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One-dimensional interfacial area transport of vertical upward bubbly flow in narrow rectangular channel

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ABSTRACT

The design and safety analysis for miniature heat exchangers, the cooling system of high performance microelectronics, research nuclear reactors, fusion reactors and the cooling system of the spallation neutron source targets requires the knowledge of the gas–liquid two-phase flow in a narrow rectangular channel. In this study, flow measurements of vertical upward air–water flows in a narrow rectangular channel with the gap of 0.993 mm and the width of 40.0 mm were performed at seven axial locations by using the imaging processing technique. The local frictional pressure loss gradients were also measured by a differential pressure cell. In the experiment, the superficial liquid velocity and the void fraction ranged from 0.214 m/s to 2.08 m/s and from 3.92% to 42.6%, respectively. The developing two-phase flow was characterized by the significant axial changes of the local flow parameters due to the bubble coalescence and breakup in the tested flow conditions. The existing two-phase frictional multiplier correlations such as Chisholm (1967), Mishima et al. (1993) and Lee and Lee (2001) were verified to give a good prediction for the measured two-phase frictional multiplier. The predictions of the drift-flux model with the rectangular channel distribution parameter correlation of Ishii (1977) and several existing drift velocity correlations of Ishii (1977), Hibiki and Ishii (2003) and Jones and Zuber (1979) agreed well with the measured void fractions and gas velocities. The interfacial area concentration (IAC) model of Hibiki and Ishii (2002) was modified by taking the channel width as the system length scale and the modified IAC model could predict the IAC and Sauter mean diameter acceptably.

1. Introduction

Gas–liquid two-phase flow in narrow rectangular channels has been the subject of increased research interest in the past few decades. It is encountered in many important applications, such as miniature heat exchangers, the cooling system of high performance microelectronics, research nuclear reactors with plate type fuels, plasma facing components of a fusion reactor as well as the cooling of the spallation neutron source target. It is anticipated that the characteristics of two-phase flow in such a narrow slit differs from those in other channel geometries, because of the significant restriction of the bubble shape which, consequently, may affect the heat removal by boiling under various operating conditions. So the knowledge about void fraction, interfacial area concentration (IAC), pressure loss, heat transfer coefficient and critical heat flux (CHF) in a narrow rectangular channel is paramount to the design and the performance and safety analysis of the systems.

A literature survey on the experimental adiabatic two-phase flow research in a narrow rectangular channel has been performed and summarized in Table 1. Most of the researchers studied the flow regime, frictional pressure loss, void fraction and gas velocity in narrow rectangular channels in the past few decades. Lowry and Kawaji (1988) and Wambsganss et al. (1992) and others observed the flow regimes of concurrent upward two-phase flow in a narrow channel with the gap size between 0.3 and 3.18 mm. Even though considerable differences exist in the various researchers' definitions of two-phase flow regimes, the flow regimes can be generally classified into bubbly flow, slug flow, churn flow and annular flow. Most of the works in Table 1 measured two-phase frictional pressure loss by using differential pressure gauge and proposed the two-phase frictional multiplier with various Chisholm's parameter correlations to be used for the calculation of the frictional pressure loss. The void fraction was investigated by using the probe, the constant electric current method, the neutron radiography (NRG) and the photograph. Since the measured void fractions were in the fully-developed flow region, the significant axial change of void fraction was not studied until now. The gas velocity was obtained by using the measurement of LDV, the double-sensor probe, the neutron radiography, the photograph and so on. The average gas

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Nomenclature

a_i	interfacial area concentration (1/m)
$\tilde{a}_i$	non-dimensional interfacial area concentration
C	Chisholm parameter
C_0	distribution parameter
C_f	liquid phase coefficient
C_f^{lam}	laminar flow coefficient
C_f^{tur}	turbulent flow coefficient
D_H	hydraulic equivalent diameter (m)
D_{Sm}	Sauter mean diameter (m)
D_{system}	system length scale (m)
$\left(\frac{dp}{dz}\right)_F$	frictional pressure loss gradient of two-phase flow (Pa/m)
$\left(\frac{dp}{dz}\right)_{f-1\phi}$	frictional pressure loss gradient when liquid component flows in pipe as a single-phase flow (Pa/m)
$\left(\frac{dp}{dz}\right)_{g-1\phi}$	frictional pressure loss gradient when gas component flows in pipe as a single-phase flow (Pa/m)
g	gravitational acceleration (m/s^2)
j	mixture volumetric flux (m/s)
j_g	superficial gas velocity (m/s)
j_f	superficial liquid velocity (m/s)
L	height of a rectangular duct, m
Lo	Laplace length (m)
$\widetilde{Lo}$	non-dimensional Laplace length
l	height of the test section in an image (m)
M_F	frictional pressure loss gradient of two-phase flow (Pa/m)
N	number of the bubbles in an image
n_b	bubble number density (1/m^3)
q	parameter of Lee and Lee (2001)
Re	Reynolds number
r	parameter of Lee and Lee (2001)
S	parameter of Lee and Lee (2001)
s	gap size of the rectangular duct (m)
v_g	velocity of gas phase (m/s)
V_{gj}	drift velocity (m/s)
w	width of a rectangular duct (m)
X	Martinelli parameter
z	height from the inlet of the rectangular duct (m)

