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Impact of wall hydrophobicity on condensation flow and heat transfer in silicon microchannels

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Abstract

While microchannel condensation has been the subject of several recent studies, the critical impact of wall hydrophobicity on the microchannel condensation flow has received very little attention. The paper experimentally studies steam condensation in a silicon microchannel 286 μm in hydraulic diameter with three different wall hydrophobicities. It is found that the channel surface wettability has a significant impact on the flow pattern, pressure drop and heat transfer characteristic. Spatial flow pattern transition is observed in both hydrophobic and hydrophilic channels. In the hydrophobic channel, the transition from dropwise/slugwise flow to plug flow is induced by the slug instability. In the hydrophilic channel, the flow transition is characterized by the periodic bubble detachment, a process in which pressure evolution is found important. Local temperature measurement is conducted and heat flux distribution in the microchannel is reconstructed. For the same inlet vapor flux and temperature, the hydrophobic microchannel yields higher heat transfer rate and pressure drop compared to the hydrophilic channel. The difference is attributed to the distinction in flow pattern and heat transfer mechanism dictated by the channel hydrophobicity. This study highlights the importance of the channel hydrophobicity control for the optimization of the microchannel condenser.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Due to its broad engineering applications, such as a plate fin heat exchanger [1], a micro refrigerating system [2], a micro heat pipe and thermal regulation in compact electronics [3], condensation in channels and tubes has attracted considerable research interest.

Most previous work has been focused on the condensation flow patterns in tubes and channels at macroscale and miniscale [4–6]. However, a visualization study [7] of condensation flow in tubes with diameters ranging from 0.1 mm to 0.56 mm clearly indicated that the asymmetrical stratified flow pattern caused by the gravity dominates the tube at macroscale and miniscale, while the axis-symmetrical liquid film exists in the tube having a diameter less than 1 mm, a good indication of the dominance of capillary force at the microscale. Other experimental work [8, 9] also showed that the condensation flow pattern in a microchannel deviates significantly from

those at macroscale and miniscale. With the decrease of the channel size and Bond number, the surface tension dominates the dynamics of liquid–vapor two-phase flow whereas body forces are generally negligible [10]. Also, the surface wettability and channel geometry are of particular importance to the condensation flow in a microchannel, due to the strong fluid–boundary interaction [11].

Nearly all work conducted so far on the microchannel condensation flow is restricted to the hydrophilic channel. In a recent experimental study [12] on condensation flow in round microchannels, a flow regime map was developed to predict the intermittent and annular flow patterns for various mixture qualities. A recent study of condensation in microchannels was reported by Wu *et al* [9] for trapezoidal microchannels having a hydraulic diameter of 82.8 μm in which various flow patterns including droplet/annular/injection/slug flow were observed. In addition to the flow pattern observation, the condensation heat transfer and flow friction in the trapezoidal

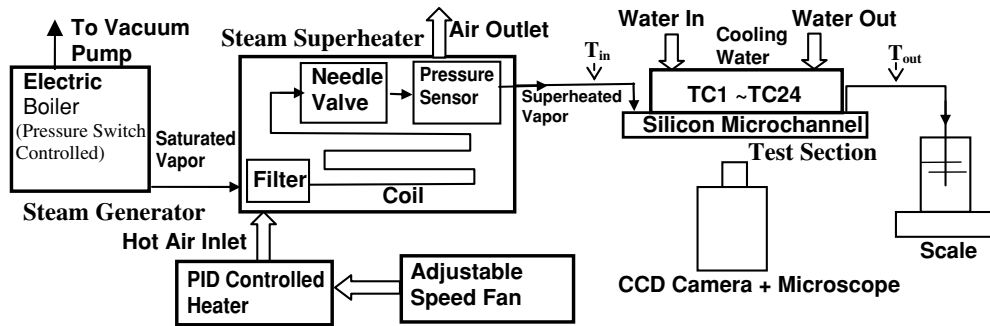


Figure 1. Schematic diagram of the experimental setup.

hydrophilic microchannels was systematically studied and it was found that the condensation Nusselt number increases with Reynolds number, and dimensionless hydraulic number [19] and the correlation for condensation heat transfer and flow friction were proposed. Also, a visualization study [13] was performed on the steam condensation in trapezoid silicon microchannels with sidewalls cooled by natural air convection. The paper theoretically predicted that the heat flux decreases with the channel diameter. Zhang *et al* [8] investigated the condensation in a single silicon microchannel with a high aspect ratio of 26.7, focusing on the shape, size and the detachment frequency of the formed bubbles. It was found that higher cooling rate results in a higher bubble generation frequency and smaller bubble size. The mechanism of bubble formation was also discussed.

Testing of the condensation on the external surface shows that the heat transfer rate yielded by the dropwise condensation which typically occurs on the hydrophobic surface is an order of magnitude higher than that given by the filmwise condensation on the hydrophilic surface [14, 15]. The high heat transfer rate of dropwise condensation on the external surface implies that the hydrophobic channel condensation may also exhibit a better heat transfer performance than its hydrophilic counterpart, which makes the hydrophobic channel condensation useful for the compact heat exchanger application. In contrast to the extensive study on the condensation on the external hydrophobic surface, very little experimental and analytical work has been devoted to the condensation flow in the hydrophobic microchannel, for which the small Bond number, high surface tension and confined channel space jointly make the flow pattern and heat transfer characteristic highly sensitive to the channel wettability. There is not a deep understanding of the impact of wall hydrophobicity on the microchannel condensation, which could be obtained by conducting a systematic flow pattern visualization and heat transfer measurement on microchannels with a variety of hydrophobicities.

The present work aims at performing a visualization study on the condensation flow pattern in microchannels with a fixed geometry of $200\ \mu\text{m}$ by $500\ \mu\text{m}$ and three distinct hydrophobicities using high speed imaging. Three major types of flow patterns, i.e. dropwise/slugwise flow, dropwise/stratified flow and film/stratified flow, are observed in hydrophobic, hydrophilic and semi-hydrophobic channels, respectively. In addition to the visualization experiment, a

thermocouple array consisting of 24 independent channels is developed to measure the temperature distribution in microchannels, based on which the heat flux distribution is reconstructed. Measurement indicates that under the same channel geometry and inlet vapor flux, condensation in the hydrophobic channel yields a higher heat transfer rate and pressure drop than the hydrophilic channel. The study of the spatial flow pattern transition indicates that the slug instability induced by the contact angle hysteresis might be responsible for the flow transition from dropwise/slugwise flow to plug in the hydrophobicity channel, while the periodic pressure variation is responsible for the transition from stratified flow to bubbly flow in the hydrophilic channel. The investigation also shows that the liquid escape microchannel, a novel design suppressing the flow transition, may substantially enhance the heat transfer rate of the microchannel condensation.

