical value, suggesting a transition from the boiling limit regime to the capillary limit regime. The brown dashed lines represent such transition points at various wick thicknesses for a given pore diameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

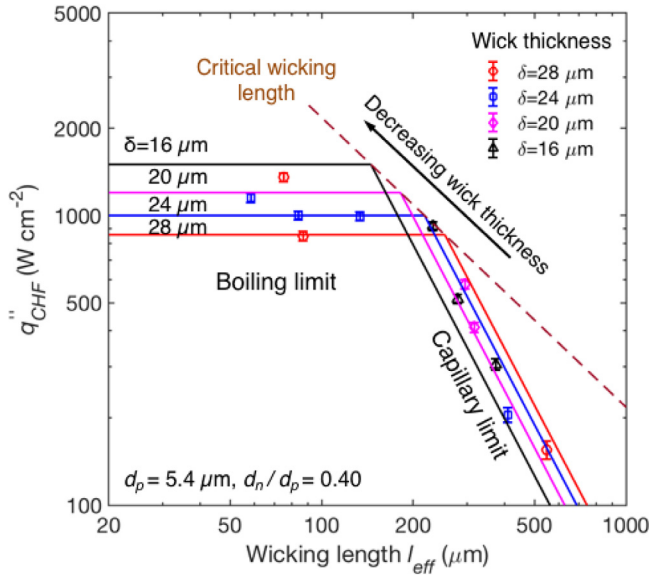


Fig. 6. Effect of liquid wicking length on the CHF of capillary-driven boiling from IO samples having $d_p = 5.4 \mu\text{m}$ and $16 \mu\text{m} < \delta < 28 \mu\text{m}$. Predictions from the semi-analytical modeling are plotted by solid lines with liquid and vapor relative permeabilities of $K_{rl} = 0.15$ and $K_{rv} = 0.11$, respectively. The critical wicking length where the transition between boiling limit and capillary limit occurs is shown to decrease with wick thickness.

The intersection point of the capillary limit and boiling limit decides the critical wicking length, l_{cri} , at which the transition between two regimes occurs. By equating Eqs. (3) and (7), we derive an analytical expression for l_{cri} depending on wick thickness and thermophysical properties of the working fluid as

$$l_{cri} = \frac{\delta}{\rho_v} \left[\frac{8K_{rl}\sigma\mu_v T_s(\rho_l - \rho_v) \cos \theta}{K_{rv}h_{fg}\mu_l d_p \Delta T} \right]^{1/2} \quad (8)$$

Compared to IO wicks of $d_p = 3.2 \mu\text{m}$, l_{cri} of IO wicks of $d_p = 10.2 \mu\text{m}$ is shown to increase from $\sim 100 \mu\text{m}$ to $\sim 300 \mu\text{m}$, largely attributed to an increase in wick thickness (from $11 \mu\text{m}$ to $34 \mu\text{m}$). For IO wicks of a given d_p , l_{cri} is expected to increase linearly with δ . To validate the effect of wick thickness on the critical wicking length, we investigate CHF for IO structures of a fixed pore diameter ($d_p = 5.4 \mu\text{m}$) but of different wick thicknesses (IO samples S8-S19), as shown in Fig. 6. Increasing IO wick thickness facili-

tates liquid transport by reducing its viscous pressure drops, hence the transition between boiling limit and capillary limit regimes of CHF occurs at a larger liquid wicking distance.

4.2. The effect of wick thickness on CHF of capillary-driven boiling

To further investigate the effect of wick thickness on the maximum heat fluxes, IO wicks with similar l_{eff} but different δ ($2 < \delta/d_p < 6$) are characterized (IO samples S5-S7, S20-S25, S30-S32, as in Table 1). As shown in Fig. 7, for constant d_p and l_{eff} , a trade-off between the increased cross-sectional area for liquid supply and the increased transport resistance to vapor flow exiting the wick leads to the existence of an optimal wick thickness that maximizes the heat transfer performance. In the capillary limit regime where δ is small, increasing δ results in an increase in flow cross-sectional area for liquid wicking and a concomitant decrease in the viscous losses of liquid supply, which in turn leads to a linear increase in CHF. The increase in maximum heat flux, however, is shown to decrease after reaching an optimal δ (i.e., δ_{opt}), beyond which point the increased drag resistance on vapor flow escaping the wick dominates over the gain in liquid transport capability. Further increase in δ adds to vapor pressure losses with CHF shown to decrease as δ increases, suggesting a transition to the boiling limit regime. The optimal wick thickness δ_{opt} can be determined by

$$\delta_{opt} = \rho_v l_{eff} \left[\frac{K_{rv}\mu_l h_{fg} d_p \Delta T}{8K_{rl}\mu_v \sigma T_s(\rho_l - \rho_v) \cos \theta} \right]^{1/2} \quad (9)$$

