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A B S T R A C T

Flow boiling with deionized water in silicon (Si) microchannels was drastically enhanced in a single annular flow boiling regime enabled by superhydrophobic Si nanowire inner walls. Part I of this study focuses on characterizing enhanced flow boiling heat transfer. Part II focuses on revealing mechanisms in governing pressure drop and critical heat flux (CHF). Compared to flow boiling in plain-wall microchannels without using inlet restrictors (IRs), the average heat transfer coefficient (HTC) and CHF were enhanced by up to 326% and 317% at a mass flux of 389 kg/m\textsuperscript{2} s, respectively. Additionally, compared with flow boiling in microchannels with IRs, HTC of flow boiling in the single annular flow was enhanced by up to 248%; while CHF in the new flow boiling regime was 6.4–25.8% lower. The maximum HTC reached 125.4 kW/m\textsuperscript{2} K at a mass flux of 404 kg/m\textsuperscript{2} s near the exits of microchannels. The significantly promoted nucleate boiling, induced liquid film renewal, and enhanced thin-film evaporation in the self-stabilized and single flow boiling regime are the primary reasons behind the significant heat transfer enhancements during flow boiling.

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1. Introduction

Flow boiling in microchannels has been extensively studied in the last decade \cite{1–4} as it advantages for a range of applications including cooling high power microelectronics \cite{1,5,6}, compact heat exchangers, and chemical reactors \cite{7–10}. Significant progress has been made in understanding two-phase heat transfer mechanisms \cite{11,12}, two-phase flow instabilities \cite{13–15}, and critical heat flux (CHF) mechanisms \cite{16–18}. Various techniques such as micro reentry cavities \cite{19}, microporous structures \cite{12}, nanostructures \cite{20–22}, inlet restrictors (IRs) \cite{15,23}, pin fins \cite{24}, microjets \cite{25}, and seed bubbles \cite{26,27} were developed to promote flow boiling in microchannels. Specifically, micro cavities and micro/nanostructures can improve nucleate boiling by increasing active nucleation site density. IRs can improve CHF conditions by effectively suppressing reverse flows and hence flow boiling instabilities. Microjets were used to promote convections by disturbing flows in microchannels. However, these reported techniques have various drawbacks, such as the dramatically increased pressure drop resulting from IRs \cite{15}, reduced reliability induced by complex structures \cite{25–27}, and low HTC on IRs and finned boiling surfaces \cite{4,15,23,24,28}. Most recently, thermally induced high frequency two-phase oscillations were induced to generate mixing and hence significantly enhance flow boiling in microchannels \cite{29,30}. However, none of these techniques aimed to enhance flow boiling in microchannels through manipulating or even controlling two-phase flow structures, i.e., regimes.

During flow boiling in microchannels, boiling surfaces play critical roles in governing bubble nucleation, growth, separations, interactions, and two-phase flow regimes. Microchannels are usually microfabricated on silicon substrates by wet-etching or deep reactive ion etching (DRIE) \cite{6,8,31,32}. The peak-to-peak roughness of etched silicon wafers can be as low as 3 nm at the bottom wall \cite{33} and less than 300 nm at scalledp sidewalls \cite{34}, which are not favored by nucleate boiling due to the lack of favorable nucleation cavities, consequently, result in explosive boiling and low heat transfer rate because of high onset of nucleate boiling (ONB) \cite{35}. Various artificial nucleation cavities were developed to enhance nucleate boiling \cite{12,36,37}. Recently, one dimensional (1D) nanostructures such as nanowires (NWs) \cite{38,39} and carbon nanotubes (CNTs) \cite{40–42} were used to enhance nucleate pool boiling and convective boiling in microchannels \cite{20–22,43,44}. Enhanced HTC and CHF were reported because of the higher nucleation site density and enhanced wettability. However, the role of

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the boiling surface on the bubble size and controlling the dominant surface tension force, and hence controlling two-phase flow patterns/regimes and heat transfer modes has not yet been resolved. To date, flow boiling in microchannels is still dominated by bubble confinements [45,46], laminar and capillary flows, which result in multiple and stochastic flow pattern transitions [11,47], which tend to induce severe flow boiling instabilities and to suppress evaporation and convection.

