

Optimization of hybrid wick structures for extreme spreading in high performance vapor chambers

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ABSTRACT

The demand for increasingly aggressive heat spreading in high power electronics has pushed the limits of existing vapor chamber wick technology. For optimal thermal performance, a vapor chamber wick must be able to provide enough capillary pressure to sustain fluid delivery while still maintaining a low thermal resistance. To minimize thermal resistance and increase capillary forces, small feature sizes are typically desired near the hotspot. The low porosity and permeability of these small feature size regions, however, often provide too much fluid resistance to sustain capillary driven flow through the entire wick. Hybrid and biporous wicks have therefore emerged as promising solutions where high permeability, high thermal resistance structures are used to feed fluid to low permeability, low thermal resistance structures located above the hotspot. In this study, a novel hybrid wick structure is investigated that increases the total heat transfer rate by repurposing typically low thermal performance fluidic routing structures as additional extended areas for heat transfer. A coupled semiempirical heat transfer and numerical fluid flow model is developed to optimize the total heat transfer and pressure drop for a variety of wick geometries and material properties.

KEYWORDS: vapor chambers, porous materials, hybrid wick

NOMENCLATURE

A	area	.....	[cm ²]
d	diameter	.....	[μm]
h	heat transfer coefficient	.....	[W/m ² -°C]
H	height	.....	[μm]
k	thermal conductivity	.....	[W/m-°C]
K	permeability	.....	[m ²]
t	thickness	.....	[μm]
T	temperature	.....	[°C]
q	heat flux	.....	[W/cm ²]
Q	power	.....	[W]
W	width	.....	[μm]

Greek symbols

ϕ	porosity	.....
Φ	area ratio	.....
ψ	contact angle	.....
θ	temperature excess	 [°C]

Subscripts

r	routing properties
CIO	CIO properties
∞	ambient

INTRODUCTION

After decades of increasing device density in integrated circuits, the performance growth of high power electronics is now predominantly limited by thermal design. Extreme heat dissipation requirements cause devices to exceed reliable operating temperatures, and simultaneous demands in both packaging and form factor necessitate a new class of aggressive heat spreaders. Vapor chambers are promising two-phase, passive cooling solutions that have demonstrated much higher effective thermal conductivities than traditional solid heat spreaders [1].

Vapor chamber wick materials with smaller pore sizes have demonstrated advantages such as high capillary pressures, minimal conduction thermal resistances, and increased effective heat transfer areas [2]. The low permeability of these materials, however, prevents their usage as the sole wicking material across large length scales. Hybrid and biporous wicks resolve these tradeoffs by utilizing combinations of different porous materials and pore sizes to achieve simultaneous optimization of multiple wick performance parameters [3–10]. Lewis et al. fabricated an all polymer vapor chamber with a graded micropillar wick to optimize the pressure drop in different regions of the device [11]. Weibel et al. [12] performed a numerical study of carbon nanotubes (CNTs) integrated with sintered copper feeder structures and found that the feeder structures were able to significantly lower the total pressure drop. Coso et al. studied biporous wicks consisting of microscale pin fins separated by microchannels and observed an overall increase in heat transfer coefficient with smaller pore sizes [13].

The maximum possible heat dissipation from hybrid wicks remains limited in part by the 2D nature of the designs, however, as a certain amount of the total wick area must be devoted to lower thermal performance, higher fluidic performance structures. This paper therefore presents a novel hybrid wick design that repurposes the fluidic routing structures as extended surface areas for heat transfer through an additional coating of high heat transfer performance material. The proposed structure consists of regions of high thermal performance copper inverse opals (CIOs) interspersed with sintered copper fluidic routing coated with an additional layer of CIOs. CIOs are microporous metal films fabricated with templated electrodeposition, where close-packed, sacrificial spheres are used to define the size and shape of the CIO pores. The resulting structures are highly regular with precisely sized pores that can generate significant capillary suction within the wick, and 5 μm CIOs have recently experimentally demonstrated the capability of supporting heat fluxes exceeding 1200 W/cm² with less than 10 °C superheat [14]. CIOs therefore have great potential as high performance vapor chamber wick materials for high heat flux applications, but the high viscous resistance associated with pore sizes as small as 5 μm requires the addition of the sintered copper routing.

