Analysis of parallel mini-channels’ complex flow boiling and dryout dynamics based on the pressure drop signals

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A R T I C L E   I N F O

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A B S T R A C T

Based on a heat exchange experiment, the authors used R141b as the working medium, and analyzed the differential pressure signal of parallel mini-channels (N = 9, L = 250 mm, Wc = 2 mm, H = 2 mm). Different flow patterns (bubble flow, slug flow, annular flow, dryout, mist flow) have different pressure drops. Flow boiling characteristics were analyzed by the adaptive optimal kernel time–frequency representation (AOK-TFR), auto-regression (AR) power spectrum and recurrence plot (RP). Then, the dryout kinetics of working fluids were revealed. Finally, through the combination of three recursive characteristic parameters, the dryout prediction based on the differential pressure signal was proposed, which provides the theoretical basis for the dynamic characteristics of boiling heat transfer. At the same time, it gives a solution for prevention of the second type of heat transfer deterioration in a project.

1. Introduction

The heat exchange apparatus is one of the important units of equipment for realizing cold and heat exchange in the chemical production process [1]. Improving the heat transfer performance of micro heat exchange equipment has become a research hotspot in the chemical industry. Due to the complex phase changes and the heat and mass transfer process of the heat exchange equipment, the heat transfer efficiency is affected by many conditions. The dryout phenomenon in the channel is especially problematic because it can cause heat transfer to deteriorate. In order to improve the heat transfer efficiency, it is necessary to study the boiling heat transfer phenomenon of the mini-channel. The flow pattern in the mini-channel is different from the other channels during the boiling heat transfer process. Bubble flow, annular flow, dryout, mist flow, ring flow or throat-annular flow occur in the channel [2,3]. The occurrence of dryout affects the heat transfer efficiency of the channel, which has led to a large number of related studies on the critical heat flux density (dryout).

The microchannel has various shaped structures, including rectangular, spiral tube, and triangular structures. The structure of the channel will cause changes in the channel’s heat transfer performance. Peng et al. [4] studied the change of channel pressure drop when a rectangular mini-channel reaches its critical heat flux density (CHF) under natural circulation. They found that as the heat flux density increases, the annular fluid film gradually dries and the flow pattern becomes diffuse. This causes the frictional pressure to drop rapidly. Although the drop in gravity shows a significant upward trend, the total differential pressure decreases and the natural circulation flow increases significantly. Zong et al. [5] studied the boiling heat transfer instability in the triangular silicon-based microchannels. They found that in the single-phase liquid region, the pressure drop increases slightly with the increase of the heat flux density. The temperature rises linearly. In the two-phase flow area, as the heat flux density increases, the pressure drop also increases rapidly, and the temperature increases exponentially. Du et al. [6] studied the boiling CHF characteristics in micro-ribbed channels. They found that the existence of micro-ribs greatly reduced the instability of flow boiling and the reverse flow of boiling, and the CHF of the micro-rib array channel is higher than the smooth microchannel. Mao et al. [7] also studied the effects of pressure, mass flow and wall heat flux on critical heat flux. Through the above studies, it can be found that the advantages and disadvantages of mini-channels of different structures are different. Among these different cross sections, the rectangular mini-channel has the advantages of a simple structure, easy formation of bubbles and easy to seal. Therefore, many scholars have studied the dryout characteristics of rectangular mini-channels.

