Wavelet decomposition method decoupled boiling/evaporation oscillation mechanisms over two to three timescales: A study for a microchannel with pin fin structure

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Boiling/evaporation heat transfer in a microchannel with pin fin structure was performed with water as the working fluid. Simultaneous measurements of various parameters were performed. The chip wall temperatures were measured by a high spatial-time resolution IR image system, having a sensitivity of 0.02 °C. The flow pattern variations synchronously changed wall temperatures due to ultra-small Bi number. The wavelet decomposition method successfully identified the noise signal and decoupled various temperature oscillations with different amplitudes and frequencies. Three types of temperature oscillations were identified according to heat flux \( q \) and mass flux \( G \). The first type of oscillation occurred at \( q/G < 0.62 \) kJ/kg. The approximation coefficient of wavelet decomposition decided the dominant cycle period which was \( /C24 \)3 times of the fluid residence time in the microchannel, behaving the density wave oscillation characteristic. The detail coefficients of wavelet decomposition decided the dominant cycle period, which matched the flow pattern transition determined value well, representing the flow pattern transition induced oscillation. For the second type of oscillation, the wavelet decomposition decoupled the three oscillation mechanisms. The pressure drop oscillation caused the temperature oscillation amplitudes of 5–10 °C and cycle periods of 10–15 s. The density wave oscillation and flow pattern transition induced oscillation are embedded with both the pressure rise and decrease stages of the pressure drop oscillation. The third type of oscillation happened at \( q/G > 1.13 \) kJ/kg, having the density wave oscillation coupled with the varied liquid film evaporation induced oscillation. The liquid island, retention bubble induced nucleation sites and cone-shape two-phase developing region are unique features of microchannel boiling with pin fin structure. This study illustrated that pressure drop oscillation and density wave oscillation, usually happened in large size channels, also take place in microchannels. The flow pattern transition and varied liquid film evaporation induced oscillations are specific to microchannel boiling/evaporation flow.

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Introduction

Recently, Ruspini et al. (2014) thoroughly reviewed various oscillations in boiling systems. Ledinegg (1938) did the pioneer work on two-phase flow oscillations. During 1960s and 1970s, many researchers were attracted to investigate the two-phase oscillations due to the development of high power density boilers and pressurized water reactors (PWRs). Two-phase flow oscillations in large size channels or heat exchangers are well understood and documented in the literature.

Two-phase oscillations consist of both static and dynamic ones (Ruspini et al., 2014; Xu et al., 2005a; Thome, 2006).

The static oscillation can be characterized based on the demand curve of pressure drops against mass fluxes. Onset of oscillation (OFI) is identified as the minimum point of the demand curve. A lower flow rate than that at the OFI condition leads to a flow rate excursion between single-phase liquid flow and two-phase flow. For the forced boiling flow in large size channels, it is recognized that three typical types of oscillations may occur: pressure drop oscillation, density wave oscillation and thermal oscillation. Considering a boiling system with N-shaped demand curve of pressure drops versus mass flow rates, the pressure drop oscillation would occur if there is a sufficiently large amount of compressible volume upstream of the boiling channels, which was systematically analyzed by the pioneer studies of Stenning (1964), Stenning and Veziroglu (1966), etc.

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The density wave oscillation is widely studied in large size channels, which is related to the delay in the propagation of disturbances and the feedback processes conditioning the inlet parameters. The cycle period is about 1.5–2 times of the fluid residence time in the channel at high void fraction outlets. Fukuda and Kobori (1979) classified density wave oscillations due to gravity in the chimney section, friction in the heated section and the chimney section, and inertia-momentum in the heated section. These mechanisms cause the disturbances of the void fractions to alter the pressure drop and heat transfer between the fluid and the channel wall. There are other types of oscillations such as thermal oscillation and acoustic oscillation. Detailed comments on these oscillations are beyond the scope of this paper.

The microchannel heat sink was proposed in 1980s. The boiling phenomena in microchannels are more attractive compared with that of the single-phase liquid heat transfer. Two-phase oscillations in microchannels received great attention in the past ten years. Several scientific issues related to this topic are summarized as follows.

Compressible volume effect

A forced convective loop containing a microchannel heat sink certainly has large compressible volume at the microchannel upstream, which can be the liquid tank, the connection tube, etc. The compressible volume induced pressure drop oscillation in a microchannel is more serious than that in a large size channel. Various observations (Wu et al., 2006; Wang et al., 2007; Xu et al., 2005a) observed the large amplitude/long cycle period pressure drop oscillations. Because this mechanism is similar to that in large size channels, the inject pressure throttling technique was investigated to mitigate the oscillation (Wang et al., 2008; Zhang et al., 2010).

Confined bubble effect

Microchannels have significant large surface area over its volume to yield the confined bubble effect, causing the bubble growth along the axial flow direction only after the bubble diameter approaches the channel diameter. During this process, severe pressure fluctuations are observed and the two-phase flow behaves the cyclic characteristic. Physically, the flow pattern transition oscillation is due to the confined bubble effect, which was reported by Barber et al. (2009, 2011), Bogojevic et al. (2009), Cheng et al. (2009), Kuo and Peles (2009), etc.

Thermal non-equilibrium effect

The thermal non-equilibrium is important due to the smooth microchannel surface by silicon etching. Roughness of channel walls may be varied from case to case, but it should be in nanometers. Lin (1998) reported a polysilicon surface to have a roughness of 6.5 nm, approaching the homogeneous bubble nucleation size for water. Boiling incipience needs very high temperature. This effect lacks the bubble nucleation sites on the channel wall surface to yield strong thermal non-equilibrium between the two-phases. Xu et al. (2005b) observed that bubble nucleation sites are preferable to occur in channel corners. The thermal non-equilibrium causes severe explosive boiling phenomenon in silicon microchannels (Xu et al., 2005b; Hetnarski et al., 2005). The thermal non-equilibrium effect caused the alternative liquid flow and two-phase flow in time series. Xu et al. (2009) injected seed bubbles to microchannels to suppress the oscillations. Kandlikar et al. (2006) investigated the inlet pressure throttle and the etched artificial cavities on channel walls to mitigate the oscillations. Even though many studies on microchannel boiling oscillations have been performed in the past ten years, the phenomenon has not been fully understood yet. The following questions may arise:

1. What are the oscillation mechanisms?
2. Do most of oscillations in large size channels also happen in microchannels?
3. What are the unique features when boiling occurs in microchannels?
4. How to decouple oscillations with different spatial and timescales?

