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Two-phase flow instabilities of forced circulation at low pressure in a rectangular mini-channel

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ABSTRACT

An experimental study has been carried out in a rectangular mini-channel to investigate the two-phase flow instabilities of a forced flow at low pressure. The inlet mass flux is gradually reduced by decreasing the rotational speed of the primary pump until the flow becomes unstable, while maintaining all other thermal parameters including system pressure, inlet temperature and heat flux unchanged. Three types of flow instabilities, density wave oscillation (DWO), pressure drop oscillation (PDO) and Ledinegg instability (LED) are identified during the experiment. The onset of flow instability (OFI) is determined by the demand curves and shows good agreement with Roach and Stoddard's correlations. The OFI is consistent with the boiling incipience and saturated condition. The stability map is obtained on the plane of subcooling number (N_{sub}) and phase change number (N_{pch}). DWO and PDO occur at the region between the outlet steam quality $x_e = -0.001$ and $x_e = 0.012$, while the LED region becomes narrow with increasing subcooling. Finally, the mechanisms of flow instabilities in our experiment are analyzed. The results show that the PDO observed in this work is not accompanied by CHF (dryout) which is supposed to be the most common phenomenon of flow instabilities in mini-/micro-channels. DWO occurrence is determined by the relation between external forces (gravitational force and pump driving force) and surface tension. As the external forces are dominant, Type-I DWO at low outlet steam quality (DWO_I) occurs. However, with reduction of the inlet mass flux, the surface tension begins to play a dominant role. Thus Type-II DWO at high outlet quality (DWO_{II}), which is expected in most ordinarily sized channels, has not been observed during this work.

1. Introduction

The thermal hydraulic performance of mini-/micro-channels attracts much attention in the engineering field over the last few decades due to its prominent advantages, such as high heat removal capability and compact configuration. Flow boiling instabilities in narrow spaces such as mini- and micro-channels are also of great concern since even more severe pressure drop and temperature oscillations than macro-channels could be found.

Kew and Cornwell [1] suggested the threshold of instability to be when the initial bubble diameter approached the channel hydraulic diameter. Kennedy et al. [2] defined the OFI as the minimum point of the demand curve. Hetsroni et al. [3–6] carried out a series of experiments in parallel triangular micro-channels to investigate the flow instabilities. They stated the presence of liquid phase in part of the parallel micro-channels at low heat flux region, while flow reversal accompanied by quasi-periodical rewetting and refilling, which was regarded as explosive boiling, occurred at high heat flux region. Simultaneous visualization and measurement investigations on flow boiling instabilities in parallel micro-channels with trapezoidal cross-section have been performed by Wu and Cheng [7–9]. Three types of flow instabilities were observed characterized by: (1) the liquid/two-phase alternating flow (LTAF) at low heat flux and high mass flux, (2) the continuous two-phase flow (CTF) at medium heat flux and medium mass flux, and (3) the liquid/two-phase/vapor alternating flow (LTVAF) at high heat flux and low mass flux. The trigger mechanisms of these flow instabilities were discussed based on the visualization and the fluctuations of temperature, pressure and mass flux. Nonlinear analyses have been done by Mosdorfa and Cheng [10] for these 3 unstable boiling cases by using correlation coefficient, attractor reconstruction, correlation dimension and largest Lyapunov exponent, and the processes responsible for appearance of chaotic oscillations in microchannels were discussed. Wang and Cheng [11,12] have done further study on flow boiling instabilities in a single channel and in parallel channels. Two unstable flow boiling regimes characterized by long-period oscillation (more than 1 s)

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Nomenclature

General symbols

Bo	Bond number
D_h	hydraulic diameter, mm
G	mass flux, kg/(m^2 s)
H	enthalpy, kJ/kg
h	heat transfer coefficient, kW/(m^2 K)
L	length of the channel, mm
l_c	capillary length
N_{pch}	phase change number
N_{sub}	subcooling number
p	pressure of the system, MPa
q	heat flux, kW/m^2
Q	electrical heating power, kW
W	mass flow rate, kg/s
T	temperature, °C
v	the specific volume, m^3/kg
x	distance along the axial direction, mm
x_e	equilibrium quality
Δp	pressure drop of the channel, kPa

Greek letters

η	thermal efficiency
δ	thickness of the heating wall, m
Φ	volume internal heat source, kW/m^3
λ	thermal conductivity, kW/(m K)
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

