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

Wenming Li, Jiaxuan Ma, Tamanna Alam, Fanghao Yang, Jamil Khan, Chen Li

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 thermophysical 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 micronozzles 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/m² s to 1155 kg/m² s. The effective two-phase heat transfer coefficients (HTCs) are ranging from 6 kW/m² K to 117 kW/m² 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/m² 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/m². Significantly reduced pressure drop is achieved by integrating bypass and the enhanced confined bubble removal. A peak CHF value of 216 W/cm² is achieved at mass flux of 2772 kg/m² s in the present microchannel configuration with inlet temperature at room temperature.

© 2018 Elsevier Ltd. All rights reserved.

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/m³ at saturated temperature of 61 °C, which is ~17 times higher than the steam density of 0.6 kg / m³. 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/m² s [8], Lee and Mudawar [8] have successfully managed these issues caused by the high vapor momentum and achieved a
CHF value of ~700 W/cm² 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 significantly 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/cm² 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/m² 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.
The surface tension force per unit area is expressed as \( F_s = \frac{\alpha \cos \theta}{h^2} \). Inertia force per unit area is expressed as \( F_i = \rho \cdot u^2 \).

Shear force per unit area is expressed as \( F_s = -\frac{\rho \cdot u}{K} \). Buoyancy force per unit area is expressed as \( F_b = (\rho_v - \rho) \cdot g \cdot \cos \phi \). Evaporation momentum force per unit area is expressed as \( F_m = \left( \frac{q_{EV}}{h} \right) \cdot \frac{1}{\rho} \cdot \frac{\gamma}{\cos \theta} \).

In above equations, \( \alpha \) is the surface tension, \( \theta \) is the contact angle, \( D \) is the relevant dimension \( (D = D_h) \), \( u \) is average fluid velocity, \( \rho = \alpha \cdot \rho_v + (1 - \alpha) \rho_i \) is the fluid average density, where \( \alpha \) is the void fraction. More details about aforementioned equations can refer to our previous study [31].

Fig. 1 compares shear force, surface tension force and inertia force on water and HFE-7100 at different mass fluxes. The surface tension force and inertia force of HFE-7100 are lower than those of water. However, the shear force of HFE-7100 is higher than that of water due to its large dynamic viscosity. Fig. 1 also indicates that the inertia and shear force increase with increasing mass flux. Surface tension force is dominant at relatively low mass fluxes, but surpassed by inertia force with mass flux increasing. The higher surface tension force and inertia force can facilitate formation of thin liquid film and enhance rewetting. Hence, the flow boiling performances on water outperform that on HFE-7100.

By changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8]. The vapor flow reversal can be suppressed by changing working temperature, effects of these forces acting on HFE-7100 liquid-vapor interfaces can be relatively changed. Reducing coolant temperature can delay the onset of boiling (ONB), reduce bubble size and coalescence effects, leading to enhanced CHF [8].

Enhanced capillary effect is an effective approach to enhance flow boiling performances of HFE-7100 besides pre-cooling it. Enhanced capillary effect can better facilitate the liquid spreading on the heating surface, forming durable thin liquid film. Enhanced flow boiling performances have been achieved owing to the enhanced capillary effect in our previous study on water [30]. However, it is extremely challenging to enhance surface tension in flow boiling on HFE-7100 at room temperature due to its low surface tension. Our previous study [31] has demonstrated that the surface tension force can be significantly enhanced by reducing the contact angle through the integration of nanowires in microchannels compared to plain-wall microchannels on water. Nanowires can generate an order of magnitude higher capillary pressure than a plain-wall does. As a result, HTC is drastically increased in nanowire microchannels on both water [31] and HFE-7000 [3]. However, the CHF enhancement is insignificant, or even negative at high mass flow rate [3]. Although HFE-7100 is a highly wetting fluid with nearly zero contact angle on all types of surfaces, it is very difficult to sustain a continuous and long thin liquid film on the heating surface due to its low surface tension. In this study, capillary pressure enhanced by microcavity arrays, which were fabricated along the sidewall of each main channels, can sustain numerous short thin liquid film sections and hence, effectively compensate the effect of the HFE-7100 low surface tension.

