Research on flow boiling in microchannel based on visualized flow pattern

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Abstract. Flow boiling in microchannel has become an effective solution for high-heat-flux cooling of electronic components and heat transfer equipment, research on flow boiling in microchannel benefits society. Visualization plays a key role in the research, flow patterns obtained by visualized tools contribute to the study of flow boiling in microchannels, it is embodied in the following two aspects: heat and mass transfer mechanism, flow pattern dynamics. Above two aspects are introduced and analysed so as to provide a reference for researchers who explore flow boiling in microchannels based on visualized flow pattern.

1. Introduction
Microchannel heat exchangers are some channel structures whose diameters range from 0.01 mm to 2 mm (Fig 1), resulting in very large A/V ratios [1]. Flow boiling in microchannel heat exchangers removes high-heat-flux effectively, fluid undergoes phase change processes in microchannel when high heat flux is input, it’s the main source of absorption of high heat flux, which has received great attention from researchers around the world [2-4]. Flow boiling in microchannel heat exchangers have used in saving energy and cutting emissions, such as connecting microchannel made of silicon or copper to electrical components to prevent core components from thermal damage, making a significant increase in electronic component life, or using microchannel evaporators and condensers in commercial refrigeration equipment to reduce refrigerant charge, improve system COP and reduce GWP and ODP [5-8]. The research and application of flow boiling in microchannel are at the forefront of the world, and has produced significant innovations in overall energy efficiency, system size and cost.

Flow boiling in microchannels is in essence a complex phase change process, focusing on flow patterns with visualized tools, researchers have gained a deeper understanding of flow boiling [9]. Flow patterns recognized and named are mainly bubble flow, confined bubble flow, slug flow, elongated bubble flow and annular flow, researchers conduct research on these flow patterns [10-13]. As early as 1996, Moriyama and Inoue [14] observed the flow boiling process of R-113 in rectangular glass microchannels by high-speed camera, and obtained data about the liquid film variation of elongated
bubble, which contributed to deriving mechanism between heat and mass transfer, Thome et al. [15] established a classical three-zone model based on the data of Moriyama and Inoue [14,16]. Fu [17] observed the formation and development of bubble flow, slug flow and annular flow of liquid nitrogen flow boiling in a 1.33 mm circular glass microchannel with high-speed camera, revealed the bubble dynamic theory at onset of boiling (ONB) and the mechanism of flow pattern development. Zong [18] simulated the development process of seed bubbles, and found that the heat transfer in the slug flow stage was deteriorated due to single phase flow, and the heat transfer of annular flow was enhanced due to the existence of the liquid film. Recent decades, great progress has been made in heat mass transfer mechanism and flow pattern dynamic, this paper introduces the critical research to provide reference for follow-up research. Combined with practical engineering, mainly discusses two types of microchannels, circular microchannel: the heated surfaces are the wall of the tube, mostly used in refrigeration equipment such as evaporators, converter valves, rectangular microchannel: the heated surface is the bottom, for example heat sink, mostly used in high-power electronic devices cooling [19,20].

Fig 1. Microchannel heat exchangers [1]

2. Visualization
Visualization tools are indispensable for the study of microscale problems, it has been widely used in the fields of medicine, biology and chemical engineering [21-24]. The study of complex phase change in microchannels is also accompanied by the aid of visualized tools, which enable phase change to be quantified, that is, the images obtained by visualization are specially processed to observe different characteristic flow patterns [25-28]. Fluids undergo flow boiling in microchannels, where the flow pattern is confined, there are energy and mass exchanging adequately, enhancing heat transfer from micro [29] and even making the heat transfer worse [30]. The flow patterns are commonly found in microchannels and recognized by researchers mainly bubbly flow, confined bubble flow, elongated bubble flow, slug flow, annular flow and the inversion of each flow pattern. Table 1 lists some of the researchers’ visualization studies.