A novel boiling surface with engineered submicron pores (formed by NW bundles) surrounded by nanoscale pores (created by individual NWs) were developed [48]. Applying these NW surfaces on all inner walls of the microchannels, the transitional flow boiling regimes in microchannels can be reduced to a single annular flow starting from ONB to CHF condition by controlling the flow structure in two aspects: reducing bubble size and transforming the direction of the surface tension force from the cross-sectional plane to the inner-wall plane [48]. In this experimental study, enhanced flow boiling heat transfer on deionized water (DI) in the single annular flow regime systematically characterized. The subcooling temperature at inlet was \( \theta = 40^\circ C \). The mechanisms of enhanced heat transfer are discussed.

2. Design of nanostructured boiling surfaces

Compared to mono-cavities (Fig. 1a) [34], the nucleation site density can be dramatically enhanced on bi-porous cavities formed on the nanostructured boiling surfaces [39,49] because the microscale cavities can be activated by vapor molecules generated in nanoscale cavities during the entire boiling process (Fig. 1b) [39]. In this experimental study, the nucleation cavity size was

![Fig. 1. Design of SiNW boiling surfaces. (a) Schematic drawing of bubble size in plain-wall microchannels. (b) Schematic drawing of bubble size in SiNW microchannels. (c) Optimal range of cavity diameters that can be formed by superhydrophilic SiNWs.](image-url)
optimized to enhance HTC by reducing the superheat, \( \Delta T \), i.e., the temperature difference between wall and saturation temperature. As shown in Fig. 1c, the range of active cavity opening diameter, \( D_c \), was estimated from Eq. (1) [50].

\[
D_{c_{\text{max,min}}} = \frac{\delta_t \sin \theta}{2(1 + \cos \theta)} \left( \frac{\Delta T}{\Delta T + \Delta T_{\text{sub}}} \right) \cdot \left[ 1 \pm \sqrt{1 - \frac{8\sigma\gamma(\Delta T + \Delta T_{\text{sub}})T_{\text{sat}}(1 + \cos \theta)}{\rho_l h_f \delta_t \Delta T^2}} \right]
\]  

where \( h_f \), \( \Delta T_{\text{sub}} \), \( \theta \), \( \sigma \), \( \rho_l \), and \( \delta_t \) denote latent heat of vaporization, subcooling temperature, contact angle, surface tension, vapor density, and thermal boundary layer thickness, respectively. With Eq. (1), the optimal range of nucleation cavity size on superhydrophilic surfaces for water was estimated to be between 100 and 2000 nm when assuming the apparent contact angles between 0.1° and 1°.

Guided by the classic nucleate boiling theory [50] and previous work [39], boiling surfaces with micropores (formed from NW bundles) surrounded by nanoscale gaps (created by individual NWs) as shown in Fig. 2c were created by Si nanowires (SiNWs) using the nanocarpet effect [51]. The SiNWs and their coverage in microchannels are illustrated in Fig. 2. The scanning electron microscope (SEM) images were taken with a tilt angle as shown in Fig. 2a. These images clearly show that the inner walls, including the side walls (Fig. 2b) and bottom wall in a microchannel (Fig. 2c and Fig. 2d), were nearly uniformly coated with SiNWs (approximately 20 nm in diameter and 5 \( \mu \)m in length). The top surfaces of the microchannel array were covered by Pyrex glass for visualization (Fig. 3). The SiNWs were oxidized to achieve superhydrophilicity (approximately 0° apparent contact angle) using the Wenzel effect [52,53]. This type of boiling surfaces intrinsically comprise of interconnected microscale and nanoscale cavities created by hydrophilic SiNWs and were used to improve nucleate boiling [38,39,54] and induce capillary flow and hence, thin film evaporation.

3. Experimental apparatus and procedures

3.1. Design of micro devices

As shown in Fig. 3a, the micro device consists of five parallel straight microchannels (width, depth, length: 200 \( \mu \)m \( \times \) 250 \( \mu \)m \( \times \) 10 mm). A flow stabilizer was placed in front of the inlets. Two pressure measuring ports were located at the inlet and the outlet to measure pressure drop. Thermal insulation air gaps were created to reduce heat loss during flow boiling tests. The thin-film heater was integrated on the backside to supply heat and was also used as a thermistor to measure the average surface temperature. Additionally, as shown in Fig. 3b, three thermistors (i.e., thermistors 1 to 3) were integrated underneath the microchannel array to measure the local temperatures. Specifically, thermistors #1, #2 and #3 were located near the inlet, one third the channel length downstream the inlet, and 2/3 the channel length of the channel downstream the inlet, respectively.

