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Boiling instability in parallel silicon microchannels at different heat flux

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Abstract

In this paper, a series of experiments have been carried out to study different boiling instability modes of water flowing in microchannels at various heat flux and mass flux with the outlet of the channels at atmospheric pressure. Eight parallel silicon microchannels, with an identical trapezoidal cross-section having a hydraulic diameter of 186 μm and a length of 30 mm, were used in this experiment. When the wall heat flux was increased from 13.5 to 22.6 W/cm^2 and the time average mass flux of water was decreased from 14.6 to 11.2 g/cm^2 s, three kinds of unstable boiling modes were observed in the microchannels. These were (1) the liquid/two-phase alternating flow (LTAF) at low heat flux and high mass flux, (2) the continuous two-phase flow (CTF) at medium heat flux and medium mass flux, and (3) the liquid/two-phase/vapor alternating flow (LTVAF) at high heat flux and low mass flux. Simultaneously, periodic oscillations of wall temperature, inlet and outlet water temperatures and pressures, and instantaneous mass flux were measured. Among the three unstable boiling modes, oscillation amplitudes in LTVAF were the largest with oscillations of pressures and mass flux nearly out of phase. Oscillation amplitudes in CTF were the smallest with oscillations of pressures and mass flux nearly in phase. Oscillation amplitudes in LTAF lied in between LTVAF and CTF with oscillations of pressures and mass flux nearly out of phase. Also, the oscillation period (including two-phase period, liquid period and vapor period) depends greatly on the amounts of heat flux and mass flux. Bubbly flow and some peculiar two-phase flow patterns were observed in the microchannels during two-phase flow periods.

Keywords: Boiling heat transfer; Microchannels; Instability

1. Introduction

It is well known that boiling instabilities occur in *macrosystems* and many mechanisms can lead to such unstable behaviors. Depending on the mechanism, various types of static and dynamic instabilities (such as nucleation instabilities, flow pattern instabilities, Ledinegg instabilities, thermal oscillations, density-wave type oscillations, pressure-drop type oscillations) may arise [1–6]. Early works on boiling in microchannels and minichannels, however, were focused on the stable mode of boiling heat transfer process [7–10]. Recently, some investigators [11–13] observed boiling instability in smaller silicon microchannels. Most recently, Wu and Cheng [14] reported large-amplitude oscillations of temperature and pressures in silicon microchannels when the wall heat flux was increased beyond the incipient boiling point. They also observed that two-phase flow and single-phase liquid flow appeared alternatively with time in the microchannel at this heat flux.

In this paper, we have carried out further experimental investigations on boiling instability modes at higher heat flux in microchannels by simultaneous measurements of temporal variations of temperatures, pressures and mass flux. Flow visualization techniques

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Nomenclature

a	top width of microchannel
A_c	cross-sectional area of microchannel
A_w	heating area
b	bottom width of microchannel
D_h	hydraulic diameter of microchannel
h	depth of microchannel
L	length of microchannel
m	mass flux
N	total number of microchannels
q	heat flux
I	electric current of heater
V	electric voltage of heater
P	pressure
t	time
T	temperature
Greek symbol	
φ	heat transfer ratio
Subscripts	
i	inlet
o	outlet
w	wall

were used to observe flow patterns during the boiling process. Eight parallel silicon microchannels with identical trapezoidal cross-sections, having a hydraulic diameter of 186 μm, were used in this experiment. In addition to the liquid/two-phase alternating flow (LTAF) that was observed in our previous work [14], two more boiling modes are observed in this work. These are: the continuous two-phase flow (CTF), and the liquid/two-phase/vapor alternating flow (LTVAF). Periods and amplitudes of temperatures, pressures, and instantaneous mass flux variations during these boiling modes were recorded. It is found that oscillation amplitudes and oscillation periods in these unstable boiling modes are very much different. With the aid of a microscope and a high-speed video recording system, some peculiar flow patterns are observed during the two-phase flow periods at higher heat flux and lower mass flux. Preliminary versions of the present work were presented in [15–17].

2. Description of the experiment

2.1. Experimental setup

Fig. 1 shows the experimental setup which consisted of a constant-pressure tank, a valve regulator, a filter, a flowmeter, a test section, and a collecting container. The deionized and degassed water in the pressure tank, being pushed by the compressed nitrogen gas, flowed successively through a valve, a filter, a flowmeter, and then to the test section which was heated by a film heater. After the water was heated beyond the saturated temperature in the test section, it was collected in a container with a small hole vented to the atmosphere. The container was placed on a precision electronic balance, and the average mass flux of water was determined by calculating the mass increment per unit time.

The test section, consisting of the eight parallel microchannels etched on a <1 0 0> silicon wafer, is

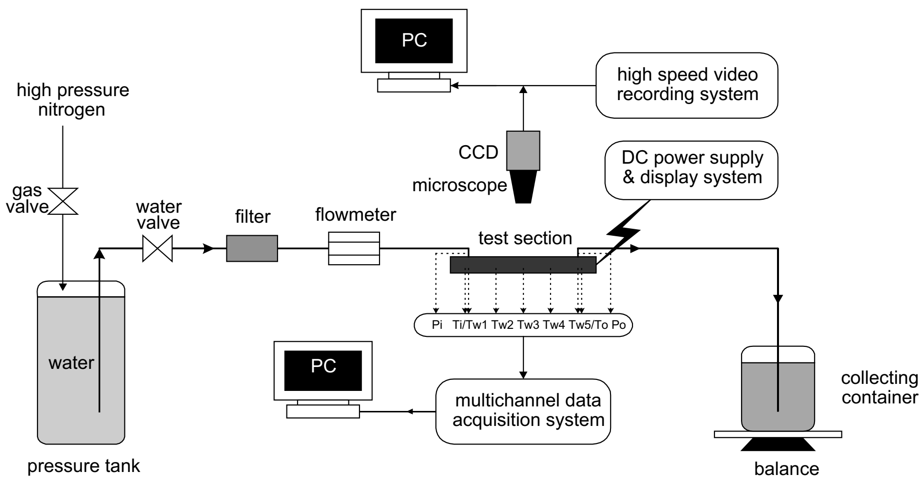

Fig. 1. Experimental setup.