A modeling methodology is developed in order to perform a

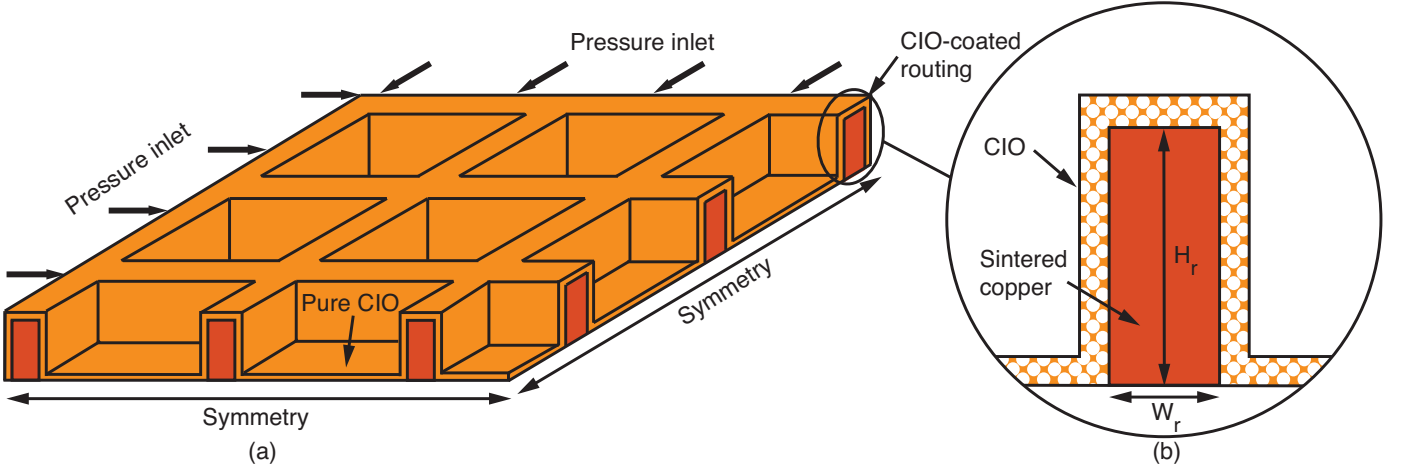


Figure 1: (a) Quarter geometry view of an example checkered wick pattern with pure CIO regions fed by sintered copper routing structures. (b) Closeup view of routing with CIO coating.

coupled heat transfer and fluidic analysis of the proposed hybrid wick. The total heat transfer rate for each wick configuration is calculated with a semiempirical model based on the experimental data from Palko et al. for capillary-fed boiling in CIOs [14]. The heat transfer rate then specifies the mass transfer boundary condition for a numerical pressure drop model. Using these coupled models, the total heat transfer rate and pressure drop are analyzed in subsequent sections for a variety of wick parameters and material properties to assess the effectiveness of the extended routing surfaces and determine optimal configurations.

NUMERICAL MODEL

The hybrid wick structure under consideration is shown in Fig. 1. Uniformly sized squares of pure CIO regions are fed by CIO-coated sintered copper routing structures (close up view shown in Fig. 1(b)) to form a checkered grid pattern. The checkered pattern design acts to reduce the total wick pressure drop by decreasing the required fluid wicking distance across the high viscous resistance, pure CIO regions. The simplicity and uniformity of the structure makes it a good candidate for parametric studies, as the complete geometry can be defined through only a few parameters. For the present analyses, the independent parameters considered are the pure CIO region area to total wick area ratio, Φ , and the checkered grid pattern discretization. Φ defines the total area covered by the pure CIO squares, and the pattern discretization defines the size and number of each individual square. The size of the squares then determines the width of the routing, W_r . The total wick area is defined as 1 cm^2 to target a 1 cm^2 hot spot, and only a quarter of the full model is simulated by taking advantage of symmetry conditions. The height of the sintered copper routing, H_r , is fixed at $500 \text{ }\mu\text{m}$. The thickness of the CIO layer for both the pure CIO regions and the routing coating, t_{CIO} , is held fixed at $50 \text{ }\mu\text{m}$.

