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Flow boiling of HFE-7100 in silicon microchannels integrated with multiple micro-nozzles and reentry micro-cavities

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ABSTRACT

Flow boiling of dielectric fluids in microchannels is one of the most desirable cooling solutions for high power electronics. However, the flow boiling of dielectric fluids is hindered by their unfavorable thermo-physical properties. Specifically, without precooling dielectric fluids, it is challenging to promote critical heat flux (CHF) due to its high vapor density, low surface tension and the resulted superior wettability. In this study, each side wall of a five-parallel silicon microchannel array was structured with an array of microscale reentry cavities and four micronozzles bypassed by an auxiliary channel. The present microchannel configuration aims to significantly enhance CHF of HFE-7100 flow boiling by improving global liquid supply using auxiliary channels and micrononozzles as well as by sustaining liquid film using capillarity induced by reentry cavity array. Equally important, these structures can promote nucleate boiling at low heat flux, generate intense mixing, and promote thin film evaporation at high heat flux, resulting in high flow boiling heat transfer rate. Flow boiling of HFE-7100 in the present microchannel configuration is characterized with mass flux ranging from 231 kg/m^2 s to 1155 kg/m^2 s. The effective two-phase heat transfer coefficients (HTCs) are ranging from 6 kW/m^2 K to 117 kW/m^2 K. Compared to the four-nozzle plain-wall microchannels, for example, the effective HTC and CHF can be substantially enhanced up to 208% and 37%, respectively, without escalating pressure drop at a mass flux of 462 kg/m^2 s. Compared to plain microchannels with inlet restrictors, CHF is considerably enhanced up to 70% with a reduction of pressure drop ~82% at a mass flux of 1155 kg/m^2 s. Significantly reduced pressure drop is achieved by integrating bypass and the enhanced confined bubble removal. A peak CHF value of 216 W/cm^2 is achieved at mass flux of 2772 kg/m^2 s in the present microchannel configuration with inlet temperature at room temperature.

1. Introduction

To assure safety and reliability of electronic microsystems, the highly wetting coolant of dielectric fluids is one of the most desirable working fluids for high power electronics cooling [1–4]. However, it is extremely challenging to enhance their flow boiling performances without precooling the coolant, particularly critical heat flux (CHF), due to their unfavorable thermophysical properties. For example, thermal conductivity of HFE-7100 is ~0.069 W/m·K, nearly one tenth of water. In addition, the latent heat of vaporization of HFE-7100 is 111.6 kJ/kg, which is ~20 times smaller than that of water. On the other hand, compared to water, its nearly 5 times lower surface tension of 13.6 mN/m makes it difficult to promote CHF of HFE-7100 by enhancing surface wettability as these effective methods (such as nanowires [3,5,6] and hydrophilic coatings [7]) on water. Moreover, the low surface tension makes it hard to sustain highly desirable and long thin liquid film on the heating surface. The dielectric fluid tends to be blown away from the heating wall by vapor flows, particularly, in smooth-wall microchannels.

Due to the difficulty in promoting thin film evaporation, nucleate boiling as well as liquid spreading, hence, the enhancements of dielectric fluid flow boiling performances in microchannels in terms of heat transfer coefficient (HTC) and CHF are usually limited. Additionally, the vapor density of HFE-7100 is 10.535 kg/m^3 at saturated temperature of 61 °C, which is ~17 times higher than the steam density of 0.6 kg/ m^3. HTC and CHF would be deteriorated by the severe vapor reversal flow resulted from vigorous vapor generation. Severe flow reversal would prevent the liquid renewal in channels and lead to high pressure drop. Through cooling the inlet temperature to −30 °C and the use of mass flux up to 5550 kg/m^2 s [8], Lee and Mudawar [8] have successfully managed these issues caused by the high vapor momentum and achieved a

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Nomenclature

A	area, m^2
A_c	cross-sectional area of channel, m^2
A_i	bubble interface area, m^2
A_{pl}	shear plane area, m^2
C_p	specific heat of water, kJ/kg·K
D_h	hydraulic diameter, m
F_b	buoyancy force, N
F_i	inertia force, N
F_M	evaporation momentum force, N
F_s	surface tension force, N
F_τ	shear force, N
g	gravitational acceleration, m/s^2
G	mass flux, kg/m^2 s
h	heat transfer coefficient, kW/m^2 K
H	height, m
h_{fg}	latent heat of vaporization, kJ/kg
k_s	conductivity of silicon
K	slope of linear function, Ω/K
L	length, m
m	parameter for fin efficiency
$\dot{m}$	mass flow rate, kg/s
q''	Heat flux, W/cm^2
p	pressure, N/m^2
Δp	pressure drop, N/m^2
P	power, W
R	resistance, Ω
S	slip coefficient
t	substrate thickness, m
T	temperature, °C
$\bar{T}$	average temperature, °C
u	average velocity, m/s
V	volume of bubble, m^3
W	microchannel width, m