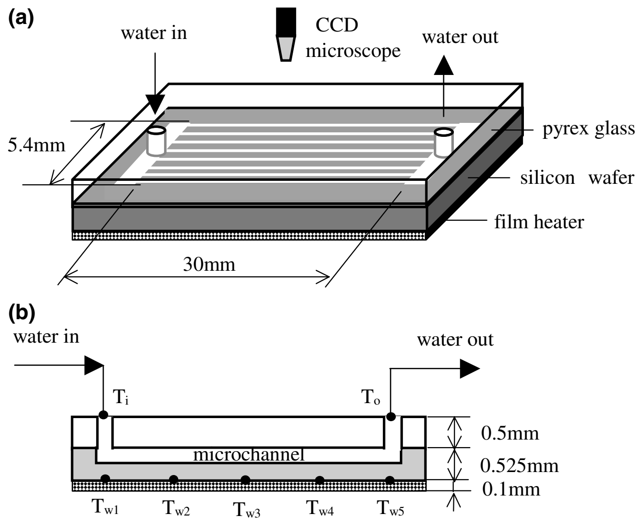

Fig. 2. Test section.

shown in Fig. 2a. The microchannels were sealed from the top by a thin pyrex glass plate which allowed visualization of the boiling phenomena occurring inside the microchannels. A microscope and a high-speed video recording system, located above the microchannels, were used for the visualization study. Two type-T thermocouples having a diameter of 0.25 mm and a response time of 0.2 s were used to measure water temperatures at the inlet and outlet of the microchannels (T_i, T_o). The wall temperatures (T_{w1}, T_{w2}, T_{w3}, T_{w4}, T_{w5}) were measured by five type-T thermocouples, having a diameter of 0.1 mm and a response time of 0.1 s. The longitudinal locations of these thermocouples are shown in Fig. 2b. The detailed experimental procedure was discussed in our previous paper [14] and will not be repeated here.

Fig. 3 shows the geometry and dimensions of the eight parallel microchannels having the same trapezoidal cross-sectional area on a silicon substrate. The top width, bottom width, and depth of these trapezoidal microchannels were 427, 208 and 146 μm, respectively. These microchannels had a hydraulic diameter of 186 μm and a length of 30 mm. The distance between two neighboring microchannels was 281 μm. Using an atomic force microscope (AFM), the channel surface roughness was measured to be 48 Å. Since this roughness is very small in comparison with the hydraulic diameter of 186 μm, the surfaces of these microchannels can be regarded as smooth ones. The transverse location of wall thermocouples is also shown in Fig. 3.

2.2. Determination of heat flux and mass flux

The heat flux, q, is computed from $q = \varphi VI/A_w$, where V and I are the input voltage and current to the film heater, A_w is the area of heated wall, and φ is the ratio of the heat absorbed by the working fluid to the total power input to the film heater. The value of φ was determined by a method similar to that used by Hetsroni et al. [13], which was also used in our previous paper [14]. The average mass flux of water is given by $m = \Delta M/(\Delta t \cdot N \cdot A_c)$, where ΔM is the total mass increment in the container measured by the electronic balance during the time interval Δt, N is the total number of microchannels, and A_c is the cross-sectional

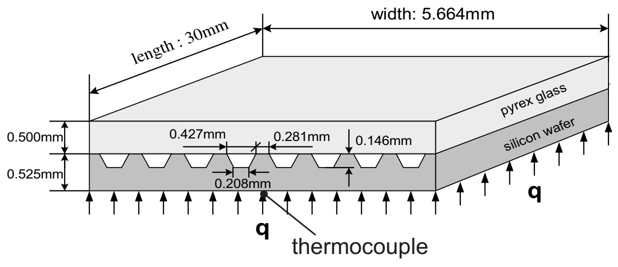

Fig. 3. Arrangement of parallel microchannels on silicon wafer.

area of the microchannel. The instantaneous mass flux measured by the flowmeter was previously calibrated by the weighing method. Therefore, it has the same accuracy as the measurement of average mass flux. As indicated in the previous paper [14], the uncertainties in determining the heat flux and mass flux were 6.52% and 4.98%, respectively.

3. Experimental results and discussions

As pointed out in the previous paper [14], when the heat flux was at a relatively low level and the flow everywhere in the microchannels was still in single-phase, all of temperature, pressure, and mass flux data remained constant with time. However, as the heat flux was gradually increased (with corresponding decrease in mass flux while all other conditions remained unchanged) and the water temperature near the outlet of the channel reached the saturated condition, some bubbles began to appear near channel outlets, and this state is usually referred to as the incipient boiling. At the incipient boiling condition, small temporal variations of temperatures, pressures, and mass flux were observed. As the heat flux was increased further, while other conditions in the experimental system remained unchanged, boiling occurred rapidly everywhere in all eight microchannels, and three unstable boiling modes were observed. These unstable boiling modes were (1) liquid/two-phase alternating flow (LTAF), (2) continuous two-phase flow (CTF), and (3) liquid/two-phase/vapor alternating flow (LTVAF). Simultaneously, periodic oscillations of wall and water temperatures, pressures, and mass flux, were measured. Fig. 4 shows the photos