For similar $l_{eff} \approx 150 \mu\text{m}$, δ_{opt} varies within a small range ($15 \mu\text{m} < \delta_{opt} < 20 \mu\text{m}$) for IO structures of different d_p ($3.2 \mu\text{m} < d_p < 10.2 \mu\text{m}$). This is mostly due to an increase in wick superheat at maximum heat dissipation as d_p decreases. The maximum heat flux of boiling, however, is very sensitive to the choice of d_p , as CHF enhances from $\sim 500 \text{ W cm}^{-2}$ to $\sim 1100 \text{ W cm}^{-2}$ while d_p increases from $3.2 \mu\text{m}$ to $10.2 \mu\text{m}$ owing to an improvement in wick absolute permeability K ($K \propto d_p^2$ for similar wick porosities). For IO structures of a fixed d_p , as δ_{opt} varies linearly with l_{eff} , a thicker wick is desired for porous wicks of large footprints (hence large liquid wicking lengths). However, achieving high heat fluxes as wick thickness increases is difficult, since the maximum heat flux that can be sustained by the wick (i.e. the boiling limit of CHF) decreases as wick thickness increases ($q''_{boil, CHF} \sim \delta^{-1}$). This suggests a competing mechanism between optimizing the CHF and increasing wick footprint. To extend heated area while still achiev-

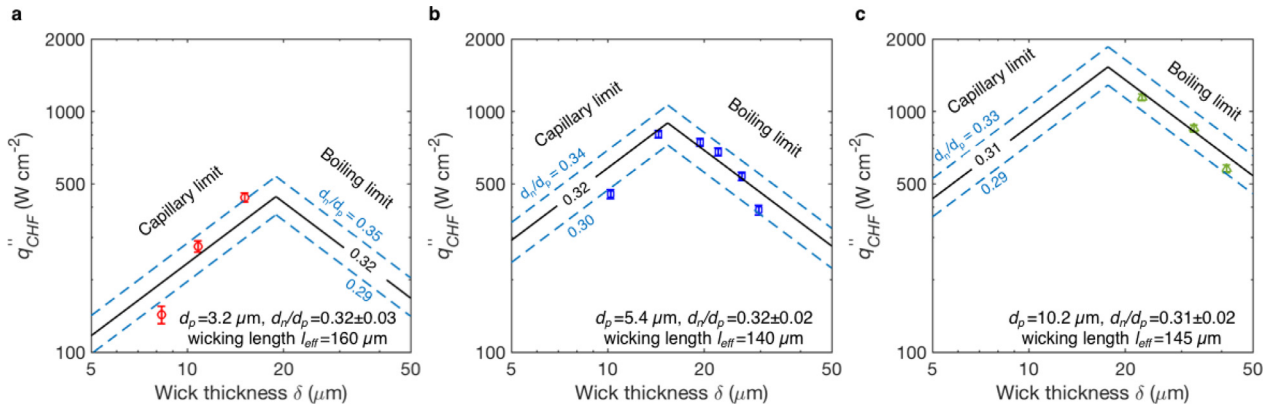


Fig. 7. Effect of wick thickness on the critical heat flux of capillary-driven boiling from IO samples having (a) $d_p = 3.2 \mu\text{m}$, $l_{\text{eff}} \approx 160 \mu\text{m}$, (b) $d_p = 5.4 \mu\text{m}$, $l_{\text{eff}} \approx 140 \mu\text{m}$, and (c) $d_p = 10.2 \mu\text{m}$, $l_{\text{eff}} \approx 145 \mu\text{m}$. Both experiments and model (black solid lines) show that there is an optimum wick thickness that maximizes the boiling CHF for a given liquid wicking length. Both upper and lower limit of the CHF modeling (blue dashed lines) are plotted by including the standard deviation of neck to pore diameter ratio (d_n/d_p) into wick permeability calculations, and most experimental data are shown to lie within the range of predicted heat fluxes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

