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Research paper

Hierarchical biphilic micro/nanostructures for a new generation phase-change heat sink

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HIGHLIGHTS

- A new concept is proposed for designing two-phase heat sinks.
- In this approach, bubbles are pulled away from the heated surface and discharged from the flow.
- Also, the heat sink does not have a liquid outlet thus delivers a 100% vapor quality at all conditions.
- Heat sink operates at 1–2 orders of magnitude lower mass flux compared to other heat sinks.
- An unprecedented heat transfer coefficient is achieved at 100% exit vapor quality.

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ABSTRACT

Pushing the critical heat flux (CHF) limit in boiling has been a century-old challenge. Overcoming this challenge can greatly benefit advancements of myriad devices in which a large quantity of heat must be removed from a small surface. The occurrence of CHF is accompanied by the formation of significant vapor adjacent to the heated surface, such that liquid cannot rewet the surface. Here, a new concept is implemented to ensure that liquid always displaces the vapor near the heated surface. In the new approach, flow is constrained within a hydrophilic microstructure by a hydrophobic vapor-permeable nanostructure. A bubble bounded between the two structures is pulled away from the hydrophilic heated structure and discharged from the flow, thus leading to a fundamental change in CHF dynamics. The performance of a device based on this principle exceeded that of prior studies, with some metrics exhibiting an order of magnitude improvement.

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1. Introduction

The ever-increasing generation of waste heat has become an impediment to advancements and the efficient operation of many electronics and energy applications, such as power and RF electronics, high performance computers, solid-state lasers, and concentrated solar cells. It is now generally acknowledged that the cooling requirements of these applications exceed the heat-removal capability of conventional techniques and new cooling methods must be developed. For example, advancements in high voltage MOSFET and diode chips [1–4], and in GaN MMICs (Monolithic Microwave ICs) [5–8] hinge upon the development of cooling techniques that can remove die-level heat generation rate on the order of 100s W/cm^2. A recent study by Hamann and Klein [9] suggests that a viable chip-scale hot spot cooling approach that can significantly reduce the thermal resistance between the chip-junction and the ambient could greatly reduce the energy demand in Data Centers (DCs), since a large fraction of the energy required in DCs is utilized for cooling electronics. DCs use up to 3% of all the electricity generated in the US [10] and this consumption is increasing at a staggering annual rate of 20% [9] to keep pace with the economic, social, and scientific needs of the rapidly expanding digital world.

The liquid cooling process has been considered a remedy for the thermal management of high heat flux devices. The phase change liquid cooling process, in particular, has received significant attention due to its small streamwise temperature change and low liquid flow rate. There have been numerous efforts focused on maximizing the heat dissipation capability of two-phase devices [11–19]. However, the critical heat flux (CHF), a century-old limit associated with the boiling heat transfer process, has been the main challenge in these efforts. CHF is the highest heat flux a surface can

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exchange with a boiling fluid before the individual bubbles merge into a vapor layer that isolates the surface from the liquid (i.e. prevents surface wetting). This challenge is exacerbated in boiling within confined geometries (e.g. microchannels) since the physics of scale greatly limit the available flow cross-section (which scales with L^2). Small flow cross-sections result in an exceedingly high flow velocity, as the fluid volume increases by 2–3 orders of magnitude as a result of liquid evaporation. Maintaining a stable liquid layer over the heated surface (i.e. wetting the surface) at a high vapor volumetric flux is a challenge that has yet to be overcome.

In the past, the main strategy for increasing the CHF limit has been to enhance the surface wettability by increasing the roughness of a hydrophilic surface [20–24] and, more recently, through the implementation of micro- and nanostructures [25–33]. While these strategies have resulted in some improvements in pool boiling heat transfer [25,26,30,33], a similar benefit has not been realized in microchannels boiling due to limitations in the permeability of micro- and nanostructures [29,31] and surface tension forces to maintain the heated surface wet. In addition, attempts have been made to displace the vapor from the vicinity of the heat transfer surface either through a vapor venting cap [34] or forming a divergent open space over the flow channel [35]. The later approach has shown a promising performance of 281 W/cm^2 at a low flow pressure drop.

Here, a new concept is implemented to fundamentally alter the CHF dynamics. In the following sections, first, fundamentals of the new concept are introduced through an adiabatic visualization study that illustrates the utilization of surface tension and pressure forces to remove bubbles from a surface immediately above the nucleation site, such that the surface is rapidly rewetted. Then, the architecture of a heat sink, designed based on the proposed concept, is introduced and its associated performance characteristics are analyzed.