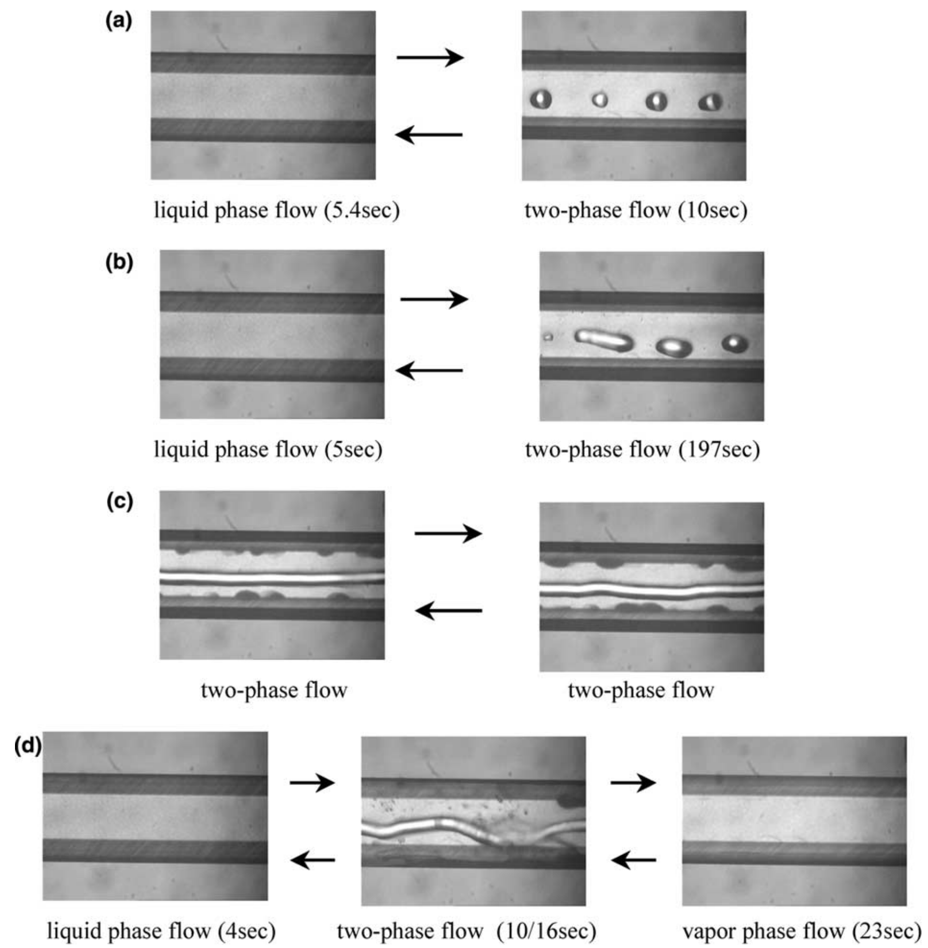

Fig. 4. Unstable boiling modes at different heat flux and mass flux. (a) Liquid/two-phase alternating flow (LTAF): $q = 13.5$ W/cm^2 and $m = 14.6$ g/cm^2 s, (b) liquid/two-phase alternating flow (LTAF): $q = 16.6$ W/cm^2 and $m = 12.7$ g/cm^2 s, (c) continuous two-phase flow (CTF): $q = 18.8$ W/cm^2 and $m = 11.9$ g/cm^2 s, (d) liquid/two-phase/vapor alternating flow (LTVAF): $q = 22.6$ W/cm^2 and $m = 11.2$ g/cm^2 s.

of typical flow patterns during three kinds of unstable boiling modes at different heat flux and mass flux. These photos were enlarged by a microscope and recorded by a high-speed video recording system located above the mid-section of the microchannels (see Fig. 1).

Figs. 5–8 show temporal variations of temperatures, pressures and mass flux at different heat flux with the corresponding mass flux. Here, the term "corresponding mass flux" is used because it is a heat flux-dependent quantity when other experimental conditions in the system remain the same. As the heat flux was increased while other conditions remained unchanged, the time-average mass flux was decreased due to the variance of fluid properties and phase change in the test section [14]. It should be noted from Figs. 5–8 that (1) since the outlet of the microchannels was connected to the atmosphere, the oscillation of the outlet pressure was smaller than that of the inlet pressure for all cases; and (2) due to the existence of side heat loss, the highest wall temperature may appear near the middle location (T_{w3} or T_{w4}) instead of at the outlet location (T_{w5}) for some cases.

To compare different instability modes, oscillation amplitudes and oscillation periods of all measurements under different heat flux and mass flux conditions are presented in Table 1. Note that time-average values of these quantities and their oscillation amplitudes were obtained based on a 10-min data acquisition sample. In the following sections, we will discuss in details the appearance of different boiling instability modes when the heat flux was increased beyond the incipient boiling point.

3.1. Case 1A: LTAF at $q = 13.5$ W/cm^2 and $m = 14.6$ g/cm^2 s

Fig. 4a shows the photos of the liquid/two-phase alternating flow (LTAF) in the microchannel when the heat flux was increased to 13.5 W/cm^2 and the corresponding mass flux was 14.6 g/cm^2 s. In this unstable LTAF mode with a period of 15.4 s, it began with a single phase that lasted for 5.4 s, and it changed to bubbly flow for 10 s before it suddenly changed back to the liquid phase again. During this period, about 35% of time (5.4 s) was occupied by the liquid-phase flow while about 65% of time (10.0 s) was occupied by the two-phase flow. As the experiment continued, this alternation from single-phase liquid flow to two-phase flow repeated itself. The visualization study also showed that bubbly flow was the dominant flow pattern during the two-phase flow period at this heat flux and mass flux.

Fig. 5a shows that the outlet water temperature in Case 1A was almost constant at the saturation temperature of 100 °C with occasional subcooling while the time-average inlet water temperature was 43.2 °C (varying from the lowest 30 °C to the highest 91.1 °C).