2.2. Design and fabrication of microchannel devices

Enhanced capillary effect can compensate the low surface tension of HFE-7100 to increase liquid spreading. Our previous study of multiple jets microchannels with reentry cavities (in Fig. 3) has demonstrated enhanced HTC and CHF on water owing to the enhanced capillary effect [30]. Enhanced HTCs have been achieved by enhancing capillary effect through integration of reentry cavities [4] and nanowires [3] in microchannels. High density reentry cavities fabricated along the side wall of microchannel can enhance capillary effect, which can promote the liquid spreading and favor formation of thin liquid film. The improved liquid spreading under enhanced capillary effect can boost nucleate boiling and promote thin film evaporation. Hence, HTC is expected to be improved on HFE-7100. On the other hand, enhanced CHF can be also achieved by improving liquid supply at global level on HFE-7000 through evenly-distributed multiple micronozzles. The current improved configuration as shown in Fig. 3 has been demonstrated to effectively improve global liquid supply on water [30].

A tested device of the improved design (in Fig. 3) was fabricated to experimentally investigate the flow boiling performances of HFE-7100. The tested device consists of five parallel main channels. The dimensions (length \( \times \) width \( \times \) depth) of the main channels, auxiliary channels, and restrictors are 10 mm \( \times \) 200 mm \( \times \) 250 \( \mu \)m, 8 mm \( \times \) 60 mm \( \times \) 250 \( \mu \)m, and 400 \( \mu \)m \( \times \) 20 \( \mu \)m \( \times \) 250 \( \mu \)m, respectively. To enhance liquid distribution, four micronozzles were fabricated evenly along the channels at a pitch of 2 mm. Converging nozzles with 20 \( \mu \)m throat were fabricated in the auxiliary channel to generate jetting flows. The effect of cavity size on the onset of bubble nucleation and nucleate boiling have been investigated [33,34]. In this study, to significantly enhance nucleate boiling, reentry cavities (cavity dimensions: diameter = 30 \( \mu \)m, opening = 6 \( \mu \)m, distance = 100 \( \mu \)m) were fabricated on side walls of main channels. More information about the design are detailed in our previous study [30].

Before etching processes on topside of the chip, thin metal film resistor (10 mm \( \times \) 2 mm) made of 1.2 \( \mu \)m thick of aluminum was deposited on the backside of the chip to generate uniform constant heat flux. Micro-resistor also serves as thermistor to measure the average temperature of heater. After etching processes, anodic
boiling was applied to bond a 500 μm thick Pyrex glass wafer to a 500 μm thick silicon wafer substrate. Visualization study can be carried out through the glass window as well.

2.3. Measurements

A test system as illustrated in our previous study [35] was used to collect experimental data in this study. Major components of the experimental setup include an optical imaging system, a data acquisition unit, and an open coolant loop. A pressurized tank was used to supply HFE-7100, which was degassed prior to tests. Two pressure transducers acquiring the inlet and outlet absolute pressures were used to derive pressure drops. The flow rate was measured and controlled by a mass flow meter of Krohne Optimass 3300c with a ±0.1% resolution (density with ±2 kg/m³). The average temperature on the heater was derived by pre-calibrating the electric resistance of micro-heater as a linear function of working temperature. The inlet and outlet fluid temperatures were monitored by two K-type thermocouples. Electrical power was supplied by a high precision digital programmable power supply (BK-PRECISION XLN10014). Flow rate, local pressure, inlet and outlet temperature, and voltage and current were collected by an Agilent 34972A data acquisition system and recorded by a customized data acquisition system developed from NI LabVIEW®. A visualization system comprised of a high-speed camera (Phantom V 7.3) and an Olympus microscope (BX-51) with 400 times amplification was used to study the bubble dynamics and two-phase flow structures. All measurements were carried out at 1 ATM and room temperature of ~18 °C.