In this experimental study, as shown in Fig. 3c, flow boiling in three types of microchannel configurations was studied and compared. The objective is to achieve a better understanding of the enhancement mechanisms of flow boiling in the single annular flow by comprehensively comparing to two baseline configurations: plain-wall microchannels with and without IRs. All three configurations have nearly identical channel dimensions. To reflect HTC enhancement resulted from high nucleation site density and the single annular flow in SiNW microchannels [49], flow boiling data in plain-wall microchannels [32] was collected and used for comparisons. Moreover, plain-wall microchannels with IRs (width, depth, length: 20 \( \mu \)m \( \times \) 250 \( \mu \)m \( \times \) 400 \( \mu \)m) were further compared to demonstrate the enhancements induced by rewetting flows and enhanced thin-film evaporation in the new single annular flow boiling regime [49].

3.2. Micro device fabrications and SiNWs integration

The microchannel heat exchangers were made from a silicon wafer bonded to a Pyrex wafer by micro/nanofabrication processes.
Thin-film heaters and thermisters on the backside were integrated on the micro devices for flow boiling tests in order to improve the measurement accuracy. The fabrication processes started with a ∼500 μm thick, 100-mm-diameter <100> heavily doped P-type silicon wafer. 500 nm dense oxide layers were grown on both sides of the silicon wafer as an isolation layer by thermal
oxidation (Fig. 4a). 10-nm-thick titanium and 200-nm-thick aluminum were deposited by DC sputtering and patterned as thermistors and metal connection pads, respectively (Fig. 4a and Fig. 4b). Subsequently, thin-film heaters were patterned by wet-etching (Fig. 4c). Aluminum metal connections for electrical power were also patterned by wet-etching as shown in Fig. 4c. A 500-nm silicon oxide layer and a thick photoresist layer (SPR 220-7.0) were then deposited and spin-coated to protect the backside of the devices (Fig. 4d). On the front side of the wafer, five parallel microchannels were etched by deep reactive ion etching (DRIE) (Fig. 4e).

Various techniques were developed to create nanostructured boiling interfaces, such as sputtering [39], electrochemical etching [38] and electrochemical deposition [20,38,54]. However, to the best of the authors’ knowledge, functional nanostructures on vertical walls to enhance heat transfer were not studied before. In this experimental study, an electroless electrochemical etching technique was employed and improved to directly grow SiNWs on the vertical and the bottom walls of the microchannels using silver nanoparticles (AgNPs) as catalysts [55,56]. Although previously AgNPs were used to form two-dimensional (2D) arrays of NWs [22,38,51], AgNPs coating on high aspect ratio structures, such as microchannel arrays to create SiNWs on all inner walls was demonstrated by the authors in previous study[49]. A 4.5 M hydrofluoric acid and 0.005 M silver nitrite solution were prepared for the deposition of the catalysts. The wafer was then carefully placed into the solution and a layer of AgNPs thin film on the inner walls was formed by slowly stirring the solution (Fig. 4f). The AgNPs were attached onto the smooth surfaces of the microchannels as etching catalysts while the remaining areas were protected in preparation for binding by an oxide or nitride layer. The wafer was rinsed in DI water to remove residual Ag+ and then was etched for about 15 min in 4.8 M hydrofluoric acid and 0.15 M hydrogen peroxide solution to achieve 5-µm-long SiNWs as shown in Fig. 4g. These SiNWs were naturally oxidized and became super-hydrophilic (approximately 0° apparent contact angle) using the Wenzel effect [38,43]. To reduce the vapor bubble departure diameter and enhance nucleate boiling, the height of the SiNWs was designed and carefully controlled during the etching process to form bi-porous boiling surfaces with optimized openings using the nanocarpet effect [51]. The morphology of the SiNWs can be controlled by varying the AgNPs deposition density and etching time. Denser AgNPs layer and longer etching time create higher porosities, and hence, larger cavities.

After integrating the SiNWs, four thorough vias were formed by DRIE to create two pressure ports, one liquid inlet, and one outlet as detailed in Fig. 4h. As shown in Fig. 4i, a Pyrex glass wafer was anodically bonded onto the silicon substrate to seal the microchannels and also to serve as a window for optical visualization. The individual microchannel testing chips (length, width, thickness: 30 mm x 10 mm x 1 mm) were cut from the wafer by a dice-saw.

4. Data measurements and reduction

4.1. Data measurements

Subcooled DI water was used as the working fluid. The flow boiling testing system was built and calibrated in previous work [29]. The pressures in the inlet and outlet were measured by two pressure transducers and used to estimate pressure drops in transient and steady states. The flow rate was measured by a Sensiron ASL1600 flowmeter with a 0.03 kg/m²s resolution. The average temperature of heater was measured by the thin film aluminum heater. All measurements were carried out at 1 atm and room temperatures (~22 °C). All experimental data were collected by an Agilent data acquisition system.