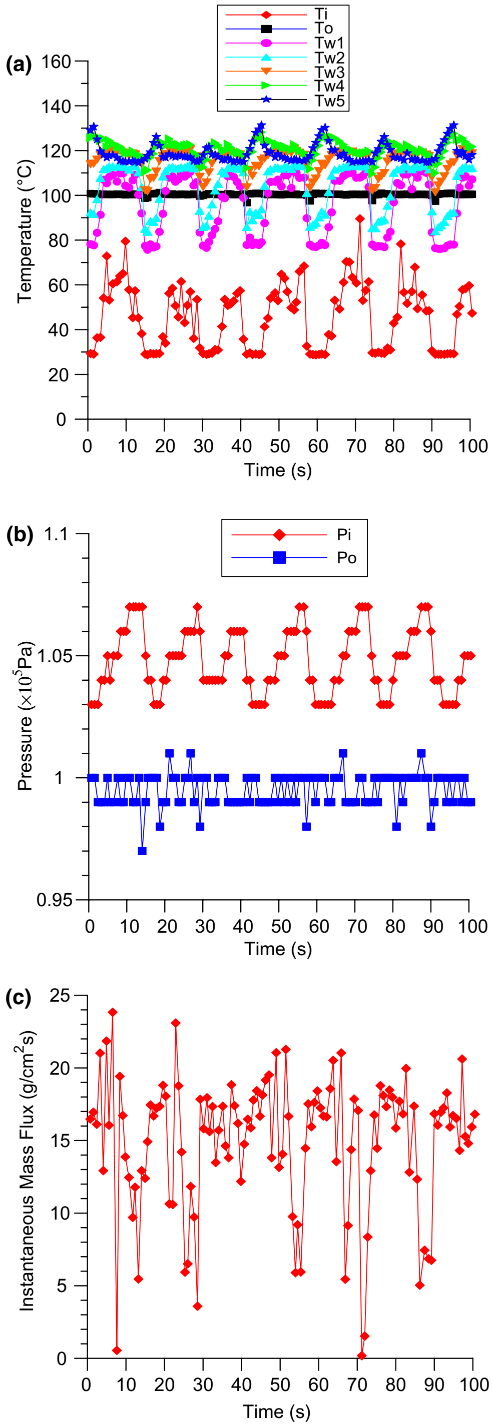

Fig. 5. Oscillation of various measurements at $q = 13.5$ W/cm^2, $m = 14.6$ g/cm^2 s.

Other measurements including temporal variations of wall temperatures, pressures, and instantaneous mass

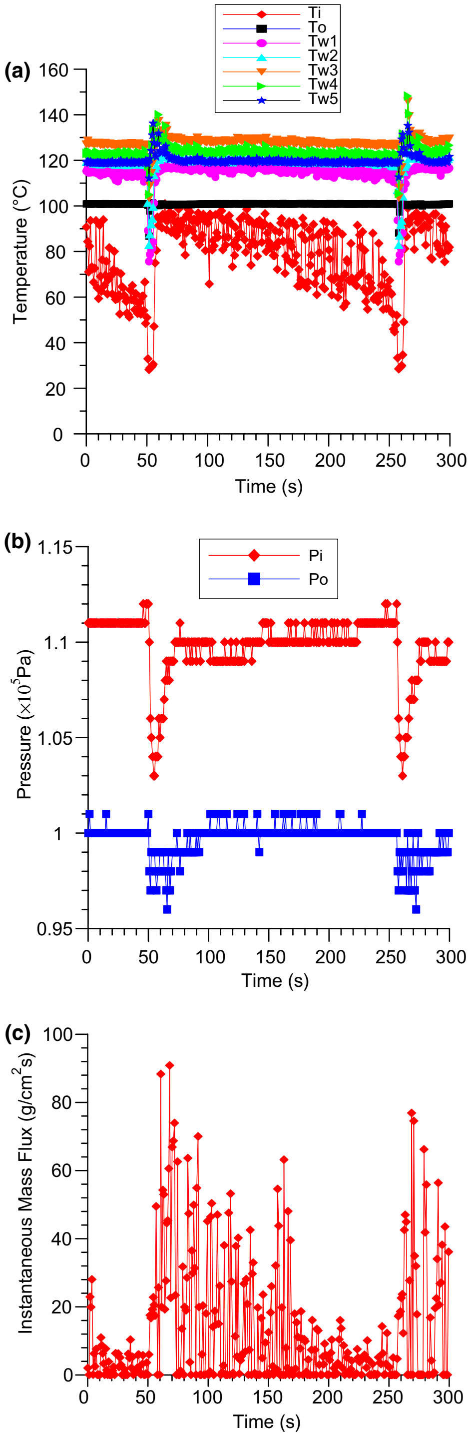

Fig. 6. Oscillation of various measurements at $q = 16.6$ W/cm^2, $m = 12.7$ g/cm^2 s.