2.4. Data reduction

To accurately estimate the heat flux applied to the heating area, the total input power, \( P \), was firstly calculated by multiplying the DC voltage (\( V \)) with current (\( I \)). The heater resistance was equal to \( V \) divided by \( I \), \( R = V/I \). The effective heat flux was calculated after subtracting the heat loss, \( Q_{loss} \), (pre-calibrated between the ambient environment and the test device) from \( P \), as follow,

\[
q_{eff} = \frac{P - Q_{loss}}{A}
\]

where \( A \) is the heating area. The latent heat contributed to boiling heat transfer was derived as,

\[
Q_{latent} = P - Q_{loss} - Q_{sensible}
\]

where \( Q_{sensible} \) is the sensible heat due to the temperature increase of liquid flows. It was derived as,

\[
Q_{sensible} = GAC_p(T_o - T_i)
\]

Based on the pre-calibrated linear relationship between temperature and electrical resistance of micro-heater, an average temperature of the micro-heater (on the backside of the device) was calculated as,

\[
T_{wall} = T_{heater} - \frac{q_{eff}t}{k_s}
\]

where \( t \) and \( k_s \) are the substrate thickness, thermal conductivity of silicon, respectively.

The fin efficiency, \( \eta_f \), of a finite fin was estimated from

\[
\eta_f = \frac{\tanh (mH)}{mH}
\]

The equation of \( \eta_f \) is used to characterize fin performance and to calculate the average effective HTC, where the parameter \( m \) was calculated as,

\[
m = \sqrt{2h(L + W)/k_sWL}
\]

Then, the effective two-phase HTC considering fin efficiency, \( h_{tp} \), was evaluated by,

\[
h_{tp} = \frac{Q_{latent}}{\left(\sum(WL + 2HL\eta_f)/(T_{wall} - T_{sat})\right)}
\]

where \( T_{sat} \) is the saturated temperature of working fluid. Note: we used the whole channel length (\( L \)) for the calculation of two-phase heat transfer coefficient \( h_p \) because the entire channel length is occupied by two-phase flows after ONB in this study. This is different from the water flow boiling.

The overall HTC based on the heating area was estimated as

\[
h = \frac{P_{eff}}{A_0(T_{wall} - T_{sat})}
\]

\( A_0 \) is the heated area. Major physical properties of dielectric fluid HFE-7100 are given in Table 2. \( T_{sat} \) is a function of working pressure (\( p \)) in the middle of a microchannel, which is estimated as,

\[
p = p_i - \frac{\Delta p}{2}
\]

where \( p_i \) is the inlet pressure; and \( \Delta p \) is the pressure drop.

<table>
<thead>
<tr>
<th>( T )</th>
<th>( \mu \text{ (kg/m} s \text{)} )</th>
<th>( \sigma \text{ (mN/m)} )</th>
<th>( c_p \text{ (kJ/kg K)} )</th>
<th>( \rho \text{ (kg/m}^3 \text{)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30 °C</td>
<td>8.5 × 10⁻⁴</td>
<td>18.2</td>
<td>1073</td>
<td>1606</td>
</tr>
<tr>
<td>25 °C</td>
<td>3.8 × 10⁻⁴</td>
<td>13.6</td>
<td>1133</td>
<td>1481.6</td>
</tr>
<tr>
<td>Vapor (61 °C)</td>
<td>2.7 × 10⁻⁴</td>
<td>N/A</td>
<td>N/A</td>
<td>10.535</td>
</tr>
</tbody>
</table>

Fig. 2. Effects of inlet temperature of 25 °C and −30 °C on major forces in microchannel on HFE-7100.
2.5. Uncertainty analysis

The measurement uncertainties of flow rate, pressure, voltage, current, temperature, and microfabrication resolution are ±0.1%, ±1.5%, ±0.5%, ±0.5%, ±1°C, and 3 μm, respectively [36]. Uncertainty propagations were calculated using methods developed by S. J. Kline and F. A. McClintock [37]. Uncertainties of the present CHF, overall HTC, and pressure drop have been estimated to be less than ±2 W/cm², ±1.6 kW/m² K, 1.2 kPa, respectively.

