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Hydraulic and thermal characteristics of a vapor venting two-phase microchannel heat exchanger

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ABSTRACT

In the present work we design, model and experimentally characterize a two-phase vapor venting parallel microchannel heat exchanger capped with a 220 nm pore, hydrophobic PTFE membrane that vents the vapor phase into separate vapor transport channels. We compare the performances of a traditional non-venting heat exchanger and the vapor-separating version operating at heat fluxes of up to 820 kW/m^2 and water mass fluxes of between 102 and 420 $kg/s\,m^2$. We find ∼60% improvement in the normalized pressure drop and up to 4.4 °C reduction in the average substrate temperature between the control and vapor venting device under similar operating conditions.

1. Introduction

Effective thermal management is essential for the development of next generation computational systems. The International Technology Roadmap for Semiconductors (ITRS) predicts total power dissipation requirements of over 200 W per package, junction temperatures less than 70 °C and thermal resistances less than 0.2 °C/W [1]. Reliability, size, noise and power consumption of the cooling solution also need to be considered for practical applications. The introduction of 3D IC architectures also requires that the cooling solution be integrated within the die stacks [2,3]. Traditional cooling solutions such as fans and heat pipes are reaching their limit for providing high performance cooling while meeting the variety of geometrical and cost constraints.

Liquid cooling using microfabricated structures is promising owing to small dimensions and very high thermal conductances as demonstrated by Tuckerman and Pease's seminal work using forced liquid convection in silicon microchannels to dissipate 790 W/cm^2 and obtain a thermal resistance of less than 0.1 °C/W [4]. However, single-phase liquid cooling using microchannels [4–7] require large pressure heads to deliver the coolant at a rate such that the temperature non-uniformity across the chip, caused due to sensible heating of the fluid, is maintained below a required level. The large pressure head requires larger pumps and more power consumption, which increases the size and cost of the overall system. One widely researched solution to reduce this pressure head while providing large heat flux dissipation is two-phase convection in microchannels [8–11]. The large latent heat of vaporization enables comparably smaller flow rates than single-phase counterparts. Phase change also provides high heat transfer coefficients, leading to smaller thermal resistances, and may also improve temperature uniformity by maintaining the working fluid at the saturation temperature. Despite these advantages and the ease of fabrication of microchannels in a variety of substrates, two-phase cooling faces major technical challenges that limit commercial application.

The growth and advection of vapor bubbles in microchannels leads to an increase in the pressure-drop due to the added friction of the two-phase flow and the acceleration of the fluid during vaporization. This increase in pressure drop during two-phase flow in a variety of tubes and channels has been extensively studied and the fundamental aspects are discussed in several texts [12–14]. The large increase in the two-phase pressure drop with the vapor quality necessitates a larger, more power consuming pump, negating some of the benefit of using two-phase cooling over single-phase cooling. The increase in pressure results in an increase in the saturation temperatures and delays the onset of boiling; this manifests itself as an added thermal resistance in addition to the conductive and convective thermal resistances.

The large rise in the pressure drop also leads to single and multi-channel instabilities. Wu and Cheng [15] studied flow instabilities in parallel, 186 μm silicon microchannels and discuss the

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existence of multiple types of instabilities that occur at different mass flux and heat input rate combinations. Low-mass flux, high-heat flux conditions were found to result in large fluctuations in pressure-drop and wall temperatures. Static Ledinegg instabilities in parallel microchannel heat exchangers results in boiling in only a few channels leading to redistribution of liquid to the cooler single-phase channels and flow starvation in the hotter two-phase channels [16]. This problem can also manifest itself in larger systems such as server racks with blades being liquid cooled in parallel; boiling in heat exchangers on the hottest blades would result in flow mal-distribution at the rack level with less coolant being delivered to where it is needed the most.

Zhou et al. [17] proposed vapor removal through a porous hydrophobic membrane in order to mitigate some of the problems observed during flow boiling in microchannels. A schematic of the vapor venting heat exchanger discussed in this paper is shown in Fig. 1. The key component in the heat exchanger is the porous hydrophobic membrane that, through capillary forces, prevents the liquid from leaking out of the device but provides minimal flow resistance to the vapor phase. The vapor flows through the membrane into a separate set of parallel channels on the other side of the membrane. The vapor can then be reintroduced into the coolant flow downstream of the microchannels where the impact of having two-phase flow is less significant to the system. The removal of the vapor phase is predicted by both compact 1D/2D simulations (discussed in Section 4) and full 3-D [18] FLUENT (ANSYS Inc.) simulations to significantly improve the pressure drop, lower device temperatures, and delay dry-out.

Previous experimental work has focused on the separation of a dissolved gas from a gas–liquid two-phase flow. Passive gas venting from water and methanol solutions has been investigated by Meng et al. [19,20] for degassing applications in Direct Methanol Fuel Cells (DMFC), where CO_2 formed at the anode inhibits delivery of the methanol to the fuel cell. Active degassing was demonstrated by Yang et al. [21] for portable dialysis applications where ultrasonic transduction was used to coalesce dissolved gas in the working fluid, which was then removed through hydrophobic treated side channels.