The above questions inspired us to perform this study. Here the boiling/evaporation heat transfer in a single microchannel with pin fin structure was investigated. High spatial-time resolution IR image system was used to detect temperature variation. This is equivalent to arrange a large quantity of temperature sensors on the silicon wall to measure temperatures. The basic concept to correlate flow patterns inside the microstructure with wall temperatures is due to the ultra-small Bi number, representing negligible heat conduction resistance of silicon wall relative to convective heat transfer resistance inside the microstructure. The wavelet decomposition method removed the noise signal from the mother signal and decoupled the temperature time series into different oscillation amplitudes and timescales. In this way, the coupled temperature oscillations were separated. Three types of oscillations were identified altogether, which will be discussed in the results and discussion section.

Micro pin fins inside microchannels enhanced two-phase heat transfer due to enhanced nucleation sites and increased surface area between solid walls and fluids. These studies were reported by several researchers such as Kuo and Peles (2009), Koz and Kosar (2010), Wei et al. (2009), Qu and Siu-Ho (2009), Ndao et al. (2012), Kosar et al. (2010) investigated pressure drop fluctuations in micro-pin-fin heat sinks with water as the working fluid under unstable boiling condition. To the authors’ knowledge, there are no investigations to decompose different oscillation mechanisms in microchannels.

Experiment setup and test section

Fig. 1 shows the experimental setup, consisting of four subsystems: a water tank, a forced convective loop, a microchannel test section and a measurement system. The deionized water was stored in the tank. An electrical heater was immersed at the tank bottom. The heater was combined with a temperature controller to control the water temperature at a desired value with an uncertainty of 0.5 °C. The flow rate was provided by a gear pump. Across the pump inlet and outlet was a bypass line to regulate the flow rate to the test section. The main flow rate was passing through a hot water bath, which was running at a constant temperature. Two porous filters, one with 5–10 μm and the other with 2–5 μm pore size, were arranged in the loop to prevent solid particles from entering the test section.

The mass flow rate to the test section was measured by a coriolis mass flow meter (DMF-1-1AB). The mass flow meter had the accuracy of 0.5% and response time of 0.1 s. A pressure transducer (Rosemount 3051) measured pressures at the test section inlet and a differential pressure transducer (Rosemount 3051) measured pressure drops across the test section. The pressure transducers had the accuracy of 0.1% and response time of 0.1 s. The K type thermocouples (Omega) measured fluid temperatures at the test section inlet and outlet. The thermocouples had the accuracy of 0.2 °C and response time of 0.2 s. The sampling rates of pressure and temperature sensors were 500 samples per second. The sampling time was 20–40 s. The sampling rate and sampling time for all the transducers were all the same. It is noted that during the runs the mass flow rate through the test section and the inlet fluid temperature were not constant due to oscillations within the
microchannel test section and the presence of large compressible volume upstream the test section.

A comprehensive measurement system was applied in this study, consisting of a high speed data acquisition unit, a high speed camera adapted with a microscope, and a high speed IR imaging system. The three equipments were synchronized by a synchronization control hub. During experiments, the optical system and data acquisition system were in the waiting mode. The synchronization hub sent a signal to trigger functions of these measurement systems. The maximum time difference of the initial function of these systems after they received the triggering signal was less than 1 μs. A central control computer collected all image files and data.

The Yokogawa DL750 (Japan) high speed data acquisition system was used. The system collected the pressure (voltage signal) and fluid temperature signal. The sampling rate could be up to 10 MHz when the sixteen channels are used. In this study, the data sampling rate was 500 Hz. The IDT Motion pro V4 (USA) high speed camera system was used. The spatial resolution was 1280 pixels by 1024 pixels. The maximum recording speed was 58000 Hz. The camera system was used. The spatial resolution was 1280 pixels by 5500 m, corresponding to 99 pixels by 190 m in this study. This equipment was synchronized by a synchronization line of pin fins with respect to the horizontal axis (see A-A cross section in Fig. 2a). The gap between two neighboring pin-fins was 109 μm. The back silicon wall was deposited by a thin platinum film with its thickness of 300 nm. The deposition area was exactly the same as the microchannel area. Two gold pads were populated at the two margins of the platinum area. The thin film was acted as the heater to evaporate the liquid inside the microchannel. The electrical resistance was 64.8 Ω at 24 °C. The heater was driven by a DC voltage module. Great attention was paid to three locations at the back thin film surface, marked as $T_1$, $T_2$ and $T_3$ (see Fig. 2b). They were symmetrically positioned on the axial line and had the distance of 5000 μm between two neighboring points. Fig. 2c shows the SEM image for a single pin fin.

Data reduction

Mass flux $G$

For each case, the mass flux $G$ was defined as $G = \frac{m}{A_{c20}}$, where $m$ is the mass flow rate, $A_{c20}$ is the cross section area of the single microchannel, which was the channel width of 5500 μm times the channel depth of 75 μm, assuming there are no pin fin structures inside.

Heat flux $q$

Now the heat flux on the heater area of 20000 μm by 5500 μm was estimated. The power applied to the heater area was $Q = V \times I$, where $V$ is the voltage across the heater film and $I$ is the current in the heater film. The heat loss to the environment, $Q_{\text{loss}}$, should be considered. Barber et al. (2011) suggested that $Q_{\text{loss}}$ includes the...
convective heat transfer component, \( Q_{\text{loss, conv}} \), and the radiation heat transfer component, \( Q_{\text{loss, rad}} \). In this study, \( Q_{\text{loss}} \) was estimated before the two-phase experiment. The silicon wall temperature was maintained for single-phase liquid flow which was almost identical to those for the boiling flow in the microchannel. The liquid temperature difference \( \Delta T \) was measured across the microchannel inlet and outlet to yield \( Q_{\text{loss}} = mC_{\text{pf}}\Delta T \), where \( C_{\text{pf}} \) is the water specific heat. The two-phase experiment was running at the atmospheric pressure, the wall temperatures were in the range of 95–120 °C, under which \( Q_{\text{loss}} \) was measured in the range of 4–5 W. The heat flux on the heater film was \( q = \frac{Q}{A} \), where \( A \) is the thin film area of 20000 \( \mu \text{m} \) by 5500 \( \mu \text{m} \).