4.2. Data reduction

The temperature of the heater, \( T \), was calculated as a linear function of its resistance, \( R \), with a correlation coefficient larger than 0.9999.

\[
T = K(R - R_{ambient}) + T_{ambient}
\]

(2)

\( T_{ambient} \) and \( R_{ambient} \) are the ambient temperature and resistance. The slope, \( K \), was pre-calibrated [29]. The heat loss, \( Q_{loss} \), between the micro heat exchanger and the ambient was evaluated as a function of the corresponding temperature difference[29]. Additionally, the sensible heat from subcooled fluid, \( Q_{subcooled} = m \cdot C_p \cdot \Delta T_{sub} \), was excluded. The electrical power, \( P \), was calculated from the product of voltage and current, \( P = V \times I. \) The effective heat input from phase change, was reduced from

\[
P_{\text{eff}} = P - Q_{loss} - Q_{subcooled}
\]

(3)

Table 1

<table>
<thead>
<tr>
<th>Microchannel dimensions.</th>
<th>( W_{wall} (\mu m) )</th>
<th>( W_{w} (\mu m) )</th>
<th>( W (\mu m) )</th>
<th>( H (\mu m) )</th>
<th>( t_w (\mu m) )</th>
<th>( t (\mu m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>180</td>
<td>220</td>
<td>250</td>
<td>250</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. A cross-section map of a microchannel unit. \( W_{wall} \) is the width of wall between each channel and \( t \) is the thickness of the silicon wafer.

Table 2

<table>
<thead>
<tr>
<th>Name of variables Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flux, ( G )</td>
</tr>
<tr>
<td>Voltage on the heater, ( V )</td>
</tr>
<tr>
<td>Current on the heater, ( I )</td>
</tr>
<tr>
<td>Ambient temperature, ( T_{ambient} )</td>
</tr>
<tr>
<td>Electrical power on the heater, ( P )</td>
</tr>
<tr>
<td>Electrical resistance, ( R )</td>
</tr>
<tr>
<td>Average temperature, ( T )</td>
</tr>
<tr>
<td>Heat transfer coefficient, ( h_g )</td>
</tr>
</tbody>
</table>
Then, the exit vapor quality of the two-phase flow was estimated as

\[ \varepsilon_e = \frac{P_{\text{eff}}}{(h_{\text{fg}}/\dot{m}_1/C_1 \cdot A_{\text{c}})} \quad \text{(4)} \]

The effective heat flux based on the heating area, \( q_{\text{eff}}^0 \), was estimated through

\[ q_{\text{eff}}^0 = \frac{P_{\text{eff}}}{A_{\text{eff}}} \]

The wall temperature was calculated from

\[ T_{\text{wall}} = T_{\text{sat}} - \frac{q_{\text{eff}}^0}{(k_s/\dot{m}_1 \cdot A_{\text{eff}})} \quad \text{(5)} \]

where \( t_w \) is the thickness of wall, \( k_s \) is the thermal conductivity of silicon and the effective heating area, \( A_{\text{eff}} = 5 \cdot W_{\text{unit}} \cdot L \), is 20 mm² (2 mm × 10 mm). Considering the fin efficiency, the two-phase heat transfer coefficient, \( h_{\text{2p}} \), based on the wall areas is given by

\[ h_{\text{2p}} = \frac{q_{\text{eff}}^0 \cdot W_{\text{unit}}}{(T_{\text{wall}} - T_{\text{sat}})(W + 2 \cdot \eta \cdot H)} \quad \text{(6)} \]

where \( W_{\text{unit}}, W, \) and \( H \) are the unit width, the channel width and the channel height, respectively (Table 1 and Fig. 5). The fin efficiency, \( \eta \), is calculated as

\[ \eta = \frac{\tanh(m \cdot H)}{m \cdot H} \quad \text{(7)} \]

The fin parameter, \( m \), is given by

\[ m = \sqrt{\frac{2h_{\text{2p}}}{k_s \cdot W_w}} \quad \text{(8)} \]

The heat transfer coefficient was iteratively solved using Eqs. (6)–(8).

4.3. Data uncertainty and repeatability

The uncertainties of the measured variables and parameters were estimated based on the specifications of instruments as specified in Table 2. The uncertainties of the derived parameters were calculated using the propagation of uncertainty analysis [57].