Shen et al. [8] simulated the dryout phenomenon and transient heat transfer of the evaporator and found that the length of the preheating...
zone and the nucleate boiling zone increased when the coolant mass flow rate and enthalpy decreased on the primary side. At the same time, the superheat of the outlet steam is lowered, and the dryout point moves downstream. Jiang et al. [9] found that heat flux has a significant effect on heat transfer coefficient during the boiling heat transfer process with carbon dioxide as the working fluid. An increase in heat flux accelerates nucleate boiling heat transfer, increases heat transfer coefficient, and accelerates the drying process. At the same time, changes in heat flux can affect the quality of the vapor in the dry phase. Sun et al. [8] built a model of the thermal deviation phenomenon after dryout. Sun et al. [10] found that the occurrence of dryout caused the wall to come in contact directly with the steam, the wall temperature increased, and the heat transfer performance decreased sharply. Statham et al. [11] proposed that when the heat flux density is high, and the mass flow rate is low, the deposition of droplets is not enough to cool the surface, so dryout occurs when the continuous liquid film is destroyed by heating. Bao et al. [12] conducted a dryout test in a square trough. The experimental results show that as the mass flow rate increases and the inlet steam quality decreases, the dryout heat flux increases. In addition, as the heat flux density increases, the wall temperature at the dryout point gradually increases, and the positioning of the dryout point moves toward the inlet of the test section. Dalkılıç et al. [13] found that the heat transfer coefficient is mainly affected by the heat flux at low vapor masses, while the effect of mass flux is negligible. Before the dryout, as the heat flux increases, convective heat transfer becomes the main heat transfer mode, and the heat transfer coefficient increases with the increase of steam mass and mass flow.

This paper focuses on the mini-channel boiling heat transfer process as an important means of analyzing heat transfer characteristics of critical heat flow, or to predict critical heat flux (CHF) through thermodynamic models. Little research has been done on the dynamics of different flow patterns. Assessment of the dryout occurrence is still achieved by monitoring the wall temperature. On the one hand, the dryout point monitoring error can be caused by the arrangement of temperature measuring elements. On the other hand, there is also monitoring lag. Aiming at the above problems, this paper proposes a dryout dynamics analysis and prediction method based on the pressure drop signal. First, this paper will calculate the thermodynamic parameters of different regions. The heat transfer coefficient distribution with the change of dryness is obtained, and the accuracy of the region division is verified. Secondly, the pressure drop signals are analyzed by three signal analysis methods (AOK-TFR analysis, AR power spectrum, and the recurrence plot method). The dynamic transition characteristics of different flow regimes in the mini-channel boiling heat transfer process were obtained. Finally, a prediction model for dryout is proposed based on three recursive characteristic parameters in the recurrence plots. This paper’s research will supplement the theory of the boiling heat transfer of mini-channels and provide the theoretical basis for the study of the second type of heat transfer deterioration phenomenon in mini-channels.

2. Mini-channel structure and test system

The structure of the experimental section is shown in Fig. 1. The test bench consists of a 4-layer structure. The lower layer is an aluminum plate, and there are four temperature measuring holes with diameter d = 1.5 mm, and the above is composed of nine parallel mini-channels (as shown in Fig. 2: Wc = 2 mm Wb = 2 mm H = 2 mm). The channel has inlet and outlet pressure measuring holes, and inlet and outlet temperature measuring holes. The upper part of the channel is covered with a quartz glass cover to facilitate visualization of the test section. The uppermost aluminum plate is used for fixing the passage.

The experimental system includes a working fluid circulation system, a refrigeration system, and a data acquisition system, as shown in Fig. 3. The working fluid circulation system includes a liquid reservoir, a microfluidic pump, and a preheater. The working cycle is as follows: The pump extracts the working fluid from the liquid storage bottle, and the working medium enters the preheater through the flow meter. After the working medium reaches the saturation temperature, it enters the experimental section. After heated in the experimental section, the working medium flows out of the experimental part and then flows through the cooling device. The working fluid is filtered by the filter and returned to the liquid storage bottle. The test uses Pico PT100 platinum resistance thermometer probes (Harbin, China), which have an outer diameter of 5 mm, and an accuracy ± 0.2 °C. The pressure at the inlet and outlet of the channel was measured using a pressure sensor (Model: ND20A5GKE2A2C1R2 with a measuring range of 0–0.1 MPa, accuracy ± 0.25 Pa). The driving equipment of the experimental system was a Longer Model BT100M digital speed type peristaltic pump with a Longer Model YZ1515x pump head (Baoding, Hebei, China), the flow rate range is 0.007–380 ml/min, and the flow rate error is less than 5%. The highspeed camera used in the experiment was Photron Fastcam-Ultima APX, which has the highest spatial resolution of 1024 × 1024 pixels, and the frame rate can vary from 50 fps to 120,000 fps. The experimental working fluid is R141b, and the physical property parameters are shown in Table 1.