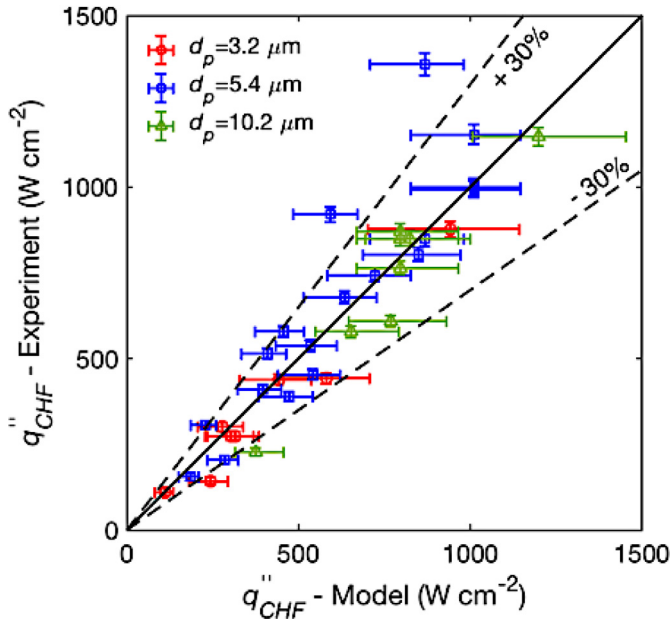


Fig. 8. Comparison between the experimentally characterized CHF of capillary-driven boiling from IO wicks and the model prediction. The semi-analytical model agrees reasonably well with our experiments by fitting liquid and vapor relative permeabilities $K_{rl} = 0.15$ and $K_{rv} = 0.11$. The black solid line is a 45° line for comparison between modeling and experiments and the +30% and -30% dashed lines show the upper and lower bounds of comparison, respectively. The uncertainty bars on the model critical heat flux are obtained from the measurement uncertainty in microporous wick thickness and fluid permeability via error propagation analysis.

ing high heat fluxes, reducing l_{eff} of working fluid supply using bi-porous wick designs (with low flow resistance channels enabled by larger pores) or incorporating three-dimensional manifold to uniformly distribute liquid can be pursued in future study.

All experimental data of IO wicks are plotted against model predictions in Fig. 8. By fitting liquid and vapor relative permeabilities $K_{rl} = 0.15$ and $K_{rv} = 0.11$ at maximum heat fluxes, the experimental data agrees with the model prediction within $\pm 30\%$ accuracy. The discrepancy between experimental data and CHF modeling is partially accounted for by variations in absolute permeability K caused by nonuniform neck diameter of IO microstructures (Fig. 2). In Fig. 7, we plot the upper and lower limits of predicted heat fluxes by including the standard deviation of neck diameter

distribution into permeability calculations, and most experimental data are shown to lie within the range of predicted heat fluxes. Additionally, local variability in the microstructure of capillary wicks can also lead to variation of heat density and nonuniform temperature across the active area, while in our model we assume uniform wick temperature and bubble generation rate. This simplifying assumption can be another contributing factor for the discrepancy between experiment and modeling.

Prior experimental studies have shown that the relative permeability in a given multiphase flow system primarily depends on the void fraction, or saturation, occupied by a fluid phase [50–52]. Within the experimental range of this work, liquid and vapor relative permeabilities at maximum heat fluxes remain roughly constant for IO wicks of different pore diameters, suggesting a similar two-phase flow pattern (hence similar liquid and vapor phase saturations) in IO structures at boiling crises resulted from similarity in pore morphology. Porous wicks of different structural morphologies, such as micropillars and sintered particles, likely offer distinct combinations of liquid and vapor relative permeabilities. For example, capillary-driven boiling from silicon micropillars has shown a liquid saturation of 0.65 at maximum heat dissipation in the capillary-limited regime, which corresponds to a liquid relative permeability of ~ 0.12 [19]. Moreover, boiling experiments from bi-porous glass particle wicks have shown that vapor preferably fill the larger pores while liquid mainly flows through the smaller pores [53]. Thus heterogeneous porous wicks offer the opportunity of enhancing the heat dissipation capability of capillary-driven boiling by tailoring the saturation conditions and relative permeabilities of liquid and vapor phases. Aside from wick design optimization, liquid and vapor transport in porous wicks may also rely on the flow direction of one phase with respect to the other. Boiling heat transfer performances may potentially benefit from separating the liquid and vapor transport pathways within the porous wicks during phase change processes, such as utilizing suspended porous wicks with liquid flow in parallel to vapor flow instead of in perpendicular direction [41,54]. The manufacturing difficulty of such liquid supply configuration and its applicability to two-phase heat spreaders such as vapor chambers and micro heat pipes would require careful consideration.