The sintered copper routing is assumed to consist of $50 \text{ }\mu\text{m}$ diameter particles with a porosity of 0.66. The permeability of the sintered copper routing K_r is calculated as $4.15 \times 10^{-11} \text{ m}^2$ from existing correlations for packed sintered spheres [15], where

Table 1: Model input parameters.

Parameter	Value	Unit
H_r	500	μm
d_r	50	μm
K_r	4.15×10^{-11}	m^2
ϕ_r	0.66	-
t_{CIO}	50	μm
d_{CIO}	5	μm
K_{CIO}	1.09×10^{-12}	m^2
ϕ_{CIO}	0.7	-

$$K_r = \frac{d_r^2 \phi_r^3}{150(1 - \phi_r)^2} \quad (1)$$

and d_r and ϕ_r are the particle diameter and porosity, respectively. The thermal conductivity of the routing used in the heat transfer analysis presented in a later section is approximated simply as a function of porosity as

$$k_r = (1 - \phi_r)k_{cu} \quad (2)$$

where k_{cu} is the thermal conductivity of pure copper.

The CIO pore size and porosity are chosen as $5 \text{ }\mu\text{m}$ and 0.7, respectively, to match with the properties of the samples used in the study by Palko et al. that were able to dissipate over 1200 W/cm^2 with capillary-fed boiling [14]. The permeability is taken from experimental results for the given pore size and porosity as $1.09 \times 10^{-12} \text{ m}^2$ [16]. The working fluid is assumed to be water with thermophysical properties evaluated at $100 \text{ }^\circ\text{C}$. Table 1 provides a summary of the sintered copper and CIO properties used in subsequent calculations.

Heat transfer analysis

Based on experimental data for capillary-fed boiling in CIOs and sintered copper, CIOs demonstrate much higher heat dissipation rates at low ($< 10 \text{ }^\circ\text{C}$) superheats [10, 14, 17]. Heat transfer due to boiling within the sintered copper routing is therefore

assumed to be negligible at low superheats compared to heat transfer due to boiling in the CIOs, and the CIO-coated sintered copper routing is instead modeled as an extended surface for heat transfer. Fig. 2 shows the experimental data reproduced from Palko et al. for heat flux q versus superheat θ obtained with a $5\ \mu\text{m}$ diameter, $40\ \mu\text{m}$ thick CIO sample. This data provides a conservative estimate of the possible heat transfer performance with a $50\ \mu\text{m}$ thick layer considered in this study. θ is defined as the temperature excess above $T_{sat} = 100^\circ\text{C}$. Note that the experimental data is obtained for capillary-fed boiling in ambient conditions, resulting in a finite heat flux at $\theta = 0$ due to evaporative heat transfer at temperatures below T_{sat} . This evaporative component is removed in the subsequent calculations to represent a vapor chamber working environment of pure vapor. For the heat transfer model used in the present analyses, a superheat dependent effective heat transfer coefficient, h , is extracted from the data for q versus θ as

$$h(\theta) = \frac{q}{\theta} \quad (3)$$

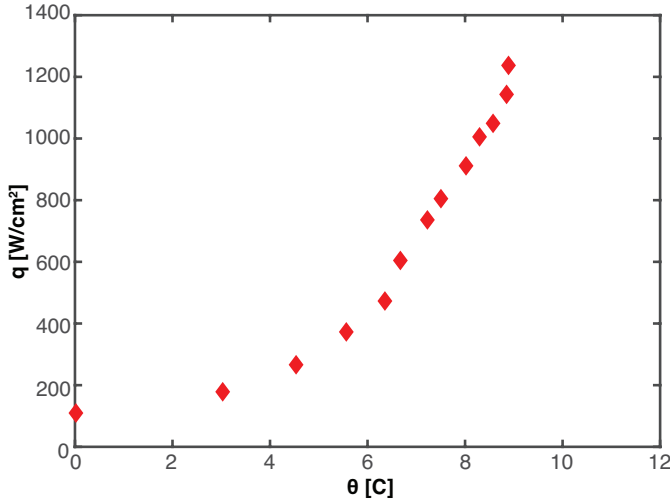


Figure 2: Experimental data for heat flux versus superheat for capillary-fed boiling in CIOs reproduced from Palko et al. [14].