In this paper, the temperature signal and the pressure signal are divided into five regions according to the flow pattern (Fig. 4 are flow pattern pictures of the parallel mini-channel). The frequency of this experiment is 200 Hz, the sampling time is 180 s, and each group data contains 36,000 sampling points with a flow range is 0.0007–0.0011 L/s. The data acquisition system of this experiment uses a National Instruments DAQ-9174 chassis with an NI9213 and an NI9205 data acquisition module. The differential pressure signals of five typical flow patterns under the flow rate of 0.0011 L/s is shown in Fig. 5. The temperature difference curve between the inlet and outlet is shown in Fig. 6. In this paper, the calculation of dryness and heat transfer coefficient is carried out by using different regional temperature values. Three kinds of analysis methods (AOK-TFR, AR power spectrum, and the recurrence plot method) are used to analyze the differential pressure signals of different flow regimes. From Fig. 6 we can see that the temperature difference will reach a peak region when the annular flow appears. After the annular flow pattern, the dryout will occur. Thus, we can define the annular flow as the dryout warning area. If we can find the annular flow accurately, the dryout will be accurately predicted accordingly.

3. Research on heat transfer characteristics of flow boiling

In this section, the heat transfer coefficient and vapor quality of the bubble flow, the slug flow, the annular flow, the dryout and the mist flow are calculated. The channel is subjected to variable power heating. The heating power is 60–220 W. A stable flow pattern is obtained by adjusting the power. When the ideal flow pattern appears in the channel, stop adjusting the power. When the temperature parameter in the channel is ≤ 0.3 °C within 3 min, it is determined that the flow pattern is stable. The temperature value in this state is the value of the temperature parameter used in the calculation. Adjust the flow and repeat the experiment. The mass flow rate of the experiment is 36–44 kg/m²·s.

3.1. The vapor quality (x) calculation

Vapor quality (x) calculation:

\[
x = \frac{Q_{heating} + Q - g_{ref} (T_{sat} - T_{pre,in})}{m_{h_{ref}}}
\]  \(1\)

where \(Q_{heating}\) is the heating power of the preheater, \(w\); \(Q\) is the heating plate heating rate, \(w\); \(g\) is the refrigerant mass flow rate, kg/s \(^{-1}\); \(c_{ref}\) is the specific heat of the refrigerant, J/kg \(^{-1}\) K \(^{-1}\); \(T_{sat}\) is the refrigerant

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This paper focuses on the mini-channel boiling heat transfer process as an important means of analyzing heat transfer characteristics of critical heat flow, or to predict critical heat flux (CHF) through thermodynamic models. Little research has been done on the dynamics of different flow patterns. Assessment of the dryout occurrence is still achieved by monitoring the wall temperature. On the one hand, the dryout point monitoring error can be caused by the arrangement of temperature measuring elements. On the other hand, there is also monitoring lag. Aiming at the above problems, this paper proposes a dryout dynamics analysis and prediction method based on the pressure drop signal. First, this paper will calculate the thermodynamic parameters of different regions. The heat transfer coefficient distribution with the change of dryness is obtained, and the accuracy of the region division is verified. Secondly, the pressure drop signals are analyzed by three signal analysis methods (AOK-TFR analysis, AR power spectrum, and the recurrence plot method). The dynamic transition characteristics of different flow regimes in the mini-channel boiling heat transfer process were obtained. Finally, a prediction model for dryout is proposed based on three recursive characteristic parameters in the recurrence plots. This paper’s research will supplement the theory of the boiling heat transfer of mini-channels and provide the theoretical basis for the study of the second type of heat transfer deterioration phenomenon in mini-channels.
saturation temperature, K; \( T_{\text{pre,in}} \) is the condenser inlet temperature, K; \( h_{\ell} \) is the latent heat of the refrigerant, J·kg\(^{-1}\). Fig. 7 shows the vapor quality distribution of working fluids in different regions under different flow rates.

