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Experimental study on vertical downward air-water two-phase flow in a large diameter pipe

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ABSTRACT

Downward two-phase flows in large diameter pipes are important in various industrial applications, especially for the safety analysis in nuclear reactors. To address the issue that few data of downward flow in large diameter pipes is available for model evaluation, experiments of air–water downward flow in a pipe with inner diameter of 203.2 mm have been performed. Area-averaged void fraction and pressure measurement, as well as flow visualization, have been conducted at several axial locations. The flow conditions for superficial gas velocity range from 0.05 m/s to 3.00 m/s and for superficial liquid velocity range from 0.1 m/s to 1.5 m/s, which cover cap-bubbly flow, churn-turbulent flow and annular/falling film flow. The flow structure at several axial locations and the transition from churn-turbulent flow to annular/falling film flow have been discussed. Current available drift-flux models developed for downward flow in regular pipes as well as for upward flow in large pipes are evaluated using newly collected data. For churn-turbulent flow, the data indicates a larger drift velocity than the model prediction. Corresponding drift-flux constitutive equations are suggested which can reduce the prediction error from 34.37% to 11.79%.

1. Introduction

Two-phase flow in large diameter pipes is often encountered in various industrial applications. In chemical and petroleum industries, the large bubble column chemical reactor and pump system are commonly used. In the nuclear industry, two-phase flow often occurs in large channels. Thus, the fundamental knowledge of two-phase flow in large diameter pipes is especially important for the nuclear safety. A large diameter pipe is defined as a pipe whose diameter is larger than the maximum cap bubble size, which is proposed by Kataoka and Ishii [1] as

$$D_H^* \equiv \frac{D_H}{\sqrt{\frac{\sigma}{g\Delta\rho}}} \geqslant 40 \tag{1}$$

where the D_H is the hydraulic diameter of channel, σ is the surface tension, g is gravitational acceleration, $\Delta\rho$ is the density difference between the liquid and gas phases. Once the flow channel diameter is larger than this critical size, the slug bubble bridging the entire channel can no longer exist due to the Taylor instability, which results in the disintegration of large cap bubbles and induces three-dimensional recirculatory behaviors [2]. Therefore, the bubble behavior, void fraction and velocity profiles in large pipes can be very different from those in small pipes, in which slug bubbles can be sustained. These changes cause different physical mechanisms of gas and liquid transport, implying the models developed for small-diameter pipes may be no longer applicable for large diameter channels [1]. The capability to accurately predict the two-phase flow in large channel system is extremely important for nuclear safety.

The drift-flux model [3,4] and the two-fluid model [5] are two most commonly used models to formulate a general transient two-phase flow problem. Compared with the rigorous two-fluid model, the drift-flux model is an approximate formulation but can provide acceptable prediction accuracy with much less computational efforts. In addition, the one-dimensional two-fluid model requires a drift-flux relation as a constitutive equation to calculate the area-averaged relative velocity for the interfacial drag, and the advanced computer codes typically used in the nuclear system analysis, such as RELAP and TRACE, are based on one-dimensional form of the two-fluid model. Therefore, a complete set of drift-flux models covering various flow systems and geometries is necessary for the accurate prediction of these codes.

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Nomenclature

Latin characters

A	cross section area [m^2]
C_0	distribution parameter [–]
C_i	interfacial friction factor [–]
C_w	wall friction factor [–]
D	hydraulic diameter [m]
G	gravitational acceleration [m/s^2]
j	superficial velocity [m/s]
$J(\alpha)$	function of the averaged void fraction [–]
p	pressure [Pa]
v	velocity [m/s]
V_{gj}	drift velocity [m/s]
z	axial location [m]

Greek characters

α	void fraction [–]
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ_i	interfacial shear [Pa]
τ_w	wall shear [Pa]
μ	viscosity [Pa s]

Sub/Superscripts

f	quantity for liquid phase
g	quantity for gas phase

Operators

$\langle\ \rangle$	area-averaged quantity
$\langle\langle\ \rangle\rangle$	void-weighted area-averaged quantity