The Bi number

The silicon chip made by the MEMS technique had very small \( Bi \) number which is defined as \( Bi = \frac{h\delta}{k} \), where \( h \) is the heat transfer coefficient between fluid and channel wall surface, \( \delta \) is the effective thickness (the thickness between the channel bottom wall and the back silicon surface) of the silicon chip, and \( k \) is the silicon thermal conductivity. Here, \( Bi \) was equal to 0.02 for \( h = 10^8 \text{W/m}^2\text{K}, \delta = 325 \mu\text{m} \) and \( k = 149 \text{W/m K.} \) Physically, \( Bi \) represents the heat conduction resistance of silicon wall related to the convective heat transfer resistance inside the microchannel. The ultra-small \( Bi \) number indicates that the thermal conduction resistance can be neglected compared with the convective heat transfer resistance. Therefore, the temperatures measured by the IR image system can trace the temperatures at the inside wall surface, simultaneously. Besides, the varied flow patterns in the microchannel can simultaneously alter the back silicon wall temperatures. This is the basic reason to apply the synchronization measurement method to identify the temperature variations over different spatial-time scales.

The wavelet decomposition method

The wavelet transform (WT) is a well developed time frequency analysis method, having good time resolution at high frequencies and good frequency resolution at low frequencies. It can be
considered as a sort of mathematical microscope because different parts of the time series are examined by adjusting the focus automatically. In this way, a family of scaled and translated wavelets is created to catch different frequency information embedded in a time series. Each wavelet is a sort of band-pass filter that can be used for decomposition of the original time series into different frequency bands, thus allowing a multi-resolution analysis of the signal. The wavelet decomposition method used here was similar to Elperin and Klochko (2002).

The discrete wavelet transform (DWT) of a square integrable function is defined as its decomposition into an orthogonal set of functions (Mallat, 1989)

\[ w_{jk}(t) = 2^j \psi(2^j t - k), \quad \text{with} \quad j, k \in \mathbb{Z} \]  

which are derived by shifting and scaling the single function \( \psi(t) \) called a “mother wavelet”, \( j \) is the decomposition level. In order to be a wavelet, the function \( \psi(t) \) has to satisfy the admissibility condition

\[ \int_{-\infty}^{\infty} \psi(t) dt = 0 \]  

To form an orthonormal basis of \( L^2(\mathbb{R}) \), it must be orthogonal to its translations \( \psi(t-k) \) and scaled versions \( \psi(2^j t) \) for all integers \( j, k \). The “mother wavelet” must be well localized in both physical and Fourier spaces. The coefficients of the wavelet transform of a function \( f(t) \in L^2(\mathbb{R}) \) are defined as its orthogonal projection onto the wavelet basis:

Fig. 3. The wavelet decomposition for a single-phase liquid flow case (\( T_m = 93.3^\circ C, G = 328 \, \text{kg/m}^2 \, \text{s}, q = 0, T_{\text{room}} = 24.0^\circ C \), where \( T_{\text{room}} \) was the room temperature).
Therefore, any function \( f(t) \) can be decomposed as

\[
d_j = \int_{-\infty}^{\infty} f(t) \psi_j(t) dt
\]

Due to the localization properties of the wavelets, the wavelet coefficients \( d_j \) can be viewed as the measure of fluctuations of the analyzed function near the time \( 2^j \) and in the frequency band whose endpoints are proportional to \( 2^j \), or at the scale \( 2^j \). The localization behavior in both time and frequency domains, interdependent by the uncertainty principle, turns the wavelet transform into a superior tool for analysis of non-stationary and transient signals. A sampled discrete signal \( f(t) \), \( t = 1, 2, \ldots, N \) is usually identified with the approximation at the scale 1, the wavelet decomposition is

\[
f(t) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} d_{jk} \psi_j^k(t)
\]

where \( J \leq \log_2 N \) is the maximum decomposition level, \( d_{jk} \) and \( a_{jk} \) are called the detail and approximation coefficients, respectively, at the scale \( 2^j \) (or at the level \(-j\)):

\[
a_{jk} = 2^{j/2} f(t), \psi(2^j t - k), \quad d_{jk} = 2^{j/2} (f(t), \psi(2^j t - k))
\]

such that the set of functions \( \phi_j(t), \psi_j(k), j, k \in Z \) \( J \geq j \), constitutes an orthonormal basis for a wide class of functions.

The wavelet analysis strongly depends on the choice of the wavelet basis. The original signal should be represented in the most parsimonious way, that is by a small number of essentially non-zero wavelet coefficients which will pick up the fundamental features.
The Shannon entropy of the unit norm vector $v$ is defined as
\[ S = -\sum_j |f_j|^2 \log |f_j|^2 \] (9)

and the sparsity is quantified using norms in spaces of finite real sequences:
\[ ||f||_p = \left( \sum_j |f_j|^p \right)^{1/p} \] (10)

for $p < 2$. The smaller $p$, the more pronounced the quality of the representation is. The best wavelet basis for a given signal is that the wavelet decomposition coefficients attain the minimum value.

In order to find a suitable wavelet among the collection of basic well-known wavelets (Misiti et al., 1995), we compared the sparsity (Eq. (10)) of the wavelet representation for the wide set of the experimental time series. Daubechies’ least symmetric wavelet of order four (Daubechies, 1988), which reduces the sparsity by 40% on average with respect to the time domain representation, was chosen for the analysis of the wall temperature time series.