3.2. The heat transfer coefficient calculation

The heat absorbed by the refrigerant is:

\[
Q_l = g_{\text{pre}}(T_{\text{out}} - T_\text{in})
\]

where \( T_{\text{out}} \) is the outlet temperature of the channel, K; \( T_\text{in} \) is the inlet temperature of the channel, K.

The thermal deviation is:

\[
\xi = \frac{|Q - Q_l|}{Q}
\]

After calculating the thermal deviation within 2%, the accuracy requirement can be achieved.

Based on the two-phase heat transfer characteristic analysis method of rectangular mini-channels [14], we used the energy conservation equation to obtain the heat transfer coefficient, \( h \).

\[
h = \frac{q(W_w + W_c)}{(T_w - T_{\text{in}})(W_w + 2qH)}
\]

where \( h \) is the boiling heat transfer coefficient, kW/(m\(^2\)·K); \( q \) is the heat flux density, w/m\(^2\); \( W_w \) and \( W_c \) respectively represent the wall width and channel width, mm; \( T_w \) is the wall temperature, K; \( \eta \) is the rib efficiency, and \( H \) is the groove depth, mm.

The rib efficiency is defined as:

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

where \( m \) is the rib parameter, which is defined as:

\[
m = \sqrt{\frac{2h}{\lambda W_w}}
\]

In this experiment, the output power of the heating plate was controlled by a voltage regulator. The heat flux density \( q \) is calculated as:

\[
q = \frac{\lambda(T_{\text{in}} - T_{\text{up}})}{\delta}
\]

where \( \lambda \) is thermal conductivity, w/(m·℃); \( T_{\text{in}} \) is Wall temperature at the bottom of the housing, ℃; \( T_{\text{up}} \) is Wall temperature at the top of the housing, ℃; \( \delta \) is the distance between the temperature measurement
The wall temperature $T_w$ is calculated as:

$$T_w = T_{up} - (T_{in} - T_{up}) \frac{\delta_1 - \delta_2}{\delta}$$

(8)

where $\delta_1$ is the distance from the bottom of the channel to the contact surface, m; $\delta_2$ is the distance between the temperature measurement point on the upper part of the housing and the contact surface, m.

Fig. 8 shows the distribution of the heat transfer coefficients under different flow regimes.

**Fig. 8.** Five typical flow pattern pictures.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>R141b physical parameter.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (°C)</td>
<td>Relative molecular mass</td>
</tr>
<tr>
<td>32.05</td>
<td>116.95</td>
</tr>
</tbody>
</table>

- (a) Bubble flow
- (b) Slug flow
- (c) Annular flow
- (d) Dryout
- (e) Mist flow
The thermodynamic characteristics of the parallel mini-channel are as follows: As the vapor quality increases, the heat transfer coefficient increases first and then decreases. The heat transfer coefficient in the annular flow zone is the largest. When the annular flow changes to the dryout zone, the decrease in heat transfer coefficient is obvious. Clearly, the occurrence of dry spots greatly affects the heat transfer performance of the parallel mini-channel. Fig. 8 shows that the effects consistent with the variation law of boiling flow, which proves that the experimental data is credible, and the flow pattern partition is reasonable.