5. Conclusion

In conclusion, we experimentally investigate capillary-driven boiling performance in well-ordered copper inverse opals wicks with pore diameter ranging from $3.2 \mu\text{m}$ to $10.2 \mu\text{m}$ and wick

thickness ranging from 10 μm to 40 μm . A thermal-fluidic model is developed to corroborate the experimental critical heat fluxes of capillary-driven boiling by simultaneously considering both liquid and vapor transport within the microporous wicks. Our model and experiments show a transition of CHF from the capillary limit to the boiling limit for a given IO wick thickness as the liquid wicking distance decreases. Below this critical wicking length, vapor transport exiting the wick plays a dominant role in determining the maximum heat fluxes. Furthermore, the model and experiments show that there is an optimum wick thickness that maximizes the boiling heat fluxes for a given heating area. While thin microporous wicks can potentially achieve high boiling limit of CHF, they concurrently act to increase liquid lateral transport resistances thus demanding shorter liquid wicking lengths. The competing mechanism of improving the CHF and increasing wick footprint requires careful wick design and detailed liquid supply considerations.

Our experimental results are directly applicable to thermal management of high heat fluxes. Heat fluxes exceeding 1 kW cm^{-2} can be dissipated at low wick superheat ($\sim 10^\circ\text{C}$) via boiling from the nanoengineered/heated IO area using passive capillary wicking. Additionally, the IO wicking structures with thicknesses below 50 μm are of particular interest for integration into ultra-thin vapor chambers with total device thicknesses of less than 1 mm. While IO structures represent an important class of porous morphologies, the thermal-fluidic model outlined here can be adopted to analyze two-phase flow transport capabilities leading to CHF in other porous wicks, such as sintered copper, micropillar arrays, or nanowire networks. Our model will assist to better understand the liquid and vapor transport in nanostructured porous metals during capillary-driven boiling and provide useful guidelines to wicking structure design of high-performance phase-change systems.

Associated content

The following supplementary information are available. Copper inverse opal synthesis and characterization, Additional details of self-assembly of colloidal spheres, Controlling IO thickness with electrodeposition time, Computational fluid dynamic (CFD) simulation of fluid permeability of IO structure, Resistive temperature detector (RTD) calibration, Experimental characterization of capillary-driven boiling, Determining liquid and vapor relative permeabilities from best fit of experimental data, Characterization of parasitic heat losses, Electrical measurement and uncertainty analysis (PDF).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Chi Zhang: Methodology, Investigation, Data curation, Validation, Writing – original draft. **James W. Palko:** Conceptualization, Methodology, Supervision. **Michael T. Barako:** Methodology, Supervision, Writing – review & editing. **Mehdi Asheghi:** Conceptualization, Supervision, Project administration. **Kenneth E. Goodson:** Conceptualization, Supervision, Writing – review & editing, Project administration.

Acknowledgment

This work was supported in part by funding from the Department of Energy's Advanced Research Projects Agency-Energy's (ARPA-E) OPEN 2018 funding opportunity, as well as ASCENT, one of six centers in JUMP, a Semiconductor Research Corporation (SRC)

program sponsored by DARPA. This work was also partially funded by the U.S. National Science Foundation Engineering Research Center on Power Optimization of Electro-Thermal Systems (POETS) with cooperative agreement EEC-1449548. Part of this work was performed at the Stanford Nano Shared Facilities (SNSF), supported by the National Science Foundation under Award No. ECCS-1542152.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijheatmasstransfer.2021.121241.