The decomposition results $a$ and $d$ are further analyzed by the Power Spectrum Density (PSD), which is a function of frequency $\omega$, written as
\[ PSD(\omega) = \frac{4\pi^2 |X(\omega)|^2}{\omega_0^2 (\omega_2 - \omega_1)} \] (11)

where $X(\omega)$ is the magnitude of the FFT of the temperature signals obtained from IR imaging system, $\omega_0$ is the original sampling
frequency, and $t_1$ and $t_2$ represent the start and end time of the signal. In this study, the wavelet toolbox in Matlab software package was used for the data reduction.

Results and discussion

Noise signal identification

In order to identify what is the variance band of the noise signal for a given system, the experiment with single-phase liquid flow was performed in the microchannel with pin fin structure. Fig. 3 shows the results for $T_m = 93.3^\circ C$, $G = 328$ kg/m$^2$ s with the bottom heater turned off. Fig. 3a shows the source $T_3$ signal (Fig. 2b for $T_2$ location). Fig. 3a was first decomposed to $a_1$ and $d_1$ at the level 1 (see Fig. 3b and c), $a_1$ was further decomposed to $a_2$ and $d_2$ at the level 2 (see Fig. 3d and e). The third level decomposition yields $a_3$ and $d_3$ (Fig. 3f and g). Thus, the information in Fig. 3 has the following relationship: $S(T_2) = a_1 + d_1 = a_2 + d_2 + d_1 = a_3 + d_2 + d_1$. The approximation coefficients of $a_1$, $a_2$, and $a_3$ were obtained by removing the noise signal gradually. Attention shall be paid to the detail coefficients of $d_1$, $d_2$, and $d_3$ (see Fig. 3c, e, and g). The variance bands of these coefficients covered the ranges of $(-0.04–0.04)^\circ C$, $(-0.02–0.02)^\circ C$ and $(-0.02–0.02)^\circ C$, respectively, showing the decreased variance band range from $d_1$ to $d_2$ and $d_3$. The variance amplitude of $0.04^\circ C$ for $d_1$ can be considered as the noise signal for the temperature measurement, which was almost two times of the temperature sensitivity of the IR image system. The variance amplitude of $0.02^\circ C$ for $d_2$ and $d_3$ (see Fig. 3e and g) was exactly equal to the temperature sensitivity of the IR image system. Therefore, $0.04^\circ C$ was considered as the noise signal for the stable liquid flow in the silicon chip. The noise may come from the environment temperature variation, vibration of the test section, flow rate variation, etc.

Fig. 4a shows $T_3$ in a time span of 3.0 s for the boiling flow in the microstructure with $q = 84.76$ kW/m$^2$. Fig. 4b–g shows the three levels of wavelet decomposition. The detail coefficients of $d_1$ and $d_2$ had the variance amplitudes of $0.04^\circ C$, which can be considered as the noise signal by comparing with Fig. 3. Removing the noise signal by two times yields the detail coefficient $d_3$ with the variance amplitude significantly larger than $0.04^\circ C$ (see Fig. 4g).

It is concluded that the source $T_3$ signal can be represented by $a_4$ and $d_3$ with removed noise signal, in which $a_4$ indicates the larger amplitude/lower frequency oscillation and $d_3$ reflects the lower amplitude/higher frequency oscillation. It is emphasized that the useful $d_3$ coefficients were obtained only after the noise was removed.

The signal removal and wavelet method are summarized as follows. Initially the variance amplitude of noise signal should be identified by testing single-phase flow. For the boiling flow, the treatment is to decompose the source signal to the level $l$ at which the variance amplitudes of the detail coefficients $d_l$ begin to apparently exceed that of the noise signal. In this way, the useful approximation coefficients $a_l$ and detail coefficients $d_l$ are obtained by gradually removing the noise signal through wavelet method. Then $a_l$ and $d_l$ are used to detect the complicated mechanisms embedded in these coefficients. It should be noted that the level $l$ at which the coefficients of $a_l$ and $d_l$ are useful may be different for different boiling cases, however, this does not influence the application of the wavelet method for the boiling heat transfer analysis in microchannels.

The three types of temperature oscillations

The boiling/evaporating heat transfer in the microstructure was performed at the nearly saturated water temperature inlet, i.e., $T_m = 81.7–94.2^\circ C$. The following data ranges were covered: mass flux $G = 317–671$ kg/m$^2$ s, $q = 50.61–383.17$ kW/cm$^2$. Table 2 summarized the runs conducted in this paper. Because unsteady heat transfer were treated, $T_m$ (inlet water temperature), $P_{in}$ (inlet pressure) and $AP$ (pressure drop) were given in a range values. Three types of temperature oscillations were identified (see Fig. 5), which were mapped according to a two-dimensional plot of $q$ and $G$. Other studies such as Bogojevic et al. (2009) and Cheng et al. (2009) also used the $q–G$ plot to identify the stable and unstable boiling flow regimes in microchannels. This paper identified the following three types of oscillations:

1. The first type of oscillation (region I): density wave oscillation coupled with flow pattern transition induced oscillation (two timescales oscillations).
2. The second type of oscillation (region II): pressure drop type oscillation coupled with density wave oscillation and flow pattern transition induced oscillation (three timescales oscillations).
3. The third type of oscillation (region III): density wave oscillation coupled with varied liquid film evaporation induced oscillation (two timescales oscillations).

These coupled temperature oscillations were analyzed by the wavelet decomposition method. Different oscillation mechanisms were identified by separation of the source temperature signal with removed noise signal, together by the high speed visualization of dynamic flow patterns. The separation process involved two to three timescales.