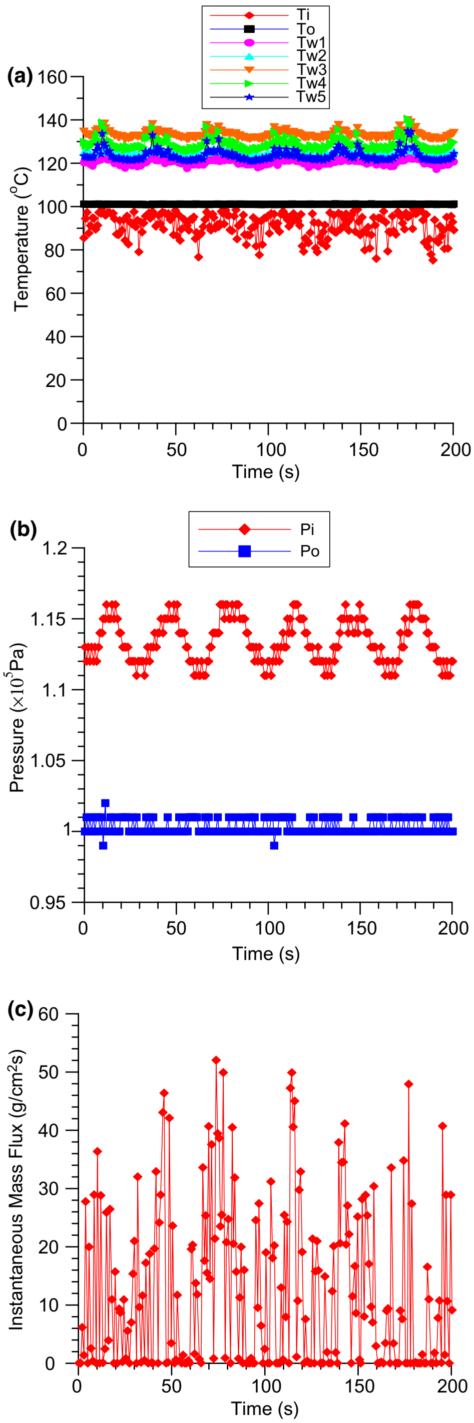

Fig. 7. Oscillation of various measurements at $q = 18.8$ W/cm^2, $m = 11.9$ g/cm^2 s.

flux with different oscillation amplitudes are also presented in Fig. 5. It can be seen that (1) the oscillation amplitude of inlet water temperature was largest (about 61.1 °C) while the oscillation amplitude of outlet water temperature was smallest (about 7.6 °C). The oscillation

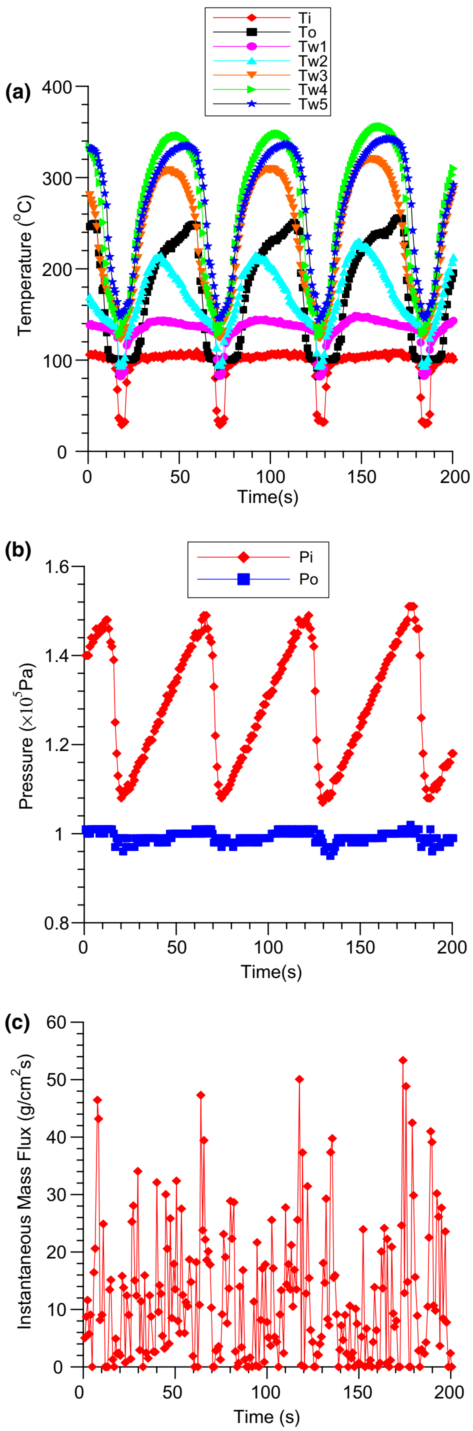

Fig. 8. Oscillation of various measurements at $q = 22.6$ W/cm^2, $m = 11.2$ g/cm^2 s.

amplitudes of various wall temperatures are between the inlet and outlet water temperatures, decreasing from the value of 36.7 °C near the inlet to the value of 20.9 °C near the outlet; (2) the oscillation periods of various measurements were about 15.4 s, which is in agreement with that by the visualization study. This confirms that the large oscillations of various measurements were caused by the flow pattern alternation, that is, by the liquid/two-phase alternating flow in the microchannels; (3) oscillations of inlet water temperature (see Fig. 5a) and inlet pressure (see Fig. 5b) were nearly in phase, but oscillations of inlet pressure (Fig. 5b) and instantaneous mass flux (Fig. 5c) were nearly out of phase.

3.2. Case 1B: LTAF at $q = 16.6$ W/cm^2 and $m = 12.7$ g/cm^2 s

Fig. 4b shows the snapshots of the boiling flow pattern as the heat flux was further increased to 16.6 W/cm^2 and the corresponding average mass flux was decreased to 12.7 g/cm^2 s. The boiling flow pattern is similar to Case 1A, i.e., liquid/two-phase alternating flow (LTAF) in which liquid phase and bubbly flow appeared periodically. However, due to the increase in heat flux and decrease in the corresponding mass flux, the two-phase period for this case (at $q = 16.6$ W/cm^2 and $m = 12.7$ g/cm^2 s) was greatly prolonged when compared with that of Case 1A (at $q = 13.5$ W/cm^2 and $m = 14.6$ g/cm^2 s). Consequently, the period of Case 1B is also much longer than Case 1A. According to visualization results, the total period, the two-phase period, and the liquid phase period of Case 1B, observed at the mid-length of the test section, were approximately 202, 197 and 5 s, respectively (see Table 1). This means that, during this LTAF cycle, about 97.5% of time was occupied by the two-phase flow period whereas only 2.5% time was occupied by the single-phase liquid flow. This case with a long two-phase period (197 s) and a relatively short liquid-phase period (5 s) can be regarded as a transition state between the LTAF mode of Case 1A and the next boiling mode of continuous two-phase flow (CTF) to be discussed as Case 2 in the following section. As in Case 1A, the bubbly flow was also the dominant flow pattern during the two-phase flow period in Case 1B.