References

- [1] H. Ghasemi, G. Ni, A.M. Marconnet, J. Loomis, S. Yerci, N. Miljkovic, G. Chen, Solar steam generation by heat localization, *Nat. Commun.* 5 (2014) 4449.
- [2] H.J. Cho, D.J. Preston, Y. Zhu, E.N. Wang, Nanoengineered materials for liquid–vapor phase-change heat transfer, *Nat. Rev. Mater.* 2 (2) (2017) 16092.
- [3] M.T. Barako, V. Gambin, J. Tice, Integrated nanomaterials for extreme thermal management: a perspective for aerospace applications, *Nanotechnology* 29 (15) (2018) 154003.
- [4] A. Bar-Cohen, K. Matin, N. Jankowski, D. Sharar, Two-phase thermal ground planes: technology development and parametric results, *J. Electron. Packag.* 137 (1) (2015) 010801.
- [5] J.W. Palko, H. Lee, C. Zhang, T.J. Dusseault, T. Maitra, Y. Won, D.D. Agonafer, J. Moss, F. Houshmand, G. Rong, J.D. Wilbur, D. Rockosi, I. Mykyta, D. Resler, D. Altman, M. Asheghi, J.G. Santiago, K.E. Goodson, Extreme two-phase cooling from laser-etched diamond and conformal, template-fabricated microporous copper, *Adv. Funct. Mater.* 27 (45) (2017) 1703265.
- [6] S. Adera, D. Antao, R. Raj, E.N. Wang, Design of micropillar wicks for thin-film evaporation, *Int. J. Heat Mass Transf.* 101 (2016) 280–294.
- [7] R. Wen, S. Xu, Y.-C. Lee, R. Yang, Capillary-driven liquid film boiling heat transfer on hybrid mesh wicking structures, *Nano Energy* 51 (2018) 373–382.
- [8] A. Bar-Cohen, P. Wang, Thermal management of on-chip hot spot, *J. Heat Transf.* 134 (5) (2012) 051017.
- [9] D. C so, V. Srinivasan, M.-C. Lu, J.-Y. Chang, A. Majumdar, Enhanced heat transfer in biporous wicks in the thin liquid film evaporation and boiling regimes, *J. Heat Transf.* 134 (10) (2012) 101501.
- [10] J.A. Weibel, S.V. Garimella, Visualization of vapor formation regimes during capillary-fed boiling in sintered-powder heat pipe wicks, *Int. J. Heat Mass Transf.* 55 (13) (2012) 3498–3510.
- [11] J. Palko, C. Zhang, J. Wilbur, T. Dusseault, M. Asheghi, K. Goodson, J. Santiago, Approaching the limits of two-phase boiling heat transfer: high heat flux and low superheat, *Appl. Phys. Lett.* 107 (25) (2015) 253903.
- [12] C. Zhang, J.W. Palko, M.T. Barako, M. Asheghi, J.G. Santiago, K.E. Goodson, Enhanced capillary-fed boiling in copper inverse opals via template sintering, *Adv. Funct. Mater.* 28 (41) (2018) 1803689.
- [13] D.S. Antao, Y. Zhu, E.N. Wang, Boiling on enhanced surfaces, in: *Handbook of Thermal Science and Engineering*, Springer, 2017, pp. 1–47.
- [14] K. Baraya, J.A. Weibel, S.V. Garimella, Simultaneous wick and fluid selection for the design of minimized-thermal-resistance vapor chambers under different operating conditions, *Int. J. Heat Mass Transf.* 136 (2019) 842–850.
- [15] J.A. Weibel, S.V. Garimella, M.T. North, Characterization of evaporation and boiling from sintered powder wicks fed by capillary action, *Int. J. Heat Mass Transf.* 53 (19) (2010) 4204–4215.
- [16] C. Li, G. Peterson, Y. Wang, Evaporation/boiling in thin capillary wicks (I)—wick thickness effects, *J. Heat Transf.* 128 (12) (2006) 1312–1319.
- [17] C. Li, G. Peterson, Evaporation/boiling in thin capillary wicks (II)—effects of volumetric porosity and mesh size, *J. Heat Transf.* 128 (12) (2006) 1320–1328.
- [18] S. Ravi, D. Horner, S. Moghaddam, Monoporous micropillar wick structures, I-mass transport characteristics, *Appl. Therm. Eng.* 73 (1) (2014) 1371–1377.
- [19] S.Q. Cai, A. Bhunia, Geometrical effects of wick structures on the maximum phase change capability, *Int. J. Heat Mass Transf.* 79 (2014) 981–988.
- [20] S. Ryu, J. Han, J. Kim, C. Lee, Y. Nam, Enhanced heat transfer using metal foam liquid supply layers for micro heat spreaders, *Int. J. Heat Mass Transf.* 108 (2017) 2338–2345.
- [21] T. Semenic, I. Catton, Experimental study of biporous wicks for high heat flux applications, *Int. J. Heat Mass Transf.* 52 (21–22) (2009) 5113–5121.
- [22] S. Sudhakar, J.A. Weibel, S.V. Garimella, Experimental investigation of boiling regimes in a capillary-fed two-layer evaporator wick, *Int. J. Heat Mass Transf.* 135 (2019) 1335–1345.
- [23] Y.S. Ju, M. Kaviani, Y. Nam, S. Sharratt, G. Hwang, I. Catton, E. Fleming, P. Dussinger, Planar vapor chamber with hybrid evaporator wicks for the thermal management of high-heat-flux and high-power optoelectronic devices, *Int. J. Heat Mass Transf.* 60 (2013) 163–169.
- [24] R. Hale, R. Bonnecaze, C. Hidrovo, Optimization of capillary flow through square micropillar arrays, *Int. J. Multiph. Flow* 58 (2014) 39–51.
- [25] C. Zhang, J.W. Palko, G. Rong, K.S. Pringle, M.T. Barako, T.J. Dusseault, M. Asheghi, J.G. Santiago, K.E. Goodson, Tailoring permeability of microporous

