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Experimental Thermal and Fluid Science 30 (2006) 523–534
Experimental Thermal and Fluid Science
www.elsevier.com/locate/etfs

Flow pattern and pressure drop of vertical upward gas–liquid flow in sinusoidal wavy channels

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Received 1 July 2005; accepted 16 October 2005

Abstract

Flow patterns and pressure drop of upward liquid single-phase flow and air–water two-phase flow in sinusoidal wavy channels are experimentally studied. The test section is formed by a sinusoidal wavy wall of 1.00 m length with a wave length of 67.20 mm, an amplitude of 5.76 mm. Different phase shifts between the side walls of the wavy channel of 0°, 90° and 180° are investigated. The flow phenomena, which are bubbly flow, slug flow, churn flow, and dispersed bubbly flow are observed and recorded by high-speed camera. When the phase shifts are increased, the onset of the transition from the bubbly flow to the churn flow shifts to a higher value of superficial air velocity, and the regions of the slug flow and the churn flow are smaller. In other words, the regions of the bubbly flow and the dispersed bubbly flow are larger as the phase shift increases. The slug flow pattern is only found in the test sections with phase shifts of 0° and 90°. Recirculating gas bubbles are always found in the troughs of the corrugations. The recirculating is higher when the phase shifts are larger. The relationship between the two-phase multipliers calculated from the measured pressure drops, and the Martinelli parameter is compared with the Lockhart–Martinelli correlation. The correlation in the case of turbulent–turbulent condition is shown to fit the data very well for the phase shift of 0° but shows greater deviation when the phase shifts are higher.

Keywords: Two-phase flow; Flow pattern; Pressure drop; Sinusoidal wavy channels

1. Introduction

Two-phase gas–liquid flow through a confined gap is encountered in several engineering applications including boiling behavior in mini-channels, cooling systems of various types of equipment such as high performance microelectronics, supercomputers, high-powered lasers, medical devices, and high heat-flux compact heat exchangers in spacecraft and satellites, etc. It can be expected that the restriction of the bubble space in the mini-channel is the cause of the differences in the two-phase flow characteristics from those in conventional channel geometries. This may also affect heat-mass transfer characteristics during the change of phase.

It is not possible to understand the two-phase flow phenomena without a clear understanding of the flow patterns encountered. It is expected that the flow patterns will influence the two-phase pressure drop, holdup, system stability, exchange rates of momentum, and the heat and mass during the phase-change heat transfer processes. The ability to accurately predict the type of flow is necessary before relevant calculation techniques can be developed.

Two-phase flow characteristics in small circular tubes have been studied by a number of researchers while those in mini-non-circular channels have received comparatively little attention in literature.

Zhao and Rezkallah [1] proposed a system parameter to elucidate the effects of inertia and surface tension in

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0894-1777/$ - see front matter
doi:10.1016/j.expthermflusci.2005.10.004

Nomenclature

A	cross-sectional area [m^2]
D	diameter [m]
f	friction factor
g	gravitational acceleration [m s^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
h	heat transfer coefficient [kW m^{-2} K^{-1}]
J	superficial velocity [ms^{-1}]
P	pressure [Pa]
Re	Reynolds number, $\rho V D_h/\mu$
S	wetted perimeter [m]
V	velocity [m/s]
X	Martinelli parameter
z	length [m]

Greek symbols

μ	dynamic viscosity [Pa s]
θ	phase shift between the side walls [degree]
ρ	density [kg m^{-3}]
ϕ^2	two-phase multiplier

Subscripts

F	frictional term
G	gas
h	hydraulic
L	liquid
T	total
TP	two-phase

micro-channels at micro-gravity. Their flow regime map was divided into three zones: surface tension-dominated zone (bubbly and slug flow regimes), inertia-dominated zone (annular flow regime), and the transition zone.

Wilmarth and Ishii [2,3] observed the flow patterns, and measured the void fraction and the interfacial area concentration, of adiabatic co-current vertical and horizontal air–water flow in narrow rectangular channels with gaps of 1 and 2 mm. The developed flow regime maps were compared with those obtained for a round pipe.

Bonjour and Lallemand [4] performed experiments to elucidate the flow regimes of natural convective boiling of R113 in upward two-phase flow in vertical narrow rectangular channels with gap sizes ranging between 0.5 and 2 mm. Three flow boiling regimes, namely nucleate boiling with isolated deformed bubbles, nucleate boiling with coalesced bubbles, and partial dry-out, were observed. A new flow regime map based on the Bond number and a ratio of the heat flux to the critical heat flux was developed to confine the boiling.

Xu et al. [5,6] investigated an adiabatic co-current vertical two-phase flow of air and water in vertical rectangular channels (12×260 mm) with narrow gaps of 0.3, 0.6 and 1.0 mm. Flow patterns for gaps of 0.6 and 1.0 mm were similar to those reported in the literature. By decreasing the channel gaps, the transition from one flow regime to another appeared at a lower gas velocity. However, for the gaps of 0.3 mm, even at very low gas flow rates, bubbly flow was never found.

Hibiki and Mishima [7] developed a mathematical model to predict the flow regime transition for vertical upward flows in narrow rectangular channels. The model was based on that of Mishima and Ishii [8] for vertical upward two-phase flows in round tubes. The developed model was compared with the measured data of air–water flows in rectangular channels with gaps of 0.3–17 mm.

Zhao and Bi [9] conducted experiments to visualize the co-current upward air–water two-phase flow patterns in vertical equilateral triangular channels with hydraulic diameters of 0.866, 1.443 and 2.886 mm. The observed flow patterns obtained from the larger hydraulic diameters (1.443 and 2.886 mm) were found to be similar to those obtained from conventional, large-sized vertical circular tubes. For the smallest channel (0.866 mm), the dispersed bubbly flow pattern was not found.

Akbar et al. [10] compared the measured data reported in open literature with a Weber number-based two-phase flow regime map which was previously developed by Zhao and Rezkallah [1], and Rezkallah [11]. Balasubramanian and Kandlikar [12] used high-speed photography for the observation of flow behaviors (nucleate boiling, slug formation, dry-out, reverse flow and flow at the exit manifold) during flow boiling of water in a single rectangular minichannel. Satitchaicharoen and Wongwises [13] studied the flow patterns of vertical upward gas–liquid two-phase flow in mini-gap rectangular channels. The effects of gap size, channel width and liquid viscosity on the flow pattern transitions were examined.

There are only a few studies dealing with the flow characteristics in a non-parallel-wall channel. Wang and Vanka [14] studied the convective heat transfer in periodic wavy passages by using an accurate numerical scheme. The transition between steady flow and self-sustained oscillatory flow was found at Re of around 180. In the steady flow region, the Nusselt numbers for the wavy channel were slightly larger than those for the parallel-plate channel. The friction factors for the wavy channel were almost constant in the transition region and double in the steady flow region.

Rush et al. [15] studied the local heat transfer and flow behavior in sinusoidal wavy passages. The test section was a horizontal channel having an aspect ratio of 10:1 and bound by two wavy walls. They paid special attention to the onset of macroscopic mixing in both the steady and unsteady flows. It was found that the location of the onset of macroscopic mixing was dependent on the channel geometry and the Reynolds number, and the onset of mixing corresponded to the increase of the heat transfer.