Considering that the flow and heat transfer have a strong coupling mechanism, this study focused on the flow characteristics of the dryout area. Based on the analysis of the differential pressure time series, the dynamic characteristics of the boiling flow in the mini-channels were studied. At the same time, the three recursive characteristic parameters, (1) recurrence rate (RR), (2) determinism (DET) or percentage of recurrence points forming diagonal lines, and (3) laminarity (LAM) or the percentage of recurrence points forming vertical lines. These parameters of the recurrence plots were used to predict the dryout process.

4. Study on the dynamic characteristics of boiling flow

In this paper, the time-frequency conversion of different flow patterns is carried out. The pressure drop signal collected by the mass flow rate of 44 kg·m$^{-2}·s^{-1}$ and the heating power of 180 W is taken as an example to analyze the spectrum of different flow patterns.

4.1. Analysis based on AOK-TFR

The AOK-TFR is a new time-frequency analysis approach that has a significant advantage on wave signal dynamic revealing. There were some applications to two-phase flow for this algorithm. In [15] the AOK-TFR method was utilized to reveal the dynamic characteristic of gas-liquid two-phase flow in a small rectangular channel. Fig. 9 is the AOK-TFR time-frequency spectrogram of the differential pressure signals when the working fluid mass flow rate is 44 kg·m$^{-2}·s^{-1}$ and heating power is 180 W. Fig. 9(a) is an AOK-TFR spectrogram of the bubble flow. This spectrogram has a significant energy concentration in the high frequency range (0.45–0.50 Hz), and the energy bar interval is large. Fig. 9(b) is a spectrogram of a slug flow, which is concentrated in three high-frequency ranges (0.45–0.50 Hz)—an intermediate frequency (0.25 Hz) and a low frequency (0.00–0.05 Hz). The energy gathering strips exist intermittently, and the energy strip spacing becomes smaller until the boundary is clear. Fig. 9(c) is the spectrogram of annular flow, in which only a small amount of energy is concentrated in the high frequency band (0.45 Hz). This spectrogram has the smallest interval, slender energy bars, and dense distribution. Fig. 9(d) is the spectrogram of a dryout zone, where only a few parts of the energy concentration still exists. There is no periodicity in this spectrogram, and the energy concentration bars are significantly less. Fig. 9(e) is the mist flow spectrogram, which has only one significant energy concentration.
concentration, and the energy strip of the entire spectrum gradually becomes blurred. In the AOK-TFR analysis of the bubble flow zone and the slug flow zone, the blurring is caused by the intermittent generation of bubbles in the channel. In addition, the bubble generation period in each channel is different, which causes the boundary of the energy bar to be blurred. The bubble in the slug flow is larger than the bubble in the bubble flow; thus, the energy concentration spectrogram of the slug flow is concentrated in the energy spectrum. In the annular flow zone, the vapor is surrounded by a liquid film. The thickness of the liquid film continuously changes with the fluctuation of the heat flux density, so the distribution of the energy bars in the spectrogram is uniform and dense. In the dryout zone, only a few bleed points appear, which represent that part of the channel’s liquid film, which evaporated to dryness and, thus, a dry spot appears. However, due to the existence of the reflow phenomenon, the dry point was repeatedly infiltrated and only appeared instantaneously. A large area of dryout occurred in the channel of the mist flow zone. The liquid phase is uniformly distributed in the vapor phase. At the same time, because the kinetic energy of the vapor phase is small, and the distribution in the energy spectrum is uniform, only one bleed point appears in the spectrogram.

The dynamic characteristics of the boiling flow obtained by AOK-TFR analysis show that as the heat flux density increases, the vapor in the channel gradually increases and the liquid phase gradually decreases. The average density of working fluids is reduced. As the experimental flow rate is constant, the working medium density decreases, causing the average flow rate to increase and the frictional resistance to increase. When dryout occurs in the channel, boiling instability increases. The dry spots move up quickly, forming a steam plug, which causes the pressure drop to drastically reduce.