2. Experimental setup

2.1. Experimental test loop

Experimental apparatus is designed to generate steam flow at designated temperature, pressure and flowrate, as well as facilitate flow visualization and measurement. Figure 1 shows the steam generator, steam superheater, test section, hot air control module and optical visualization stage. A press-switch-controlled electric boiler supplies saturated steam at the designated pressure and temperature. To de-air the steam, the boiler is evacuated and then filled with degassed water, which is obtained by ultrasonically heated water in a vacuum chamber for 2 h. The steam supplied by the boiler flows through a needle valve for precise flowrate regulation and an Omega PX-15 pressure gauge for channel inlet pressure measurement. To compensate for the heat loss and avoid the condensation of steam before entering the microchannel, tubing and components between the boiler and the test section are enclosed in a superheater whose temperature is regulated by blowing in hot air. The power of the airflow heater and the dc fan speed are subject to a PID control loop for airflow temperature stabilization. The spatial and temporal uniformity of the temperature ($\Delta T_{\text{spatial}} < 2^\circ\text{C}$ over the entire chamber, $\Delta T_{\text{temporal}} < 1.5^\circ\text{C}$ over 1 h) in the superheater chamber is ensured by maintaining a high and stable airflow velocity ($> 2\ \text{m s}^{-1}$). The outlet of the microchannel test section is open to the atmosphere, where the temperature and pressure are also

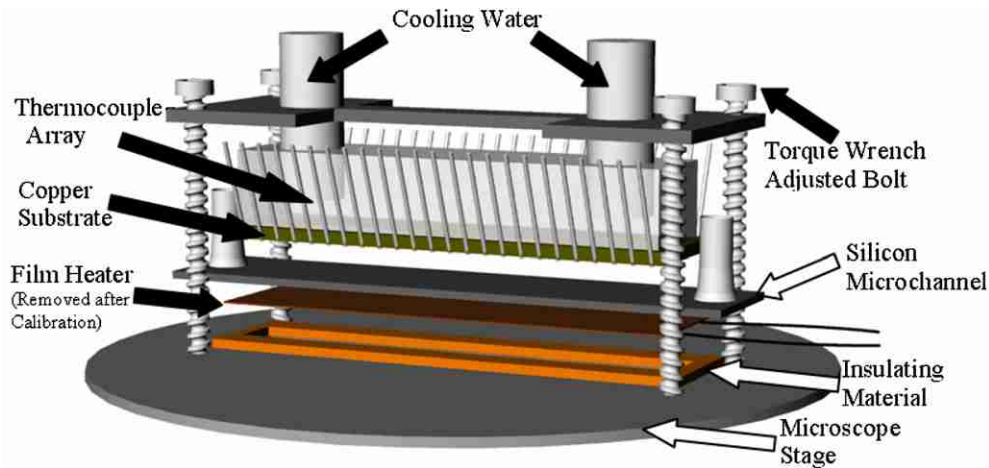


Figure 2. Close-up view of the setup for local temperature measurement.

recorded. The mass flowrate of the condensate is determined using an electronic scale.

2.2. Instrumentation for heat transfer measurement

Figure 2 shows the architecture of the test section for flow pattern visualization and local temperature measurement. A cooling water chamber made of copper is used to draw the heat from the microchannel. The cooling water flowrate is high such that the temperature rise of the water in the water chamber is negligible. To enable the measurement of the local temperature distribution on the microchannel surface, a thermocouple array is assembled by machining 24 trenches on a copper substrate, in which 24 channels of type K thermocouples 0.2 mm in diameter are buried. The buried parts of the thermocouples are painted and wrapped by the Teflon tape to ensure electric insulation and minimize inter-channel electric coupling. After the test section is finally assembled, the copper heat sink is attached to the back surface of the microchannel. The thermocouple junctions are in direct contact with the microchannel substrate, and thereby the temperature distribution on the chip surface can be measured with a 1.5 mm resolution. Thermal grease is applied between the silicon channel and copper heat sink to reduce the contact resistance. The bottom surface of the microchannel chip is well insulated against the microscope stage; thus, the heat in the microchannel can only be dumped through its top surface and removed by the cooling water.

To reconstruct the heat flux distribution in the microchannel, the contact thermal resistance between the copper heat sink and the silicon chip must be determined. Strongly dependent on the surface condition and the contact pressure, the contact resistance is re-calibrated each time the chip in the test section is changed. To measure the contact resistance, a uniform heat flux is applied to the bottom surface of the chip by attaching a Kapton film heater, and the contact resistance can be determined following the procedure detailed in section 4. The cooling-chamber-thermocouple-array-assembly is mounted onto the microscope stage by four bolts screwed on using the torque wrench, ensuring the same

contact pressure is applied between the heat sink and chip surface for each round of testing.

2.3. Optical visualization system

Figure 3(a) shows a schematic of the optical system for flow pattern visualization. A Nikon TE2000U inverted microscope operated in reflective imaging mode with 4 $\times$ and 10 $\times$ objectives is employed. Image is captured by a Phantom v6.3 high speed CCD camera, which can work at the speed of 10 000 frames s⁻¹ with a resolution of 1200 $\times$ 800 pixels. In addition to the normal optical imaging, an optical interferometry is employed to obtain the topology of the thin liquid film present in the upstream region of the hydrophilic microchannel. A similar approach was also used by Gokhale *et al* [16] for the measurement of contact angle and droplet curvature in a constrained vapor bubble. A beam of monochromatic green light from a fluorescent lamp passes through a 520 nm filter and is partially reflected by a 50% beam splitter in the microscope to illuminate the microchannel through the microscope objective. The light reflected by the sample then passes through a beam splitter and is captured by the high speed CCD camera. Fringes (figure 3(b)) appear due to the interference of the light reflected by the liquid–solid and liquid–vapor interfaces. The fringes represent the contour of the liquid film thickness, with the points on two neighboring fringes differing in thickness by one wavelength, i.e. 520 nm. The 3D profile of the liquid film can thereby be constructed from the 2D fringe pattern. Real-time imaging of fringes indicates the transient variation of the film structure.

2.4. Microchannel fabrication

In the present study, single straight microchannels are microfabricated on the silicon wafer in (1 0 0) orientation. The microchannels have rectangular cross-section, and are 200 μ m in depth, 500 μ m in width and 6 mm in length. Instead of using the wet etching approach [13] which typically yields a trapezoidal cross-section, the present fabrication process utilizes a plasma etching process known as deep

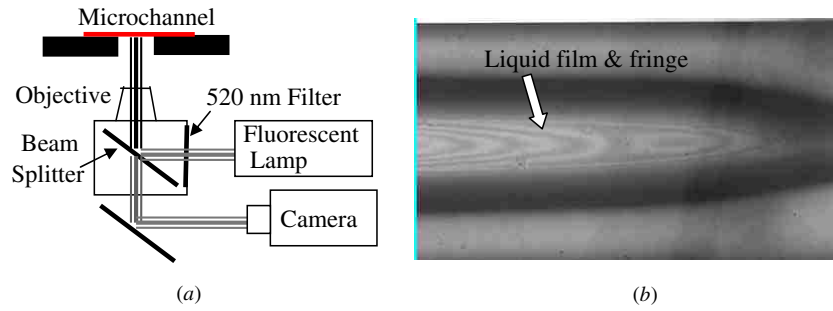


Figure 3. Visualization setup configuration. (a) Light path. (b) Interference fringe image indicating film topology.

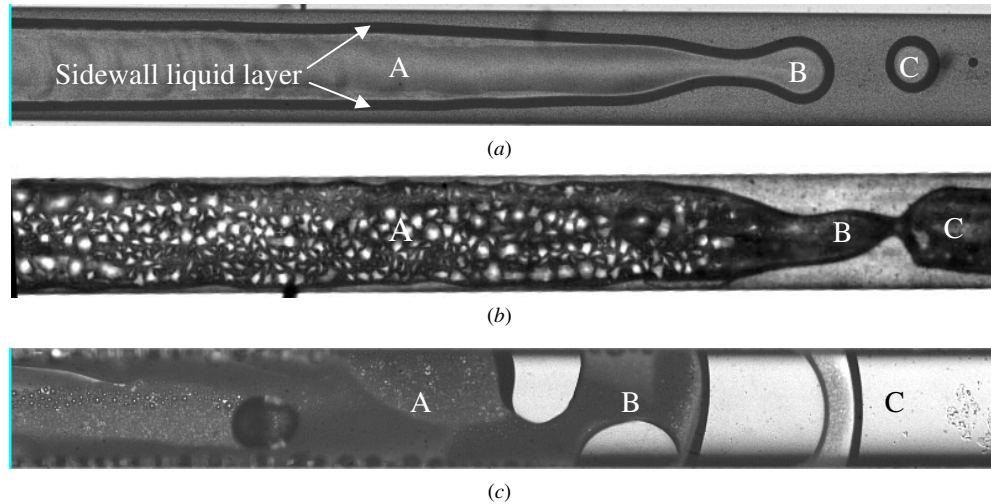


Figure 4. Condensation flow patterns in microchannels with three levels of wettability. (a) Hydrophilic channel 2, film/stratified flow pattern. (b) Semi-hydrophobic channel 3, dropwise/stratified flow pattern. (c) Hydrophobic channel 1, dropwise/slugwise flow pattern.