- copper structures through template sintering, *ACS Appl. Mater. Interfaces* 10 (36) (2018) 30487–30494.
- [26] G. Rong, J.W. Palko, D.I. Oyarzun, C. Zhang, J. Hämmerle, M. Asheghi, K.E. Goodson, J.G. Santiago, A method for quantifying in plane permeability of porous thin films, *J. Colloid Interface Sci.* 530 (2018) 667–674.
- [27] I.-L. Ngo, C. Byon, Permeability of microporous wicks with geometric inverse to sintered particles, *Int. J. Heat Mass Transf.* 92 (2016) 298–302.
- [28] S. Ryu, W. Lee, Y. Nam, Heat transfer and capillary performance of dual-height superhydrophilic micropost wicks, *Int. J. Heat Mass Transf.* 73 (2014) 438–444.
- [29] C. Byon, S.J. Kim, Capillary performance of bi-porous sintered metal wicks, *Int. J. Heat Mass Transf.* 55 (15–16) (2012) 4096–4103.
- [30] C. Byon, S.J. Kim, Study on the capillary performance of micro-post wicks with non-homogeneous configurations, *Int. J. Heat Mass Transf.* 68 (2014) 415–421.
- [31] Y. Nam, S. Sharratt, C. Byon, S.J. Kim, Y.S. Ju, Fabrication and characterization of the capillary performance of superhydrophilic Cu micropost arrays, *J. Microelectromech. Syst.* 19 (3) (2010) 581–588.
- [32] Q. Pham, M. Barako, J. Tice, Y. Won, Microscale liquid transport in polycrystalline inverse opals across grain boundaries, *Sci. Rep.* 7 (1) (2017) 10465.
- [33] M.T. Barako, A. Sood, C. Zhang, J. Wang, T. Kodama, M. Asheghi, X. Zheng, P.V. Braun, K.E. Goodson, Quasi-ballistic electronic thermal conduction in metal inverse opals, *Nano Lett.* 16 (4) (2016) 2754–2761.
- [34] Q. Zhou, P. Dong, L. Liu, B. Cheng, Study on the sedimentation self-assembly of colloidal SiO₂ particles under gravitational field, *Colloids Surf. A* 253 (1–3) (2005) 169–174.
- [35] R. Mayoral, J. Requena, J.S. Moya, C. López, A. Cintas, H. Miguez, F. Meseguer, L. Vázquez, M. Holgado, Á. Blanco, 3D Long-range ordering in ein SiO₂ submicrometer-sphere sintered superstructure, *Adv. Mater.* 9 (3) (1997) 257–260.
- [36] Q. Yan, Z. Zhou, X. Zhao, Inward-growing self-assembly of colloidal crystal films on horizontal substrates, *Langmuir* 21 (7) (2005) 3158–3164.
- [37] P.A. Kralchevsky, N.D. Denkov, Capillary forces and structuring in layers of colloid particles, *Curr. Opin. Colloid Interface Sci.* 6 (4) (2001) 383–401.
- [38] F. Zeng, Z. Sun, C. Wang, B. Ren, X. Liu, Z. Tong, Fabrication of inverse opal via ordered highly charged colloidal spheres, *Langmuir* 18 (24) (2002) 9116–9120.
- [39] Q.N. Pham, B. Shao, Y. Kim, Y. Won, Hierarchical and well-ordered porous copper for liquid transport properties control, *ACS Appl. Mater. Interfaces* 10 (18) (2018) 16015–16023.