| Researcher       | Visualization method | Microchannel | Flow patterns                          |
|------------------|----------------------|--------------|----------------------------------------|
| Qi [30]          | High-speed camera    | Circle       | Bubble, slug, annular                  |
| Ali [31]         | High-speed camera    | Circle       | Bubble, confined bubble, annular       |
| Fayyadh [32]     | High-speed camera    | Rectangular  | Bubble, confined bubble, annular       |
| Liu et al. [33]  | High-speed camera    | Rectangular  | Bubble, elongated bubble, annular      |
| Alam et al. [34] | High-speed camera    | Rectangular  | Bubble, slug, annular                  |
| Tannaz et al. [35]| High-speed camera    | Rectangular  | Bubble, confined, slug, annular        |
| Mohamed et al. [36]| High-speed camera   | Circle       | Bubble, slug, annular                  |
| Gedupudi et al. [37]| High-speed camera  | Rectangular  | Bubble, confined, slug, annular        |
| Celata et al. [38]| High-speed camera   | Circle       | Bubble, confined, slug, annular        |
The above table shows that researchers mainly used high-speed camera tools or computer simulations to visualize flow boiling and observed various flow patterns. Visualization tools recorded the flow pattern development process down in microchannels, the phase change in microchannel are better understood.

2.1. High-speed camera

High-speed camera [47] combines supporting software (for example Motion BLITZ Cube /XCAPSV) to capture the original data of the flow pattern, and then further observe and analyze the required flow pattern data through Graphic analysis software, for example MATLAB, Adobe Photoshop, IMAQ Vision Builder [48]. Through the above processing, gas fraction, gas-liquid interface, geometry size and distribution of flow patterns are obtained. In this way, the heat and mass transfer in the microchannel can be explored by visualizing the change of flow pattern. However, this visualization method has limitations and challenges, firstly, at present high-speed cameras view flow patterns from the outside in experiment, which requires the microchannel to be transparent or partially transparent. Secondly, the biggest challenge faced is three-dimensional visualization, most researchers have obtained two-dimensional visualization, don’t reflect the true information of the flow patterns, 3D visualization is widely used in medicine, such as CT, MRT and other methods, but they are expensive. Fu [17] achieve 3D reconstruction by building a simple dual-view visualization system, then used MATLAB to convert two-dimensional pictures from two angles into three dimensions successively, three-dimensional visualization makes the research more authentic. Song [49] performed 3D reconstruction based on binocular vision and image recognition network architecture algorithm, this 3D reconstruction method can also achieve good results, but it has not been applied in microchannel two-phase flow.

2.2. Numerical simulation

The numerical simulation software integrates various physical models and core algorithms, and iterates the discretization equation by using the fast compute ability of the computer, thus obtaining the visual flow field [50]. Currently, the commercial ANSYS software does a good job in numerical simulation of multiphase flow [51,52], which owns rich pre-processing functions, algorithms, stable solvers and powerful post-processing functions, and is favored by people. It should be noted that the numerical calculation is based on the simplified mathematical model, rather than the actual physical model of engineering, therefore, it is necessary to enrich the model through UDF [53] and obtain the flow field close to the actual physical model [54,55]. In recent years, ANSYS has been constantly expanding its modules through acquisitions and partnerships, making ANSYS a powerful assistant for researchers in simulation analysis. The study of bubbles dynamics and Gas-liquid interface is very important in the study of the flow pattern of flow patterns, and the VOF (volume of fluid) [56] model coupled with the Level Set method [57] are often used to trace the gas-liquid interface for the purpose of flow visualization [58]. In the research process, experimental platforms are generally used to obtain realistic flow information, and simulation are used to study the extreme or difficult parts of the experiment, to predict and verify the effect [59].