In the subsequent analyses, a fixed superheat of θ_B is assigned to the base of the wick. Due to the high heat transfer coefficients associated with boiling, the base temperature distribution is assumed to be uniform. The heat transfer rate from the pure CIO regions can be easily calculated from the experimental data for q versus θ , but the heat transfer rate from the CIO-coated sintered copper routing structures requires additional analysis. Since the heat transfer due to boiling in the sintered copper routing is assumed negligible compared to the heat transfer from the CIOs at the low superheats considered, and the routing is treated as an extended surface with a temperature dependent heat transfer coefficient due to boiling in the CIO coating.

The temperature distribution in the wick is assumed to vary along the length of the routing only, making the routing essentially equivalent to a one-dimensional fin. An energy balance on a differential routing element in the z -direction gives the fol-

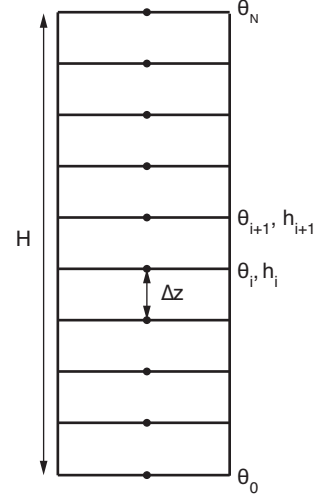


Figure 3: Example central difference discretization scheme for a simple rectangular fin.

lowing relation for the temperature distribution

$$k_r A_r \frac{d^2 T}{dz^2} - h P_r (T - T_\infty) = 0 \quad (4)$$

where k_r is the thermal conductivity of the routing, A_r is the cross sectional area of the routing, P_r is the wetted perimeter of the routing, and T_∞ is the ambient temperature. Taking T_∞ to be $T_{sat} = 100^\circ\text{C}$, the equation can be written in terms of θ as

$$k_r A_r \frac{d^2 \theta}{dz^2} - h P_r \theta = 0 \quad (5)$$

Since $h = h(\theta)$, a closed form solution to the equation is not easily obtainable. A central difference discretization method is therefore used to generate a system of non-linear equations that are solved with an iterative process to find the temperature excess at each node in the system. Fig. 3 shows an example discretization scheme for a simple rectangular fin structure. For a system with N nodes, the zeroth node refers to the node at the base of the fin with a prescribed temperature excess of θ_B , and the N th node represents the node at the tip of the fin. Discretizing Eqn. 5 about a node i gives the following relation for a general fin applicable to all interior nodes ranging from $i = 2$ to $i = N - 1$ as

$$\theta_{i-1} - (2 + \Delta z^2 \frac{h_i P}{k A}) \theta_i + \theta_{i+1} = 0 \quad (6)$$

Δz is the discretization step size, defined as H/N . To enforce the boundary condition of a prescribed temperature excess at the fin base, the equation for node $i = 1$ reduces to

$$-(2 + \Delta z^2 \frac{h_1 P}{k A}) \theta_1 + \theta_2 = -\theta_B \quad (7)$$

To enforce a convective tip boundary condition at the end of the fin, and the fin equation discretization around the N th node gives

$$2\theta_{N-1} - (2 + \frac{2\Delta z h_N}{k} + \frac{\Delta z^2 h_N P}{k A}) \theta_N = 0 \quad (8)$$

Combining the two boundary conditions with the interior node equations gives a system of N nonlinear equations with N unknowns, since h_i can be expressed as a function of θ_i . These equations are directly applied to the routing structure after substituting the appropriate material properties and parameters, then solved iteratively with the Trust Region Dogleg implementation in MATLAB for the temperature excess at each node [18]. The heat flux at each node is calculated from the temperature excess based on the empirical data for q versus θ for capillary-fed boiling in the CIOs, and the total heat transfer is found by summing the heat flux contribution from each node.

Fluid routing and pressure drop

The maximum supportable viscous pressure drop in a given wick configuration is limited by the supplied capillary pressure, where

$$P_c = \frac{2\sigma \cos(\psi_c)}{r_p} \quad (9)$$

σ is the surface tension of the working fluid, ψ_c is the solid-liquid contact angle, and r_p is the pore radius of the wick material. Assuming an r_p equivalent to the pore radius of the CIO structure and $\psi_c = 70^\circ$ from data for water on copper at 100°C [19], the maximum generated capillary pressure to drive fluid flow within the wick is 10.3 kPa.