- [40] Z. Lu, I. Kinefuchi, K.L. Wilke, G. Vaartstra, E.N. Wang, A unified relationship for evaporation kinetics at low Mach numbers, *Nat. Commun.* 10 (1) (2019) 1–8.
- [41] Q. Wang, R. Chen, Ultrahigh flux thin film boiling heat transfer through nanoporous membranes, *Nano Lett.* 18 (5) (2018) 3096–3103.
- [42] H. Lee, T. Maitra, J. Palko, D. Kong, C. Zhang, M.T. Barako, Y. Won, M. Asheghi, K.E. Goodson, Enhanced heat transfer using microporous copper inverse opals, *J. Electron. Packag.* 140 (2) (2018) 020906.
- [43] N.S. Dhillon, J. Buongiorno, K.K. Varanasi, Critical heat flux maxima during boiling crisis on textured surfaces, *Nat. Commun.* 6 (1) (2015) 1–12.
- [44] A.R. Betz, J. Jenkins, D. Attinger, Boiling heat transfer on superhydrophilic, superhydrophobic, and superbiphilic surfaces, *Int. J. Heat Mass Transf.* 57 (2) (2013) 733–741.
- [45] Q.N. Pham, S. Zhang, S. Hao, K. Montazeri, C.-H. Lin, J. Lee, A. Mohraz, Y. Won, Boiling heat transfer with a well-ordered microporous architecture, *ACS Appl. Mater. Interfaces* 12 (16) (2020) 19174–19183.
- [46] V.P. Carey, *Liquid Vapor Phase Change Phenomena: an Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer Equipment*, CRC Press, 2018.
- [47] Q.N. Pham, S. Zhang, L. Cheng-Hui, S. Hao, Y. Won, Boiling heat transfer performance of three-dimensionally ordered microporous copper with modulated pore diameters, in: 2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, 2018, pp. 1–6.
- [48] D.A. Kofke, Direct evaluation of phase coexistence by molecular simulation via integration along the saturation line, *J. Chem. Phys.* 98 (5) (1993) 4149–4162.
- [49] Y. Nam, Y.S. Ju, Bubble nucleation on hydrophobic islands provides evidence to anomalously high contact angles of nanobubbles, *Appl. Phys. Lett.* 93 (10) (2008) 103115.
- [50] F.A. Dullien, *Porous Media: Fluid Transport and Pore Structure*, Academic Press, 2012.
- [51] K. Pruess, Y. Tsang, On two-phase relative permeability and capillary pressure of rough-walled rock fractures, *Water Resour. Res.* 26 (9) (1990) 1915–1926.
- [52] K.S. Udell, Heat transfer in porous media heated from above with evaporation, condensation, and capillary effects, *J. Heat Transf.* 105 (3) (1983) 485–492.
- [53] C. Byon, S.J. Kim, Effects of geometrical parameters on the boiling limit of bi-porous wicks, *Int. J. Heat Mass Transf.* 55 (25–26) (2012) 7884–7891.
- [54] Z. Lu, K.L. Wilke, D.J. Preston, I. Kinefuchi, E.F. Chang-Davidson, E.N. Wang, An ultra-thin nanoporous membrane evaporator, *Nano Lett.* 17 (10) (2017) 6217–6220.