3. Flow patterns and mechanism

The nucleate boiling and convective boiling mechanisms of fluid flow in macro channels have become
a consensus among researchers, but the details of mechanisms in microchannels differ from those in macro channels due to microscale effects. More researchers have conducted more in-depth studies on the heat transfer mechanism through visualization tools, contributing to studying the heat and mass transfer mechanism of the gas-liquid interface, flow patterns development and bubble motion. Many researchers have explored the heat mass transfer mechanism based on visual flow patterns as shown in Table 2.

Table 2. Researchers have explored the heat mass transfer mechanism based on visual flow patterns

| Researcher | Primary study patterns | Flow patterns |
|------------|------------------------|---------------|
| Balasubramanian et al [60] | Annular | Liquid film evaporation |
| Alam et al. [34] | Bubble, elongated bubble | Liquid film evaporation |
| Thome et al. [15] | Elongated bubble | Liquid film evaporation |
| Fu [61] | Bubble, annular | ONB, liquid film evaporation |
| Borhani and Thome [62] | Annular | CHF |
| Fayyadh et al. [14] | Bubble slug, annular | Liquid film boiling |

Balasubramanian et al. [60] investigated the flow boiling heat in a copper-based rectangular microchannel with a cross-sectional area of (0.3 mm × 1.2 mm), the variation of the flow pattern was investigated by visualization, a clear and sustained annular flow boiling was observed (Figure 2), research found that the bubble, confined bubble and slug flows are unstable flow patterns and quickly turned to annular flow when high heat flux was input. Flow boiling heat transfer coefficient curve at \( G = 511 \text{ kg/m}^2\text{s} \) along with the existent flow boiling regimes was plotted, the curve shapes ‘M’ (Figure 3), which differ from the curve shape ‘V’ in macro channel [63]. Thin film evaporation was inferred the dominant heat transfer mechanism in high heat fluxes based on annular flow, similar work has been done, Ali et al. [34] found that nucleate boiling only occurs in the inlet under the condition of high heat flux by flow pattern observation, while convective evaporation occurs in the liquid film of elongated bubbles. In the above research, the flow pattern behavior is described in detail and mechanism is deduced qualitatively, heat and mass transfer in liquid film evaporation can be further discussed.
According to visualized flow patterns data, Thome et al. [15] developed a three-zone model (Figure 4), the liquid film evaporation mechanism of three-zone is deduced and quantitatively studied. Thome et al. [15] makes important assumptions based on experimental data that bubbles nucleate quickly and grow to the confined bubble such that growth in length and successive formed elongated bubbles, and a thin film of liquid was captured between the bubble and the inner tube wall, obviously, this hypothesis is consistent with a large number of experimental facts. The model describes the evaporation of liquid film supplemented by liquid slug, and the liquid film at the tail evaporates completely to form gas slug, until a new liquid slug passes through to form a new cycle, three-zone flow boiling model qualitatively and quantitatively attempts to describe all the observed heat transfer trends noted, for example the sharp peak in the heat transfer coefficient at low vapor qualities, which is shown through the present model to be caused by the local onset of dryout at the end of elongated bubbles, Balasubramanian et al. [60] also thought that the continuous evaporation of liquid film reduces the mass transfer resistance and makes the local heat transfer coefficient rise sharply. It’s note that a time-averaged local heat transfer coefficient was put forward and illustrated it had strong dependency of heat transfer on the bubble frequency, the minimum liquid film thickness at dryout zone. The research made a deep understanding on visual flow pattern, which accelerated the research direction of heat and mass transfer based on visual flow pattern, however, it still needs a lot of visualization work to verify and enrich.