3. Results and discussion

3.1. Flow boiling curves

Fig. 4 shows s-shaped boiling curves of the present study on highly wetting HFE-7100. Boiling hysteresis is pronounced on HFE-7100. The slopes of boiling curves are very small in the temperature excursion region. It is clearly observed that the wall superheats drop sharply after the ONB as the further increase of heat fluxes. For example, the wall temperature overshoot is 50 K at a low mass flux of 231 kg/m²s, and then it drops to 12 K. Boiling hysteresis is the main reason for the temperature overshoots. Fig. 4 also shows that the temperature overshoots decrease with the increase in mass fluxes. The delayed boiling incipience would deteriorate the heat transfer rate in single phase region. More discussion on boiling hysteresis is presented in Section 3.2.

To evaluate the boiling heat transfer performance, overall HTCs based on the heating area are calculated and plotted versus effective heat flux and superheat in Fig. 5. The results show the overall HTCs ranging from 11 kW/m²K to 256 kW/m²K gradually decline with the increase of effective heat fluxes and superheats. Besides overall HTCs, HTCs considering all effective heat transfer areas termed as effective HTCs are also evaluated. The effective HTCs versus effective heat fluxes and exit vapor qualities are plotted in Fig. 6. The effective HTCs are ranging from 6 kW/m²K to 117 kW/m²K. For mass flux ranging from 231 kg/m²s to 1155 kg/m²s, the exit

---

Table 2

<table>
<thead>
<tr>
<th>Name</th>
<th>HFE-7100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat of vaporization (kJ/kg)</td>
<td>111.6</td>
</tr>
<tr>
<td>Specific heat, 25°C, 1 ATM (J/kg K)</td>
<td>1183</td>
</tr>
<tr>
<td>Liquid thermal conductivity (W/m K)</td>
<td>0.069</td>
</tr>
<tr>
<td>Boiling point, 1 ATM (°C)</td>
<td>61</td>
</tr>
<tr>
<td>Liquid density, 25°C (kg/m³)</td>
<td>1520</td>
</tr>
<tr>
<td>Kinematic viscosity (cSt)</td>
<td>0.37</td>
</tr>
<tr>
<td>Surface tension, 25°C (mN/m)</td>
<td>13.6</td>
</tr>
<tr>
<td>Vapor pressure, 25°C (kPa)</td>
<td>26.9</td>
</tr>
</tbody>
</table>
vapor quality varies from 0.4 to 1. Both Fig. 5 and Fig. 6 have demonstrated that heat transfer rate declines with the increase of effective heat flux, superheat and exit vapor quality. The main reason shall be the occurrence and development of local dry-out starting from the outlet region, which deteriorates the boiling heat transfer rate.

The analysis of forces acting on liquid-vapor interface is conducted to explain the HTC trends. Fig. 7 shows the comparison of major forces on HFE-7100 flow boiling. The evaporation momentum and shear forces are much smaller than inertia and surface tension forces. However, evaporation momentum and shear forces have a significant effect on flow boiling heat transfer performances. Our previous study has discussed the influences of major forces acting on liquid-vapor interface on HTC [31]. Shear force can maintain the liquid thin film and promote thin film evaporation. However, evaporation momentum force is dominant over shear force at all the working conditions. In Fig. 7, the evaporation momentum force also increases with the increase of heat fluxes. The increase of

Fig. 4. The boiling curves of the present study.

Fig. 5. Overall HTCs based on the heating area versus (a) effective heat flux and (b) superheat are plotted.

Fig. 6. Effective HTCs considering fin efficiency versus (a) effective heat flux and (b) exit vapor quality are plotted.

Fig. 7. Effect of heat flux on major forces in microchannels during boiling process. (The bubble diameter is 100 µm on HFE-7100 for the calculation of buoyancy force.)
evaporation momentum force against inertia force would lead to serious reversal vapor flow. Channel rewetting would be prevented by the vapor flow reversal near CHF conditions. Therefore, local dry-out occurs and HTCs are drastically reduced as shown in Fig. 6. Our previous study has demonstrated that the decrease trend of HTCs is induced by local dry-out as the further increase in evaporation momentum force on water as well [31].