Table 1. List of tested microchannels.

Channel ID	Depth (μm)	Width (μm)	Aspect ratio	Hydraulic diameter (μm)	Equilibrium contact angle (external surface)	Hydrophobicity
1	200	500	2.5	285.7	123°	Hydrophobic
2	200	500	2.5	285.7	25°	Hydrophilic
3	200	500	2.5	285.7	91°	Semi-hydrophobic

reactive ion etching (DRIE) to carve out the rectangular channels in silicon wafer substrates. DRIE is also used to create thru holes in the substrate that serve as inlets and outlet for the fluids. A glass cover is anodically bonded to the wafer substrate to allow the flow visualization and to seal the structure. Channel depth is roughly controlled by the etching time, but can be accurately measured post fabrication. In order to render the channels with a variety of wettabilities, the structures are treated with a molecular vapor deposition (MVD) process at Applied Microstructures Inc. [21], during which a layer of self-assembled monolayers is deposited on the channel inner surface to enhance its hydrophobicity. Contact angle measurements carried out on the external surface of the chip both prior to and after the experiment return the material hydrophobicity. The internal surface is expected to have similar hydrophobicity with the external surface considering both of them were subject to the same coating process. The surface wettability is found to

be stable subject to the temperature and humidity used in the current experiment over the entire period of the experiment. A full list of tested channels with the corresponding geometries and hydrophobicities is shown in table 1.

3. Flow pattern visualization

To study the influence of the surface wettability on the condensation flow and heat transfer, microchannels with the same geometry and three different surface hydrophobicities (see table 1) are tested. As shown in figure 4, three major types of flow patterns, namely dropwise/slugwise flow, dropwise/stratified flow and film/stratified flow, are observed in microchannels with high, medium and low hydrophobicity, respectively. Stable flow patterns are present in all three channels and static images are sufficient to illustrate the major features of flow patterns in each microchannel.

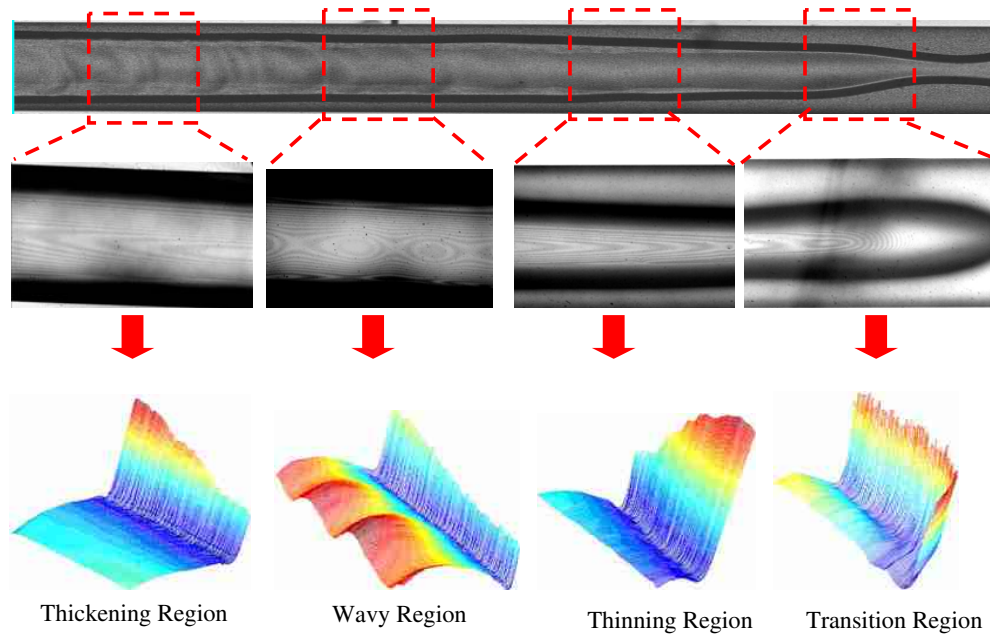


Figure 5. Thin liquid film profile in hydrophilic microchannel 2. Profile is obtained using interferometry (row 1: flow pattern, row 2: interference fringe, row 3: constructed liquid film topology).

3.1. Flow pattern in the upstream region

3.1.1. Hydrophilic microchannel. In the hydrophilic microchannel 2 with the aspect ratio of 2.5 (figure 4(a)), the channel wall is completely wetted by the liquid phase. Therefore, the upstream region of the channel has its front and back surfaces covered by stable thin liquid films (figure 4(a), point A) and its sidewalls covered by stratified liquid layers. Figure 5 shows the thin film profile evolution (figure 5, row 3) along the hydrophilic channel 2, which is constructed based on the interference fringe (figure 5, row 2) captured by the optical interferometry described in section 2.3. The presence of the fringe indicates the amplitude of the film thickness variation is comparable to the wavelength of 520 nm used by the interferometer. Moving from the channel inlet to the outlet, the variation of film topology undergoes four major phases, including thickening, wavy fluctuation, thinning and flow transition. Detailed discussion of the liquid film profile is presented elsewhere. As shown in figure 4(a), the longitudinal evolution of the liquid–vapor mixture features the thickening of the sidewall liquid layer, narrowing of the thin film region, and the shrinkage of the vapor core at the channel center. The thin film region narrows at an increasing rate longitudinally, until the liquid layers adhering to the top and bottom walls touch, marking the flow transition from stratified flow to bubbly flow. A similar pattern was also observed in the trapezoidal silicon microchannel [9, 17, 18].

3.1.2. Hydrophobic microchannel. In contrast to the hydrophilic channel wall, the surface of the hydrophobic channel is barely wettable to the liquid phase, and the vapor–liquid–solid triple phase contact line exists. A close-up view of the upstream region of the hydrophobic microchannel illustrates that, as shown in figure 6, dropwise condensation occurs on the front and back surfaces. Similar to that

on the external surface [14], dropwise condensation in the microchannel also generates a population of randomly distributed small droplets with an average size on the order of a few microns. For dropwise condensation on the external surface, small droplets typically grow to a critical size by the coalescence between neighboring droplets until departure occurs [15]. The droplets in the microchannel, in contrast, rarely reach their departure size. Instead, the small droplets on the front/back surface are periodically swept away by the giant slugs moving along the sidewall from the upstream. Figures 6(a)–(c) show a typical process in which a queue of small sidewall slugs is initially formed, followed by the growth of slugs due to the coalescence between neighboring slugs. The slugs reaching their departure size are convected to the downstream by the vapor flow and wipe away the small droplets in its way, leaving a cleaned surface behind on which a new cycle of droplet nucleation, growth, coalescence and sweeping process takes place (figure 6(d)).

