Experimental Thermal and Fluid Science 54 (2014) 47–60

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Flow pattern map and time–frequency spectrum characteristics of nitrogen–water two-phase flow in small vertical upward noncircular channels ☆

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ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form 21 January 2014
Accepted 27 January 2014
Available online 5 February 2014

Keywords:
Small channel two-phase flow
Flow pattern map
Time–frequency representation

ABSTRACT

We experimentally investigate the vertical upward gas–liquid two-phase flow in a 2 × 0.81 mm small rectangular channel and an equilateral triangle channel with a 2 mm side length. The two channels have same hydraulic diameters ($D_h = 1.15$ mm). We first present an experimental flow pattern map with nitrogen and water superficial velocities ranging from 0.08 m/s to 11.82 m/s and 0.12 m/s to 1.52 m/s, respectively. We also compare the flow pattern transition criteria between the triangle and rectangular cross sections by using the same hydraulic radius. We employ the influence rule that small passage geometry limits the flow pattern transition criteria. Thereafter, we comparatively analyze the transition boundaries of experiment flow patterns with other results in literature and classical prediction models. Results show that the cross-sectional shapes and experimental conditions of the experimental pipeline significantly affect the changes in the flow regime. Given the differential pressure signal of the two-phase flow, we propose two effective quadric time–frequency representations, namely, the adaptive optimal kernel time–frequency representation (AOK TFR) and data reduction sub-frequency band wavelet (DA SFBW) to investigate the complex behavior of vertical upward gas–liquid flows. We extract the positive power spectral density of the singular value–frequency entropy, singular value–frequency entropy, damping ratio, and vibration mode to characterize the evolution of flow patterns. The results suggest that the AOK TFR method can reveal flow dynamic details, whereas the DA SFBW based method is a powerful tool for characterizing the dynamical characteristics of different vertical upward gas–liquid flow patterns.

1. Introduction

Gas–liquid two-phase flow in narrow rectangular channels has been the subject of increased research interest in the past few decades. This exist commonly in power engineering, petrochemical, heat/mass transfer, and chemical engineering equipment, such as evaporators, condensers, reactors, and heat exchangers. In gas–liquid two-phase flow, the flow pattern is the basis of heat and mass transfer research. Different flow patterns have different heat transfer mechanisms, i.e., the appearance of a flow pattern (e.g., slug flow and mist flow) can cause heat transfer deterioration which is very dangerous in the high temperature and pressure conditions. Therefore, the accurate identification of two-phase flow patterns, the understanding of its internal flow characteristics for two-phase flow industrial system optimization design, and the dynamic monitoring of working conditions are of practical significance. Research on conventional-sized channel flow pattern has a good foundation. However, comparisons of the flow pattern in tiny channels with the flow pattern in conventional-sized passages may produce significant differences because of the decrease in geometric magnitude of channel dimensions. In recent years, the rapid development of micro-chemical and biological microfluidic technology has caused an increase in the use of irregular noncircular cross sections. More and more domestic scholars have begun to relate to experiments study, and have made some achievements.

Mishima and Hibiki [1] adopted the direct parameters (void fraction) of the two-fluid model as bases for flow pattern transition by using the flow pattern transition criteria of Mishima and Ishii [2] in vertical rectangular narrow channels. By comparing the existing experimental data of vertical upward gas–liquid two-phase flow in narrow rectangular channels with gap ranges of 0.3–17 mm, the prediction capability of the flow pattern transition

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☆ Project supported by the National Science Foundation of China (Grant No. 512760033) and Northeast Dianli University Doctoral Research Startup Fund (Grant No. BSJXM-201208) and Northeast Dianli University Scientific Research Improve Fund (Grant No. KYTSQN-201204)

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http://dx.doi.org/10.1016/j.expthermflusci.2014.01.017
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Nomenclature