3.2. Boiling hysteresis

Large temperature overshoots have been observed in Fig. 4. The possible reason is the boiling hysteresis of highly wetting fluids [38,39]. Boiling hysteresis is highly affected by flow conditions and heating surface topologies. For example, Fig. 8 shows the variations of boiling incipience temperature in three microchannels with different surface conditions. The integration of micronozzles and reentry cavity would result in a larger superheat excursion compared to those on plain-wall microchannels. The superheat excursion is also greatly affected by the mass fluxes in engineered microchannels. In plain-wall microchannels, superheat excursion is not significantly influenced by mass flux, as shown in Fig. 8. Particularly, high temperature overshoot was observed due to the introduction of artificial reentry cavities in a previous study [4]. In this study, the surface superheat at initiated boiling is around 50 K at a low mass flux of 231 kg/m²s, and then decreases with the increase of mass flux, while boiling incipience surface superheats in plain-wall microchannels are much lower.

The boiling hysteresis is also closely related to the activation of vapor embryo in artificial reentry cavity [39]. On conventional working fluids such as water, the vapor embryo is easily trapped inside the cavity due to the high surface tension and large advancing contact angle. As such, the ONB occurs at a low heating surface superheat. In contrast, boiling hysteresis accompanied with high superheat is very common for highly wetting fluids owing to the deactivation of vapor embryo in artificial cavities. The low surface tension and the resulted small contact angle makes dielectric fluids super-wetted and refill the cavity more effectively. Consequently, it becomes more difficult to trap the vapor embryo, requiring a higher surface superheat to initiate ONB as observed in the present study (Fig. 8).

Fig. 8. Variation of boiling incipience temperature in three different microchannels.

Fig. 9. Significantly enhanced overall HTC based on heating area is achieved in the present study compared to the four-nozzle microchannel configuration [29]. (a and b) Overall HTC versus effective heat flux, (c and d) overall HTC versus wall superheat.
Fig. 10. Significantly enhanced effective HTC is achieved in the present study compared to four-nozzle microchannel configuration [29]. (a and b) HTC versus effective heat flux, (c and d) HTC versus exit vapor quality.

Fig. 11. Enhanced bubble nucleation after ONB in the present configuration microchannels. The bubble departure/removal frequency is ~400 Hz from the microcavity with a diameter of ~100 µm at a heat flux of 58 W/cm² and a mass flux of 462 kg/m² s in the present study. (Scale bar is 200 µm.)

Fig. 12. Bubble nucleation after ONB in the four-nozzle configuration microchannels: the bubble departure frequency is ~1000 Hz from the micronozzle with an average diameter of ~150 µm at a heat flux of 25 W/cm² and a mass flux of 462 kg/m² s in four-nozzle microchannels [28,29,42]. (Scale bar is 200 µm.)
3.3. Enhanced HTC

Fig. 9 shows the overall HTCs based on the heating area versus effective heat flux and wall superheat. The results indicate that significant enhancement has been achieved in the present design compared to the four-nozzle configuration [28,29]. A high overall HTC of 265 kW/m² K is achieved at a mass flux of 1155 kg/m² s. At a mass flux of 462 kg/m² s, ~195% and ~110% enhancements are achieved for a given effective heat flux and wall superheat, respectively (Fig. 9(a and c)). As the mass flux increases to 693 kg/m² s, the enhancement drops to ~76%. Fig. 9(c and d) also indicates that the ONB of the present design is much smaller than that of four-nozzle microchannels at different mass fluxes. The microcavities can enhance nucleate boiling and drastically reduce the wall superheat.

By considering the fin effect, Fig. 10 shows that the values of effective HTCs are much smaller than those of overall HTCs (Fig. 9) after using effective heat transfer areas. The enhancement of effective HTC is ~208% at an exit vapor quality of ~0.7 compared to four-nozzle configuration for a mass flux of 462 kg/m² s. Fig. 10(c and d) also shows that the exit vapor qualities of the present study are significantly higher than those of the four-nozzle configuration, indicating a more effective utilization of latent heat. As shown in Fig. 10(c), the exit vapor quality can approach nearly 1, implying a nearly complete vaporization of coolant and a superior design of liquid supply mechanism that has been realized in the present microchannel configuration. A higher working heat flux (Fig. 10(a and b)) leads to a larger exit vapor quality for the same mass fluxes. As shown in Fig. 10(c and d), the effective HTCs at CHF conditions are substantially higher than those in the four-nozzle microchannel configuration, indicating that highly desirable thin liquid film evaporation has been successfully sustained during HFE-7100 flow boiling by the microcavity arrays.