The total pressure drop within the wick is calculated with a numerical model by treating the sintered copper and CIOs as effective porous media represented by their respective permeabilities and porosities. A quarter of the geometry is simulated using symmetry boundary conditions. Each wick geometry considered is discretized with a hexahedral mesh, and mesh independent results are ensured by performing a mesh independency study for each case. For each mesh, moving to a finer discretization resulted in a less than 0.2% difference in the total pressure drop. The governing equations for steady, incompressible flow in porous media are solved throughout the geometries using the commercially available ANSYS®Fluent finite-volume CFD solver. The pressure-velocity coupling is treated using the SIMPLE algorithm, and a second order numerical scheme is used for all discretization schemes. Pressure inlet boundary conditions are specified at the outer faces of the wick, and separate mass fluxes are specified at the base of the pure CIO regions and sintered copper routing regions based on the total calculated heat transfer rate for each component through the relationship

$$\dot{m} = \frac{Q}{h_{fg} A_{base}} \quad (10)$$

Note that A_{base} for the routing represents the total base area footprint only, and not the total extended surface area. The calculated mass fluxes represent mass sink terms due to boiling phase change within the wick, which is assumed as the only mode of mass transfer. The mass flux assigned at the base of the sintered copper routing includes the mass transfer due to boiling in the extended surface CIO coating, representing an upper bound on the total pressure drop within the structure.

RESULTS AND DISCUSSION

Effect of routing discretization

To explore the effect of different grid discretizations for the checkered wick pattern, the pure CIO region area to total wick

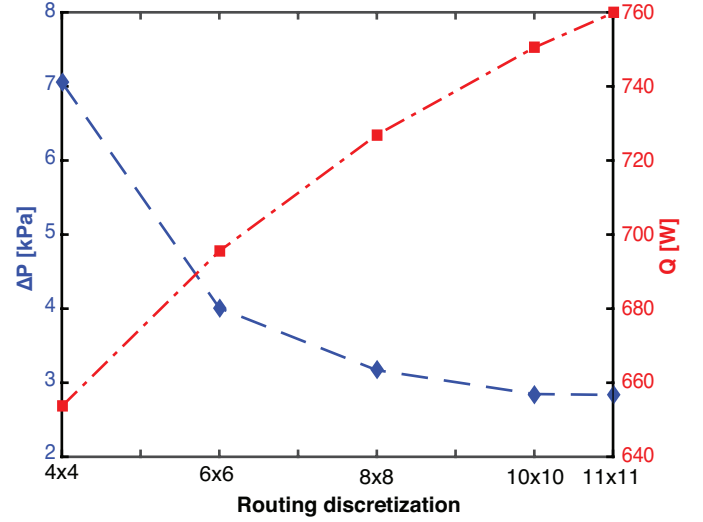


Figure 4: Pressure drop and total heat transfer rate dependence on checkered pattern grid discretization for $\Phi = 0.5$.

area ratio, Φ , is held fixed at 0.5. The pure CIO grid discretization is varied from a 4x4 pattern of 16 squares to an 11x11 pattern of 121 squares. Since Φ is fixed, increasing the number of squares decreases the width of the routing channels, W_r . W_r is limited in this study to a minimum value of $150\ \mu\text{m}$, as smaller widths begin to approach the particle size of the sintered copper. The 11x11 pattern results in a W_r of $152\ \mu\text{m}$, and is therefore the maximum possible grid discretization for a Φ of 0.5.

Fig. 4 shows the total pressure drop and heat transfer rate for each grid discretization considered with an assigned θ_B of 8.7°C . With a fixed base superheat of 8.7°C , the calculated dissipated heat flux from the pure CIO regions with the semiempirical model is equivalent to $1000\ \text{W}/\text{cm}^2$, or 500 W total. The total heat transfer rate from the routing structures is calculated with the extended surface heat transfer analysis described in the previous section, and the total heat transfer rate reported is then the sum of the two values. As seen in Fig. 4, the total heat transfer rate increases with increasing grid discretization. Since the heat transfer from the pure CIO regions remains the same for all discretizations, this increase in total heat transfer can be attributed to an increase in the total extended surface area from the routing as the grid discretization becomes finer. The total pressure drop decreases with increasing grid discretization, though there appears to be a finite limit to the lowest achievable pressure drop for the given Φ . Moving from the 4x4 pattern to the 6x6 pattern decreases the total pressure drop from 7.1 kPa to 4.0 kPa, an improvement of approximately 43 %, but moving from a 10x10 pattern to an 11x11 pattern results in a less than 0.5 % improvement. Therefore, even if a smaller routing width were allowed, moving to a finer discretization would likely have a negligible effect on lowering the total pressure drop.