The nucleation boiling could be enhanced by trapped air/gas [58] or residual particles [59] in cavities. However, this type of enhancements cannot sustain and be repeated. A repeat experimental studies were carried out for more than 400 h in two years (from 2011 to 2013). The repeat boiling curves within 8 month in a mass flux of 303 kg/m²s are nearly overlapped as illustrated in Fig. 6. It should be noted that wall temperatures were slightly

![Fig. 6. The repeat test at a mass flux of 303 kg/m²s.](image-url)

![Fig. 7. Characterization of the single annular flow in microchannels enabled by SiNWs. (a)–(f) A sequence of images representing important phases of the new flow boiling regime in a typical cycle. These images were captured from the top-view by a high-speed camera (Phantom V7.3) and an optical microscope (Olympus BX-51). Images were taken for mass flux of 303 kg/m²s and heat flux of 250 W/cm². The white/gray areas denote vapor bubbles and black/dark areas stand for liquid or droplets. (g)–(l) the schematic maps of the top views and cross-sectional views of the new flow boiling regime in a cycle.](image-url)
reduced after eight months (Fig. 6), which could be caused by more hydrophilic SiNWs resulting from longer time oxidation [60].

5. Results and discussion

5.1. Single annular flow boiling regime

The behaviors of flow boiling in microchannels were fundamentally altered when the bubble size was reduced down to nanometer or submicrometer (<5 μm) as schematically shown in Fig. 1 [61,62]. As a result, a single annular flow as illustrated in Fig. 7 was induced by superhydrophilic SiNWs grown on all inner walls inside the microchannels [49]. In the new flow boiling regime, a vapor core at the center of the channels periodically grows and shrinks (Fig. 7a, b, c, g, h and i) because of the induced rewetting flows (Fig. 7d, e, f, j, k and l) by SiNWs with a frequency larger than 24 Hz (Fig. 15b) [49]; while liquid films are on walls. The cross-sectional viewed vapor core is schematically illustrated in Fig. 7 to assist visualization of the fluid structure in the single annular flow. The characteristics of the new flow boiling pattern are favorable for heat and mass transfer. Specifically, the rapid rewetting process [49] triggered by capillary flows on the superhydrophilic bi-porous interfaces can greatly increase \( CHF \) conditions by improving the global liquid supply and further enhancing \( HTC \) by introducing thin film evaporation and nucleate boiling as well as capillary-assisted liquid film renewal [49].

5.2. Heat transfer curves and major heat transfer modes

5.2.1. Average heat transfer coefficient

Flow boiling curves (i.e., heat flux versus superheat), \( HTC \) versus superheat, and \( HTC \) versus vapor quality are depicted in Figs. 7-9, respectively. Flow boiling in smooth-wall microchannels and microchannels with IRs (Fig. 3c) were compared to reveal the enhanced flow boiling in the single flow boiling regime enabled by SiNWs [49].

From Fig. 8, for a given superheat, the working heat fluxes, \( q_{\text{eff}} \), in the SiNW microchannels were the highest among the three types of microchannel configurations with mass fluxes, \( G \), ranging from 160 to 389 kg/m² s. For example, \( q_{\text{eff}} \) increased from 155 W/cm² (smooth-wall microchannels) or 240 W/cm² (microchannels with IRs) to 350 W/cm² in SiNW microchannels at \( \Delta T = 28 \) K and \( G = 389 \) kg/m² s.

Comparisons of \( HTC \) curves are shown in Figs. 9 and 10, respectively. The heat transfer coefficient was drastically enhanced by up to 326% in the SiNW microchannels compared to that in smooth microchannels. For example, \( HTC \) was enhanced from 25.2 kW/m² K in the smooth-wall microchannels to 65.2 kW/m² K in the SiNW microchannels at a condition of \( \Delta T = 28 \) K and \( G = 389 \) kg/m² s. A maximum \( HTC \) enhancement is up to 326% (i.e., from 29.6 kW/m² K to 96.3 kW/m² K) with \( \chi = 0.07 \) and \( G = 230 \) kg/m² s. Performance of Microchannels with IRs is between the smooth-wall microchannels and SiNW microchannels [63].