The first type of oscillation

This type of oscillation happen at low heat flux (see Fig. 5). Fig. 6 shows $P_{in}$, $T_m$, $T_{out}$, $T_{wave}$, $T_1$, $T_2$, $T_3$ versus time for run 19, in which $T_{wave}$ is the wall temperature averaged over the whole heater surface. $T_m$, $T_{in}$, $T_{out}$, $T_{wave}$ are quasi-stable with oscillation amplitudes in the transducer accuracy range. For example, $P_{in}$ was varied in the range of 123.16–123.91 kPa. However, wall temperatures of $T_1$, $T_2$ and $T_3$ were oscillating with apparent amplitudes. The amplitudes were increased from $T_1$ to $T_3$. This is because run 19 had low heat flux and the boiling happened in the microchannel downstream.
Fig. 7a shows $T_3$ in a time span of 15.0 s for run 19. A short time span of 3.0 s was focused in Fig. 7b, which was analyzed by the wavelet decomposition technique. The first and second levels of decomposition were not shown because these two levels contained the noise signal. The $d_1$ and $d_2$ coefficients had the variance amplitude less than 0.04 °C. Useful information was obtained at the third level (see $a_3$ and $d_3$ in Fig. 7c and d), after the decomposition processes were performed. The PSD results were given in Fig. 7e using $a_3$ data and Fig. 7f using $d_3$ data. The frequency corresponding to the maximum PSD value was 7.3 Hz (lower frequency) for $a_3$ and 44.9 Hz (higher frequency) for $d_3$. These two frequencies are obviously different from each other. In order to show the benefit of the wavelet method, the PSD result was plotted in Fig. 7g by avoiding the wavelet method but using the original temperature signal. The dominant frequency of 7.3 Hz was shown in Fig. 7g, matching the frequency shown in Fig. 7e. But Fig. 7g did not show the high dominant frequency of 44.9 Hz such as shown in Fig. 7f. In other words, the PSD analysis without using the wavelet tool only detected a single timescale frequency. The high frequency part is lost, yielding incomplete information. The PSD analysis based on detail coefficients of wavelet decomposition is useful for the high frequency detection.

The density wave oscillation. The dominant frequency of 7.3 Hz in Fig. 7e referred to the dominant cycle period of 137 ms. The approximation $a_3$ coefficient represents the density wave oscillation. This conclusion was drawn by comparing the dominant cycle period of 137 ms with the fluid residence time in the microchannel. The whole channel length was divided into the liquid flow length of $l_{sp}$ and the boiling flow length of $l_{tp}$. The fluid residence time in the liquid flow section was $\tau_{sp} = \rho_{f}q_{f}l_{sp}/G$, where $\rho_{f}$ is the liquid density, $l_{tp}$ was computed as
where $h_{fg}$ is the latent heat of evaporation. Thus, the average vapor mass quality in the two-phase region was $x_m = 0.5x_{out}$. The slip ratio $\delta$ in the two-phase region was defined as the vapor velocity divided by the liquid velocity, which was estimated as (Smith, 1969),

$$\delta = 0.4 + 0.6\sqrt{0.4 + 0.6x_m}$$ (15)

Thus, the average void fraction $x_m$ in the two-phase region was

$$x_m = \frac{1}{1 + \frac{1}{2}\frac{\tau_p}{\tau}}$$ (16)

where $\rho_g$ and $\rho_l$ are the vapor and liquid densities, respectively. Thus the two-phase mixture density was

$$\rho_m = \rho_g x_m + \rho_l (1 - x_m)$$ (17)

Then the fluid residence time across the whole microchannel length was

$$\tau = \tau_{sp} + \frac{\rho_f l_{sp}}{G} + \frac{\rho_l (l - l_{sp})}{G}$$ (18)

For run 19 shown in Fig. 7, the fluid residence time $\tau$ was 46.4 ms. Thus, the $d_5$ approximation coefficient determined cycle period of 137 ms was 2.95 times of the fluid residence time of 46.4 ms. The $d_5$ signal varied from 103.89 °C to 106.18 °C with the amplitude of ~1 °C. The $d_6$ signal reflected the density wave oscillation. Any disturbance influences the spatial-time void-fraction distribution to affect the two-phase mixture density and velocity. Thus, the wall temperature oscillation is self-sustained. Such mechanism widely happens in large size boiling systems. It should be noted that in large size boiling channels the dominant cycle period of density wave oscillation is about 1.5–2.0 times of the fluid residence time.

It should also be noted that Eq. (15) is suitable for the slip ratio computation in large size tubes. Because there is no suitable correlation of slip ratio in microchannel with pin fin structure, Eq. (15) is used in this study. When microscale is considered, the velocity gradient is very large to increase the shear stress on the vapor–liquid interface, yielding the slip ratio to approach one. If one used $\delta = 1$, the fluid residence time was 49.7 ms. The difference between fluid residence time is not large when different $\delta$ was used.

The flow pattern transition induced oscillation. Now the mechanism reflected by the detail coefficient $d_5$ was analyzed. The dominant frequency corresponding to $d_5$ was 44.9 Hz (see Fig. 7f), equivalent to the cycle period of 22 ms. Fig. 8a shows $T_3$ focused in a short time span of 9.46–9.57 s. The consecutive cycle periods can be determined by measuring the time span between two neighboring signal peaks, such as the cycle period of 22 ms between the peaks at $t = 9.478$ s and 9.500 s. Fig. 8b plotted the distribution of cycle periods determined by temperature signal over the time span of 3.0 s. The cycle period was 24 ms at the maximum distribution.

In order to explore the reason of varied temperatures at higher frequency, we plotted the flow pattern decided cycle periods with the dominant cycle period of 23 ms (see Fig. 8c). We counted the total cycle number based on the visualization image files in the time span of 3.0 s, corresponding exactly to the time span during which temperatures were recorded in Fig. 7b. The image files showed periodic behavior. Assuming the local visualization area completely covered by liquid at $t_1$ (time), then the local area was in two-phase state and until it was returned to the liquid state at $t_2$. Thus, a full cycle was completed with the cycle period recorded as $\tau_0 = t_2 - t_1$. We divided the cycle periods into several groups, each having a specific cycle period range, for instance, $\tau = 2.5-7.5$ ms, $\tau = 7.5-12.5$ ms, etc. Then, we counted the cycle number for each

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**Fig. 8.** The cycle periods of the flow pattern transition oscillations (run 19, a: temperature oscillations in a narrow time span, b: wall temperature determined values, c: flow pattern determined values).
cycle period range (group). The distribution of cycle period was defined as the cycle number with each cycle period group divided by the total cycle number in the time span of 3.0 s. Different cycle period group had different distribution value. Thus, Fig. 8c was formed to yield the dominant cycle period of 23 ms. Thus, the temperature determined cycle period matched the flow pattern determined value well. By comparing Fig. 7f with Fig. 8b and c, the detail coefficient $d_3$ represents the flow pattern transition induced oscillation mechanism.

