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Experimental study on interfacial area transport of two-phase bubbly flow in a vertical large-diameter square duct

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ABSTRACT

In this paper, an experimental study on the atmospheric upward bubbly air–water flows in a vertical large-diameter square duct flow channel (cross-sectional sizes, 100 mm × 100 mm, hydraulic equivalent diameter, $D_H = 0.1$ m and height, 3 m) have been performed by mainly using four-sensor probes. The four-sensor probes with the latest four-sensor probe method of Shen and Nakamura (2014) were applied in the local measurements at 3 axial positions ($z/D_H = 8.3$, 18.3 and 28.3) to obtain interfacial area concentration (IAC), 3D bubble velocity vector and bubble diameter for the complex flow structure. The measurements were carried out locally at 66 points in an octant symmetric triangular zone in the cross-section at each axial position. The agreements between these local measurement results of the four-sensor probes and the measured results from the differential pressure gauges and the air flow meters are ± 7.97% in average relative measurement error for void fraction and ± 8.67% in average relative measurement error for superficial gas velocity. The obtained void fraction, IAC, 3D bubble velocity vector and bubble diameter serve as a valuable database relating to the cross-sectional local profiles and axial flow development and provide valuable insight into the local flow structure and behavior in the corresponding flow regimes. Although the interfacial area transport equation (IATE) and its bubble coalescence and breakup models have already played an important role in predicting the IAC in general two-phase flow fields now, they are mainly developed based on the two-phase flow experimental data taken in round pipes or small diameter channels with different shapes. To confirm their usability in the two-phase flow in large-diameter square duct, this study has evaluated the 1D one-group IATE with its 6 sets of bubble coalescence and breakup models with the presently-obtained database. The IATE with the bubble coalescence and breakup model of Sun et al. (2004a) has been concluded to give the best prediction for the IAC in the two-phase bubbly flow in the large-diameter square duct with a mean absolute relative error of 25.10%. It is highly desirable to develop a more accurate bubble coalescence and breakup model considering the complex turbulence in large-diameter square ducts.

1. Introduction

The behavior of gas–liquid two-phase flow covers a wide range of phenomena of industrial and academic significance. It is indispensable to clearly know the behavior in designing and evaluating the performance, efficiency and safety of some important facilities in chemical processes, petroleum exploitation, nuclear power system and so on. The advanced two-fluid model (Ishii, 1975; Ishii and Hibiki, 2010), which describes the two phases with different mass, momentum and energy equations and treats their mutual interaction at interface, is currently used to predict the two-phase flow behavior in many computational fluid dynamic codes and safety analysis codes. In this model, the treatment of the interfacial interaction between the two phases is of importance. The interfacial interaction is expressed by a product of interfacial area concentration (IAC) and potential-driven flux. The IAC is defined by the interfacial area per unit volume of the mixture and also designated as interfacial area density. The potential-driven flux includes mass flux, momentum flux (namely surface force) and energy flux for mass, momentum and energy conservative equations respectively. It should be mentioned here that the potential-driven flux is newly used to replace the traditional driving force characterizing

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Nomenclature

A	cross-sectional area (m^2)
a	half length of a side in the cross-sectional square of a square duct (m)
a_i	all bubble IAC (1/m)
C	constant (dimensionless)
C_D	bubble drag coefficient (dimensionless)
C_{dv}	aspheric shape factor of a bubble (dimensionless)
C_{RC0}	constant (dimensionless)
D_H	the flow channel hydraulic equivalent diameter (m)
D_h	arithmetic mean bubble diameter (m)
E_{MAR}	mean absolute relative error (dimensionless)
E_R	relative error (dimensionless)
F	a parameter (any unit)
j_f	superficial velocity for liquid phase (m/s)
j_g	superficial velocity for gas phase (m/s)
K	constant (dimensionless)
l	the l-th data (dimensionless)
N	total data number (dimensionless)
R_{Bj}	change rate of bubble number density caused by the j-th bubble breakup ($1/(m^3s)$)
R_{Ck}	change rate of bubble number density caused by the k-th bubble coalescence ($1/(m^3s)$)
Re	Reynolds number (dimensionless)
r_{rec}	ratio of receding bubbles among all sensed bubbles (dimensionless)
r_{tran}	ratio of transversal/missing bubbles among all sensed bubbles (dimensionless)
t	time (s)
u_r	bubble terminal velocity (m/s)
$\mathbf{v}_g$	velocity for gas phase (m/s)
v_{gz}	component of gas phase velocity in z direction (m/s)
$\mathbf{v}_i$	interfacial velocity (m/s)
v_{iz}	component of interfacial velocity in the main flow (z) direction (m/s)
V_z	bubble velocity component in the main flow (z) direction (m/s)
We	Weber number (dimensionless)
x	x coordinate (m)
y	y coordinate (m)
z	height (m)