As shown in Fig. 10, flow boiling in the smooth-wall microchannel cannot work at high exit vapor qualities, \( \chi \) (i.e., usually less than 0.1) because of premature \( CHF \) [64]. On the other hand, flow boiling in microchannels with IRs is still effective at exit mass qualities as high as 0.55 (Fig. 10c), but the IR configurations can only achieve a maximum \( HTC \) of 40 kW/m² K. However, without using IRs, SiNW microchannels can operate at an exit vapor quality up to 0.52 (Fig. 10a) with a significantly higher averaged \( HTC \) up to 60 kW/m² K by promoting thin film evaporation and nucleate boiling as well as capillary-assisted liquid film renewal [49].
implies that IRs can be used to effectively suppress flow instabilities, but not as efficient as SiNWs in enhancing HTC as demonstrated in this experimental study.

5.2.2. Local heat transfer coefficient

To further reveal heat transfer mechanisms, the local heat transfer coefficient was illustrated in Fig. 11. T1 to T3 that denote local thermistors are labeled in Fig. 3b. The local dependency of HTC in SiNW microchannel is consistent with the distribution of liquid film thickness (Fig. 7), suggesting significant enhancement with thin film evaporation. Additionally, Hysteresis in the region of nucleation incipience [65] was observed in all locations as shown in Fig. 11a, c, and e. Thus, nucleate boiling was a basic heat transfer mode in the SiNW microchannels.

Specifically, HTC near the entrance indicated by T1 were always the lowest. As shown in Fig. 7, the entrance region is dominated by single-phase convection and nucleate boiling. Thus, the lower HTC in the entrance region is a result of the absence of thin film evaporation heat transfer and capillarity-induced high frequency liquid film renewal. The higher HTC downstream the entrance region can be attributed to enhanced nucleate boiling, thin film evaporation, and capillary-induced liquid film renewal in the single annular flow [49]. Note that the highest HTC, located at the 2/3 of channel length (i.e., the thermistors 3 in Fig. 3b), was 90% higher than the second highest HTC, located 1/3 of channels length downstream the entrance, and 150% higher than the lowest value near the entrance area. Because of the ultra-efficient thin film evaporation and fast liquid film renewal adjacent to the front of the rewetting region, the local HTC reached a maximum value of up to 125.4 kW/m² K at a mass flux of 404 kg/m² s.

5.2.3. Heat transfer modes

As discussed earlier, nucleate boiling is an important heat transfer mechanism throughout the boiling process. Its importance, however, might be confined to certain areas (i.e., the upstream of the two-phase region where the mass quality is low) in SiNW microchannels. Equally important is thin film evaporation at moderate and high mass qualities, which significantly enhances overall flow boiling HTC in the SiNW microchannels. The high rewetting frequency induced by superhydrophilic SiNWs creates fast liquid film renewal [49].

As schematically shown in Fig. 12, three major heat transfer modes were involved during flow boiling in the SiNW microchannels. These include nucleate boiling, thin film evaporation, and liquid film renewal.

5.3. Enhanced nucleate boiling

Visualization study and theoretic analysis were conducted to reveal bubble dynamics in SiNW microchannels. Using novel and optimized SiNW boiling surfaces in microchannels, the bubble diameter during flow boiling were reduced to be less than 5 μm, i.e., termed nanobubbles (NBs). It was experimentally demonstrated that the SiNW boiling surfaces not only reduce the bubble departure diameter [43,49], but also greatly increase the nucleation site density. In this study, the active bubble nucleation sites,
marked by the dashed lines in Fig. 13a and b, was estimated to be on the order of $10^{10} \text{m}^2/\text{C}_0^2$ on the SiNW boiling surfaces because of the interactions between interconnected and super-hydrophilic nano/micro-cavities [39]. As shown in Fig. 13c, this value is five orders of magnitudes larger than that in plain-wall microchannels during flow boiling [34]. The significant increase of nucleation site density is primarily due to enhanced surface wettability [43] as well as the reduced cavity size [39]. Both of them are critical to determine the bubble departure diameter and frequency.

A theoretical study was conducted to obtain better understandings on current experimental results. An equation to describe bubble departure process, was developed from a force analysis [66],

$$F_{QS} + F_{AM} \approx F_C,$$

where $F_{QS}$, $F_{AM}$, and $F_C$ are quasi-steady drag force, added mass force (or inertia force), and anchoring capillary force. The quasi-steady drag force, $F_{QS}$, can be estimated from the equation developed in [66],

$$F_{QS} = 3\pi \cdot \rho_l \cdot v \cdot (\bar{u} - u_b) \cdot D_b \cdot \left\{ \frac{2}{3} + \frac{12}{Re_b} + 0.75 \left( 1 + \frac{3.315}{Re_b^{0.5}} \right) \right\}^{-1}$$