Figure 5 shows the pressure contours at the base of the wick for each pattern discretization. As seen in the contours, the majority of the pressure drop in the 4x4 case occurs in the pure CIO regions. Since only a quarter of the geometry is simulated, the maximum pressure drop occurs in the bottom right CIO square as the fluid flow approaches the center of the equivalent full

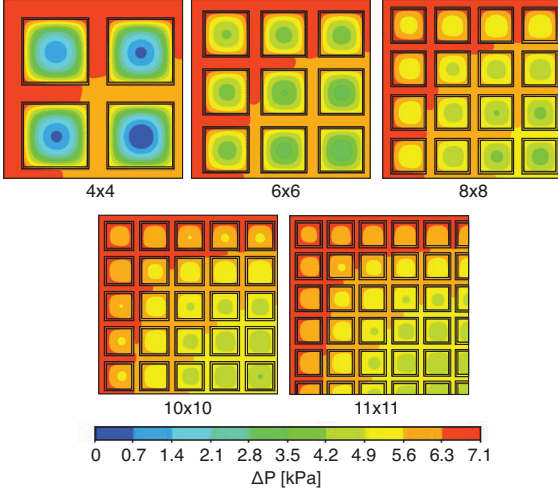


Figure 5: Pressure contours for each checkered pattern grid discretization with $\Phi = 0.5$. Only a quarter of the geometry is shown due to symmetry.

geometry. As the grid discretization is increased and the area of each individual pure CIO region becomes smaller, the pressure drop across the individual pure CIO regions decreases. The pressure drop in the routing, however, increases due to the narrower routing channels and minor losses that result from the higher number of 90° bends along the fluid flow path. These combined effects lead to the contours shown for the 10x10 and 11x11 cases, where the pressure drops across the wick begin to approach uniform radial distributions.

Effect of pure CIO area ratio

To assess the effect of varying the pure CIO to total wick area ratio, Φ , two additional area ratios were considered of $\Phi = 0.4$ and $\Phi = 0.6$. With $\Phi = 0.4$, a 14x14 grid discretization pattern is possible without reaching the routing width limit of $150 \mu\text{m}$. For $\Phi = 0.6$, the finest possible grid discretization is an 8x8 pattern. The resulting routing widths for each grid discretization and area ratios of $\Phi = 0.4 - 0.6$ are tabulated in Table 2.

Table 2: Routing width, W_r , for various grid discretizations and area ratios Φ .

		Φ			
		0.4	0.5	0.6	
Grid Discretization	4x4	655	506	371	μm
	6x6	439	333	236	μm
	8x8	320	237	162	μm
	10x10	243	175	-	μm
	11x11	-	152	-	μm
	14x14	152	-	-	μm

Figure 6 shows the total heat transfer rate versus pressure drop for $\Phi = 0.4, 0.5$, and 0.6 with grid discretizations ranging from 4x4 to 14x14, 11x11, and 8x8 patterns, respectively. The total pressure drops in all cases remain below the capillary limit of 10.3 kPa, and the 4x4 pattern with $\Phi = 0.6$ has the high-

