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An experimental investigation of flow boiling instability in a natural circulation loop

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ABSTRACT

An experimental investigation of flow boiling instability in a single macro-channel natural circulation loop at high inlet subcooling and low pressure is performed. Flow boiling instabilities without and with flow reversal which are classified as pressure drop oscillations are observed. The characteristics of flow reversal in a single macro-channel are illustrated. Flow reversal is verified on the basis of three evidences: negative inlet flowrate, inlet water temperature pulse and large amplitude pressure oscillations in the compressible volume. The mechanism of flow reversal is given by correlating experimental heat fluxes with CHFs predicted by Umekawa correlation and Zhao correlation. It can be concluded that flow instability induces the premature of CHF. Flow reversal is caused by the onset of CHF and accompanied by periodic dryout and rewetting. Flow regime in the heated channel is depicted based on the exit water temperature oscillations, heating surface temperature profile and periodic dryout. A comparison has been made for the mechanism of flow reversal between macro-channel and micro/mini-channel. Three prerequisites contribute to the occurrence of flow reversal in a macro-channel: (1) low pressure natural circulation, (2) long two-phase region and (3) upstream compressible volume. Lastly, a stability map which distinguishes the boundaries of flow instabilities without and with flow reversal is given.

1. Introduction

Flow boiling instabilities have attracted copious amount of investigations over the last few decades by virtue of their potential damage to heat exchangers or nuclear reactors. There have been a considerable number of theoretical and experimental researches on flow boiling instabilities in different heated channels, such as macroscale and microscale channels. Channel size has a significant influence on heat transfer characteristics, bubble behavior and flow regime. Heated channels are classified as micro-channel, mini-channel and macro-channel by Kew and Cornwell [1], Kandlikar et al. [2,3], Cheng and Wu [4] according to different criteria as listed in Table 1.

Micro/mini-channels have been widely used in the cooling of microelectronic components and compact heat exchangers due to their large surface area to volume ratio and high heat transfer coefficients. Kew and Cornwell [1] introduced a Confinement number *Co*, and suggested that heat transfer correlations for conventional sized channel can't be applied to channels having a Confinement number above 0.5. Furthermore, confined bubble growth in narrow space can cause pressure increase due to the blockage of flow path. Flow stagnation and reversal are common phenomena in micro/mini-channels as a result. Visualization is an effective way to obtain intuitive image of flow regime in heated channels. It has been observed that liquid-vapor interfaces of the bubble expand towards both the inlet and exit of the channel inducing flow reversal [5–7].

Flow reversal can be easily caused by the violent vapor evolution in a single micro/mini-channel. Generally a compressible volume is needed upstream of the heated channel to absorb the overpressure generated by bubble growth and evolution. Huh et al. [8] performed a visualization experiment on flow boiling of water in a single micro-channel. Flow instability with long period and large amplitude is founded to be the result of two alternating flow patterns: a bubbly/slug flow and an elongated slug/semi-annular flow. The elongated slug bubbles grow both in the flow direction and counter to the bulk fluid flow. Wang and Cheng [9,10] found similar long period and large amplitude fluctuations in a single micro-channel. It's noted that large bubbles can be flushed downstream under stable flow boiling mode. However, bubble expands toward upstream and downstream directions due to the confinement of

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Nomenclature

a	model constant
Bo	Bond number
Co	Confinement number
C_p	specific heat [kJ/kg °C]
D	diameter [m]
$F_{p,lim}$	reduction limit of the normalized periodic dryout heat flux
G	mass flux [kg/m^{2}s]
h	enthalpy [kJ/kg] or heat transfer coefficient [kW/m^2 °C]
I	current [A]
N_{pch}	phase change number
N_{sub}	subcooling number
L	length [m]
L^*	dimensionless heated length
q_v	volumetric heat flux [kW/m^3]
q	heat flux [kW/m^2]
r	distance along the radial direction [m]
R	radius [m]
t_{tr}	transit time of the inlet flow [s]
T	temperature [°C]
U	voltage [V]
W	mass flowrate [kg/s]

Greek symbols

θ	wall superheat [°C]
λ	thermal conductivity [kW/m°C]
τ	period of flow oscillation [s] or time constant [s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
φ	heat transfer efficiency