Fig. 6 shows temporal variations of temperatures, pressures, and instantaneous mass flux for Case 1B. It can be seen that (1) the outlet water temperature was at the saturation temperature with occasional subcooling, which is represented as a horizontal line with a few dips in Fig. 6a while the time-average inlet water temperature was at 76.9 °C, which was much higher than that of Case 1A; (2) because of the much longer two-phase flow period, all measurements including temperatures, pressures, and instantaneous mass flux, show longer period of oscillations than Case 1A. For example, the oscillation period of 202 s in this case as compared with 15.4 s

Table 1
Various quantities at different heat flux and mass flux[a]

		Case 1A (LTAF)	Case 1B (LTAF)	Case 2 (CTF)	Case 3 (LTVAF)
q		13.5 W/cm^2	16.6 W/cm^2	18.8 W/cm^2	22.6 W/cm^2
m	Average value	14.6 g/cm^2 s	12.7 g/cm^2 s	11.9 g/cm^2 s	11.2 g/cm^2 s
	Oscillation amplitude	25.5 g/cm^2 s	97.9 g/cm^2 s	52.2 g/cm^2 s	56.4 g/cm^2 s
T_i	Average value	43.2 °C	76.9 °C	90.6 °C	96.5 °C
	Oscillation amplitude	61.1 °C	72.7 °C	43.8 °C	80.5 °C
T_o	Average value	100.3 °C	100.7 °C	101.1 °C	177.9 °C
	Oscillation amplitude	7.6 °C	14.6 °C	0.5 °C	176.0 °C
T_{w1}	Average value	94.5 °C	114.0 °C	120.5 °C	133.3 °C
	Oscillation amplitude	36.7 °C	42.8 °C	7.7 °C	66.6 °C
T_{w2}	Average value	103.5 °C	118.8 °C	124.6 °C	168.3 °C
	Oscillation amplitude	31.4 °C	44.0 °C	8.1 °C	136.9 °C
T_{w3}	Average value	115.1 °C	127.6 °C	133.6 °C	239.2 °C
	Oscillation amplitude	21.5 °C	42.4 °C	13.7 °C	197.1 °C
T_{w4}	Average value	120.3 °C	123.8 °C	129.3 °C	270.3 °C
	Oscillation amplitude	22.9 °C	43.2 °C	22.2 °C	229.3 °C
T_{w5}	Average value	118.7 °C	119.9 °C	124.1 °C	272.5 °C
	Oscillation amplitude	20.9 °C	26.0 °C	22.4 °C	203.8 °C
P_i	Average value	104.9 kPa	109.9 kPa	113.6 kPa	129.5 kPa
	Oscillation amplitude	5.0 kPa	10.0 kPa	8.0 kPa	44.0 kPa
P_o	Average value	99.6 kPa	99.8 kPa	100.3 kPa	99.3 kPa
	Oscillation amplitude	5.0 kPa	5.0 kPa	3.0 kPa	7.0 kPa
	Oscillation period[b]	15.4 s	202 s	32 s	53 s
	Liquid period[b]	5.4 s	5 s	0	4 s
	Two-phase period[b]	10.0 s	197 s	32 s	10 s/16 s
	Vapor period[b]	0	0	0	23 s

[a] All data are based on the samples collected within 10 min.
[b] Values are based on the observation using a high-speed video located at the mid-length of the test section.

of Case 1A (see Table 1); (3) the sudden drop and rise of inlet water temperature and inlet pressure at the end of the long two-phase period in this case was much more obvious than that in Case 1A; (4) during the long two-phase flow period, there existed small-amplitude and short-period oscillations in inlet water temperature and in instantaneous mass flux due to the bubble dynamic instabilities during this period; (5) oscillations of pressures and temperatures were in phase, but oscillations of pressures and instantaneous mass flux were almost out of phase which was more obvious than Case 1A; (6) both the time-average values and the oscillation amplitudes of temperature and pressure measurements for Case 1B were larger than the corresponding values for Case 1A as shown in Table 1; (7) a comparison of Cases 1A and 1B shows that oscillation periods, oscillation amplitudes, and the average values of various measurements at the LTAF boiling mode increase with the increasing heat flux and decreasing mass flux.

3.3. Case 2: CTF at $q = 18.8$ W/cm^2 and $m = 11.9$ g/cm^2 s

When the heat flux was further increased to 18.8 W/cm^2 and the corresponding average mass flux was decreased to 11.9 g/cm^2 s, the liquid-phase period disappeared completely, and a new boiling mode: the continuous two-phase flow (CTF) was observed throughout the parallel microchannels. As shown from the photos in Fig. 4c, the two-phase flow pattern of this case was much different from the bubbly flow appearing in the LTAF boiling modes (Fig. 4a and b). In addition to many bubbles generated from the bottom corners of the microchannels, there appeared a bright vapor core (due to the coalescence of large bubbles) moving in the middle of microchannels. This peculiar two-phase flow pattern was observed here for the first time.

