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Experimental study of augmented flow boiling in a dielectric fluid due to backward and forward facing stepped microchannels

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This study explores the thermal performance of novel backward-facing-step and forward-facing-step structures in microchannel heat sinks. Tests are conducted at mass fluxes of 444–1776 kg/m^2 s and inlet subcoolings of 5–20 °C using FC-72 as the coolant. The effects of step change on boiling curve, flow pattern, pressure drop and heat transfer coefficient are discussed in this paper. The saw-toothed steps enhance the heat transfer performance by greater than 30% across the entire range of input parameters tested, with a peak enhancement of 100% at the highest mass flux. Pressure drop penalties range from 30% to 70% for the range of parameters tested. The forward-facing configuration leads to a larger bubble population in the channels, causing more effective mixing. These microchannel structures offer the promise of improved thermal performance without the complex fabrication processes associated with nanostructured or re-entrant geometries.

1. Introduction

Flow boiling in microchannels is very attractive for the cooling of high-power electronics since it has small hydraulic diameter flow passages and utilizes latent heat through the liquid-vapor phase change process. However, flow boiling instabilities have been the largest road block to the practical implementation of microchannels. Flow boiling instabilities cause pressure and temperature oscillations, vibration, and thermal stress cycling. More importantly, they can lead to early Critical Heat Flux (CHF). Kandlikar [1] visualized two-phase flow in microchannels and concluded that rapid bubble growth is responsible for flow instabilities. After the inception of nucleation, bubbles grow rapidly and occupy the entire channel cross-section. Then they elongate to form vapor slugs. Balasubramanian and Kandlikar [2] investigated flow instabilities in parallel minichannels. It was shown that slug flow played a significant role in high surface temperature and flow reversal, since the slugs were large enough to block the channels. Steinke and Kandlikar [3] observed flow reversal in parallel microchannels in which the trailing vapor interface moves counter to the bulk fluid flow. Qu and Mudawar [4] identifies two types of two-phase hydrodynamic instabilities: severe pressure drop oscillation and mild parallel channel instability. The first occurred when the upstream control valve was fully open. A significant amount of vapor was observed and precipitated a sudden severe pressure drop oscillation, causing vapor to enter the inlet plenums. By throttling the upstream control valve, the severe pressure drop oscillations could be eliminated. The flow pattern within each channel oscillated between bubble nucleation and slug flow, which was classified as mild parallel channel instability.

In order to suppress the instabilities in microchannels, techniques including re-entrant cavities, nanostructured surfaces, and phase separation have been proposed. Goyal et al. [5] first brought up a novel re-entrant cavity heat sink and reported a two-step anisotropic etching process to fabricate these cavities. Ever since that, re-entrant cavities have been found in many publications [6–13]. These cavities serve as vapor-trapping sites and trigger the onset of nucleate boiling earlier compared to plain microchannels. Nanowires [14,15] have been employed in microchannels since the gaps, separating clusters formed by nanowires, provide active nucleation sites. Also, they increase the wettability of the surfaces. Research shows that nanowires can improve both the CHF and heat transfer coefficient in microchannels, and reduce the pressure drop. Implementation of phase separation in microchannels is another method to address the issue of flow instabilities [16–20]. Zhou et al. [16] first proposed a vapor escape microchannel heat exchanger in which a porous membrane was introduced to allow vapor to vent to a vapor chamber and prevent liquid from entering the vapor chamber thereby effectively separating the phases. David et al. [18] designed a copper heat exchanger with PTFE membrane sandwiched between liquid microchannels and vapor microchannels.

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Nomenclature

h_{tp}	average two-phase heat transfer coefficient (W/m^2 K)
H_{ch}	channel height (μm)
I	power supply current (A)
k	thermal conductivity of silicon (W/m K)
m	fin parameter
$\dot{m}$	mass flow rate (kg/s)
q_{total}	power supplied (W)
$q_{net,fluid}$	heat transfer (W)
q_{loss}	heat loss to the ambient (W)
t_b	fin base thickness (μm)
T_i	inlet plenum temperature (°C)
T_o	outlet plenum temperature (°C)
T_b	copper film heater temperature (°C)
T_{sat}	saturation temperature at the average pressure in the microchannels (°C)
T_w	wall temperature (°C)
V	power supply voltage (V)
W_{cell}	microchannel heat sink unit cell width (μm)
W_w	averaged width of half fins (μm)
W_{ch}	channel width (μm)
η	fin efficiency

Pressure drop in the venting device was lower than that for the non-venting devices. Fazeli et al. [19] investigated a new heat sink with a PTFE membrane bonded on the entire device. It had only one liquid connection (i.e. an inlet) so that the liquid had to fully evaporate to exit the microchannels. Another new phase-change heat sink was introduced by Fazeli et al. [20]. At low wall superheats, the surface structure formed capillary-controlled menisci to allow thin films to directly evaporate into the vapor channels. At higher superheats, nucleate boiling occurred and the menisci broke down. The bubbles were forced to exit through a vapor-permeable membrane bonded on the structure.