Fig. 9 shows flow patterns focused on the $T_2$ area, corresponding exactly to the time span during which temperatures were recorded in Fig. 8a. The focused area was liquid at $t = 9.477$ s, however the two-phase was occupied at $t = 9.478$ s, indicating the explosive boiling happened within 1 ms. The area returned to liquid at $t = 9.490$ s and lasted till at $t = 9.498$ s. The two-phase re-appeared at $t = 9.500$ s. The flow pattern switch between liquid and two-phase matched the temperature signal in Fig. 8a very well. The temperature decrease from peak to bottom corresponded to two-phase state, and the temperature rise from bottom to peak corresponded to liquid state.

Micro pin fins increased nucleation sites and provided more wall surface area to enhance heat transfer. The flow observations identified: (a) Explosive boiling: Explosive boiling in the microchannel is related to the liquid superheat, which occurred for the first and second types of oscillations in this study. (b) Liquid island: The liquid island was identified (see Figs. 9 and 10). When two-phase mixture flushed the microstructure, liquid films are attached on micro pin fin walls. The merged liquid films between a set of neighboring pin fins form an enclosed envelop that contains liquid inside. Outside of the liquid island are the two-phase mixture with vapor flowing in the pin fin gap and liquid films attached on pin fin walls. A connection line of B-B was marked for an inclination angle of 45° with respect to the axial flow direction (see the photo at

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**Fig. 8c:**

- 9.477 s
- 9.478 s
- 9.479 s
- 9.487 s
- 9.488 s
- 9.490 s
- 9.498 s
- 9.499 s
- 9.500 s

**Fig. 9:** The flow pattern transition in the cycle period corresponding to Fig. 8a (run 19).
The second type of oscillation occurred in region II (see Fig. 5). Fig. 11 shows $P_{in}$, $T_{in}$, $T_{out}$, $T_{wall}$, $T_1$, $T_2$, and $T_3$ for run 12. The locations of $T_1$, $T_2$, and $T_3$ can be seen in Fig. 2 ($x = 5.0$ mm for $T_1$, 10.0 mm for $T_2$ and 15.0 mm for $T_3$, where $x$ is the axial coordinate). Flow pattern in the upstream of microchannel at $T_1$ location was liquid. But $T_2$ dynamically varied due to varied flow rates. Flow patterns in the middle and downstream of microchannel switched between liquid and two-phase. The temperatures were oscillating in three timescales.

Pressure drop oscillation. Fig. 11 shows large amplitude/long cycle period oscillations for various parameters. Cycle periods were identical for these parameters and almost the same for consecutive cycles, which were marked as $t_p = 13.20$ s. Oscillation amplitudes were larger: for example, $T_1$, $T_2$, and $T_3$ were changed in the ranges of $98.42–104.52$ °C, $101.23–105.31$ °C, and $101.68–105.99$ °C, respectively. The marked cycle consisted of two stages: the pressure drop increase stage during $t = 6.42–13.20$ s, and the pressure drop decrease stage during $t = 13.20–19.62$ s. In the first stage, the pressure drop was increased due to more vapor in the microchannel, and in the second stage, the pressure drop was decreased due to less vapor in the microchannel. Because $T_1$, $T_2$, and $T_3$ had different axial locations, they reacted differently in the two stages due to varied interface location between liquid and two-phase in the microchannel. In the first stage, $T_1$ (black curve) was sharply increased and maintained at a higher temperature level due to the decreased mass flow rate, $T_2$ (red curve) was slightly decreased from its cycle maximum value to reach a relatively higher level, but $T_3$ (blue curve) were sharply decreased to a lower level due to violent boiling/evaporation heat transfer in the channel downstream (see Fig. 11). Alternatively, the second stage held inverse responses for $T_1$, $T_2$, and $T_3$ compared with the first stage. $T_3$ was maintained at a higher level due to weakened boiling/evaporation heat transfer in the channel downstream. Because there was sufficient compressible volume such as liquid tank and connection tube at the chip upstream, the pressure drop oscillation would happen, which is similar to that occurs in large size channels. Fig. 12 shows the IR images focused on the heater area of 20.0 mm by 5.5 mm, in which the files from $t = 6.42$ s to 13.20 s corresponded to the first stage, and the files from $t = 13.20$ s to 19.63 s corresponded to the second stage.

The large amplitude/long cycle period oscillation belonged to the pressure drop oscillation, caused by the large compressible volume upstream the microchannel. The liquid tank and connection tube could be the compressible volume. Our visualization image files showed alternative liquid flow and two-phase flow in the microchannel. During the liquid flow stage, flow rate to the microchannel was increased due to smaller pressure drop across the microchannel. However, flow rate was decreased during the two-phase stage due to larger pressure drop across the microchannel. Because the liquid pump was continuously running, the upstream compressible volume could "release" more liquid flow rate to the microchannel when the pressure drop was small during the liquid flow stage. The compressible volume could "store" more liquid when the pressure drop was large during the two-phase flow.
The pressure drop oscillation caused the variation of inlet fluid temperatures. It occurred in the negative slope region of the hydraulic demand curve of pressure drops against the mass flow rates. Such type of oscillation can also be found in Xu et al. (2005a) and Wang et al. (2007, 2008). The pressure drop oscillation widely occurs in large size boiling systems.

Fig. 13 identified small amplitude/high frequency oscillations coupled with the large amplitude/low frequency temperature oscillations, which were described as follows.