Fu [61] obtained the visualization data of bubble flow at the ONB in a 1.33 mm circular glass microchannel through a high-speed camera, Fu [61] has made great contributions to the research of bubble growth, heat transfer, boiling suppression, and flow pattern backflow. In the bubble growth study, it’s found that two linear phases of bubble growth and the existence of a slip process along the wall during bubble growth (Figure 5.(a)), verified by VOF visualization in numerical simulations and achieved conclusions similar to those of experiments, through the statistics and calculation of certain bubbles, the relationship between detachment period and diameter of bubbles similar to the macro channels when high heat flux was input, it inferred that the microscale effect of microchannels cannot be embodied, it can be used for reference in the follow visualization research and save a lot of work content. Flow pattern diagram is drawn based on the visual flow pattern, annular flow is the main flow
pattern in the whole flow boiling (Figure 5.(b)), so the heat and mass transfer mechanism is studied based on annular flow. Balasubramanian et al. [60] also used a similar research method to find that annular flow is the main flow pattern, it is obvious that drawing flow pattern based on visual flow pattern has become an important research method in the study of heat and mass transfer mechanism of microchannel fluid. In the study of annular flow with high heat flow input, it is found that the multi-gasification core will be activated, but the liquid film will inhibit the bubble from growing, when the liquid film is thick, the bubble will grow during a period of time and escape from the wall, but it will be absorbed by the liquid film, the thinner the liquid film is, the more difficult the bubble nucleation, these studies based on visual flow patterns enrich the theory of flow pattern transformation in microchannels. The reverse flow behavior of each flow pattern due to pressure change was also observed, and the bubble of downstream bubbles into the upstream enhances the upstream boiling heat transfer, backflow is a common phenomenon, which is not considered in the three-zone model, and there are deviations in the process of model verification, Fu [61] visualization work plays a guiding role in the mechanism of heat and mass transfer, and many research work based on visualization flow pattern is worth carrying out.

Figure 5.(a) Two linear phases of bubble growth 5.(b) Flow pattern diagram [61]

Borhani and Thome [62] explored the details of R245 flow in silica-based rectangular microchannels by high-speed camera visualization, it revealed profound details of the liquid film evaporation of annular flow. Periodic vaporization core produces bubble growth and keeps sliding along the wall, which produces shearing action with the gas-liquid interface, the impact force produced by bubble rupture breaks the liquid film, resulting in local the gas direct contact the wall, which makes the heat transfer worse (Figure 6). the liquid film in this state is named metastable film, However, the prediction model of metastable membrane for CHF has not been established in this paper.

Figure 6. Bubble breaks metastable film [62]
Fayyadh [32] carried out visualization experiment of flow boiling heat transfer of R134a in rectangular microchannel, visualization mainly discusses the influence of mass flow rate and heat flow rate on bubble nucleation and flow pattern development, it is found that the diameter and frequency of bubble detachment increase with the increase of heat flux based on observing a nucleation point, and the flow reversal is very obvious when the lowest mass flow rate was input, linking external input with flow pattern will promote microfluidic research. Different from Fu [61] visualization research, nucleate boiling was observed in the annular flow liquid film (Figure 7), and then corrugated annular flow appeared, under the same condition of high heat flow, the mass flux may affect the probability of nucleate boiling of liquid film, based on the above reasons, it cannot be considered as the mechanism of liquid film evaporation, and there is also the influence of state boiling, and it is obvious that the mass flux in Fu [61] experiment is much higher. With the increasing heat dissipation of equipment, it is necessary to explore the influence of input quantity on flow pattern.

![Figure 7. Boiling in liquid film [32]](image)

Other works focused on the heat and mass transfer mechanism was conducted by numerical simulation, according to the various mechanisms derived from the visual experimental research, the numerical simulation was carried out to complete the model to verify the experiment, and all achieved good results. Fu [61] simulated boiling at the initial point of boiling (ONB), Andredaki et al. [55] simulated liquid film evaporation and CHF phenomenon, Avramenko et al. [64] simulated the special phenomenon of liquid film boiling, the result is consistent with the experiment. In the future, more boiling phenomena will be simulated, and new boiling phenomena will be predicted. In a summary, it has become a research method to explore the heat and mass transfer mechanism of microchannel fluid flow boiling based on visual flow pattern, which plays an irreplaceable role in the in-depth study of bubble generation and bursting (ONB), flow pattern distribution, flow pattern transformation, liquid film evaporation and tearing. With the more accurate and in-depth visualization, more heat and mass transfer mechanisms will be discovered.