(10)

where $D_b$ is the bubble departure diameter, $Re_b = D_b \cdot (\bar{u} - u_b)/v$ is the bubble Reynolds number, $\rho_l$ is the density of the liquid, $\bar{u}$ is average flow velocity, $u_b$ is the bubble growth velocity; and $v$ is the kinematic viscosity. $F_{AM}$ is calculated according to [66]

$$F_{AM} = 2\pi \cdot \rho_l \cdot D_b^2 \cdot \bar{u} \cdot \bar{u}$$

(11)

where the bubble inclination angle is neglected as the gravitational force diminished at the micro scale. The anchoring capillary force is estimated from:

$$F_C = \pi \cdot D_c \cdot \gamma \cdot \sin \theta$$

(12)

In a previous study [67], bubble growth rate in term of bubble diameter, $D_b$, was assumed to be a positive constant. While a bubble is growing at a nucleation site, drag force $F_{QS}$, and inertial force, $F_{AM}$, can balance, capillary force, $F_C$, to assist bubble departure as indicated in Eq. (9). Additionally, Eqs. (10) and (11) suggest that drag force, $F_{QS}$, and inertial force, $F_{AM}$, increase with bubble departure diameter. This is in agreement with experimental results [34,67] demonstrating that the departure diameter of conventional size bubbles on smooth surface with a contact angle of approximately $36^\circ$ has a characteristic length scale of about one millimeter. However, when the apparent contact angle on a super-hydrophilic bi-porous interface was assumed to nearly zero (estimated at less than $0.1^\circ$) [38,43], according to the Eq. (12), a smaller contact angle, $\theta$, leads to a smaller anchoring capillary force, $F_C$. It implies that bubbles can be departure at smaller size because the required forces to assist the departure of bubbles, i.e., drag force, $F_{QS}$ and inertial force, $F_{AM}$, are reduced. Note that the drag force, $F_{QS}$, is an order of magnitude higher than capillary force, $F_C$ when the bubble diameter is less than 5 $\mu$m [49].
Fig. 11. Comparisons of local heat transfer performance in microchannels. $T_1$, $T_2$ and $T_3$ represent the thermistors locations at the entrance, 1/3 length and 2/3 length along the channel from the entrance, respectively. (a), (c) and (e) the effective heat fluxes as a function of superheat temperatures at various mass fluxes and positions. (b), (d) and (f) the local HTC as a function of superheat temperatures under various mass fluxes.

Fig. 12. A comprehensive schematic map of heat transfer mechanisms in SiNW microchannels including nucleation boiling heat transfer, convective heat transfer, and thin-film evaporation heat transfer.
In the previous section, the enhanced nucleate boiling was discussed and analyzed. In this section, the capillary flows and the resulting thin film evaporation, which was induced by the superhydrophilic SiNWs on all inner walls of the microchannels, as evidenced by the rapid liquid renewal along walls in microchannels (Fig. 14a), are discussed.

As the liquid film thickness decreases downstream (as shown in Fig. 14a), SiNWs were eventually exposed to vapor and hence meniscus were formed. As a result, rapid liquid renewal occurred in a periodic pattern because of the induced strong capillary force generated by superhydrophilic SiNWs. Instead of nucleate boiling, thin film evaporation and liquid film renewal on the downstream inner walls of the microchannels dominated the heat transfer process. The rewetting velocity profile along the length of the channel is plotted in Fig. 14b. The strong liquid film renewals were evident by the high liquid renewal velocity, which is approximately five times faster than the average flow velocity as shown in Fig. 14c. Additionally, the fast liquid renewal can greatly improve the global liquid supply. The local dry-out inside the microchannels can be eliminated by the capillary flows generated by the superhydrophilic SiNWs. As detailed in Part II of this study, the much improved liquid supply in the single annular flows resulted in high CHF [49]. The significantly extended thin-film region is a primary enhancer of heat transfer as it diminishes the thermal resistance across the thickness of the liquid film [68]. However, the length of the thin-film region in traditional microchannels is limited to several hundred nanometers as a result of the domination of intrinsic meniscus in a vapor slug [69,70]. On the contrary, in this study, the vapor slugs inside the microchannel were not observed during the entire flow boiling region and process. The transitional flow regimes were reduced to a single annular flow regime [49]. As a result, the thin film evaporating region, as schematically shown in Fig. 12, is extended to nearly the entire length of the microchannels accompanied by rapid liquid renewal.