The embedded oscillations in the first stage. Fig. 13a re-plotted \( T_3 \) curves (source signal), in which the lower temperature level \( (T_{3L}) \) was focused in the time span of \( t = 7.0–10.0 \) s (see Fig. 13b). The wavelet decomposition technique achieved the useful \( a_2 \) and \( d_2 \) coefficients by erasing noise signal (see Fig. 13c and d). The \( a_2 \) and \( d_2 \) coefficients had obviously different variance band ranges. The variance band for \( a_2 \) was quite larger than that for \( d_2 \). The PSD analysis for \( a_2 \) yielded the dominant frequency of 28.2 Hz (see Fig. 13e). The corresponding cycle period of 36 ms was in the same order of the fluid residence time in the microchannel, representing the density wave oscillation. The analysis was given in the above section and not repeated here. The PSD analysis for \( d_2 \) yielded the dominant frequency of 69.2 Hz (see Fig. 13f), corresponding to the cycle period of 15 ms, matching the flow pattern transition determined dominant cycle period. Fig. 14 shows \( T_3 \) in
a narrow time span of $t = 8.62–8.68$ s, in which two cycles were marked with the cycle periods of 30 ms and 17 ms, respectively. The flow patterns in the channel downstream showed the temperature decrease stage such as from $t = 8.629$ s to 8.647 s referring to the two-phase stage and the temperature rise stage referring to the liquid warm up stage (see Fig. 15). Violent evaporation happened and the whole focused area was occupied by the two-phase fluid at $t = 8.629$ s. The liquid flow was established at $t = 8.647$ s. The two-phase state was re-established at around $t = 8.657$ s. Thus, the density wave oscillation and the flow pattern transition induced oscillation were identified, which were embedded with the pressure drop oscillation.

The embedded oscillation in the second stage. Similar procedure was carried out for the second stage, in which the higher temperature level $T_3$ was focused in the time span of $t = 12.0–15.0$ s (see Fig. 16). The wavelet decomposition technique yielded $a_2$ and $d_2$ coefficients by removing the noise signal. The dominant frequency was 7.7 Hz (see Fig. 16e), corresponding to the dominant cycle period of 130 ms for the density wave oscillation. Several peak PSD values appeared for $d_2$ coefficient (see Fig. 16f) to indicate more complicated flow pattern transitions in the microchannel. The maximum peak PSD value had the frequency of 74.2 Hz. Fig. 17 shows the flow pattern transitions in a very narrow time span. Again, the flow was switched between the liquid-warm-up stage and the two-phase stage.

Summary of the second type of oscillation. Three types of oscillations were identified with different magnitudes of amplitudes and cycle periods. The wall temperature oscillation induced by the pressure drop oscillation had the variance amplitude of $7 ^\circ C$ and cycle periods of $\sim 13$ s. The wavelet decomposition decoupled the density wave oscillation and the flow pattern transition induced oscillation from the pressure drop induced oscillation. The density wave oscillation had the temperature amplitude of $\sim 1 ^\circ C$ and the cycle period of $\sim 100$ ms. The flow pattern transition induced oscillation had the amplitude of less than $1 ^\circ C$ and the cycle period of $\sim 10$ ms. The pressure drop oscillation had the pressure drop increase and decrease stages. Because the spatial-time void fractions in the pressure drop increase stage was larger than those in the pressure drop decrease stage, the oscillation frequency of 28.2 Hz in Fig. 13e was larger than that of 7.7 Hz in Fig. 16e for the density wave oscillation. More vapor population yields faster fluid traveling speed to yield higher density wave oscillation frequency. For the flow pattern transition induced oscillation, the oscillation frequency of 69.2 Hz in the pressure drop increase stage approached the value of 74.2 Hz in the pressure drop decrease stage. These frequencies are related to the liquid warm-up time.
The third type of oscillation

The third type of oscillation occurred in region III (see Fig. 5). Fig. 18 shows $P_{in}$, $T_{ave}$, $T_{out}$, $T_1$, $T_2$ and $T_3$ versus time. The third type of oscillation displayed quasi-stable parameters except of $T_1$, $T_2$ and $T_3$. The averaged temperature over the whole heater surface also yielded quasi-stable $T_{ave}$. But the local temperatures of $T_1$–$T_3$ did show apparent oscillation amplitudes (see Fig. 18b). Fig. 19a shows $T_3$ for run 15. The wavelet decomposition method used the $T_3$ data in a time span of $t = 1.0$–$4.0$ s (see Fig. 19b). Fig. 19c and d shows $a_2$ and $d_2$ coefficients. Fig. 19e and f shows the PSD analysis of $a_2$ and $d_2$. The first and second peak PSD values held the oscillations frequencies of $8.8$ Hz and $14.8$ Hz, indicating the cycle periods of $\sim 100$ ms for the density wave oscillation. Later we will show that the $d_2$ coefficient reflected the varied liquid film evaporation induced oscillation, somewhat different from the flow pattern transition induced oscillation for the first and second types of oscillations.

We focus $T_3$ on a narrow time span of $t = 3.48$–$3.80$ s in Fig. 20. It is clearly seen that the two levels of oscillations were coupled with each other. The cycle periods of $\tau_p = 108$ ms and $146$ ms for two neighboring cycles referred to the density wave induced oscillation. In addition, small amplitude/high frequency oscillations can be found. An example cycle was marked as $\tau_p = 14$ ms in the time span of $t = 3.587$–$3.601$ s. Fig. 21 examined the flow patterns corresponding to the $T_3$ local area. Because heat flux was relatively higher, the liquid film evaporation was the heat transfer mechanism. Liquid films attached on pin fin walls were thick at $t = 3.587$–$3.589$ s, corresponding to the local peak wall temperature. Liquid films became thinner at $t = 3.594$ s, behaving better heat transfer performance to yield the local minimum wall temperature. Liquid films were automatically returned to be thick at $t = 3.600$ s. Thus, the varied liquid film induced oscillation is called referring to the small amplitude/high frequency oscillation, under which the liquid film evaporation is the dominant heat transfer mechanism. It should be noted that, the small amplitude/high frequency oscillations for the first and second types of oscillations are caused by the flow pattern transition induced ones, under which the forced convective liquid heat transfer (liquid flow stage) and the bubble nucleation (two-phase stage) are the dominant heat transfer mechanisms.