The techniques shown above can suppress the instabilities to an extent. However, fabricating them in silicon substrates requires many process steps which are complex and expensive. Moreover, nanowires and the phase-separation membranes are subject to corrosion and mechanical damage caused by violent boiling activity. So techniques which are easy to manufacture and durable need to be explored.

Wavy microchannels and saw-toothed microchannels have been introduced to enhance heat transfer performance in single-phase flow in microchannels. Guzman and Amon [21,22] numerically investigated self-sustained oscillatory flows in converging-diverging channels. Results showed that the wavy shape induced the transition from laminar to chaotic flow. Sui et al. [23–25] studied single-phase laminar fluid flow and heat transfer in wavy microchannels. It was found that the heat transfer performance in wavy microchannels was much better than that in straight microchannels with a pressure drop penalty that is much smaller. Ghaedamini et al. [26,27] studied the effects of geometrical configuration on heat transfer performance and fluid flow in wavy microchannels. It was observed that expansion factor and Reynolds number were the two main factors in controlling the presence of chaotic advection. Chaotic advection caused a significant increase in heat transfer. Mohammed et al. [28] studied single-phase flow over a backward facing step (BFS) in a vertical duct using nanofluids. A recirculation region formed directly behind the step and the thickness of the recirculation decreased as the distance from the step increased. The Nusselt number was noticed to increase steeply to its maximum value near the step wall. Kherbeet et al. [29] investigated the step height of microscale backward facing step on heat transfer characteristics. It was found that the Nusselt number increased as the step height went up. However, the Reynolds number and pressure drop decreased with the increase of the step height. In the backward-facing step flow geometry, only one separated region was developed behind the step. On the other hand, the flow field was more complicated in the forward-facing geometry, there might be one or more recirculation regions being developed around the step, depending on the ratio of approaching flow boundary-layer thickness to the step height [30]. However, information on two-phase flow in microchannels with a step-change has not yet been studied.

In this paper, flow boiling in both the backward-facing configuration and forward-facing configuration has been conducted. The shape studied here is robust and easy to manufacture. Mass flux and inlet subcooling are varied. In this study flow boiling curves, heat transfer coefficients, pressure drops and flow images are presented to assess the efficacy of backward or forward facing steps.

2. Experimental set up

2.1. Flow loop

A schematic diagram of the flow loop is shown in Fig. 1. The degassing chamber filled with the coolant FC-72 (3M), a perfluorinated dielectric fluid, removes heat from the microchannel test section which is discussed in the next paragraph. A hot plate, which is placed below the degassing chamber, is used to heat up the coolant and air in the chamber. The Graham condenser, connected to the water chiller, condenses the vaporized FC-72 that returns to the degassing chamber by gravitational force. The outlet of the heat sink is maintained at atmospheric pressure since the

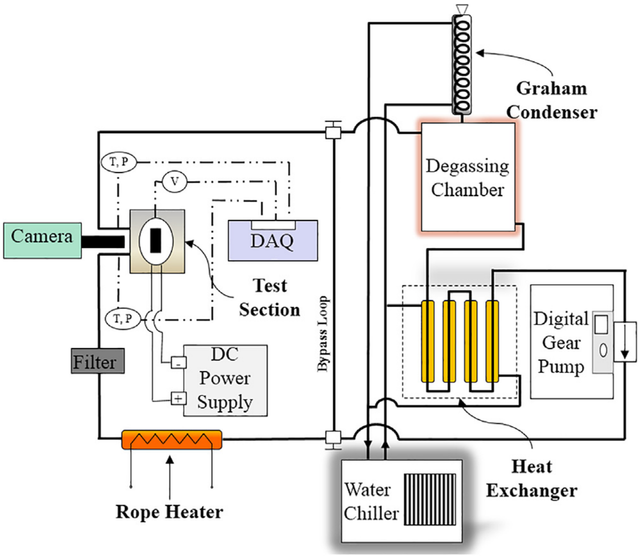

Fig. 1. A schematic view of the flow loop including a degassing chamber, test section, a filter, a rope heater which is used to control inlet subcooling, a water chiller connected to the heat exchanger and the Graham condenser, and a digital gear pump to control flow rates.