Subscripts

AVE	average
CHF	critical heat flux
f	fluid
g	gas
i	inner surface
in	inlet
MAX	maximum
MIN	minimum
o	outer surface
out	outlet
sub	inlet subcooling
w	channel wall

channel walls under unstable flow boiling mode. Wang et al. [6] identified periodic reverse and rewetting flow in micro-channel and explained the vapor expansion and recoiling based on the force analysis: flow reversal commences when the joint force of evaporation momentum change force and the force due to liquid–vapor pressure difference exceed the inertia force due to bulk liquid flow. Flow reversals are also observed in single mini-channels. Brutin et al. [11] pointed out that expanding vapor pushes the inflow back to the entrance using the buffer tank as a mass flow storage when downstream in the channel is blocked by vapor slug. Jones and Judd [7] believed that flow reversal is caused by the onset of CHF and to be the result of dryout and rewetting of the heated surface.

Flow boiling in parallel channels is susceptible to flow maldistribution owing to the dynamic interactions between channels. In fact, pressure increase in one channel can be compensated by neighbouring channels. As a result, flow reversals have been visually observed in parallel channel without the existence of upstream surge tank. Steinke and Kandlikar [12] believed that flow reversal is caused by the presence of parallel. Excess flow and pressure generated by explosive growth of nucleation bubbles can be compensated and dissipated by other channels. Hetsroni et al. [13,14] considered the saturated boiling in parallel micro-channels with periodic flow reversal as explosive boiling since the lifetime of elongated bubble is extremely short. Liquid on the upstream side of some channels are pushed back by the rapid bubble growth, at the same time, the resulting excess flow are carried away by the other parallel channels. Chang and Pan [15] observed alternative appearance of slug and annular flow in parallel micro-channels. The magnitude of pressure drop oscillations is proposed as an index for the appearance of reversed flow. Kuang et al. [16,17] identified the typical flow patterns in parallel mini-channels. Periodic reversed flow is determined to contain two stages: liquid rewetting stage and annular film evaporating stage.

Table 1
Channel classification.

Channel	Kew and Cornwell	Kandlikar et al.	Cheng and Wu
Macro-channel	Co < 0.5	D > 3 mm	Bo > 3
Mini-channel	Co > 0.5	200 μm < D < 3 mm	0.05 < Bo < 3
Micro-channel	–	10 μm < D < 200 μm	Bo < 0.05

The characteristics and mechanism of flow instability in conventional sized channels such as density wave oscillations, pressure drop oscillations, flow pattern transition instability and parallel channel instability are reviewed by Boure et al. [18], Kakac and Bon [19]. Density wave oscillations and pressure drop oscillations have been the most common instabilities in engineering application. Pressure drop oscillations have been reported to appear in combination with density wave oscillations under certain conditions in macro-channel [20–23]. Parametric studies of pressure drop oscillations have been performed experimentally and theoretically. Manavela et al. [24,25] presented the effects of pressure, inlet temperature, heating power and heat distribution on pressure drop characteristics curve. Other factors such as flowrate, compressible volume [23] and locations of compressible volume in the loop [26] have been taken into consideration to study their effects on the period and amplitude of pressure drop oscillations. Pressure drop oscillations in micro-channels have also been reported by Qu and Mudawar [27], Wang and Cheng [9], Zhang et al. [28], Yu et al. [29,30]. However, the combination of flow reversal with flow instability in macro-channel is missing.

Numerous studies have been carried out on flow boiling instability and flow reversal in micro/mini-channels. Nevertheless, there are very few detailed reports in literature addressing flow reversal in macro-channels. Wang et al. [31] made a brief reference to the large amplitude flow oscillations and flow reversal in a macro-channel. Jain et al. [32] verified the existence of flow reversal by installing a reversed pitot tube upstream of the heated channel. Steinke and Kandlikar [3] predicted that flow reversal will also be observed in conventional sized channels in parallel configuration for certain combination of pressure drop, heat flux and mass flux conditions. But no detailed evidences are provided. In this paper, a large amplitude and long period flow instability with flow reversal is found at low pressure in a single macro-channel natural circulation loop. The overall goal of this paper is to: (1) introduce the characteristics of flow boiling instability (without and with flow reversal), (2) illustrate the mechanism of flow reversal, and (3) give the boundary of flow boiling instability.