It should be noted that the same two-phase flow pattern exists in CTF boiling mode. For this reason, oscillation amplitudes of most measurements during CTF modes (owing to bubble dynamic instabilities) were generally smaller than those of LTAF. Fig. 7 shows temporal variations of different measurements for this case while Table 1 lists time-average values and oscillation amplitudes of these measurements. It can be seen that (1) the water at the outlet was at saturation temperature with practically no fluctuation, which is represented by a horizontal line in Fig. 7a while the time-average inlet water temperature was 90.6 °C which was much higher than those of 43.2 and 76.9 °C in the two LTAF modes; (2) the oscillation period was approximately 32 s, of which nearly 100% time was occupied by two-phase flow; (3) the oscillation amplitudes of most temperature measurements (T_i, T_o, T_{w1}, T_{w2}, T_{w3}, T_{w4}) of CTF were much smaller than those of LTAF (Cases 1A and 1B); (4) time-average values of various temperatures and inlet pressures of CTF were larger than those of LTAF because of the higher heat flux and lower mass flux; (5) oscillations of inlet pressure and mass flux in this case were nearly in phase, which was different from the out-of-phase oscillations in LTAF boiling mode; (6) the oscillation shape of CTF was much different from those of LTAF.

3.4. Case 3: LTVAV at $q = 22.6$ W/cm^2 and $m = 11.2$ g/cm^2 s

As the heat flux was further increased to 22.6 W/cm^2 and the corresponding mass flux was decreased to 11.2 g/cm^2 s, another new boiling instability mode: liquid/two-phase/vapor alternating flow (LTVAF), was observed inside the parallel microchannels (see Fig. 4d). This unstable boiling mode, observed at the mid-length of the microchannels, can be described as follows: after a 4 s liquid phase period, it changed to the two-phase flow that lasted about 10 s, and then it further changed to a superheated vapor flow. The superheated vapor flow lasted about 23 s, and was followed by another two-phase flow period that lasted about 16 s. At the end of this two-phase flow period, a new cycle starting from liquid-phase flow began. The LTVAF period was approximately 53 s, during which, about 7.5% of time was occupied by the liquid-phase flow, about 49.1% of time was occupied by the two-phase flow, and about 43.4% of time was occupied by the vapor flow. This three-phase alternating flow in the microchannels has never been reported in the literature.

During the two-phase period (see the middle photo of Fig. 4d), the flow pattern looks similar to that in Fig. 4c (the CTF boiling mode) except that the bright vapor core moved more violently and changed directions more rapidly. At the same time, many bubbles of various sizes generated and then disappeared rapidly in the microchannels. It can be seen that this sputtering core flow caused much more turbulence than two-phase flow patterns shown in LTAF and CTF modes (Fig. 4a–c). Therefore, it could transport higher heat flux at lower mass flux. The peculiar two-phase flow pattern, shown in the middle photo of Fig. 4d, was absent in the existing investigations on macrochannel and microchannel boiling.

Fig. 8 shows the temporal variations of various measurements in the LTVAF mode. It can be seen that (1) the outlet water temperature fluctuated from 81.2 °C (slightly subcooled) to 257.2 °C (superheated), while the time-average inlet water temperature was 96.5 °C (near saturated temperature) which was much higher than those in LTAF modes (Cases 1A and 1B) and the CTF mode (Case 2); (2) the large-amplitude temperature oscillation at the outlet of this case was much different from the small-amplitude oscillation of outlet temperatures around the saturated temperature during the LTAF and CTF modes; (3) the oscillation of various measurements had the same period of 53 s, which agrees with the period observed from the visualization study. This confirmed that large-amplitude oscillations of various measurements were caused by the liquid/two-phase/vapor alternating flow (LTVAF); (4) while oscillations of pressures and temperatures were in phase, the oscillations of pressures and instantaneous mass flux were almost out of phase; (5) both the time-average values and the oscillation amplitudes of temperatures and inlet pressure of LTVAF were much larger than those in LTAF and CTF oscillations. The oscillation amplitudes of wall temperatures, fluid temperatures, fluid pressures, and fluid mass flux were as large as 229.3 °C, 176.0 °C, 44.0 kPa and 56.4 g/cm^2 s respectively; (6) the oscillation amplitude of inlet water temperature was smaller than that of outlet water temperature because the inlet temperature oscillated between the subcooled and saturation state, while the outlet temperature oscillated from subcooled to superheated.

4. Explanation of periodic boiling in microchannels

The reason for alternating appearance of the single-phase liquid flow and two-phase flow in the LTAF mode, and the alternating appearance of three phases in the LTVAF mode, can be explained as follows: when boiling occurred in the test section, the pressure drop across the test section was suddenly increased due to generation of vapor bubbles. This increase in pressure drop caused the decrease in mass flux, which in turn caused the decrease in pressure drop. Therefore, pressure and mass flux oscillations occurred. During the period of increasing mass flux, if the constant heat flux was insufficient to boil the incoming mass flow of water, the single-phase liquid flow appeared. During the period of decreasing mass flux, if the constant heat flux was sufficient to boil the incoming flow of water, the two-phase flow period appeared. Thus, the alternating appearance of different flow patterns in the LTAF and LTVAF boiling modes, cause large-amplitude/long-period oscillations in water temperatures and wall temperatures as shown in Figs. 5,6 and 8. According to the analysis by Wang et al. [3], when the oscillation of pressure and the induced oscillation of mass flux have phase differences, large-amplitude oscillations of fluid quantities can be sustained.