1-2	the inlet section of the channel
2-3	the outlet section of the channel
exp	experimental
f	fluid
g	gas
in	the inlet of the channel
out	the outlet of the channel
sat	saturated point
sys	system
w	wall surface

and short-period oscillation (less than 0.1 s) were identified. The former was due to expansion of vapor bubble from downstream while the latter owes to the flow pattern transition from annular to mist flow. The effects of inlet/outlet configurations on flow boiling instability in parallel micro-channels were studied by Wang and Cheng [13]. Jones and Judd [14] experimentally investigated flow reversal in narrow channel with gap size of 1, 3 and 5 mm. They found good agreement between the onset of the flow reversal and the prediction of CHF under subcooled flow boiling conditions. Thus the flow reversal as a result of dryout and rewetting was deemed to be caused by the onset of CHF. Brutin et al. [15] related the bubble generation, growth, coalescence, recoiling, rewetting and refilling according to the visualization to the relevant pressure fluctuation. Steinke and Kandlikar [16] also observed the flow reversal in parallel micro-channels as well as in mini-channels and they believed that the high pressure of vapor generation is compensated by part of the channels. Back and forth oscillations with flow instabilities have been observed by Celata et al. [17] in cases of lower heat and mass fluxes. However, no complete reverse flow in the upstream direction has been observed.

The above reviewed literatures indicate that several types of flow instabilities have been identified in single or parallel mini-/micro-channels, some of which are well explained based on the visualization results. The most studied mechanism of flow instability in mini-/micro-channels is vapor recoil accompanied by alternate dryout and rewetting. Tadrist [18] suggested that dynamic instabilities such as DWO, PDO and thermal oscillations might be observed in narrow channels. However, in recent years, the mild flow instabilities in a single mini-/micro channel such as DWO have been reported by very few researchers, and there is still a lack of a comprehensive classification criterion. More work needs to be done for two-phase flow instabilities in mini-/micro-channels. This work is aimed to experimentally investigate flow boiling instabilities in a vertical rectangular mini-channel and try to find other possible mechanisms of flow instabilities in a single mini-channel.

2. Experimental facility and data processing

2.1. Experimental loop

The thermal-hydraulic experimental loop is schematically illustrated in Fig. 1, which is basically composed of tube-shell shape condenser, centrifugal pump, pressurizer, electromagnetic flow meter, electrical pre-heater and mini-rectangular test section. It is worth mentioning that the upstream pressurizer is almost 1000 mm in height and 200 mm in diameter, which can provide considerably large compressible volume for the system.

The deionized water is driven by a centrifugal pump. A frequency converter is applied to change the rotational speed of the pump and thus different flow rates could be achieved. The inlet mass flux of the test section ranges from 200 to 1700 kg/(m^2 s) in our experiment. The cold water is pumped into an electrical preheater, where water is heated to a set temperature. Then the water is heated uniformly in the test section by a DC power supply. Finally the two-phase mixture is condensed in the condenser before flowing back to the pump again and accomplishing a circulation.

The test section is a mini-rectangular channel with the internal dimension of 40 × 2 × 1000 mm, which is illustrated in Fig. 2. The channel is heated directly by a DC power supply so that it can provide a uniform heat flux. Sandwiched micanite plates are used to keep the channel electrically and thermally insulated. In addition, four Teflon washers are adopted to hold the test section electrically insulated from the other parts of the experimental loop. Besides, in order to reduce the heat loss of the channel, thermal insulation layer is applied to the whole test section. As a result, thermal balance of the test section could be guaranteed. Two N-type thermocouples are located at the two ends of the channel to measure the inlet and outlet bulk liquid temperature. Furthermore, six N-type thermocouples are welded on the outer wall surface of the test section to measure the surface temperature of outer wall. The thermocouples are located at the following locations from the inlet measured by the channel hydraulic diameter: x/D_h = 37, 82, 141, 204, 245 and 311. Three pressure taps, P1, P2 and P3, are used to measure the pressure drops $\Delta p_{1\text{-}2}$ and $\Delta p_{2\text{-}3}$ of the test section, which are located at x/D_h = 52, 259, 318, shown in Fig. 2. Thus, the test section is divided into 2 parts by the pressure taps, the inlet section 1-2 and the outlet section 2-3.

2.2. Instrumentations

During our experiment, all the data, including volume flow rate, pressure, temperature and pressure drop, are recorded by data acquisition system. Volume flow rate is measured by an