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Effect of flow instability on flow boiling friction pressure drop in parallel micro-channels

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ABSTRACT

The relation between flow instability and friction pressure drop of flow boiling in multichannel was investigated by visualization experiments and theoretical analysis. Based on visualization observation, both slug flow and liquid-plug flow were the dominating flow patterns for all operation conditions, and combing with flow instability simultaneous. With theoretical analysis, the vapor slug extension growth velocity would affect the shear force which was the main reason for friction pressure drop. In addition, the channels number and the channel length had significant effects on flow instability. With the simplified vapor growth model and the analysis on the collected database statistically, the modified friction factor, f_{inter}, and the structure factor, f_{str}, were proposed for the revised homogenous friction pressure drop correlation. By comparing with the database, the modified pressure drop correlation predicted the collected experimental data in a good agreement.

1. Introduction

To satisfy the requirement of heat dissipation for high power electronic devices, evaporators utilizing the latent heat of working fluid are regarded as the most efficient solution [1]. Multichannel heat sinks with flow boiling are widely investigated and applied in research and industry respectively. As the remarkable heat transfer performance of the heat sink with micro-channels due to the high aspect ratio of micro scale channel, numerous researchers have studied the heat transfer characteristics of the heat sink with micro multichannel for wide operation conditions [2–4]. The pressure loss in the multichannel evaporator is a key parameter in the system.

Distinguish from the flow boiling in single channel, parallel channels in evaporators are connected with inlet and outlet headers which have constriction and expansion effects on pressure characteristics. The friction pressure loss is the major part of the total pressure drop [5]. The frictional pressure drop is produced by the shear stress between liquid fluid and vapor fluid, or two phase flow and channel wall. The frictional pressure drop is generally predicted by empirical models, which includes the homogeneous equilibrium model (HEM) and the separated flow model (SFM). In order to make the pressure drop flow models to be applicable for various operation conditions, numerous researchers have carried out lots of experiments to study impact factors on flow boiling pressure drop in micro-channels [6–9].

Besides pressure drop characteristic, the two-phase flow instability is another important part for two-phase flow system. Instability flow in two-phase flow system can increase power consuming and lead to the system vibration. For the flow boiling in multi-channel, the flow distribution instability is the dominate instability form. This form phenomenon in industrial system would trigger the dry-out and may damage equipment [10]. For the flow boiling in micro-channels, the void fraction increases along the flow direction. There are compressible volumes in channels which induces the pressure drop oscillation. In some cases, the pressure drop oscillation and the distribution instability were observed simultaneously [11–13]. As enumerated above, in two phase flow, pressure drop and flow instability have close relation with each other. Nevertheless, most researches focused on the how the pressure oscillation reflected the flow instability in two phase flow. For the effect of instability flow on pressure drop, few researches have investigated it.

To address to the above topic, the present study aimed at the effect of instability flow on flow boiling friction pressure drop in parallel multi-channels. Visualization flow boiling experiments were carried out with R134a in multichannel test section. The reason for flow instability was the extension of vapor slug in slug flow. Considering the extension velocity of the vapor slug and the flow distribution in adjacent channels and channel length, a revised homogenous model was proposed based the experimental results and collected database. The mean absolute

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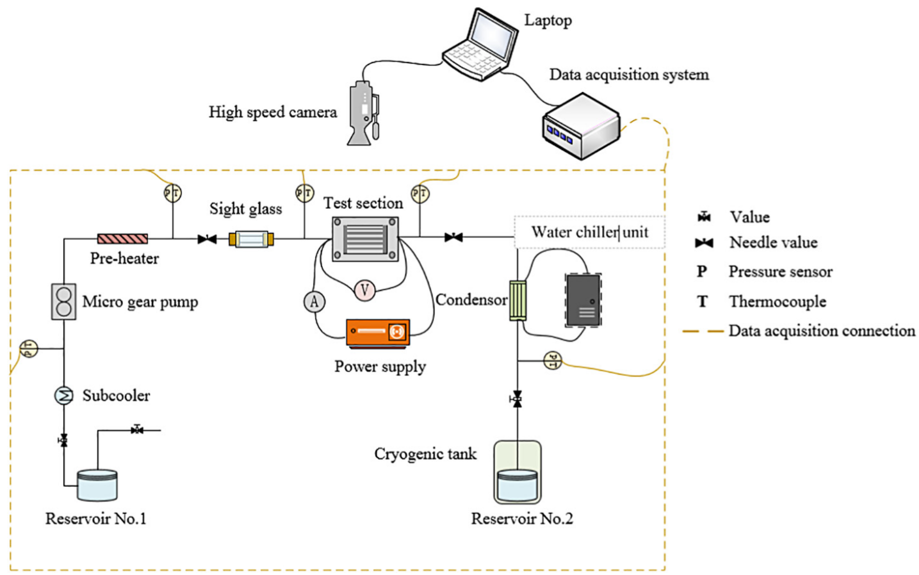