5. Concluding remarks

In this paper, simultaneous visualization and measurements of temperature, pressure and mass flux variations have been carried out to investigate boiling instabilities of water flowing through parallel silicon microchannels at different heat flux. In addition to the liquid/two-phase alternating flow (LTAF) that was reported in our previous paper [14], two other boiling modes (CTF and LTVAF) were observed in this work. The following conclusions are obtained from the present work:

1. When the wall heat flux was increased from 13.5 to 22.6 W/cm^2 and the corresponding time-average mass flux of water was decreased from 14.6 to 11.2 g/cm^2 s (with all other conditions being the same), three different unstable boiling modes were observed: liquid/two-phase alternating flow (LTAF), continuous two-phase flow (CTF), and liquid/two-phase/vapor alternating flow (LTVAF). Generally, LTAF occurred at lower heat flux (from 13.5 to 16.6 W/cm^2) with higher average mass flux (from 14.6 to 12.7 g/m^2 s); CTF occurred at the medium heat flux (18.8 W/cm^2) and medium mass flux (11.9 g/cm^2 s), and LTVAF occurred at higher heat flux (22.6 W/cm^2) and lower mass flux (11.2 g/cm^2 s).
2. The liquid/two-phase alternating flow occurs when the fluid at the outlet reaches a saturated temperature while inlet water is at a large subcooled temperature. The continuous two-phase flow occurs when the fluid at the outlet reaches a saturated temperature while inlet water is slightly subcooled. The liquid/two-phase/vapor alternating flow occurs when the water at the outlet is superheated with occasional dips to a subcooled temperature while the inlet water temperature is slightly superheated with occasional dips of subcooling.
3. Oscillation periods and oscillation amplitudes of temperature, pressure, mass flux measurements are different for the three different boiling modes. Generally, oscillation amplitudes in LTVAF are largest while oscillation amplitudes in CTF are smallest. Oscillation amplitudes in LTAF are between the LTVAF and CTF modes.
4. In general, time-average values of wall temperatures, water temperatures, and inlet pressures increase with increasing heat flux and decreasing mass flux. However, time-average values and oscillation amplitudes of outlet pressure, which was connected to the atmosphere in this experiment, show small variance with increasing heat flux and decreasing mass flux.
5. Oscillations of pressure and mass flux in the CTF boiling mode are nearly in phase while oscillations of pressures and mass flux in LTAF and LTVAF boiling modes are nearly out of phase. Because of the phase difference of pressures and mass flux, large-amplitude oscillations of pressure and temperature can be sustained.
6. Bubbly flow is the dominant flow pattern during the two-phase flow period in liquid/two-phase alternating flow. At high heat flux and low mass flux, some peculiar two-phase flow patterns (shown in Fig. 4c and d) occur in the continuous two-phase flow and liquid/two-phase/vapor alternating flow, which were reported here for the first time.

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References

[1] H. Yuncu, O.T. Yildirim, S. Kakac, Two-phase flow instabilities in a horizontal single boiling channel, Appl. Sci. Res. 48 (1991) 83–104.
[2] Y. Ding, S. Kakac, X.J. Chen, Dynamic instability of boiling two-phase flow in a single horizontal channel, Exp. Thermal Fluid Sci. 11 (1995) 327–342.
[3] Q. Wang, X.J. Chen, S. Kakac, Y. Ding, Boiling onset oscillation: a new type of dynamic instability in a forced-convection upflow boiling system, Int. J. Heat Fluid Flow 17 (4) (1996) 418–423.
[4] M. Xiao, X.J. Chen, M.Y. Zhang, T.N. Veziroglu, S. Kakac, A multivariable liner investigation of two-phase flow instabilities in parallel boiling channels under high pressure, Int. J. Multiphase Flow 19 (1) (1993) 65–77.
[5] J.M. Kim, S.Y. Lee, Experimental observation of flow instability in a semi-closed two-phase natural circulation loop, Nucl. Eng. Des. 196 (2000) 359–367.
[6] V. Heinzel, J. Holzinger, M. Simon, Fluid oscillation in flat plat boiling water collectors, Solar Energy 59 (1997) 43–48.
[7] M.B. Bowers, I. Mudawar, High flux boiling in low flow rate, low pressure drop mini-channel and microchannel heat sinks, Int. J. Heat Mass Transfer 37 (2) (1994) 321–332.

[8] W. Qu, I. Mudawar, Prediction and measurements of incipient boiling heat flux in microchannel heat sinks, Int. J. Heat Mass Transfer 45 (2002) 3933–3945.
[9] X.F. Peng, H.Y. Hu, B.X. Wang, Boiling nucleation during liquid flow in microchannels, Int. J. Heat Mass Transfer 41 (1) (1998) 101–106.
[10] L. Jiang, M. Wong, Y. Zohar, Forced convection boiling in a microchannels heat sink, J. Microelectromech. Syst. 10 (1) (2001) 80–87.
[11] L. Zhang, J.M. Koo, L. Jiang, M. Asheghi, K.E. Goodson, J.G. Santiago, Measurements and modeling of two-phase flow in microchannels with nearly constant heat flux boundary conditions, J. Microelectromech. Syst. 11 (1) (2002) 12–17.
[12] G. Hetsroni, A. Mosyak, Z. Segal, Nonuniform temperature distribution in electronic devices cooled by flow in parallel microchannels, IEEE Trans. Components Packag. Technol. 24 (1) (2001) 17–23.
[13] G. Hetsroni, A. Mosyak, Z. Segal, G. Ziskind, A uniform temperature heat sink for cooling of electronic devices, Int. J. Heat Mass Transfer 45 (2002) 3275–3286.
[14] H.Y. Wu, P. Cheng, Visualization and measurements of periodic boiling in silicon microchannels, Int. J. Heat Mass Transfer 46 (2003) 2603–2614.
[15] H.Y. Wu, P. Cheng, Liquid/two-phase/vapor alternating flow during boiling in microchannels at high heat flux, Int. Commun Heat Mass Transfer 30 (3) (2003) 295–302.
[16] H.Y. Wu, P. Cheng, Two large-amplitude /long-period oscillating boiling modes in silicon microchannels, in: Proceedings of the First International Conference on Microchannels and Minichannels, ASME, Rochester, NY, 2003, pp. 629–633.
[17] H.Y. Wu, P. Cheng, Three boiling instability modes in silicon microchannels, in: Proceedings of ASME Summer Heat Transfer Conference, HT2003-47463, Las Vegas, Nevada, 2003.