4.2. Analysis based on AR power spectrum

Power spectrum estimation is an important part of modern digital signal processing methods. This method plays an important role in the analysis of random signals [16]. The power spectrum estimation method takes various characteristics in the frequency domain as the main research content, and this method can extract useful information that is inundated by noise in the frequency domain.

The AR power spectrum shown in Fig. 10 was obtained under the flow rate of 44 kg m$^{-2}$ s$^{-1}$ and heating power is 180 w. Fig. 10(a) is the AR Power Spectrum of the bubble flow. The power density of the spectrum fluctuates between 42 and 60 dB, and the peak appears at four frequencies of 0.3 Hz, 0.9 Hz, 1.1 Hz and 1.6 Hz. Fig. 10(b) shows the spectrum of the slug flow, which also fluctuates between 42 and 60 dB. The power spectrum curve appears periodically, and four frequency peaks can also appear. Fig. 10(c) is the spectrum of annular flow. The power spectrum fluctuates between 30 and 60 dB, and the regular periodic fluctuations occur in this flow pattern. Fig. 10(d) is the...
spectrum of the dryout region. AR power spectral density in this region fluctuates between 35 and 60 dB. The fluctuation amplitude of the spectrogram decreases, and the fluctuation begins to be irregular. Fig. 10(c) is the spectrum of the mist flow. In this region, the signal fluctuates between 25 and 45 dB, and the amplitude of the fluctuation is further reduced. The fluctuation becomes intermittent with the change in frequency. Overall, the generation of bubbles in a bubble flow region is random. Therefore, fluctuations in the power spectral density exhibit random characteristics. In the slug flow zone, the fluctuation of the power spectrum begins to be periodically due to the large area of the channel occupied by bubbles, but with certain rules. In the annular flow zone, the velocity of the liquid film around the bubble is significantly smaller than the vapor phase, so that frictional stress is generated at the phase interface. Under the action of the force, the velocity of the surface liquid is greater than that of the liquid close to the wall, and the surface liquid becomes wavy. The AR power spectrum exhibits multi-peak fluctuations. In the dryout area, the liquid film at the bottom has evaporated, and the reflux and steam plugs appear in the channel. So, the power spectrum regularity is reduced, and randomness is enhanced. In the mist flow zone, the channel is mainly filled with vapor, and some droplets are carried by the vapor phase. The randomness of motion is enhanced. Therefore, the entire power spectrum’s amplitude fluctuation decreases, as well as its regularity.

4.3. Analysis of recurrence plots

For a certain dynamic system (including nonlinear and chaotic systems), which can be defined as a recursive state, the boiling heat transfer of a mini-channel is in a chaotic state. In this case, the recursive analysis shows its superiority. On the one hand, the recurrence plot method can reveal the chaotic degree of different flow regimes. On the other hand, the overall structural features and structural texture details of the recurrence plots can be used to describe the characteristics of the different flow regimes.

Fig. 11 shows the flow rate when it is 44 kgm$^{-2}$s$^{-1}$ and heating power is 180w, and the recurrence plots have different flow patterns. Fig. 11(a) is the recurrence plot of the bubble flow. The overall distribution of the recurrence plot is uniform, and no obvious energy concentration is detected. This is related to the dynamic characteristics of the channel. In the bubble flow region, bubbles are randomly generated in each branch channel and enlarge as they go upward. The different branch channel cycles are different, which makes the differential pressure fluctuate significantly. The recurrence plot of the slug flow (Fig. 11(b)) has a distinctly rectangular structure, which is symmetrically distributed along the diagonal and tends to develop in a diagonal direction. The appearance of such features is mainly due to the large volume and rapid growth rate of bubbles, which leads to the enhanced fluctuation of the pressure signal at the outlet. The recurrence plot of the annular flow region (Fig. 11(c)) shows five distinct block regions. This is because the vapor plug is destroyed, and the dispersed liquid phase is mixed with the vapor at a higher kinetic energy, resulting in stable oscillating flow characteristics. In the dryout area (Fig. 11(d)), due to the evaporation of part of the liquid film, the liquid is dry and recirculated, which further aggravates the instability of the oscillating signal, resulting in further concentration of the recurrence plot partition. Only two rectangle structures were used in this experiment. In the mist flow region (Fig. 11(e)), the energy emerges in only one partition and grows along a diagonal direction throughout the entire plane, which indicates that the pressure drop signal of the mist flow region is randomized.

