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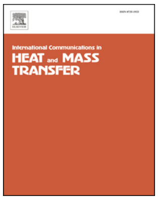

Investigation on the void fraction of gas–liquid two-phase flows in vertically-downward pipes☆

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ABSTRACT

A special experimental loop is designed and constructed to study the characteristics of the void fraction of gas–liquid two-phase flow in vertically-downward pipes. The test section is made of transparent pipe with a length of 6 m and an internal diameter of 25 mm. The void fraction ranging from 0.1 to 0.98 widely is measured using quick-closing valve method. It is found that the range of the void fraction could be divided into three regions with different flow patterns and different relationships between the void fraction and the gas–liquid volumetric flow rate ratio. Moreover, 39 correlations for calculating the void fraction collected from present literature, are classified, and evaluated using the experimental data obtained in this study. The prediction of correlations in the literature needs to be improved when the void fraction is small.

1. Introduction

Gas–liquid two-phase flow in vertically-downward pipes has an extensive application in the industrial and engineering fields, such as boilers, nuclear power plants, petroleum transportation systems or various types of chemical reactors [1]. The void fraction is one of the most fundamental and crucial parameters in studies on two-phase flow. The void fraction is essential for calculations of many parameters, such as two-phase mixture densities, two-phase viscosities, actual velocities of each phase, the frictional-pressure-drop, etc. It is very necessary to study and understand the characteristics of the void fraction, and to find a proper way to predict the void fraction.

Based on the experimental data and analysis, a lot of correlations were proposed as well to calculate the void fraction under different conditions [2]. However, most of the correlations are based on experiments on gas–liquid two-phase flows in horizontal tubes, vertically-upward tubes, or inclined pipes, and very few of them are based on experiments on the gas–liquid two-phase flows in vertically-downward pipes [3,4]. The two-phase flows are affected greatly by the body force (i.e. the buoyancy and gravity) acting on the gas phase [5]. The buoyancy acting on the gas phase slows the movement of bubbles downward along the pipe. Accordingly, the gas–liquid two-phase flows in the vertical downward pipes should have their unique characteristics. The prediction capability of correlations in the literature needs to be verified.

For the purpose mentioned above, an experimental loop for air–water two-phase flows in the downward pipe has been designed and set up, and the void fraction of two-phase flows is measured by the quick-closing valves (QCV) method. The experimental data are then used to evaluate the prediction capability of 39 correlations proposed in the existing literature.

2. Descriptions of experiments

2.1. Experimental system

The schematic diagram of the experimental system used in the present study is shown in Fig. 1. The test section is made of synthetic glass circular pipe with an internal diameter of 25 mm. The effective length of the test section is 2000 mm, with a 2000 mm upstream stabilization segment and another 2000 mm downstream stabilization segment, respectively, to ensure the full development of the two-phase flows in the test section. Two pressure transducers are installed along the pipe at positions about 2750 mm and 4250 mm from the inlet of the pipe, respectively. Water is supplied by a centrifugal pump, and the pressure and the flow rate of water is controlled by a bypass line. Air is supplied by an air compressor with adjustable flow rate controlled by a bypass line and valves, too. The pressure at the entrance of the test section is controlled to be lower than 1.0 MPa to ensure that the pressure in the test section is bearable by the synthetic glass pipe. Air and water are well-mixed in a gas–water mixing chamber, and then flow downward into the stabilization segment upstream of the test section. The flow patterns of the two-phase flow are captured by a video camera.

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Nomenclature

A	the area occupied by one phase, m^2
A_s	coefficient in correlations for the calculation of slip ratio, —
C_0	distribution parameter, —
g	gravitational acceleration, m/s^2
G	mass flux, $kg/m^2/s$
H	height of the test section pipe, m
H_{wi}	height of the water column of the i-th measurement result, m
j	superficial velocity, m/s
n	total number of measured data points of the height of the water column, —
N	total number of data points, —
Q	flow rate, m^3/s
Re_{tp}	Reynolds number of the two-phase mixture
S_p	slip ratio of the two-phase flow, —
T	temperature, °C
u	real velocity in the pipe, m/s
U_{gm}	drift velocity, m/s
x	mass fraction of the two-phase flow, —

Subscripts

1,2	number of combined parameter
∞	distribution parameter in the bubbly to churn flow conditions
G	gas
gj	drift velocity
H	the void fraction calculated by the homogeneous model
L	liquid
m	mixture
meas	measured data
cal	calculated result according to correlations

Greek symbols

α	void fraction, —
β	gas–liquid volumetric flow rate ratio, —
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
Π	combined parameter, m/s
φ	percentage of the calculated void fraction data points with the errors within ±15% compared with the experimental data of the void fraction, —
θ	angle of the pipe with respect to the horizontal direction, rad
σ	surface tension coefficient, N/m
Σ	root-mean-square error, —
$\lvert\varepsilon\rvert$	mean absolute difference, —

Exponentials

P	index used in correlations for the calculation of slip ratio
q	index used in correlations for the calculation of slip ratio
r	index used in correlations for the calculation of slip ratio

Detailed information of the test system can be found in the previous work [1].