Figure 7 shows the longitudinal evolution of the dropwise-condensation-slug-sweeping flow pattern in the upstream region of the hydrophobic microchannel 1. The frequency of the sweeping process increases with longitudinal coordinate z , resulting in a decreasing average droplet size on the front/back surface of the channel. Meanwhile, the detached droplets experience elongation, forming rivulet flows. The thickness of the rivulet increases from a few microns (figure 7(a)) to approximately 200 μm (figure 7(d)).

3.2. Spatial flow pattern transition

As shown in previous sections, the spatial flow pattern transition occurs in both hydrophobic and hydrophilic channel. The transition is induced jointly by the drastic change in the liquid–vapor mixture quality and the ratio of the liquid to vapor velocity. The pattern and location of the flow transition,

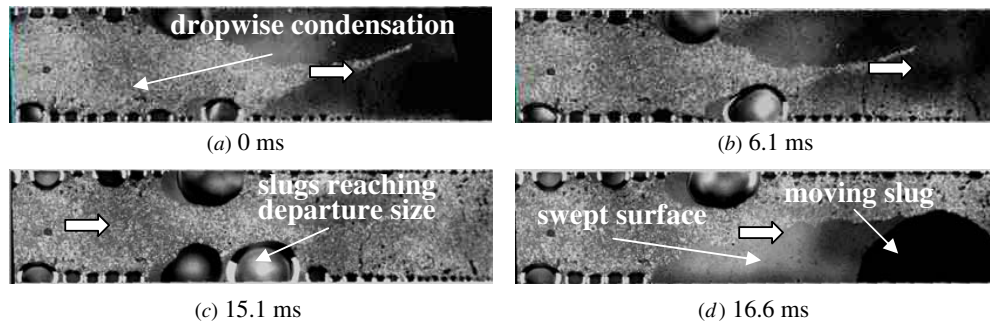


Figure 6. Sidewall slug accumulation, detachment and sweeping process in the upstream region of hydrophobic microchannel 1.

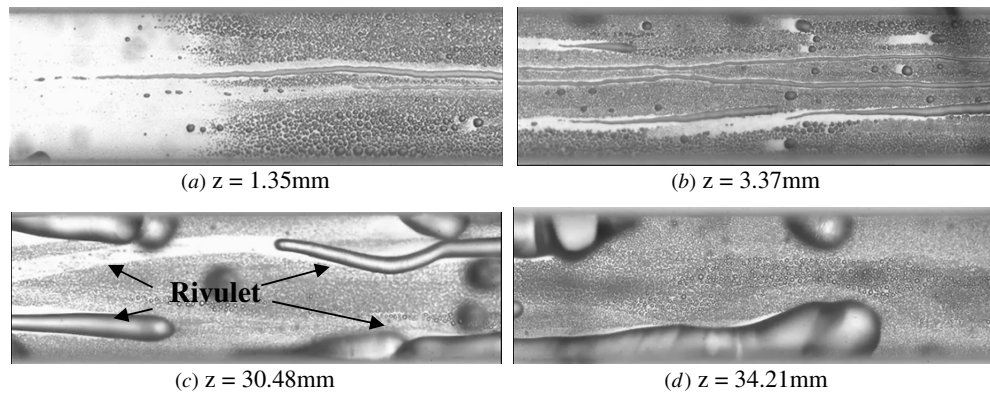


Figure 7. Spatial flow pattern evolution in the upstream region of hydrophobic microchannel 1.

however, strongly depend on the channel hydrophobicity and inlet vapor flowrate.

3.2.1. Flow transition in the hydrophilic microchannel.

Upstream to the transition point, the hydrophilic microchannel is occupied by the annular/stratified flow. The mixture quality increases along the channel and the sidewall liquid layer thickens. The shrinkage of the vapor core eventually leads to a periodic bubble formation and detachment, marking the flow transition from stratified flow to bubbly flow. Depending on the inlet vapor flux, two bubble detachment modes are observed in the hydrophilic channel, as illustrated in figure 8.

For inlet vapor flux smaller than $50 \text{ kg m}^{-2} \text{ s}^{-1}$, a typical cycle of the flow transition begins with the radial expansion of the tip of the vapor which forms a bubble (figure 8(a1)). The bubble grows and the vapor neck connecting the bubble with the vapor core narrows (figure 8(a2)). The bubble is eventually pinched off at the neck (figure 8(a3)) and convected to the downstream by the liquid flow (figure 8(a4)). The transition cycle repeats itself periodically, forming a stream of bubbles downstream to the transition point. A similar process was first reported in [9, 17, 18]. With inlet vapor flux exceeding $50 \text{ kg m}^{-2} \text{ s}^{-1}$, the abrupt buildup of the pressure in the vapor core after the bubble detachment causes the tip of the vapor core to catch up and pierce into the detached bubble (figure 8(b2)), resulting in a splitting detachment mode and the formation of a pair of small bubbles downstream to the transition point (figure 8(b3)).

3.2.2. Flow transition in the hydrophobic microchannel.

Figure 9 depicts two typical examples of flow transition in the hydrophobic microchannel. Upstream to the transition point, the slug adhering to the channel sidewall initially undergoes a growth process until the slug either departs after reaching its critical size or be swept to the downstream by the other slugs coming from the upstream region. Convected downstream by the vapor flow, the departing slug keeps growing by emerging with both small droplets on the front/back surface generated by the dropwise condensation and the other small slugs in its way. After reaching a critical combination of size and velocity, the slug may experience instability, during which the slug abruptly increases in height and decreases in length such that the slug is squeezed during moving forward (figures 9(a2) and (b2)). Meanwhile, a sudden increase of the slug height causes the vapor drag force to build up dramatically, resulting in an extremely large acceleration of the slug motion. The squeezed slug may either touch the channel wall on the opposite side (figure 9(a3)) or another slug (figure 9(b3)) adhering to the opposite wall, causing the vapor entrainment, as indicated by the formation of the vapor plug (figures 9(a4) and (b4)) downstream to the transition point. The flow transition transforms the slugwise/dropwise condensation in the upstream region into the plug flow in the downstream region, leading to an abrupt drop in the condensation rate. The vapor entrainment and flow transition in the hydrophobic microchannel relies heavily on the slug instability process, without which the slug merging process would have been much smoother.

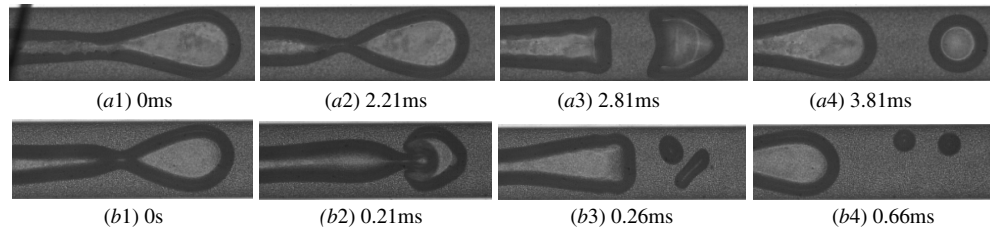


Figure 8. Flow pattern transition modes in hydrophilic channel 2.