The enhanced effective HTCs can be a result of combined effects of enhanced three major heat transfer modes: nucleate boiling, advection resulting from mixing, and thin film evaporation. Previous studies have demonstrated that the introduction of reentry cavities would considerably enhance the HTC on both water and HFE-7000 owing to the increased density of nucleation sites [4,17]. Therefore, enhanced nucleate boiling is the primary reason for the significant enhanced HTCs as shown in Figs. 9 and 10 and will be discussed in detailed in Section 3.3.1. Additionally, enhanced mixing is another factor leading to the enhanced HTC as well as detailed in Section 3.3.2. Strong mixing can be induced by the high frequency jetting flow and two-phase oscillations generated in the main channels. As discussed in Section 3.3.3, the third

---

**Fig. 13.** Enhanced mixing is achieved by high frequency two-phase oscillation and jetting flow at heat flux of 41 W/cm² and mass velocity of 231 kg/m² s. The two-phase oscillation frequency is ~76 Hz. And the frequency of jetting flow is ~167 Hz. (Scale bar is 100 μm.)

**Fig. 14.** Significant enhancement of CHF in the present study. (a) An enhancement of ~70% is achieved compared to plain wall microchannels with IRs [15]. (b) An enhancement of ~27% is achieved compared to four-nozzle microchannels [28]. (c) An enhancement of ~57% is achieved compared to reentrant cavity microchannels [4].
factor affecting the HTC is the improved thin film evaporation induced by enhanced capillary effect, which can maintain the thin liquid film along the side wall surface.

3.3.1. Enhanced nucleate boiling

Enhanced nucleate boiling is the primary enhancement mechanism of HTC. Compared to the four-nozzle microchannels, a large number of reentry cavities were fabricated along the sidewall of channel to drastically increase the nucleation sites. The nucleation site density $N_A$ is $\approx 4000$ sites/cm$^2$ in the present design. But the active site density is much smaller than 4000 sites/cm$^2$ in the boiling process according to study conducted by Kuo et al.[40]. The active nucleation site density is considerably enhanced by fabricating high density of reentrant cavity. For example, the active $N_A$ of reentrant cavity microchannels is $\approx 400$ sites/cm$^2$ at a superheat of 20 K and a mass velocity of 166 kg/m$^2$s on water. It is 5 times higher than $\approx 80$ sites/cm$^2$ predicted by a model based on smooth wall copper microchannels [34,41] under the same working conditions.

In this study, increased active nucleation sites were observed using high speed camera, as shown in Fig. 11. Eight active nucleation sites were identified from the sequential images with a resolution of 798 x 188 pixels. The active nucleation site density is $\approx 1550$ sites/cm$^2$, 14 times higher than $\approx 110$ sites/cm$^2$ of the four-nozzle microchannel configuration (in Fig. 12) at a mass flux of 462 kg/m$^2$s. The active $N_A$ of microchannel with reentrant cavity is $\approx 900$ sites/cm$^2$ at a mass flux of 302 kg/m$^2$s [40]. Most microcavities can work as the active nucleation site in the present design. However, most of the bubble nucleation occurs in the micropockets in the four-nozzle microchannels under the same mass flux. In Fig. 11, vapor slug is formed by bubble coalescences. The bubble departure frequency from microcavity is $\approx 400$ Hz with a diameter of $\approx 100$ $\mu$m. In contrast, Fig. 12 shows individual bubble from micronozzles. The bubble departure frequency from the micronozzle is $\approx 1000$ Hz with an average diameter of $\approx 150$ $\mu$m. The increased number of active nucleate sites can favorably enhance nucleate boiling. As a result, the boiling performance in terms of HTC is significantly enhanced, as shown in Figs. 9 and 10. Similar techniques such as nanowires can also drastically increase the active nucleation sites, leading to high HTC [3].