Overall, with the development of dryout, the recurrence plot of vapor-liquid two-phase flow also shows a gradual development trend as shown in the rectangular square matrix in Fig. 11(a)–(e). Further, the dryout area (Fig. 11(d)) with its transition flow pattern has the characteristics of an annular flow and mist flow combined even though the pressure drop signals of the bubble flow and the mist flow were all randomly distributed. However, the mechanism was different. The randomness of the bubble flow is caused by differences in the bubble growth period; and the randomness of the mist flow is caused by the mixture fluctuation of the vapor and droplet.

In summary, in the bubble and slug flow zone of the parallel multi-channels, the bubble growth period of each branch channel is different, so that the pressure drop signal is random, which has no obvious periodic characteristics compared with the single channel. At the beginning of the annular flow, the increase of the heat flux density makes the bubble growth cycle speed up, the number of bubbles increases, and the flow pattern of each branch pipe is gradually unified. Thus, the fluctuation of the pressure drops of the parallel multi-channels is not caused...
by the differences between different branch channels. The increase of the heat flux density is the main reason for the difference of pressure drop characteristics between multi-channels and single channels.

5. Dryout prediction

The above research on boiling dynamics is a qualitative study. To accurately predict the drying process, this section uses characteristic parameters of recurrence plots to quantitatively represent the drying process. Compared to the traditional wall temperature monitoring method, we propose a new dryout prediction method based on the pressure drop signal. This method only depends on flow dynamics; thus, other condition parameters will not affect the prediction results.

It can be found through experiments that when a circular flow occurs in the channel. A slight increase in heat flux density can cause dryness in the channel. In this paper, the annular flow can also be called the annular warning flow, that is to say, when the annular flow occurs in the channel, the dryout point will appear in the channel. Therefore, the essence of predicting dryout through the pressure drop signal is to identify the annular warning flow pattern by processing the pressure drop signal.

There are six recursive features of the recurrence plot structure proposed by Eckmann et al. [17]. Through calculation, this paper chose three of them to do the following analysis.

Recurrence rate (RR):

$$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{ij}$$

(9)

where $N$ is the number of parameters and $R_{ij}$ is the sequential mode recursive graph parameters.

Laminarity (LAM):

$$LAM = \frac{\sum_{\nu=\text{min}}^{\nu} \nu P^v(\nu)}{\sum_{\nu=\text{min}}^{\nu} \nu P^v(\nu)}$$

(10)

where $P^v(\nu) = \{\nu_i; i = 1 ... N_v\}$ denotes the frequency distribution of the lengths $l$ of vertical structures; $\nu$ is the vertical structure length, and $N_v$ is the absolute number of the vertical structure.

Determinism (DET):

$$DET = \frac{\sum_{l=\text{min}}^{\text{max}} l P^d(l)}{\sum_{l=\text{min}}^{\text{max}} l P^d(l)}$$

(11)

where $P^d(l) = \{l_i; i = 1 ... N_l\}$ is the frequency distribution of diagonal structures’ length $l$ of and $N_l$ is the absolute number of diagonal lines.

The distribution of the three recursive parameters in different flow regime regions are shown in Fig. 12.