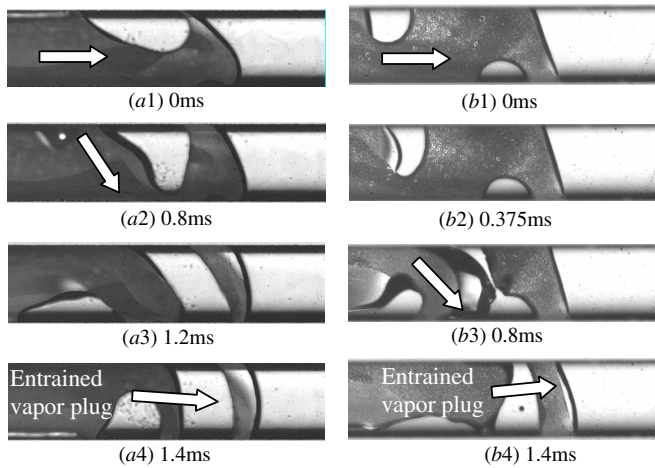


Figure 9. Slug instability during flow pattern transition in hydrophobic channel 1; the left column and right column show two independent slug instability processes with the same flow transition mode.

Similar slug instability phenomena in the hydrophobic microchannel were first reported in [10], in which the experimental visualization on sidewall liquid injection in the microchannel and numerical simulation incorporating 3D contact angle hysteresis model both indicated that the contact angle hysteresis effect is the primary factor that induces the slug instability (figure 10).

3.2.3. Impact of hydrophobicity on the flow transition position.

Figure 11 shows the correlation between the flow transition position and the vapor mass flux for channels with different hydrophobicities. It is found that the transition position increases linearly over a wide range with the inlet vapor mass flux for both hydrophobic and hydrophilic channel. For mass flux less than $40 \text{ kg m}^{-2} \text{ s}^{-1}$, transition positions for two channels overlap, whereas beyond that level, the transition occurs substantially farther downstream in the hydrophilic channel than in the hydrophobic channel.

3.3. Flow pattern in the downstream region

3.3.1. Hydrophilic microchannel. Depending on the transition modes discussed in section 3.2.1, bubbles downstream to the transition point vary significantly in size and spatial distribution in the hydrophilic channel. Figure 12(a) shows bubble pairs resulting from the splitting detachment in channel 2. In contrast, a stream of circular bubbles

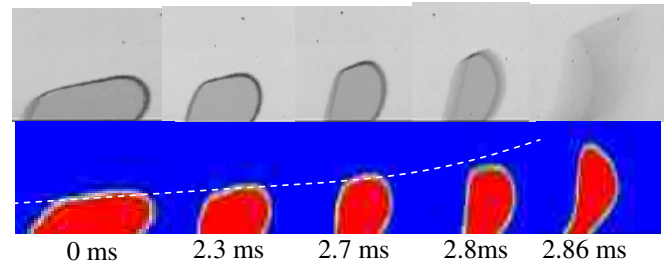


Figure 10. Comparison of contact angle hysteresis simulation and experimental visualization of slug instability for sidewall injection flow in the microchannel as presented in [10], shows a similar pattern as the slug instability process inducing the flow transition and vapor entrainment in the hydrophobic microchannel.

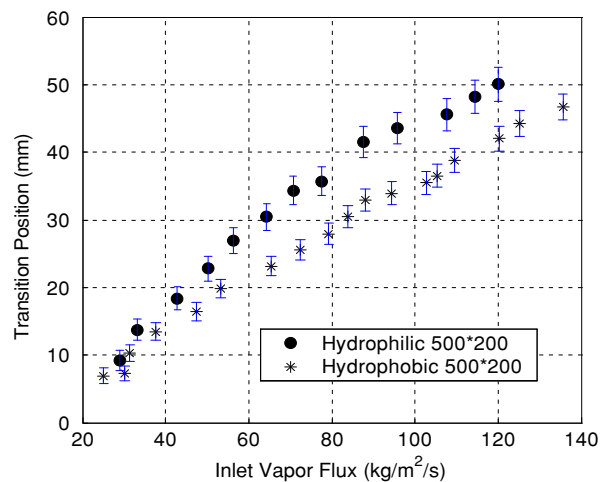


Figure 11. Transition point position versus inlet vapor mass flux.

results following normal detachment, as shown in figure 12(b). Regardless of the size and distribution, bubbles shrink and eventually vanish due to the condensation.

3.3.2. Hydrophobic microchannel. The vapor entrainment occurring at the flow transition point generates a queue of vapor plugs moving in the downstream region of the microchannel, which splits the liquid phase into segments (figure 13(a)). In contrast to the bubbles in the downstream region of the hydrophilic channel which move slower than the liquid phase, the vapor plug in the hydrophobic microchannel moves as fast as the liquid phase. Subject to the condensation during the convection, the vapor slug shrinks (figure 13(b))

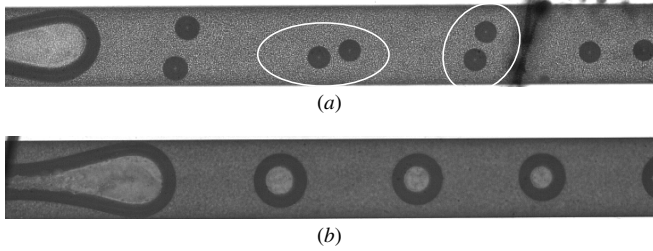


Figure 12. Bubbly flow in the downstream region of hydrophilic microchannel 2. (a) Bubble pairs downstream to splitting bubble detachment. (b) Bubbly flow downstream to normal bubble detachment.

and eventually ends up with collapsing at some points (figure 13(c)). The collapsed plugs become bubbles adhering to the channel sidewall (figure 13(d)), awaiting to coalesce with the plugs coming from the upstream, as illustrated in figure 14. The condensation and collapse of the moving vapor plugs lead to a decrease in the spatial density of the plug distribution in the longitudinal direction. However, the coalescence process shown in figure 14 causes the thickening of the plug.

3.4. Flow pattern in the semi-hydrophobic microchannel

In addition to the two major flow patterns discussed above, a third type of flow pattern is observed in the channel with intermediate wettability, as illustrated in figure 4(b). The upstream region of the semi-hydrophobic microchannel is occupied by a combination of dropwise condensation on the channel front/back surfaces and stratified flow on the channel sidewall (figure 4(b), point A). The downstream is occupied by the bubbly injection flow (figure 4(b), point C). In general, the flow pattern in the semi-hydrophobic channel highly resembles that in the hydrophilic channel, except that the thin liquid film exists on the front/back surfaces of the hydrophilic channel is replaced by the dropwise condensation. Due to the

smaller contact angle, the average size of the droplets in the semi-hydrophobic channels significantly exceeds that of their counterparts in the superhydrophobic channels. Also, since the sidewall slug is absent in the semi-hydrophobic channel, the condensed droplets on the front/back surfaces go through growth and departure processes instead of being wiped away by sidewall slugs moving from upstream.

The flow transition pattern in the semi-hydrophobic channel is very similar to that in the hydrophilic channel, which features the periodic expansion of the vapor core, followed by the detachment of the vapor bubble. The upstream dropwise condensation on the front/back surfaces does not have a strong impact on the flow transition and the downstream flow pattern.