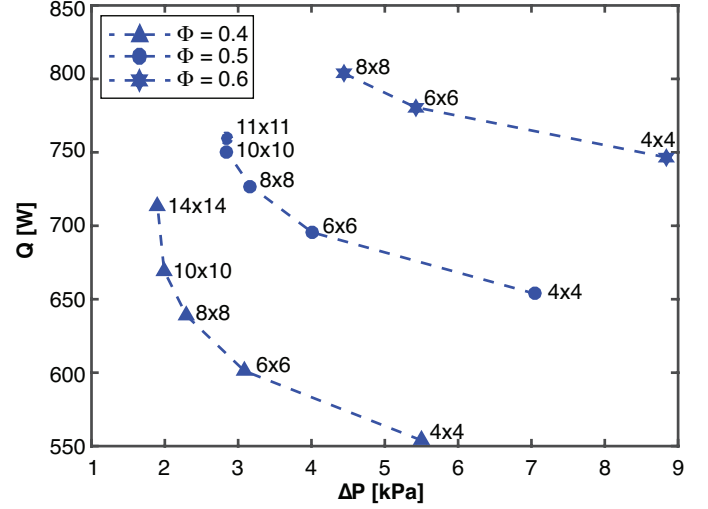


Figure 6: Total heat transfer rate versus pressure drop for various grid discretizations with $\Phi = 0.4 - 0.6$.

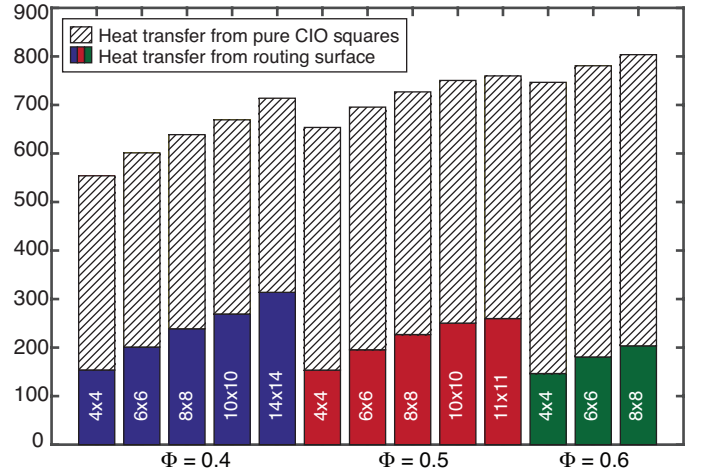


Figure 7: Total heat transfer rate for various grid discretizations and $\Phi = 0.4 - 0.6$ broken down by pure CIO and extended surface components.

est pressure drop of 8.8 kPa. For the same grid discretization, the pressure drop and total heat transfer rate decrease with decreasing Φ . As observed for the cases where $\Phi = 0.5$, the pressure drop for the cases where $\Phi = 0.4$ approaches a finite lower limit as the grid discretization is increased. The improvement in pressure drop diminishes as the grid discretization becomes finer, and the pressure drop across the 14x14 case is only 4.5% lower than the 10x10 case. The minimum pressure drop for the cases where $\Phi = 0.6$ is limited by the routing width constraint, and the large reduction in pressure drop between the 6x6 and 8x8 cases makes it likely that further increasing the grid discretization could still appreciably decrease the pressure drop.

Figure 7 shows the total heat transfer rates for the various grid discretizations considered for each Φ value broken down into the pure CIO and extended surface components. The maximum heat transfer rates for $\Phi = 0.4, 0.5$, and 0.6 occur at the maximum considered grid sizes of 14x14, 11x11, and 8x8, respec-

tively. Cases with $\Phi = 0.4$ demonstrate the highest heat transfer rates from the extended routing surface component only, but cases with $\Phi = 0.5$ and $\Phi = 0.6$ are able to achieve higher total heat transfer rates due to higher heat transfer rates from the pure CIO regions. The total pressure drop increases significantly with increasing Φ , however, so it is advantageous to obtain as much of the total heat transfer from the extended surface routing structures as possible. An optimal wick design would therefore have the lowest possible value of Φ that could still meet the desired heat flux requirements. As an example, the 10x10 wick design with $\Phi = 0.5$ can dissipate approximately the same amount of heat as the 4x4 design with $\Phi = 0.6$ (750.5 W versus 746.6 W), but the total pressure drop for the design with $\Phi = 0.5$ is approximately 47% lower than the design with $\Phi = 0.6$.