In the state-of-the-art, the constitutive equations for the drift-flux model have been well developed for vertical upward two-phase flow for a wide variety of pipe diameter (25–200 mm). Lots of works have been done for co-current upward flow in large diameter pipes and it is proved that the flow characteristics in large diameter pipes are different from that in small diameter pipes. Kataoka and Ishii [1] were the first to mention that for pipes with diameters larger than a critical value, slug bubbles can no longer be formed due to Taylor instability of cap bubbles. Then they developed drift-flux correlations for large diameter pipes. Hibiki and Ishii [6] developed a drift-flux model for bubbly flow in large diameter pipes, but they found that the drift-flux parameters at such kind of flow are greatly dependent on the inlet flow conditions. Schlegel et al. [2,7–9] performed many experiments in large diameter pipes. By summarizing previous work on drift-flux model development, they proposed a comprehensive set of drift-flux constitutive models for pipes with various hydraulic diameters [10].

Apart from upward flow, the downward two-phase flow in large diameter pipes is also widely encountered in various engineering applications, and especially the understanding of downward two-phase flow is essential for the safety analysis on the loss of coolant accidents in nuclear reactors. However, the applicability of above models based on upward experimental data to downward two-phase flow in large pipes is questionable. The void profiles and flow structures between downward and upward flow are quite different, which has been proved by lots of experimental results [11–13]. Compared with upward flow, the experimental studies on downward two-phase flow are very limited, especially for large diameter pipes. Clark and Flemmer [14] investigated the void fraction in downward flow in 100 mm diameter pipes and proposed empirical correlations of distribution parameters for upward and downward flows. Kawanishi et al. [15] performed experiments for co-current and counter-current steam-water two-phase flow in 19.7 mm and 102.3 mm diameter pipes and presented the effects of pipe diameter on the drift flux parameters (distribution parameter, C_0, and drift velocity, V_{gj}). Martin [16] studied air-water downward slug flow in round pipes of diameter 26, 101.6 and 140 mm, and suggested that the distribution parameter for downward slug flow in large pipes should be less than one because large bubbles eccentrically located off the pipe axis. Goda et al. [17] developed drift-flux constitutive equations for downward flow by assuming that the drift velocity for all downward flow regimes can be determined by one constitutive equation, which is developed by Ishii [4] for upward churn-turbulent flow. The drift-flux model with Goda's constitutive equations has been validated by extensive experimental data set with various channel diameter ranging from 16 mm to 102.3 mm.

According to Eq. (1) the critical diameter of large pipes for air-water flow under normal pressure and temperature is around 108 mm. This means that currently existing data and models for downward flow only reaches the boundary between moderate size pipe and large size pipe, where the slug flow still can exist, and the flow structure may not significantly differ from that in moderate size pipes. It should be mentioned that few experimental data can be found in the literature for downward two-phase flow in pipes with diameter lager than 150 mm, and therefore there is no experimentally validated model for the downward two-phase flow in large pipes.

In current study, the downward two-phase flow has been experimentally investigated in a facility with inner diameter of 203.2 mm. The vertical downward section is connected to the top and bottom horizontal sections with two 90° elbows, which serve as the inlet and outlet respectively. Area-averaged void fraction and pressure were measured at 6 locations in vertical and horizontal sections.

2. Experiment

2.1. Experimental facility

The schematic of the test facility is shown in Fig. 1. The test section is made of clear acrylic with inner diameter of 203.2 mm and can be divided into three parts: top horizontal section, vertical section and bottom horizontal section. The length of the top horizontal section, vertical section, and bottom horizontal section is 8.47 m, 6.42 m and 3.25 m respectively. Two PVC elbows are used to connect these three sections.

A centrifugal pump with a maximum flow rate of 0.177 m^3/s is used to circulate the water. A globe valve is used to control the liquid flow rate, which is measured by an electromagnetic flow meter with an error of 0.5% of the readings. Compressed air is supplied at 0.551 MPa, and the gas flow rate is controlled by several ball valves and measured by a set of Venturi flow meters and rotameters with the error less than 4% of the measured value. It should be mentioned that the air injector is a pipe with inner diameter of 50.8 mm, instead of commonly used porous sparger. Because it is desirable to produce separated flow at the top horizontal part to