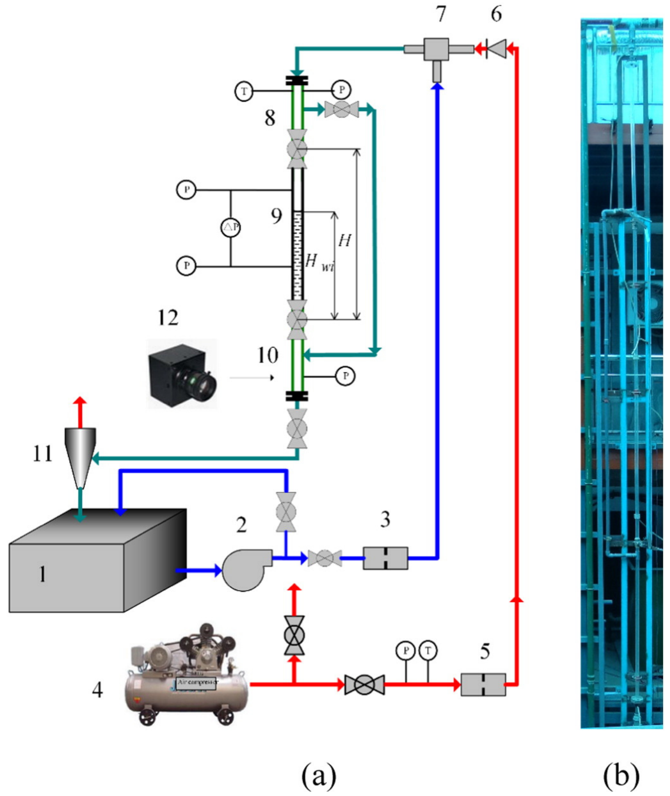

Fig. 1. Schematic diagram of the experimental setup. (a) Experimental system; (b) real picture of test section. 1 — Water tank; 2 — centrifugal water pump; 3 — electrical–magnetic flow rate meter; 4 — air compressor; 5 — orifice flow rate meter; 6 — valve; 7 — gas–water mixer; 8 — stabilization segment at the entrance of the pipe; 9 — test section; 10 — stabilization segment at the exit of the pipe; 11 — air–water separation chamber; 12 — visualization camera.

2.2. Method for measuring the void fraction

The quick-closing valves (QCV) method adopted in the present study is used to measure the two-phase flow void fraction [2,4]. Two valves are installed along the test section 1500 mm and 4500 mm away from the entrance of the pipe respectively, and another valve is installed in the bypass, as shown in Fig. 1. The average void fraction could be obtained by measuring the heights of the liquid column enclosed within the section between the two QCV valves. Eq. (1) gives the average void fraction measured by QCV in this study,

$$\alpha = \frac{\sum_{i=1}^{n}\left(1-\frac{H_{wi}}{H}\right)}{n} \tag{1}$$

where, the H_{wi} is the height of the water column of the i-th measurement, H is the distance between the two QCV valves, and n is the total number of measurements in one test regime. Here, the void fraction is obtained by averaging the results of n time measurements, and n is taken as 5 in this study.

2.3. Experimental conditions and error analysis

The pressure at the outlet of the test section is maintained at about 0.2 MPa by adjusting the valve installed at the outlet of the test section. The experimental conditions are as follows: the superficial water velocity is between 0.14 and 1.5 m/s, the superficial gas velocity is between 0.274 and 1.709 m/s, the temperature of the air–water mixture in the pipe is between 13 and 25 °C, and the experiment data of the void fraction is between 0.1 and 0.98.

The flow rate of the compressed air is measured using a measuring orifice with the uncertainty of ±2% approximately. The nominal flow rate of air can be calculated through measuring the differential pressure across the orifice by a pressure transducer with the possible error of ±4%. The uncertainty of the averaged superficial air velocity is