3.3.2. Enhanced mixing

Our previous study [30] has demonstrated that mixing can be enhanced by high frequency two-phase oscillations and jetting flows on water. In this study, two-phase oscillations induced by the growth-collapse process of confined bubble are limited. The main reason is that the evaporation momentum force is much smaller than the inertia force compared to that of water, as shown in Fig. 7. Two-phase oscillations only occurred at a low mass flux of 231 kg/m$^2$s, as shown in Fig. 13. Two-phase oscillations and jetting flows are presented in Fig. 13 at a heat flux of 41 W/cm$^2$ and a mass velocity of 231 kg/m$^2$s. The two-phase oscillation frequency is $\approx 76$ Hz. And the frequency of jetting flow is $\approx 167$ Hz. The frequency of jetting flows from micronozzles is comparable to that on water. Hence, enhanced mixing can be also achieved by high frequency jetting flows, leading to higher heat transfer rate.

3.3.3. Enhanced capillarity

The surface tension force of HFE-7100 is much smaller than that of water as illustrated in Fig. 1. It is difficult to maintain a long thin liquid film during boiling process in conventional microchannels. In this study, enhanced capillary pressure is achieved owing to the high density of microcavities along the side walls. It can compensate the low surface tension to sustain liquid on the side wall surfaces. The capillary pressure is $\approx 1.8$ kPa induced by the microcavity with a diameter of 30 $\mu$m. Liquid can be rapidly pumped into the cavity. On the other hand, sustainable local liquid spreading can also keep cavities active and hence, enhance nucleate boiling as well. More importantly, the microcavities-sustained thin liquid film can promote highly desirable evaporation as visualized in Fig. 16 (b).

3.4. Enhanced CHF

In this study, the enhanced mechanisms of CHF on water reported in our previous study [30] are examined on HFE-7100.
The comparisons in Fig. 14 show that significantly enhanced CHF is achieved on the present configuration compared to those on other three microchannel configurations, including microchannels with IRs [15], four-nozzle microchannels [42] and microchannels integrated with reentrant cavities [4]. The results shown in Fig. 14(a) show that a CHF value of 216 W/cm² is achieved at a mass flux of 2772 kg/m² s. The trend of CHF also indicates a room for a further enhancement. It is noticed that the deviation of CHF varies with increasing mass flux in Fig. 14. By comparing to microchannels with IRs [15], an enhancement of ~70% is achieved by enhancing global liquid supply and local liquid spreading through the integration of multiple jets and reentry cavities. At a mass flux around 2772 kg/m² s, the enhancement is ~57% compared to the reentrant cavity microchannels [4]. An enhancement of ~27% is achieved compared to four-nozzle microchannels [28]. The comparison in Fig. 14(b) indicates that reentry cavity plays a vital role in enhancing CHF. The local liquid spreading can be enhanced by the cavity-induced capillary flows and be the main factor leading to the enhanced CHF [30]. The enhancements of CHF are limited in the present configuration microchannels compared to other three configurations at low mass fluxes. The main reason could...
be that the multiple jets and reentry cavity are not fully activated because of insufficient coolant. As the increase of mass flux, the effects of multiple jets and reentry cavity in enhancing global liquid supply and local liquid spreading become more significant, leading to higher CHF as illustrated in Fig. 14.

Usually, a premature CHF condition can be triggered by explosive boiling, flow instabilities, and partial dry-out. For plain-wall microchannels with IRs as illustrated in Fig. 15 (a), when heat flux increases, explosive boiling is likely to occur because thermal conductivity of superheated HFE-7100 is low. Then, thin liquid film would be expelled away from walls and eventually, vapor layer forms on the heating surface near inlet regions. As shown in Fig. 15(b) in four-nozzle configuration microchannels, due to lack of nucleation sites, boiling cannot be extended to the entire channel length. The significantly enhanced CHF in this study is achieved by managing or addressing these aforementioned issues. The integration of micro-nozzles and micro-cavity array has successfully prevented the occurrence of explosive boiling, as illustrated in Fig. 15(c).