In this paper we focus on the design and characterization of copper multi-microchannel vapor venting heat exchangers attached to a silicon thermal test chip. The heat exchangers were designed to operate at temperatures up to 125 °C and gage pressures of 150 kPa (20 psi) and were able to dissipate heat fluxes of 820 kW/m^2 for water mass fluxes ranging from 102 kg/s m^2 to 420 kg/s m^2. The key goal of this work was to experimentally characterize the hydraulic, thermal and venting performance of the fabricated venting heat exchanger and to compare the findings against experimental results from a non-venting heat exchanger and a compact two-phase vapor-venting flow model. Improved hydraulic and thermal performance is an important contribution to the field of two-phase heat exchangers and opens the way for increased adoption of practical two-phase cooling for electronics.

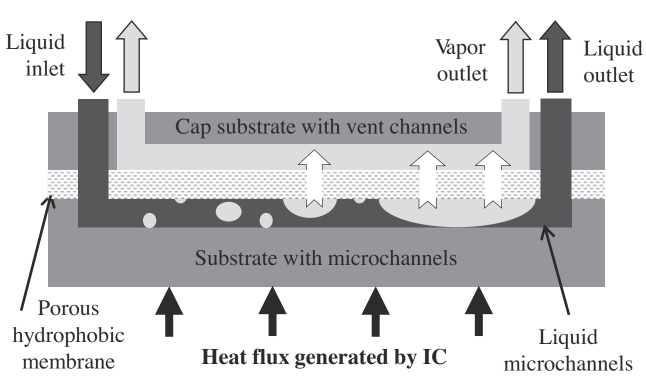

Fig. 1. Schematic of a vapor venting heat exchanger showing the three main components: the two-phase microchannels, the vapor vent channels and the porous hydrophobic membrane. The membrane separates the vapor phase from the two-phase mixture and transports it to the vent channel.

Heat exchanger design and fabrication is discussed in the following section, followed by the experimental setup and data reduction in Section 3. Section 4 provides details on the two-phase flow model and Section 5 presents the experimental results and discussion of the findings.

2. Design of the vapor separating microchannel heat exchanger

2.1. Venting membrane

The porous hydrophobic membrane is the key component in the vapor venting heat exchanger and enables the separation and transport of the vapor phase. Pore size, membrane thickness, intrinsic permeability, hydrophobicity, and thermo-mechanical stability are all important aspects that need to be considered when selecting or fabricating the phase separation membrane. The liquid leakage pressure (or breakthrough pressure) for the membrane is determined by the Young–Laplace equation, Eq. (1), and varies inversely with the pore diameter, d_{pore}, and directly with the cosine of the advancing contact angle, $\theta_{adv,max}$, and the surface tension, σ [19].

$$\Delta P_{leak} = \frac{4 \cdot \sigma \cdot \cos(\pi - \theta_{adv,\max})}{d_{pore}} \tag{1}$$

The total pressure drop across the membrane for single-phase, viscous, laminar flow, with Reynolds and Knudsen numbers less than 1, is given by Darcy Law, Eq. (2), where t_{mem} is the thickness of the membrane, G_{mem}, the mass flux, and μ and ρ, the dynamic viscosity and density of the fluid being transported. The intrinsic permeability, κ, is an intensive property of the porous material and is a measure of the ease of viscous fluid flow through the porous material on application of a normal pressure gradient

$$\Delta P_{mem} = G_{mem} \cdot \frac{\mu}{\rho} \cdot \left(\frac{t_{mem}}{\kappa}\right) \tag{2}$$

The ideal membrane for use in two-phase heat exchangers would: (i) possess a leakage pressure, ΔP_{leak}, larger than the maximum operating pressure expected across the membrane and (ii)

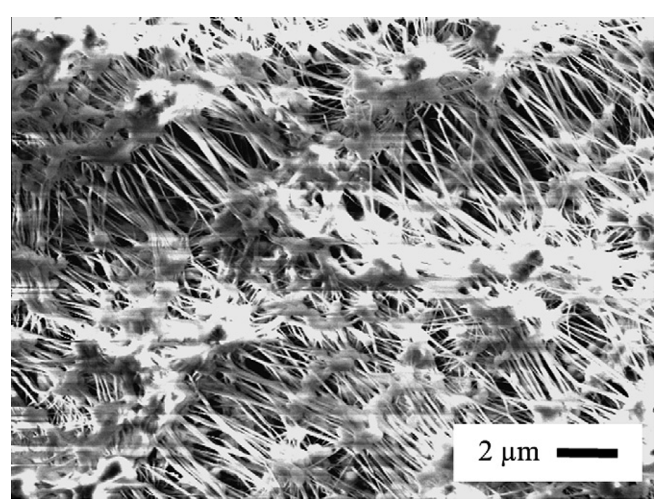

Fig. 2. SEM image of an unused PTFE membrane with manufacturer stated pore diameter of 220 nm and porosity of 0.5–0.8. Surface charging of the non-conductive organic membrane leads to variable brightness in the image and is a non-physical imaging artifact.