Fig. 1. Schematic diagram of experimental setup.

error of the comparison between the revised correlation and 265 collected data points was 18.9%, which demonstrated the instability in flow boiling affected the friction pressure drop notably.

2. Experimental facility and procedure

2.1. Experimental system

The experimental system was an open loop as shown in Fig. 1. The micro gear pump (Liquiflo 2FS-X) was installed in the front of the preheater to pump and control the flow rate of R134a in experiments. In order to make sure that the R134a flowing into the micro gear pump was liquid state, one sub-cooler was installed in the front of the pump. The sub-cooler was connected with the water chiller unit to cool R134a. The water chiller unit which could provide cool water with temperature at 7–15 °C. Before R134a flowed into the test section, the pre-heater was used to heat the subcooled R134a into saturated R134a, which could be checked with the sight glass. After R134a evaporated in the test section, the condenser connected at the outlet of test section was used to cool down the R134a vapor. The Cryogenic tank was set at 5 °C to reduce the resistance between condenser and the No.2 reservoir. Two pressure sensors were installed at the inlet and outlet of the test section to measure the pressures and pressure drop in experiments. To adjust flow rate finely, one micro-valve was placed in front of the test section. The model of high-speed camera was PHOTRON FASTCAM UX50, which had the frequency range from 2000 to 160,000. The frequency was set at 2000 fps.

The working fluid was the R134a produced by DuPont Company. The thermal and physical properties of R134a were obtained with REFPROP, listed in Table 1.

Table 1
Thermal and physical properties of R134a.

Property	R134a
Component	pure
Molar mass	102.03 g/mol
Liquid density (25 °C)	1206.7 kg/m^3
Critical temperature	101.1 °C
Critical pressure	4066.6 kPa
h_{lv}(1 atm)	216.97 kJ/kg
ODP/GWP	0/1300

2.2. Test section and heating model

In the present study, a micro scale multi-channel test section was used to study the pressure drop characteristic of R134a flow boiling. Fig. 2 shows the test section and the heating model.

Fig. 2 (a) shows the top view of the multi-channel test section. The test section was composed as a flange connection. The seal ring was installed around the plenums and micro-channels under the quartz glass. On the bottom flange plate, 20 rectangular micro-channels with dimension of 0.5 mm × 0.5 mm × 60 mm were manufactured. The dimension of inlet and outlet headers were both 5 mm × 41.5 mm × 10 mm. Fig. 2 (b) exhibits the front view of the test section and heater group. Three columns temperature holes were drilled on the bottom flange plate to measure the heat flux along heating direction. All experiments were conducted with saturated fluid, and the operation condition in this study was listed in Table.2.

3. Experimental results

In visualization experiments, five flow patterns were observed with the increase of vapor quality: bubbly flow, slug flow, churn flow, liquid plug flow and annular flow. The visualization pictures of flow patterns are shown in Fig. 3 (a). For most ranges of vapor quality, slug flow, churn flow and liquid plug flow were the dominate flow patterns. The approximate relation between pressure drop and flow patterns is exhibited in Fig. 3 (b):

In the present study, the vapor quality was represented with dynamic vapor quality of the middle location of the test section, which could be defined as:

$$x = \frac{\frac{Q}{2} - \dot{m}C_p(T_{\text{mi}} - T_{\text{in}})}{\dot{m}\cdot h_{\text{lv}}} \tag{1}$$

where, $\dot{m}$ is the mass rate, kg/s; h_{1v} is the latent heat of R134a; T_{mi} and T_{in} are the temperature of fluid at the middle and inlet of the test section.

Slug flow and liquid plug flow occupied most operation conditions as shown in Fig. 3(b), which were also the flow patterns that flow instability occurrenced. With the visual observation, the instability was produced by the expansion of vapor slugs. As the evaporation of the interface, vapor slugs expanded towards inlet and outlet, which resulting the alternation of flow directions in channels. Since all channels were connected in the inlet and outlet headers, the instability in one