Greek letters

α	void fraction (dimensionless)
$\alpha_{\max}$	the maximum possible bubble void fraction (dimensionless)
ε	bubble energy dissipation rate per unit mass (m^2/s^3)
ϕ	IAC source or sink (1/(ms))
ϕ_B	IAC change rate caused by bubble breakup (1/(ms))
ϕ_C	IAC change rate caused by bubble coalescence (1/(ms))
ϕ_{EP}	IAC change rate caused by gas expansion (1/(ms))
ϕ_{TO}	total IAC change rate (1/(ms))
ρ	density (kg/m^3)
σ	surface tension (N/m)
ψ	bubble shape factor (dimensionless)

Subscripts

0	the calculation start point, namely the axial position of $z/D_H = 8.3$
$2h$	the $2h$-th interface, viz. the h-th bubble's front interface
$2h+1$	the $2h+1$-th interface, viz. the h-th bubble's rear interface
c	critical
eff	effective bubble
f	liquid phase
g	gas phase
mea	measured value
pre	predicted value
RC	random collision mechanism
TI	turbulent impact mechanism
$true$	true value
WE	wake entrainment mechanism

Mathematical symbols

$<>$	area-averaging over cross-sectional flow area (namely $\langle F\rangle = \frac{1}{A}\int_A F dA$)
$<<>>$	cross-sectional area-averaging weighted by void fraction (namely $\langle\langle F\rangle\rangle = \frac{\langle \alpha F\rangle}{\langle\alpha\rangle}$)
$<<>>_a$	cross-sectional area-averaging weighted by IAC (namely $\langle\langle F\rangle\rangle_a = \frac{\langle a_i F\rangle}{\langle a_i\rangle}$)

the local transfer mechanisms including the degree of turbulence near interfaces and the driving potential (Ishii, 1975; Ishii and Hibiki, 2010) in the definition of the interfacial interaction term to keep the unity of the two-fluid model. Both of the IAC and the potential-driven flux must be modeled properly.

In view of the great importance of the IAC in determining the interfacial transfer of mass, momentum and energy between the two phases, a lot of creative researches have been done to understand the IAC changing mechanism and further to develop constitutive models to predict the IAC change in the two-phase flow in the past several decades. Up to now, the available constitutive models for the IAC can be divided into three types. The first type is to develop the empirical or semi-empirical correlations and models according to physical mechanisms and extensive experimental data in the two-phase flows (Hibiki and Ishii, 2001, 2002a; Ozar et al., 2012; Shen and Hibiki, 2015; Schlegel and Hibiki, 2015; Akita and Yoshida, 1974; Shen and Deng, 2016). This traditional way is widely-used now. Sometimes its IAC prediction may depend on the flow regimes. The scale effects of flow channel geometry and the dependence on fluid properties are usually included in its physical mechanisms. The second type is to predict the bubble size first through the solution of population balance equation (PBE) considering the bubble coalescence and breakup process (Lehr and Mewes, 2001; Huh et al., 2006; Liao et al., 2011) and then to obtain the IAC from the bubble size and the void fraction. The PBE may have been used in the form of number density transport equations of multiple bubble size groups (Huh et al., 2006) or bubble size fraction transport equations of multiple bubble velocity and size groups called as the inhomogeneous MuSiG (Multiple Size Group) model (Liao et al., 2011). To close the PBE, the reliable and detailed bubble coalescence and breakup models are necessary. The third type is to get the IAC from one group bubble interfacial area transport equation (IATE) for bubbly flows and two group bubble IATEs for slug and churn flows. Due to the pioneering work of Kocamustafaogullari et al. (1995) and the following work of Wu et al. (1998), Hibiki and Ishii (2000a, 2000b, 2002b), Fu and Ishii (2002a, 2002b), Ishii and Kim (2001, 2004), Sun et al. (2004a), Smith et al. (2012) and Shen and Hibiki (2013) in developing the IATE, this way has provided the possibility to accurately describe the temporal and spatial evolution of the IAC and dynamically model the interfacial mass, momentum and energy