In the recurrence plot analysis, six characteristic parameters are defined to describe the underlying system. The simplest one is to consider the RR of the sequential mode by analogy, which considers the number of scatters in time $t$ as a function of $r$ [18], and $r$ is the time delay in the recurrence plot. The recursive rate of slug flow and dryout in Fig. 12 is significantly larger than the other three flow regimes, which indicate that the number of scatter points in the recursive graph of the slug flow and the dry area is more than that of the bubble flow, annular flow and mist flow. We can get the same conclusion from Fig. 11. DET is a very simple statistic that describes diagonal segments, and LAM is a simple statistic that describes vertical segments. However,
Due to the high complexity and chaotic characteristics of the dynamics of the mini-channel during the boiling heat transfer process, it is difficult to present the dry warning by one recursive parameter (Fig. 12). However, it can be found that the signal calibration of the dry warning zone can be achieved by using a combination of three characteristic parameters. As shown in Fig. 13, when the RR is less than 0.38, the DET is greater than 0.65, and the LAM is greater than 0.82, it can be determined that the flow state is an annular warning flow region. When the channel pressure drop signal passes through the time-frequency conversion, the recursive characteristic parameter satisfies the above three conditions. A slight fluctuation in the heat flux density of the channel can cause dryness in the channel. In other words, the appearance of this pressure drop signal indicates the appearance of a dryout phenomenon in the channel. Therefore, this paper predicts the occurrence of dryout by identifying this signal. Therefore, the combination of three recursive parameters can be used to predict the occurrence of dryout. In this study, 100 sets of flow boiling heat transfer experiments with different mass flows were carried out in the mass flow range of 36~44 kg·m⁻²·s⁻¹. Recursive quantitative analysis of the pressure drop signals obtained in these 100 experiments was performed. According to the three parameter ranges summarized above, 91 groups satisfy the parameter distribution range condition (as shown in Fig. 13). In other words, when we use this method to predict dryness, the correction rate is 91%.

Since the method itself judges the flow state by the analysis of the differential pressure fluctuation characteristics, and predicts the dryout phenomenon, the similar flow pattern occurs during the boiling phase transition under any conditions. Pressure fluctuations have similar characteristics. Therefore, the judgment basis proposed in this paper is not only applicable to the working conditions used in the experiments in this paper, but also has general promotion properties, and is not affected by changes in actual working conditions.

6. Conclusions

1. The thermodynamic characteristics of the parallel mini-channels are as follows: As the vapor quality increases, the heat transfer coefficient increases first and then decreases. In the annular flow region, the heat transfer coefficient is the largest, and after the dryout occurs, heat transfer deterioration occurs in the channel.

2. All three signal analysis methods can reveal the dynamic characteristics of mini-channel boiling. However, the concerns of each method are different, especially the dynamic characteristics of different regions near the dryout point. The AOK-TFR analysis reveals that in the dryout area, due to the presence of reflow after the occurrence of the dryout point, the dryout point is infiltrated immediately after it appears. The AR power spectrum analysis reveals that the pressure drop signal in the dry-spot region not only exhibits the periodic characteristics of the annular flow, but also causes the pressure drop signal to fluctuate irregularly, which is due to the backflow and steam plug phenomenon in the dry-spot region. The recurrence plot analysis reveals the rationality of the dryout area as a transitional flow regime of the mist flow and the annular flow.

3. For parallel mini-channels, when the heating power is 60~220W, the mass flow rate is 36~44 kg·m⁻²·s⁻¹. This paper proposes a combination of three recursive parameters (RR, DET, LAM) to predict the occurrence of dryout. When the recursive parameter of the pressure drop signal meets the three conditions of RR less than 0.38, DET greater than 0.65, and LAM greater than 0.82, the dryout will soon appear in the channel. The accuracy of this method reaches 91%. Considering the characteristics of the method itself, the judgment basis is not only applicable to the working conditions in this paper, but also has general promotion properties, and is not affected by changes in actual working conditions.
Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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References


Fig. 13. Distribution of the three recursive parameters in different flow regime regions.