Special phenomena observed in microchannel with pin fins

The above sections discussed the three types of temperature oscillations. The wavelet decomposition method can be extended to other microsystems. Unique phenomena were summarized as follows.

Explosive boiling

From liquid state to two-phase state happened in the timescale of less than 1 ms, indicating the explosive boiling phenomenon.
This phenomenon was also reported by Xu et al. (2005b) and Hetsroni et al. (2005) in microchannels without pin fins.

**Liquid island**

Formation of liquid island is related to the growth of liquid films attached on pin fin walls. The coalescence of liquid films among a set of neighboring pin fins forms an enclosed envelop. Inside and outside of the envelop are liquid and two-phase mixture, respectively. One can see Figs. 9 and 10 for the structure.

**Bubble nucleation sites**

One may ask the question that where are the nucleation sites in microchannels with pin fin structure. Two types of nucleation sites were identified. Fig. 22 shows the typical nucleation sites. There are no miniature bubbles at $t = 11.089$ s in Fig. 22a, but nucleation occurred at $t = 11.090$ s. We call this as the self-bubble nucleation. Fig. 22b shows the second type of bubble nucleation. Miniature bubbles may stably retain in the gap volume among a pin-fin unit for the previous cycle. The retention bubble can be active to be nucleation sites when the pin fin wall temperature is high enough for a new cycle. We call this as the retention bubble induced nucleation sites.

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Cone-shape two-phase developing region

Once bubble nucleation sites appeared, the cone-shape two-phase developing region was formed (see Fig. 22). It is also related to the merge of liquid films on a set of pin fin walls. In contrast to the liquid island structure, the connected liquid films form an open envelop. Inside of the core-shape region was the two-phase mixture. To the authors’ knowledge, the liquid island, retention bubble induced nucleation sites, and cone-shape developing region were not reported in the literature.

Flow pattern definition in microchannel with pin fins

Finally, we defined the flow patterns for the microchannel with pin fins. The three flow patterns corresponded to the three types of oscillations based on heat flux $q$ and mass flux $G$ (see Fig. 23a). The photos for patterns 1, 2 and 3 are shown in Fig. 23b. They are described as follows:

**Liquid island and two-phase mixture coexistence pattern**: The first image of Fig. 23b shows the liquid island and two-phase mixture coexistence pattern, consisting of enclosed liquid island inside which is liquid and outside which is two-phase mixture, respectively.

**Cone-shape two-phase pattern**: The second photo of Fig. 23b shows the cone-shape two-phase pattern, consisting of cone-shape two-phase region which is moving downwards. Inside of the region is two-phase mixture and outside of the region is liquid.

**Liquid film evaporating pattern**: The third photo of Fig. 23b shows the liquid film evaporating pattern, with liquid films attached on pin fin walls and vapor flowing in the pin fin gap volume.

Fig. 19. The wavelet decomposition and PSD analysis of the third type of temperature oscillations (run 15).

Fig. 20. The wall temperature signal reflecting the density wave oscillation coupled with the varied liquid film evaporation induced oscillation (run 15).
Fig. 21. The varied liquid films in the short time period of $t = 3.587$–$3.601$ s (run 15).

Fig. 22. Two types of nucleation sites (a: self-bubble nucleation, b: retention bubble induced nucleation).
coefficients from level and coefficients were obtained by removing noise. The flow pattern definition observed in this study based on the three regions.

The formation of the above three flow patterns can be seen in Section ‘Special phenomena observed in microchannel with pin fins’.

Conclusion

Boiling/evaporation heat transfer in a microchannel with pin fin structure was investigated. The simultaneous measurements of various parameters were performed. The high spatial-time resolution IR image system directly measured chip wall temperatures, having the sensitivity of 0.02 °C. The ultra-small Bi number ensured the synchronous variations of flow patterns and wall temperatures. The wavelet decomposition decoupled various oscillation mechanisms.

• Comparing temperature signals of liquid flow and boiling flow identified the temperature noise. For the liquid flow, the wavelet decomposition identified decreased di coefficients from level 1 to level 3. The first level decomposition obtained maximum di coefficients in the range of –0.04–0.04 °C, slightly larger than the IR sensitivity value. For boiling flow, the wavelet decomposition was performed to the level 1 at which di coefficients are apparently larger than the noise amplitude of 0.04 °C. Thus, useful ai and di coefficients were obtained by removing noise.

• Three types of temperature oscillations were identified (see Fig. 5).

• For the first type of oscillation, useful ai and di were obtained. The dominant cycle period of ai was 2.95 times of the fluid residence time in the microchannel, behaving the density wave oscillation characteristic. The di coefficients determined cycle periods matched the flow pattern transition determined values well, representing the flow pattern transition induced oscillation.

• For the second type of oscillation, the pressure drop oscillation caused the temperature oscillation amplitudes of 5–10 °C and cycle periods of 10–15 s. Due to spatial-time varied void fractions, the density wave oscillation frequency was several times higher in the pressure rise stage than that in the pressure decrease stage. The flow pattern transition induced oscillation frequencies are similar for the two stages. The wavelet decomposition decoupled the three oscillation mechanisms.

• For the third type of oscillation, the wavelet decomposition decoupled the density wave oscillation and varied liquid film evaporation induced oscillation. The two mechanisms caused the frequencies of ~10 Hz and ~100 Hz, respectively. With liquid film evaporation as the dominant heat transfer mechanism, thick and thin liquid films attached on pin fin walls are automatically switched periodically.

• For boiling in microchannels with pin fin structure, explosive boiling, liquid island, self-bubble and retention bubble induced nucleation sites, cone-shape two-phase developing region were identified. Among them, formation of liquid island and cone-shape region was related to the coalescence of liquid films on neighboring pin fin walls.

• Fundamentally, the pressure drop oscillation and density wave oscillation identified in this study were similar to those that happened in large size channels. The flow pattern transition and varied liquid films induced oscillations are unique to the microstructure design.

• It is recommended the wavelet decomposition method to be used in other microsystem experiments.

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References