4. Flow measurement

4.1. Temperature distribution on the microchannel surface

With the aid of the thermocouple array illustrated in figure 2, the temperature distribution on the back surface of the microchannel can be obtained, yielding a 1.5 mm resolution. Figure 15 illustrates the temperature distribution for the condensation flow in both hydrophobic channel 1 and hydrophilic channel 2 with two inlet vapor fluxes. The temperature shown in the plot is obtained by averaging the thermocouple readings acquired over a period of 30 min. Chip surface temperature drops monotonically in the longitudinal direction, implying the decrease of the heat flux in the microchannel. Lower vapor flux leads to a flatter temperature distribution, indicating that the condensation process takes a longer distance to complete in the microchannel. In general, the temperature in the hydrophobic channel drops faster than that in the hydrophilic channel under the same vapor flux, indicating that the hydrophobic channel yields a higher heat transfer rate. Due to the thermal resistance of the channel wall, the temperature measured on the back surface of the chip deviates significantly from the temperature in the

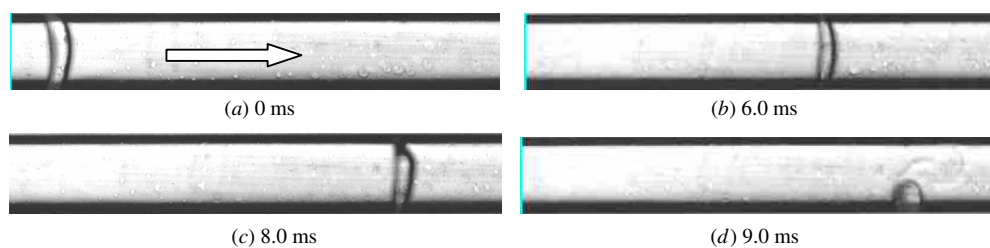


Figure 13. Collapse of plugs in downstream region of hydrophobic microchannel 1.

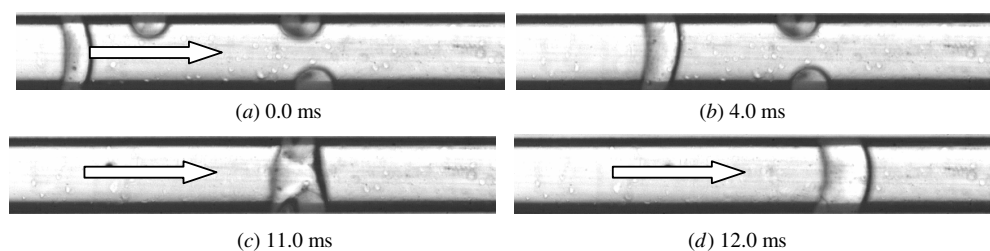


Figure 14. Coalescence of plugs in the downstream region of hydrophobic microchannel 1.

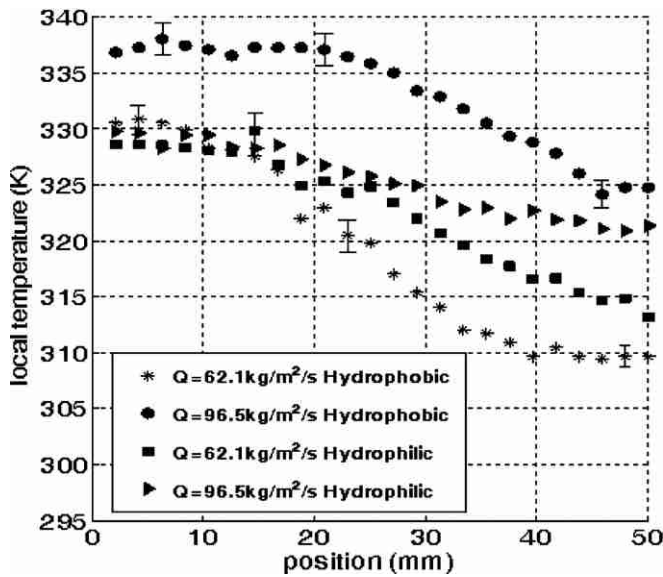


Figure 15. Spatial distribution of local temperatures on the microchannel back surface (error bar reflects fluctuation of thermocouple readings over time).

microchannel where the phase change occurs. Due to the dramatic change in the contact thermal resistance between the heat sink and the different silicon channels for each round of the experiment, the absolute value of the back surface temperature does not directly reflect the heat transfer rate. However, the measured temperature provides the information based on which the temperature and heat flux distribution in the microchannel can be constructed. Similar temperature profile was also reported in [18].

4.2. Local heat flux reconstruction

Figure 16 shows the side view of the setup for temperature measurement. The microchannel consists of a piece of Pyrex glass and a silicon substrate on which the microchannel is etched. The copper heat sink is in direct contact with the silicon substrate back surface, with thermal grease applied in between to minimize the contact resistance. Much thinner than the silicon substrate, the microchannel can be treated as a line heat source whose longitudinal heat flux distribution dictates the temperature field in the silicon substrate. The thermocouple array measures the temperature on the chip surface. Since the heat diffusion in the copper heat sink and silicon substrate tends to smooth out the temperature gradient induced by the heat flux drop, making the spatial temperature variation asynchronous with the heat flux distribution, it is necessary to solve an inverse

problem, i.e. reconstructing the heat flux distribution in the channel from the measured temperature distribution on the silicon substrate surface. The method can be summarized as follows.

- (1) Set up a full geometrical model in the simulation environment replicating the real setup sketched in figure 16.
- (2) Calibrate the thermal boundary condition of the setup, including the water cooling side of the copper heat sink, and the contact thermal resistance between the heat sink and the silicon channel. All other surfaces of the setup are assumed to be thermally insulated.
- (3) Use the finite volume method (FVM) to solve for the temperature distribution on the silicon substrate surface. The microchannel is treated as a line heat source, whose heat flux distribution is guessed and used as the input for the FVM computation.
- (4) Optimize the guessed microchannel heat flux distribution subject to the objective function that the error between the calculated silicon substrate temperature and the measured data is minimized. In practice, nonlinear constrained optimization using the Simplex-based algorithm is performed to search for the optimal combination of heat flux values on 24 evenly distributed points, i.e. a 24-dimensional search space. Given the optimized heat flux distribution on the discrete measurement points, a continuous heat flux distribution can be obtained by piecewise spline interpolation.

The heat flux reconstruction needs a thermal boundary condition: the heat transfer coefficient distribution $h_c(x)$ on the water cooling side of the copper heat sink. To that end, a Kapton® film heater with precise power control is attached to the bottom surface of the microchannel (Pyrex glass surface). The film heater can be viewed as a uniform planar heat source due to its small thickness. Cooling water with stabilized flowrate is applied and the temperature distribution on the chip surface is measured by the thermocouple array, based on which similar optimization approach combining FVM simulation and temperature measurement is employed here to determine $h_c(x)$ such that the error between the simulation result and the measurement is minimized. After the calibration step, the film heater is removed and the vapor is pumped through the channel. Since the thermal boundary condition of the water cooling surface remains unchanged, the calibrated $h_c(x)$ can be used by the channel heat flux reconstruction process.

Figures 17 and 18 show the reconstructed heat flux distribution in both hydrophobic and hydrophilic channels with inlet vapor flux at $62.1 \text{ kg m}^{-2} \text{ s}^{-1}$ and $96.5 \text{ kg m}^{-2} \text{ s}^{-1}$,

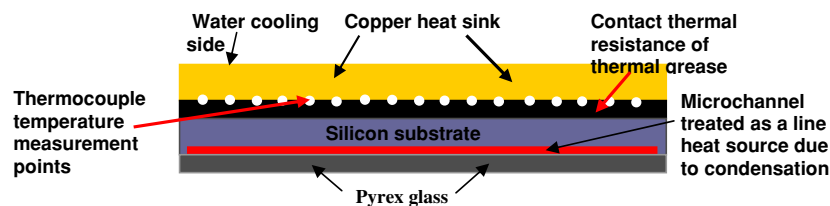


Figure 16. Schematic of the temperature measurement setup.