List of symbols

A	channel cross-sectional area
A_k	singular value decomposition matrix
$A(t, \tau, \nu)$	time-localized short-time ambiguity function
B	matrix reconstructed by the singular value
D_h	hydraulic diameters (mm)
E	total energy
f	frequency (HZ)
G_{ij}^{+}	positive cross-power spectral density
i	imaginary component
i	number of signals
j	imaginary component
j	first singular value sequence
j	superficial velocity (m/s)
k	decomposition scale
l	measuring points
N_m	modal order
N_ω	number of frequency domain points
p	number of scales
P_i	energy of each part
Q	volumetric flow rate
R	covariance matrix
r	reference measuring points
S	time–frequency entropy
S	diagonal matrix
s	original signal
T	window length
t	time (s)
t	center position of the signal window
U	singular vectors
V	singular vectors
W	wavelet coefficient matrix
z	analytic form of the original signal
z^*	conjugate analytic form of the original signal
$(.)^+$	the pseudo inverse of the matrix

Greek letters

α	kernel parameter
ν	frequency shift
τ	time-delay
Φ	2D Gaussian function
ψ	extension direction
σ	singular value
u	time (s)
ω	discrete frequency (HZ)
$\omega(u)$	symmetrical window function
ω_j	order frequency (HZ)
ξ	damping ratio
ΔP	differential pressure (kPa)
Δt	time-delay

Subscripts

G	gas
i	line order
j	column order
K	current scale
L	liquid
N	number of the column

criteria of Ishii and Mishima [3] can be improved for experimental data.

Xu et al. [4] performed an experimental study for adiabatic air–water two-phase flow in three small rectangular channels with ranges of 0.3, 0.6, and 1.0 mm of hydraulic diameter. They reported that the flow pattern observed in the two channels with gaps ranging from 0.6 to 1.0 mm was similar to those found in the previous studies. However, the observed flow pattern(cap-bubbly, slug–droplet, churn and annular–droplet flow) in the channel with the gap of 0.3 mm was different with the above two channels, and the bubbly flow pattern was not observed at a low superficial gas velocity.

Zhao and Bi [5] performed the visualization study of vertical upward gas–water two-phase flow by using an equilateral triangle channel with hydraulic diameters of 2.886, 1.443, and 0.866 mm under adiabatic conditions. A high-speed camera system was used to collect typical flow pattern images in three small channels. The results showed that flow patterns such as dispersed bubble, slug, churn, and annular flow in the conventional channel were found in two channels with large hydraulic diameters (2.89 and 1.4 mm). However, dispersed bubble flow was not observed in the triangular channel with a hydraulic diameter of 0.866 mm. On the contrary, a capillary bubbly flow characterized by a series of single ellipsoidal with bubble vertical upward flow was observed along the channel centerline. At the same time they found some bubbles were elongated in the slug flow pattern. The flow pattern map got from experiment show that transition criteria from slug flow–churn flow and churn flow–annular flow shifted to the right with increasing hydraulic diameter.

Shen et al. [6] performed 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 at seven axial locations by using the imaging processing technique. In their 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 two-phase flow structures in a narrow channel significantly 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 axial development of the flow regimes was obtained and the bubbly flow, cap-bubbly flow and slug flow were observed in the present experiment. The flow regime transition criterion of Hibiki and Mishima [3] could predict the observed flow regime boundary fairly well.

Wang et al. [7] made visualized investigation on flow regimes for vertical upward steam-water flow in a single-side heated narrow rectangular channel with having a width of 40 mm and a gap of 3 mm. The flow regimes observed in their experiment could be classified into bubbly, churn and annular flow. Slug flow was never observed at any of the conditions in their experiment. He made comparisons of the present data with existing flow regime maps. The results showed that the bubbly and annular zone in flow pattern map in this experiment were consistent with that conducted by Mishima et al. for air–water flow in a narrow rectangular channel with similar geometry. However, the intermediate flow regime between bubbly and annular flow was churn flow in this experiment, while slug and churn flow in the data of Mishima et al. [2]. Hence, bubbly transition line and annular formation line shift towards left in the flow regime map with increasing pressure.

Wang et al. [8] carried out flow visualization using a high speed video camera in a vertical narrow rectangular channel ($3.25 \times 43\ \text{mm}^2$). The characteristics of gas–liquid two-phase slug flow in a vertical narrow rectangular channel are thoroughly investigated in their experiment. The slug flow in the rectangular channel is quite different from the classical slug flow in medium size channels. Three important phenomena are observed: (i) Ideal Taylor bubbles are hardly observed in the continuous slug flow,