Greek letters

α	void fraction
χ	coefficient of a rectangular duct
ΔP_F	frictional pressure loss (Pa)
Δz	distance between 2 neighboring pressure taps (m)
$\Delta\rho$	density difference (kg/m^3)
ε	energy dissipation rate per unit mass (m^2/s^3)
$\tilde{\varepsilon}$	non-dimensional energy dissipation rate per unit mass (m^2/s^3)
Φ_f^2	two-phase friction multiplier
λ	friction factor
μ_f	viscosity of liquid phase (N s/m^2)
ν_f	kinematic viscosity of liquid phase (m^2/s)
ν_g	kinematic viscosity of gas phase (m^2/s)
ρ_f	liquid phase density (kg/m^3)
ρ_g	gas phase density (kg/m^3)
ρ_m	mixture density (kg/m^3)
σ	surface tension (N/m)
ξ	common logarithm of w/s

Subscripts

g	gas phase
f	liquid phase

Mathematical symbols

$\langle\rangle$	area averaged value
$\langle\langle\rangle\rangle$	void fraction weighted mean value

velocity in a drift flux model can be represented by the slug bubbles and the gas velocity contribution of the small bubbles in the liquid continuum was negligible in narrow rectangular channels. Although the IAC is important, limited study has been performed to measure IAC (Hibiki et al., 1995; Wilmarth and Ishii, 1997). The literature survey showed that the existing researches on the two-phase flow in narrow rectangular channels predominantly consisted of the experimental studies on the fully developed flow or the measurements at a fixed axial location.

This study aims at (i) the measurement of the axial development of fundamental flow parameters such as void fraction, interfacial area concentration, gas velocity, bubble Sauter mean diameter. bubble number density, flow regime and frictional pressure loss in a vertical narrow rectangular two-phase flow in the channel and (ii) the evaluation of the existing two-phase frictional pressure loss model, drift-flux model and interfacial area concentration model with the experimental data taken in the narrow rectangular channel.

2. Experiments

2.1. Experimental loop and measuring method

Fig. 1 shows the schematic diagram of the test loop for air–water two-phase flow in a narrow rectangular channel. It was composed of a water supply reservoir, a centrifugal pump, a filter, an air–water mixing chamber, a test section, a separator, an air compressor, flowmeters for water and air, valves and pipes. The test section was a rectangular duct made of transparent acrylic resin. It was fabricated with nominal gap of 1.0 mm. The width, w, and height, L, of the test section were 40 mm and 2000 mm respectively. The hydraulic equivalent diameter, D_H, of flow channel is 1.94 mm. The average effective gap, s, was determined by using the analytical solution of the friction factor for laminar flow as follows (Mishima et al., 1993). The friction factor, λ, for single-phase laminar and turbulent flow is given by

$$\lambda = 4C_f \mathrm{Re}_f^n \tag{1}$$

where C_f is the friction coefficient. $n = -1$ and -0.25 for the laminar and turbulent flows, respectively. Re_f is the liquid Reynolds number. The following theoretical solution for the laminar flow coefficient, C_f^{lam}, is given by Itatani (1966)

$$C_f^{lam} = \frac{128w^2}{(w+s)^2\chi} \tag{2}$$

$$\chi = 2.25241 + 5.94208\xi - 4.59384\xi^2 + 1.60646\xi^3 - 0.2071\xi^4, \xi = \log(w/s) \tag{3}$$

The average effective gap, s, was determined to be 0.993 mm from the above equations by using the measured laminar friction factor. In Fig. 2, solid line indicates the theoretical laminar friction factor with s = 0.993 m.

Air was supplied by the compressor and was introduced into the mixing chamber through an injection nozzle. The injector and mixing chamber designs are shown in Fig. 3. The injection