2. Fundamentals of the new concept

The CHF occurs when the generation of many bubbles and their merger results in formation of a stable vapor layer over much of the heated surface such that the surface rewetting process is prevented. Here, a new approach is implemented to pull the bubbles from above the surface. To demonstrate the working principle of this method, a set of adiabatic visualization tests are conducted. Fig. 1 shows the side view of a flow channel formed between a hydrophilic silicon wall (bottom) and a hydrophobic nanofibrous PTFE wall (top). The sidewalls are made from optically clear polycarbonate. The hydrophobic wall allows gas (or vapor) to exit the channel while constraining the liquid. The channel is filled with water and pressurized. First, air is injected into the channel using a syringe pump at a constant rate (100 ml/h), via a 5 μm through-hole made within the silicon wall (to resemble nucleation from a surface cavity). As seen in Fig. 1a and b, as soon as the bubble touches the hydrophobic surface a contact region forms between the two and expands (i.e. the length of the contact line on the hydrophobic surface increases). The forces generated as a result of this phenomenon pull the bubble away from the hydrophilic surface. Subsequently, the contact line recedes over the hydrophilic surface until the bubble snaps off, and liquid fully rewets the hydrophilic surface.

While surface tension controls the dynamics of bubble deformation and contact line movements over the surfaces, the pressure potential controls the rate of bubble exit through the vapor permeable wall. Thus, as seen in the images, the channel pressure level dictates the rate of bubbles rejection from the flow (i.e. a higher rate of discharge at 30.2 kPa versus 7.4 kPa). In a subsequent test, designed to resemble a significant vapor generation rate and an elongated bubble in a heat sink, the size of the through-hole was increased to 400 μm to greatly increase the air injection rate such that the bubble could laterally expand before exiting through the vapor permeable wall. Tests conducted at three different pressures show that bubble coverage of the surface is reduced as the channel pressure is increased (cf. Fig. 1c). In this condition, the liquid pressure acting on the outer surface of the bubble stops the bubble from expanding laterally and forces the bubble through the membrane.

The physics of the adiabatic processes discussed above (i.e. collecting bubbles from a surface and limiting the bubble coverage of the surface) could be exploited to enhance the CHF in two-phase

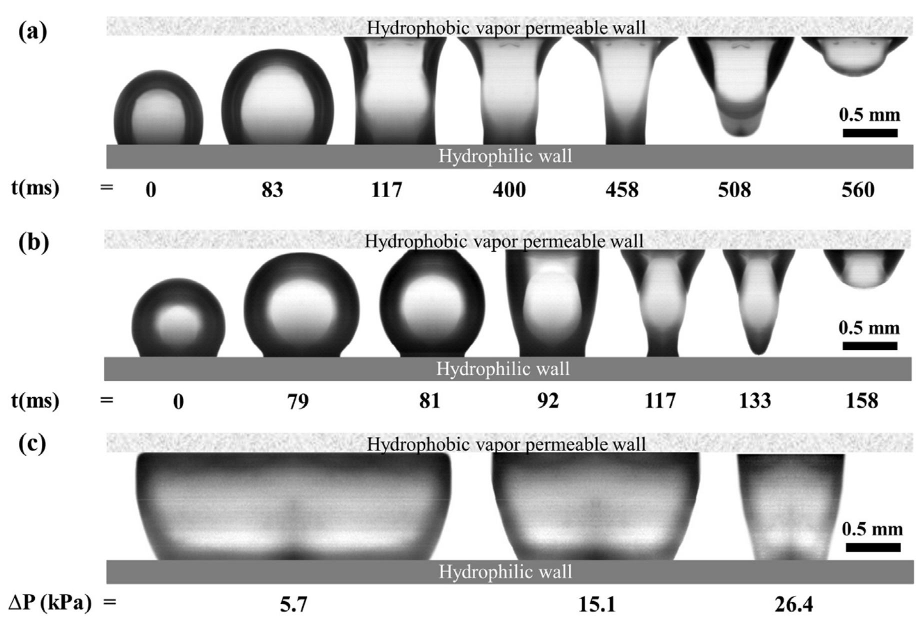

Fig. 1. Images of air bubbles injected into a 1-mm-tall channel formed between a hydrophilic silicon wall (bottom) and a vapor permeable hydrophobic wall (top). Images of bubbles injected through a 5 μm hole at a low 7.4 kPa (a) and a high 30.2 kPa (b) channel positive pressure. Maximum lateral expansion of bubbles, injected at a constant air flow rate through a 400 μm hole, at different channel pressures (c).