Greek symbols

α	void fraction
θ	contact angle
φ	heating surface orientation
μ	viscosity, kg/(s·m)
ρ	density, kg/m^3
σ	surface tension, N/m
σ_i	interfacial stress, N/m^2
η_f	fin efficiency

Subscripts

a	ambient
e	exit
eff	effective
EV	evaporative
i	inlet
l	liquid
o	outlet
sat	saturated
tp	two-phase
v	vapor

CHF value of ~700 W/cm^2 on HFE-7100. High mass flux can help to overcome reversal flows; while cold coolant can effectively manage bubble confinement and enhance the portion of sensible heat transfer.

Extensive studies have been conducted to enhance the HTC of flow boiling on dielectric fluids. For example, enhanced nucleate boiling was achieved by increasing nucleation sites, such as nanowires [3], reentrant cavities [4], porous graphite [9,10] and other porous surfaces [1]. On the other hand, highly efficient thin film evaporation can be achieved by sustaining thin liquid film through inducing capillary flows using micro/nano-structures. Some efforts have been taken to improve HTC of HFE-7100 flow boiling, such as varying microchannel diameters [11] and titling microchannels [12]. However, according to our literature review, CHF enhancements are insignificant without pre-cooling the coolant inlet temperature.

Regarding to the CHF, explosive boiling, two-phase flow instabilities, and local dry-out are three main factors triggering CHF crisis in a closed microchannel system. Premature CHF can be triggered by explosive boiling because of low thermal conductivity vapor. The low surface tension of dielectric fluids is highly likely to lead to local dry-out by forming a stable vapor film on heating surfaces due to its low surface tension. Additionally, two-phase flow instabilities induced by the rapid vigorous vapor generation is likely to lead to local dry-out due to the difficulty of liquid renewal [13,14], particularly severely near the outlet section. In last two decades, numerous techniques have been developed to enhance CHF on DI-water through regulating bubble slugs [15,16], suppressing two-phase flow instabilities [17,18], modifying surface properties [5,19–23], and promoting liquid rewetting [24–27]. However, few techniques have been reported to effectively enhance CHF on dielectric fluids at room temperature. For example, flow boiling HTC can be signficantly enhanced in microchannels through integrating nanowires [3], reentrant cavities [4], but not CHF. Although capillary flow is enhanced by integrating reentrant cavities [4] and nanowires [3], the lack of liquid supply at global level is responsible for the insignificantly enhanced CHF. As aforementioned, a high CHF of ~700 W/cm^2 has been reported by Lee et al. on pre-cooled HFE-7100 in microchannels [8]. Such a high CHF was achieved at a high mass flux of 5550 kg/m^2 s and a −30 °C inlet temperature. Hence, it is more challenging to enhance CHF of dielectric fluid flow boiling with inlet temperature at room temperature.

Enhanced CHF without escalating pressure drop is also highly desirable. It has been achieved in our previous studies in a four-nozzle microchannel configuration [28,29] and in a microchannel configuration integrated with multiple micronozzles with reentry cavities [30], but only on water.

In this study, experiments are conducted on the same device used in our previous study [30] to investigate the flow boiling performances on HFE-7100 at room temperature. Enhanced CHF can be expected in this improved microchannel configuration with the improvement of global and local liquid supply. HTC would be also significantly increased by enhancing nucleate boiling, thin film evaporation, and mixing enabled by combining the cavity array and multiple-nozzles. Two-phase pressure drop would be reduced with well managed bubble confinement.

2. Design and experiment

2.1. Challenges in enhancing HFE-7100 flow boiling in microchannels

Various forces acting on the liquid-vapor interface, including inertia, surface tension, shear, buoyancy, and evaporation momentum forces, have significant effects on two-phase flow and heat transfer. Our previous study [31] has analyzed forces acting on the liquid-vapor interface. In this study, simplified equations are adopted from that study [31] to calculate these forces.