Heating surface dryout because of low rewetting ability is one of the main factors resulting in premature CHF conditions. Enhanced liquid spreading is essential to increase CHF. Normally, surface rewetting is highly influenced by the properties of working fluid, surface conditions of heating surface and two-phase transport. However, as discussed in Section 2.1, it is challenging to increase CHF on highly wetting HFE-7100 at room temperature. In conventional plain-wall microchannels, it is difficult to maintain a thin liquid film on the heating surface using working fluid of HFE-7100 due to its low surface tension. The potential solution for this issue is to enhance capillary pressure through surface modifications such as nanowires to compensate the low surface tension. Although local rewetting is enhanced in microchannel covered with nanowires, the global liquid supply greatly suffers from its high flow resistance. As a result, the enhancement of CHF is insignificant.

In this study, an improved configuration microchannels integrated with high density microcavities would significantly increase the capillary pressure. The capillary pressure is ~1.8 kPa calculated by $\Delta P = \frac{4\sigma \cos \theta}{D_o}$. More importantly, thin liquid film can be sustained between the microcavities, effectively delaying local surface dryout. In plain-wall microchannels with IRs, the thin liquid film can be easily blown off from the heating surface, as illustrated in Fig. 15(a). It is clearly observed that a liquid core is surrounded by vapor sublayers at mass flux of 462 kg/m²s and heat flux of 61 W/cm². Liquid renewal on the heating surface is prevented by such vapor layers, leading to premature CHF conditions. The four evenly-distributed micronozzles can ensure liquid supply to entire channels. The enhanced capillary pressure can greatly improve the local liquid spreading. Fig. 16 demonstrates that rapidly rewetting is achieved at a frequency of ~143 Hz in the outlet section near CHF conditions at heat flux of 80 W/cm² and mass velocity of 462 kg/m²s.

Two-phase flow instabilities in microchannels can deteriorate flow boiling, especially near outlet section. Pre-cooled working fluid up to ~30 °C has been demonstrated to stabilize flow boiling of HFE-7100 by reducing the bubble nucleation size and vapor density [8]. The smaller bubble size and lower vapor density can benefit the liquid supply to channels. In this study, confined bubbles in the present improved configuration are well-managed in enhancing two-phase flow stabilities because of the enhanced bubble removal.

3.5. Reduced $\Delta P$

Usually, the enhanced CHF is at the penalty of pressure drop, for example, induced by orifices [15] or high mass flux [43]. Compared to the four-nozzle configuration microchannels, the pressure drops of the present study are elevated by ~16%, as shown in Fig. 17. A minor increase of pressure drop might be induced by the change of surface roughness induced by the high density of reentry cavities. However, Fig. 18 shows that the pressure drops of the present study are substantially reduced compared to microchannels with IRs. The reduced pressure drop is realized through rapidly collapsing confined bubbles and increasing bypass area using auxiliary channels and nozzles.

4. Conclusion

This work has demonstrated that flow boiling in terms of HTC and CHF on highly wetting HFE-7100 can be significantly enhanced compared to microchannels with IRs, reentrant cavity microchannels and four-nozzle microchannels. The HTC is drastically increased by coupling multiple nozzles with reentry cavity primarily owing to the enhanced nucleate boiling, mixing effect, and thin film evaporation. Moreover, CHF is significantly enhanced up to ~70% with pressure drop reduced by ~82% compared to microchannels with IRs. A peak CHF of 216 W/cm² is achieved at a mass flux of 2772 kg/m²s in this study with coolant temperature at room temperature. The enhanced global liquid supply and sustainable local liquid spreading are the two major enhancement mechanisms of the enhanced CHF.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgements

This work was supported by the U.S. Department of Defense, Office of Naval Research under the Grants N000141210724 and N000141612307 (Program Officer Dr. Mark Spector). Devices were fabricated at Institute of Electronics and Nanotechnology (IEN) in Georgia Tech, which is supported by the National Science Foundation under the Grant ECS-0335765. SEM images were taken at USC Microscopy Center.

References