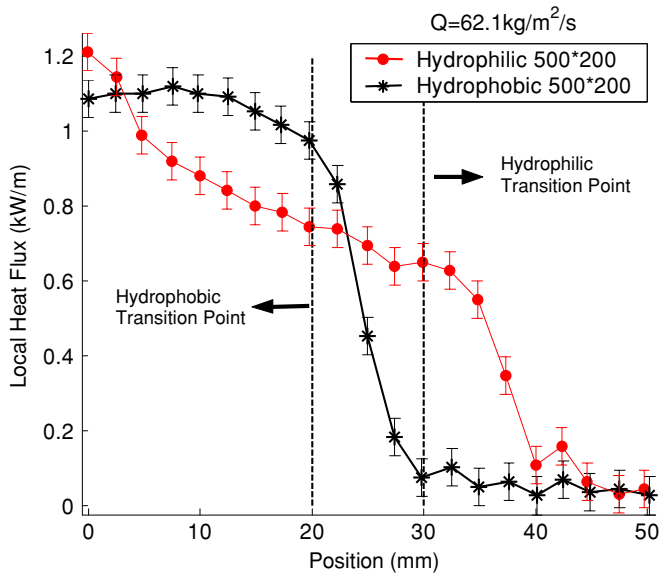


Figure 17. Reconstructed spatial distribution of local heat flux for the inlet vapor flux $Q = 62.1 \text{ kg m}^{-2} \text{ s}^{-1}$.

respectively. The flow pattern transition location is also labeled for each case in the plot. For both channels, the heat flux drops dramatically beyond the flow transition point, implying that the condensation rate decreases abruptly over the transition point. The increase in inlet vapor flux does not significantly raise the max heat flux in the channel, but it slows down the heat flux drop. The most significant distinction between the hydrophobic and hydrophilic channel condensation is that upstream to the transition point, the heat flux distribution is much flatter in the hydrophobic channel than that in the hydrophilic channel. Under the same inlet vapor mass flux, the local heat flux in the hydrophobic channel drops more rapidly than that in the hydrophilic channel.

4.3. Pressure drop measurement

Figure 19 shows the relationship between total pressure drop and inlet vapor flux for the hydrophobic and hydrophilic microchannels. For both channels, the pressure drop increases linearly with the inlet vapor flux within moderate to high flux range. It is evident that the pressure drop in the hydrophobic channel is significantly higher than that in the hydrophilic channel within the range of intermediate to high flux. The difference in pressure drop between the hydrophobic channel and the hydrophilic channel increases with the vapor flux. No deterministic distinction is found for small vapor flux.

5. Discussion

5.1. Impact of wall hydrophobicity on thermal resistance in microchannel

The heat flux distribution shown in figures 17 and 18 indicates that the dropwise condensation in the upstream region of the hydrophobic microchannel yields a higher heat flux as opposed

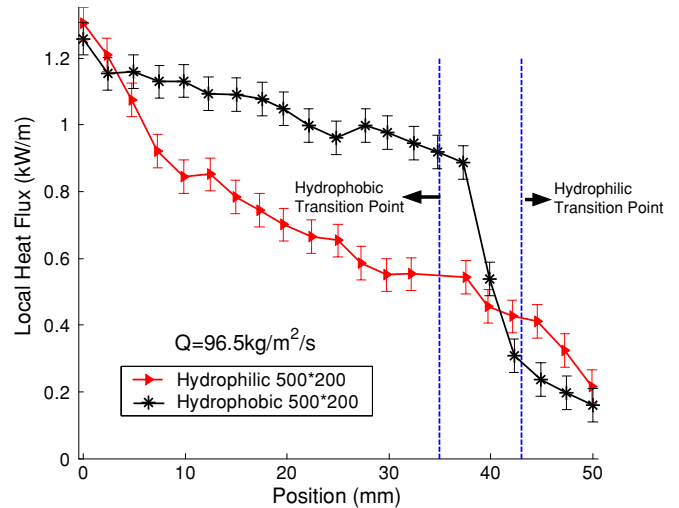


Figure 18. Reconstructed spatial distribution of local heat flux for the inlet vapor flux $Q = 96.5 \text{ kg m}^{-2} \text{ s}^{-1}$.

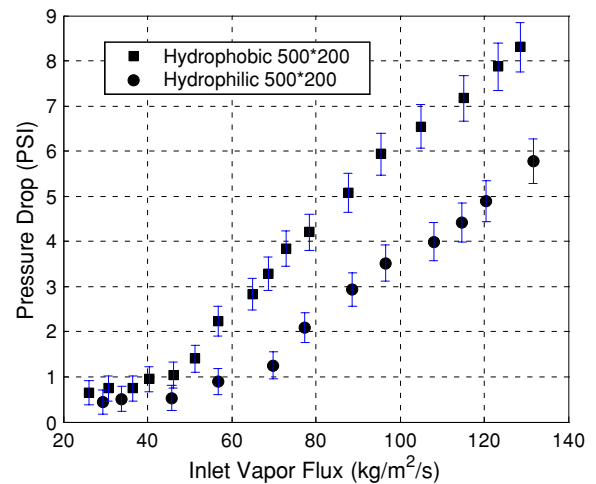


Figure 19. Pressure drop versus inlet vapor flux.

to the heat flux generated by the filmwise condensation in the hydrophilic microchannel. Previous investigations indicated that the thermal resistance of the dropwise condensation on the external surface is higher than that of the filmwise condensation [14, 15]. The present study shows that the same principle applies to the microchannel condensation. Differing from the condensation on the external surface, however, the dropwise condensation in the hydrophobic microchannel is subject to a periodic sweeping process, as discussed in section 3.1.2 and shown in figures 6 and 7. The sweeping process causes the droplet on the channel surface to undergo a cycle of nucleation, growth, coalescence and sweeping-away process in a repetitive manner, which dramatically shortens the droplet growth period and reduces the average size of the droplets. The reduced droplet size leads to a small thermal resistance upstream to the transition point, which is reflected by the stable heat flux distribution in the upstream region of the hydrophobic microchannel.

In contrast to the dropwise condensation in the hydrophobic channel, the filmwise condensation in the

hydrophilic microchannel relies on a completely different heat transfer mechanism. Due to the poor thermal conductivity of the liquid phase, the thermal resistance in the upstream region of the hydrophilic microchannel is dictated by the liquid film thickness. Therefore, the distribution of the condensation heat flux strongly correlates with the spatial evolution of the thin liquid film thickness. As shown in section 3.1.1 and figure 5, the liquid film thickens over a large fraction of the upstream channel region. In addition, the thickening of the sidewall liquid layer (figure 4(a), point A) causes the area of the channel wall covered by the thin liquid film to shrink, which reduces the effective condensation area. The thickening liquid film in conjunction with the shrinking condensation area is responsible for the rapidly decreasing heat flux distribution in the upstream region of the hydrophilic microchannel. The discussion of the hydrophobicity-dependent heat transfer mechanism and the corresponding condensation heat flux distribution in the two channels highlights the importance of the *in situ* liquid phase removal for the condensation enhancement, a concept to be discussed in section 5.3.

5.2. Impact of wall hydrophobicity on pressure drop in microchannel

Our measurement shows that the hydrophobic channel yields a higher pressure drop compared to the hydrophilic channel under the same dimension and vapor flux. In the hydrophobic microchannel, the channel wall is not completely wettable to the liquid phase, giving rise to a stable triple contact line where liquid, vapor and solid phase make contact. As elaborated in [10], driving slug and droplet in the hydrophobic microchannel involves overcoming the high wall adhesion forces due to the contact angle hysteresis. In the hydrophilic channel, in contrast, the channel wall is covered by the liquid film and no wall adhesion force induced by the contact angle hysteresis exists. To drive the liquid film to the downstream, pressure drop in the hydrophilic channel only needs to balance the viscous force of the stratified flow. The hydrophobicity dependence of the pressure drop is attributed to the distinction of the flow pattern.