4. Flow pattern and dynamics
The starting point of fluid flow boiling in microchannels originates from small bubbles, under the action of various forces, bubbles undergo various deformation and movement processes such as growth, polymerization, expansion, rupture, and develop into confined bubble flow, slug flow, annular flow. Researchers have enriched the dynamic theory of heat and mass transfer of fluid flow boiling in microchannels by analyzing these deformation and movement of flow patterns.

Researchers identified forces affecting the development of the flow patterns, Kandlikar et al. [65,66]established the forces model at the gas-liquid interface of confined bubble in microchannels (Figure 7), where $F_s$ is the surface tension, Surface tension is used to capture the liquid film and ensure evaporation, $F_1$ is the inertial force, and $F_m$ is described as a force introduced by the change in momentum due to evaporation, due to the vapor phase leave the liquid-vapor interface at a much higher velocity than the corresponding liquid velocity, this force is greater than all the other forces, the
equilibrium relationship between forces is as follows, but the viscous shear force is not taken into account, it can be confirmed that surface tension, inertial force and evaporation force play a leading role in the development of flow pattern. Yin et al. [68] based on a large number of visual experimental results, and established the forces model of the liquid film between the elongated bubble and the wall (Figure 9) shear force is caused by liquid supplementing liquid, and is divided into effective shear and ineffective shear, it is considered that there is no evaporation in the non-effective shear zone, which is quite different from Kandlikar [65,66] model. In Yin et al. [68] model, the relative magnitude between the evaporation force and the shear force through theory and numerical analysis was analyzed (Figure 10), it’s find that the evaporation momentum force acting on the liquid film can be ignored in the process of analyzing bubble extension and liquid film evaporation, at the same time, surface tension and gravity are also analyzed, which are the basis of the motion of elongated bubbles. Although the above two models are different, they provide direction and guidance for subsequent research, and it is certain that a large number of visualization experiments need to be carried out to analyze the dynamics acting on the flow pattern.

Figure 8. The force model of Kandlikar et al. [67]

Figure 9. The force model of Yin et al. [68]

Figure 10. The order of magnitude of various forces [68]

Fu [61] found that the growth rate of bubbles from gasification core to sliding growth along the wall after separation was constant in 36 ms, which was inferred as inertia force control stage, after that,
bubbles grow to the size of pipe diameter, the convective evaporation area between liquid film and wall surface increases, and the axial growth rate is much higher than before axial growth. Fu did not point out the main dominant force, and according to the Kandlikar [65,66] model, it can infer that the axial growth stage is the evaporation force control stage. In addition, in the study of bubble separation, it is found that the increase of heat flow leads to the increase of bubble growth force, the delay of bubble separation, and the increase of inertial force caused by the increase of mass flow rate accelerates bubble separation, which shows the control effect of growth force and inertial force in the early stage of bubble. The research of bubble pre-growth and detachment experiment is aimed at bubble flow, which is obviously different from his model. The viscosity of the fluid used in the study is small, the viscous force is easy to be ignored, but the shear force produced by it plays an important role in the development of liquid film. Naoki et al. [69] investigated the formation of a viscous boundary layer at the inlet due to the effect of viscosity in a horizontal, which affects the thickness of the elastomeric flow film, and when the viscosity is higher, a thicker boundary layer is formed, leading to a model to predict the elastomeric flow film. When the boundary layer is thin, the acceleration of bubbles causes the liquid film to thin and the prediction model is still to be established.