A typical evaporation process is detailed in Fig. 15a. Once the liquid films are established inside the microchannels, a vapor core at the center of a microchannel (Fig. 15a) would be accordingly formed. The size of the vapor core grew cyclically as the thin film evaporation and nucleate boiling intensified, which are indicated by the gradually decreasing liquid film thickness (Fig. 15a). When the liquid film was nearly disappeared, capillary flows resumed by

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Fig. 13. Enhanced nucleation boiling near the entrance region. (a) and (b) bubble nucleation at an effective heat flux of 70 W/cm² and a mass flux of 213 kg/m² s. (c) Active nucleation site density on a boiling surface with superhydrophilic SiNWs and smooth walls.

5.4. Promoted thin film evaporation and liquid film renewal

In the previous section, the enhanced nucleate boiling was discussed and analyzed. In this section, the capillary flows and the resulting thin film evaporation, which was induced by the superhydrophilic SiNWs on all inner walls of the microchannels, as evidenced by the rapid liquid renewal along walls in microchannels (Fig. 14a), are discussed.

As the liquid film thickness decreases downstream (as shown in Fig. 14a), SiNWs were eventually exposed to vapor and hence meniscus were formed. As a result, rapid liquid renewal occurred in a periodic pattern because of the induced strong capillary force generated by superhydrophilic SiNWs. Instead of nucleate boiling, thin film evaporation and liquid film renewal on the downstream inner walls of the microchannels dominated the heat transfer process. The rewetting velocity profile along the length of the channel is plotted in Fig. 14b. The strong liquid film renewals were evident by the high liquid renewal velocity, which is approximately five times faster than the average flow velocity as shown in Fig. 14c. Additionally, the fast liquid renewal can greatly improve the global liquid supply. The local dry-out inside the microchannels can be eliminated by the capillary flows generated by the superhydrophilic SiNWs. As detailed in Part II of this study, the much improved liquid supply in the single annular flows resulted in high CHF [49]. The significantly extended thin-film region is a primary enhancer of heat transfer as it diminishes the thermal resistance across the thickness of the liquid film [68]. However, the length of the thin-film region in traditional microchannels is limited to several hundred nanometers as a result of the domination of intrinsic meniscus in a vapor slug [69,70]. On the contrary, in this study, the vapor slugs inside the microchannel were not observed during the entire flow boiling region and process. The transitional flow regimes were reduced to a single annular flow regime [49]. As a result, the thin film evaporating region, as schematically shown in Fig. 12, is extended to nearly the entire length of the microchannels accompanied by rapid liquid renewal.

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Fig. 14. The capillary flows along the inner walls of the microchannels. (a) Visualization of capillary flows along the inner walls and the renewal of liquid film. Fast rewetting flows in a microchannel during flow boiling for \( G = 193 \text{ kg/m}^2 \text{s} \) and \( u = 0.4 \). (b) Rewetting velocity profile during a rapid and periodic rewetting process. (c) Comparison between the average velocity of rewetting flow and average velocity of inlet flow.
the high capillary pressure induced by hydrophilic SiNWs on the inner walls and consequently, triggered rapid liquid renewal. The size of the vapor core and the thickness of the liquid film grow and shrink periodically at a high frequency as observed by a high speed camera (Fig. 15b and c). The frequency of vapor core growth is equal to the frequency of liquid film renewal because the rewetting process only occurs after the vapor core filled the whole channel (Fig. 15b). It implied that the liquid film renewal is activated by unsaturated superhydrophilic silicon nanowires [48]. A typical change of the vapor core size and the liquid film thickness are depicted in Fig. 15c. The thin-film was generated and extended along the length of the microchannel in a short time period (~10 ms). No bubbles were visualized during this process. The local HTC, which was dominated by thin film evaporation, at the furthest position was measured to be up to 125.4 kW/m²K at a mass flux of 404 kg/m²s.

6. Conclusion

In this study, flow boiling was drastically enhanced in microchannels with SiNWs grown in all inner walls compared to smooth-wall microchannels with and without IRRs because the favorable heat transfer modes (i.e., nucleate boiling and thin film evaporation) are selected by the new single annular flow. Flow boiling in the new flow regime was also systematically characterized. Three heat transfer modes in the new flow boiling regime were identified including nucleate boiling, thin film evaporation, and liquid film renewals. The enhanced nucleate boiling heat transfer is primarily a result of the high active nucleation site density enabled by the engineered SiNW boiling surfaces. The rapid capillary flows or liquid renewal induced by the superhydrophilic SiNWs play critical roles in promoting thin film evaporation and liquid film renewals over the entire microchannels. Visualization study was performed to reveal the heat transfer process and flow structure in the single annular flow.

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