5.3. Concept of liquid-venting channel for condensation enhancement

The heat flux distribution in both hydrophobic and hydrophilic microchannels experiences a dramatic drop at the flow pattern transition point, indicating an abrupt deterioration of the condensation heat transfer beyond the flow transition point. This observation motivates the optimization of the microchannel condenser in order to delay the flow transition. Discussion in section 3.2 shows that flow transition is primarily induced by the decrease in the mixture quality regardless of the channel hydrophobicity. Provided the liquid produced by the condensation can be effectively removed from the channel, a high liquid–vapor mixture quality can be maintained over the whole channel. Hence, the flow transition can be substantially shifted to the downstream. In addition, the high thermal resistance caused by the liquid accumulation in the microchannel can also be mitigated provided the channel

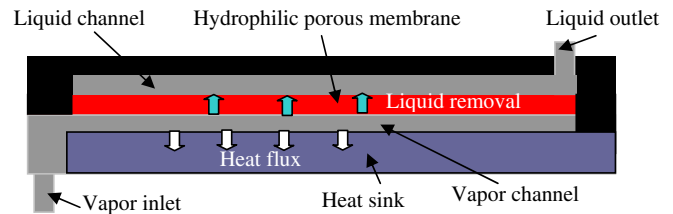


Figure 20. Schematic diagram of the liquid-venting micro-condenser.

remains dry over an extended length. Inspired by the present study, a concept of liquid-venting condenser is proposed to achieve the *in situ* liquid removal, as illustrated in figure 20. Compared to the conventional microchannel condenser, the new design replaces its sidewall by a thin hydrophilic porous membrane. While permeable to the liquid single phase, the superhydrophilic membrane can exert a high capillary force on the liquid–vapor interface, which points toward the vapor phase and prevents the vapor phase from leaking through the membrane. Therefore, the produced liquid can be removed from the microchannel during the condensation and a high pressure vapor phase flow in the microchannel is still maintained, yielding a dry vapor channel and a high condensation rate. Similar concept utilizing the hydrophobic membrane for vapor removal was first proposed in [20] for regulating the boiling flow instead.

6. Conclusions

The impact of wall hydrophobicity on the condensation flow pattern and heat transfer in the rectangular silicon microchannel of $500\ \mu\text{m} \times 200\ \mu\text{m}$ is investigated based on the high speed imaging and temperature distribution measurement. Main conclusions include the following.

- (1) Channel wall hydrophobicity significantly influences the condensation flow pattern in the microchannel. Slugwise/dropwise flow, film/stratified flow and dropwise/stratified flow dominate the upstream part of the hydrophobic, hydrophilic and semi-hydrophobic channel, respectively, while plug flow and bubbly flow dominate the downstream part of the hydrophobic and hydrophilic/semi-hydrophobic channel, respectively.
- (2) Spatial flow pattern transition appears in the microchannel regardless of the hydrophobicity. Depending on the strength of the fluid–solid interaction, the transition pattern differs dramatically from the vapor entrainment process in the hydrophobic channel to the bubble injection flow in the hydrophilic channel.
- (3) In both hydrophobic and hydrophilic channels, the condensation rate decreases abruptly over the transition point. Upstream to the transition point, the heat flux distribution shows a slower decrease in the hydrophobic channel than in the hydrophilic channel. Under the same inlet vapor flux, the condensation heat flux in the hydrophobic channel drops earlier than that in the hydrophilic channel.

- (4) The heat transfer in the hydrophilic microchannel is governed by the thin liquid film thickness evolution. The sweeping effect of the sidewall slug in the hydrophobic channel dramatically reduces the droplet average size, which in turn decreases the thermal resistance and yields a high heat transfer rate.
- (5) In the range of moderate to high vapor flux, the pressure drop in the microchannel increases linearly with the vapor flux, and the pressure drop in the hydrophobic channel is significantly higher than that in the hydrophilic channel. This difference is attributed to the fact that more pressure gradient is needed to overcome the high resistance of slug motion due to the contact angle hysteresis in the hydrophobic channel, whereas in the hydrophilic channel pressure drop only needs to balance viscous resistance of the stratified flow.
- (6) A liquid-venting microchannel condenser design utilizing the porous hydrophilic membrane may delay the flow transition, reduce the thermal resistance, and therefore enhance the condensation rate in the microchannel.

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References

- [1] Agarwal A 2006 Heat transfer and pressure drop during condensation of refrigerants in microchannels *PhD Dissertation* Georgia institute of Technology
- [2] Hu J and Chao C 2007 An experimental study of the fluid flow and heat transfer characteristics in micro-condensers with slug-bubbly flow *Int. J. Refrig.* **30** 1309–18
- [3] Zhang Y W, Faghri A and Shafii M B 2001 Capillary blocking in forced convective condensation in horizontal miniature channels *J. Heat Transfer* **123** 501–11
- [4] Garimella S 2004 Condensation flow mechanisms in microchannels: basics for pressure drop and heat transfer models *Heat Transfer Eng.* **25** 104–16
- [5] Chato J C 1962 Laminar condensation inside horizontal and inclined tubes *ASHRAE J.* **4** 52–60
- [6] Jaster H and Kosky P G 1976 Condensation in a mixed flow regime *Int. J. Heat Mass Transfer* **19** 95–9
- [7] Mederic B and Miscevic M 2005 Void fraction invariance properties of condensation flow inside a capillary glass tube *Int. J. Multiph. Flow* **31** 1049–58
- [8] Zhang W, Xu J and Thome J 2008 Periodic bubble emission and appearance of an ordered bubble sequence (train) during condensation in a single microchannel *Int. J. Heat Mass Transfer* **51** 3420–33
- [9] Wu H and Cheng P 2005 Condensation flow patterns in silicon microchannel *Int. J. Heat Mass Transfer* **48** 2186–97
- [10] Fang C, Carlos C, Wang F, Eaton J and Goodson K 2008 3-D numerical simulation of contact angle hysteresis for microscale two phase flow *Int. J. Multiph. Flow* **34** 690–705
- [11] Barajas A M and Panton R L 1992 The effect of contact angle on two-phase flow in capillary tubes *Int. J. Multiph. Flow* **19** 337
- [12] Garimella S, Killion J and Coleman J 2003 An experimentally validated model for two-phase pressure drop in the intermittent flow regime for circular microchannels *J. Fluids Eng.* **125** 887–94
- [13] Chen Y and Cheng P 2005 Condensation of steam in silicon microchannels *Int. Commun. Heat Mass Transfer* **32** 175–83
- [14] Collier J G 1981 *Convective Boiling and Condensation* 2nd edn (New York: McGraw-Hill)
- [15] Kakac S and Liu H 1998 *Heat Exchanger* (New York: CRC Press)
- [16] Gokhale S J, Plawsky J L and Wayner P C Jr 2003 Experimental investigation of contact angle, curvature, and contact line motion in dropwise condensation and evaporation *J. Colloid Interface Sci.* **259** 354–66
- [17] Quan X, Cheng P and Wu H 2008 Transition from annular flow to plug/slug flow in condensation of steam in microchannels *Int. J. Heat Mass Transfer* **51** 707–16
- [18] Wu H, Yu M, Cheng P and Wu X 2007 Injection flow during steam condensation in silicon microchannels *J. Micromech. Microeng.* **17** 1618–27
- [19] Wu H, Wu X, Qu J and Yu Meng 2008 Condensation heat transfer and flow friction in silicon microchannels *J. Micromech. Microeng.* **18** 115024
- [20] Zhou P, Goodson K and Santiago J 1996 *US Patent No.* 6,994,151 B2
- [21] http://www.appliedmst.com/technology_mvdm.htm