Effect of routing permeability

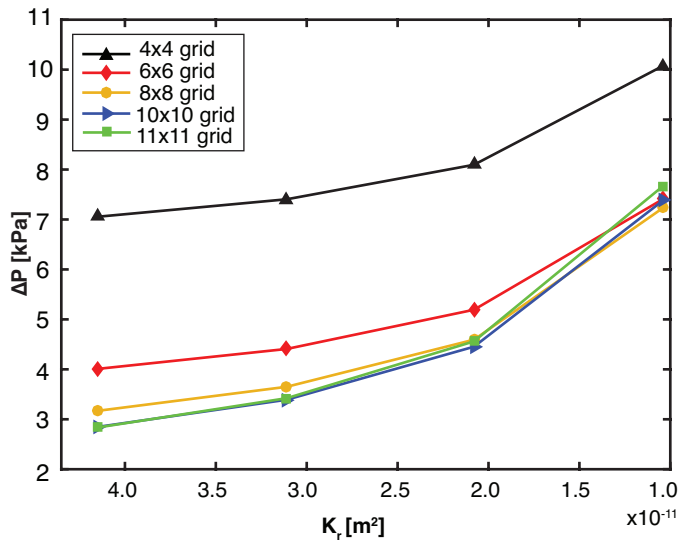


Figure 8: Variation in pressure drop with routing permeability for various grid discretizations with $\Phi = 0.5$.

To assess the sensitivity of the wick designs to the routing material properties, a series of simulations were run with varying permeabilities for the sintered copper routing. Φ is fixed at 0.5, and 5 different grid discretizations of 4x4, 6x6, 8x8, 10x10, and 11x11 patterns are considered. The routing permeability for each case is varied from the original sintered copper value of $4.15 \times 10^{-11} \text{ m}^2$ to $1.04 \times 10^{-11} \text{ m}^2$, 0.25 times the original value. Figure 8 shows the variation in total pressure drop with routing permeability for each case. As seen in Fig. 8, designs with finer grid discretizations are more sensitive to variations in the routing permeability. The difference in pressure drop among different grid discretizations decreases as the permeability of the routing is decreased, and finer grid discretizations actually have relatively higher pressure drops in certain cases. As the most extreme case, the 11x11 grid has the lowest pressure drop out of all cases for the highest permeability value considered, but shows relatively poorer performance as the permeability value is decreased and has the second highest pressure drop out of all of the cases at the lowest permeability value considered. Therefore, a finer grid discretization may not always provide the best

pressure drop performance depending on the permeability of the routing. If the permeability of routing is too low, the increase in routing viscous resistance caused by moving to finer grid discretizations becomes larger than the achievable reduction in the CIO viscous resistance. This is important to consider when designing wicks for high heat flux applications, as boiling within the wick can significantly lower the effective permeability of the routing due to the nucleation of vapor bubbles. The pressure drops for the cases considered here still fall below the capillary limit even if the effective permeability of the routing is reduced to only 25% of the original value, but wick design for higher heat fluxes may require a careful understanding of the expected reduction in routing permeability due to the presence of boiling within the wick.

CONCLUSION

The pressure drop and heat transfer in a novel hybrid wick structure consisting of a checkered combination of pure CIOs and CIO-coated sintered copper routing structures were evaluated for a range of different wick parameters. Using a semiempirical heat transfer model based on existing data for capillary-fed boiling in CIOs, the sintered copper structures are found to act as effective extended surfaces for heat transfer. A large portion of the heat dissipation still occurs in the pure CIO regions, however, and wicks with higher pure CIO to total wick area ratios are able to achieve higher total heat transfer rates. The total pressure drop across the wick also increases with increasing area ratios, so an optimal wick design should utilize the lowest pure CIO to total wick area ratio possible. If the routing permeability is high enough that the viscous pressure drop within the routing is low compared to the pressure drop in the pure CIO regions, then moving to finer grid discretizations can lower the total pressure drop within the wick. If the effective permeability of the routing material approaches the permeability of the CIO regions, however, the additional routing resistances introduced through finer grid discretizations can actually increase the total pressure drop.

The highest performing wick design considered in this paper is able to dissipate over 800 W/cm^2 with a pressure drop of 4.4 kPa, well below the capillary limit of the device. The sintered copper CIO coating is able to regain a significant amount of the heat transfer lost to the routing area footprint, reducing the tradeoffs between heat dissipation and pressure drop often introduced by integrating fluid routing. Future designs can be even further optimized by considering different routing materials, geometries, and patterns other than the checkered grid considered here.

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