Because many experiments have passed and visualized the analysis of flow pattern dynamics, the main forces are considered and the unimportant forces are ignored, the analysis of numerical simulation visualization results can verify and comprehensively analyze the flow pattern dynamics. Numerical simulation breaks through the technical and cost limitations of experiments. Through VOF and Level-set models, various UDFs are added to explore the influence of various forces on flow patterns. Agarwal et al. [70] investigated the microchannel flow pattern and heat transfer under the addition of microgravity during boiling of liquid hydrogen flow in the microchannel through numerical simulations (Figure 11). The flow pattern is more stable compared to earth gravity, and as the degree of gravity influence increases, the probability of the annular flow increases with increasing gravity influence. Research on gas-liquid two-phase flow dynamics is less reported, on the one hand, because of the complexity of the action between forces at the microscopic level, on the other hand, the complexity of the boiling phenomenon leads to the difficulty of research, with theoretical research and experimental progress, two-phase flow dynamics will be developed.

Figure 11. Boiling in microgravity and terrestrial gravity [70]

Ling [42] tracked the bubble growth and polymerization process in the three-dimensional rectangular microchannel through VOF model and abundant UDF. dynamic analysis was carried out according to cloud image (Figure 12), it is found that a single bubble keeps a spherical shape during the growth along the wall, and the surface tension plays a leading role, when the bubble grows close to the top, it is found that the temperature gradient at the liquid film is large, and the evaporation of the liquid film leads to the acceleration effect of fluid flow. It can be confirmed by the corresponding velocity cloud picture that this may be the effect of evaporation force or shear force, which is not discussed in depth in this paper. In the study of bubble merging, bubbles continue to grow and are pulled by force after contact. Combined with velocity and temperature nephogram, the gas velocity in bubbles is high, and there is
vortex around the interface, and the carrier liquid supplements the top and bottom, which has a lot to do with the participation of external inertial force (Figure 13). At present, there are few simulations on flow pattern dynamics, and many forces that have effects on bubble growth still need to be discussed. However, numerical simulation is a good research method based on visualization of flow pattern, such as electric field force, and the influence of magnetic field force on flow pattern development has not been recognized.

Based on the visualization of flow patterns, flow pattern dynamics are revealed. The boiling process of fluid flow is affected by multiple forces. The forces discussed in most studies are surface tension, inertial force, growth force, viscous shear force, evaporation force, gravity, etc. There are some undiscussed forces, such as magnetic field force and electric field force, which will also affect fluid flow and boiling under certain conditions. The visualization of flow patterns based on numerical simulation has broad prospects in revealing flow pattern dynamics. It has advantages that high-speed camera visualization does not have, such as the simulation of complex conditions, and the force of the flow pattern transition process needs to be simulated.

5. Conclusion
This paper reviews two visualization tools related research of flow boiling, the contribution of visualized flow patterns on heat mass mechanisms and the flow pattern dynamics. Summarized as follows:
A complex phase change process occurs in the microchannel, and the phase change process can be clearly observed through visualization tools, which widely used in the current research are high-speed camera and numerical simulation of ANSYS. High-speed cameras can obtain real fluid boiling scenes, combined with data processing software to facilitate subsequent research, but the disadvantage is three-dimensional reconstruction. The visualization cost of numerical simulation is low, it can verify the experiment and realize the simulation in the microscopic situation. In order to track the flow pattern, the VOF model is often combined with Level-set to track the gas-liquid interface, and UDF is added to achieve a model close to the real situation.

Many researchers use visualized flow pattern data to analyze the heat and mass transfer mechanism in the microchannel, link the quality change of the flow pattern with the external heat change, not only explain the existing theoretical mechanism, but also to establish a heat and mass transfer model. There are still many shortcomings, and a large number of visual flow pattern experiments and simulations are still needed to supplement.

The change of the visualized flow patterns interface is the result of the comprehensive action of various forces, mainly evaporation force, inertial force, growth force, shear force, gravity, etc. Each force has a different role in the flow pattern development process. Numerical simulation visualization shows greater advantages in the study of flow pattern dynamics.

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