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Evaluation of interfacial area transport equation in vertical bubbly two-phase flow in large diameter pipes

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ABSTRACT

The introduction of interfacial area transport equation (IATE) has greatly improved the overall performance of two-fluid model due to the fact that the IATE can predict the interfacial area concentration (IAC) more accurately. However, models in the source and sink terms of IATE that are developed for predicting bubble coalescence and breakup are mainly based on small diameter pipe flows. Since the two-phase flow in a large diameter pipe is characterized by its multi-dimensional nature, the IATE should be confirmed before being applied to large pipe flows. From this point of view, local measurements in air–water bubbly flow systems in a large pipe with 101.6 mm diameter were performed by using four-sensor optical probes. The radial profiles of the void fraction, IAC, bubble Sauter mean diameter and interfacial velocity were obtained at two axial locations of $z/D = 2$ and 29. The simplified one-dimensional, steady-state, adiabatic one-group IATE with eight sets of bubble coalescence and breakup models was evaluated against the present experimental data and that from the literatures. The evaluation results showed that the Sun et al. (2004a) model is the best one for large diameter pipes. This model can well reflect the interfacial transfer mechanisms and can provide a reasonable prediction in general. Besides, the models of Smith et al. (2012a) and Ishii and Kim (2001) are also recommended due to their relative good performance in the prediction of IAC. Further work should be undertaken to develop a new bubble coalescence and breakup model with extra consideration of the multi-dimensional flow behavior in large pipes, if necessary.

1. Introduction

Gas–liquid two-phase flows are frequently encountered in various fields of engineering, such as chemical industry, petroleum exploitation, nuclear power plant, and so on. In order to predict the thermal–hydraulic behavior of a two-phase flow system more accurately, reliable models with appropriate constitutive relations are of significance. Since the two-fluid model describes the phases separately and treats phase interactions at the interface, it is considered as the most detailed and possibly the most accurate model for two-phase flows. In this model, the interfacial area concentration (IAC), as one of the most important geometric parameters, characterizes the capability of the interfacial transfer of mass, momentum, and energy between two phases. However, it has to be specified in the constitutive relations concerning the detailed treatment of phase interactions. In present thermal–hydraulic system analysis codes (Justin et al., 2013; Brooks et al., 2014) like RELAP5 and TRAC, the IAC is usually given by empirical correlations. This may not be able to represent the dynamic nature of the flow interfacial structure, for these correlations depend on the traditional flow regimes and transition criteria.

To predict the IAC more accurately for improving the overall performance of the two-fluid model, it was recommended to introduce the interfacial area transport equation (IATE), which was first proposed by Kocamustafaogullari and Ishii (1995) and it can replace the traditional flow regime maps and regime transition criteria (Wu et al., 1998). Due to its distinct advantage to describe the temporal and spatial evolution of the two-phase flow structure, more and more researchers concentrate on developing or improving the IATE. However, the IATE requires several constitutive relations to model the fluid particle coalescence and breakup. The detailed insight of the mechanisms of particle coalescence and breakup as well as the accurate experimental data of local flow parameters is therefore indispensable for the development of transport equations. In consideration of the interactions among bubbles and between bubbles and turbulent eddies, Wu et al.

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Nomenclature

a_i	interfacial area concentration, m^{-1}
D	inner diameter of the pipe, m
D_{sm}	Sauter mean diameter, m
J	superficial velocity, m/s
P	pressure, Pa
r	distance between center and measurement location, m
R	inner radius of pipe, m
t	time, s
V	gas volume, m^3
$v_\imath$	interfacial velocity, m/s
v_g	gas velocity, m/s
z	axial distance from the inlet, m

Greek symbols

α	void fraction
ε	energy dissipation rate per unit mass, m^2/s^3
Ω	total sampling time, s
ρ_m	mixture density, kg/m^3
$\Delta\rho$	density difference between the two phases, kg/m^3
$\Delta\tau$	the dwelling time, s
Δt	the time difference, s
Ψ	shape factor
ξ	IAC change due to bubble coalescence and breakup
Φ_{RC}	change rate of IAC due to the random collision
Φ_{TI}	change rate of IAC due to the turbulent impact
Φ_{WE}	change rate of IAC due to the wake entrainment

Subscripts

G	gas phase
L	liquid phase

Operators

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

(1998) summarized five basic mechanisms responsible for these interactions: (1) the coalescence due to random collisions driven by turbulence (RC), (2) the coalescence due to wake entrainment (WE), (3) the breakup due to the turbulent impact (TI), (4) the shearing-off of small bubbles from larger cap bubbles (SO), (5) the breakup of large cap bubbles due to surface instability at the interface (SI). Considering the effects due to the differences in bubble size and shape, bubbles are treaded in two groups, namely, the spherical/distorted bubble group (Group 1) and the cap/slug/churn-turbulent bubble group (Group 2). As a result, there exist two transport equations for two different groups of bubbles, i.e., a two-group transport equation that involve the inner and inter group interactions (Hibiki and Ishii, 2000b; Fu and Ishii, 2002; Sun et al., 2004a; Smith et al., 2012a). The preliminary work on the two-group IATE was performed by Hibiki and Ishii (2000b) for interfacial area transport at the transition from bubbly to slug flow; and then Fu and Ishii (2002) developed a complete set of two-group modeling equations that covers a wide range from bubbly, slug, to churn turbulent flow regimes. On the basis of the framework for modeling the source and sink terms in the two-group IATE (Ishii et al., 2003), the detailed bubble interaction models were specified by Sun et al. (2004a) for confined rectangular channels and by Smith et al. (2012a) for large diameter pipes. In the development of two-group transport equation, the major challenge arises from the modeling of the complicated intra-group and inter-group bubble transport and interactions.

For simplicity, in a bubbly flow with relatively low void fraction, where no Group 2 bubbles are present, the two-group transport equations can be reduced to one-group without involvement of interactions between the two groups (Sun et al., 2004a; Smith et al., 2012a). Thus in such cases, a one-group IATE is able to describe the dynamic characteristics of the flow interfacial structure. As shown in previous studies (Wu et al., 1998; Ishii and Kim, 2001), the first three mechanisms are taken into account. However, Hibiki and Ishii (2000a) argued that the wake entrainment induced coalescence has contribution to the interfacial area transport only if the bubbly flow condition is close to or in the slug flow region. Consequently, in their model for the one-group IATE, only random collisions of bubbles for the sink term and turbulent impact for the source term are considered as main mechanisms.

Due to the different understanding of the coalescence and breakup mechanisms, unfortunately, the expression forms or the modification factors in source and sink terms are surprisingly different from author to author, as can be found in Table 1. In the sink term of RC, by considering the time interval for a binary collision and the mean traveling length between neighboring bubbles, Wu et al. (1998) established a bubble coalescence rate model in which a constant coalescence efficiency is employed; different from Wu et al. (1998), Hibiki and Ishii (2000a) assumed that the bubble movement is analogous to ideal gas molecules, and applied the kinetic theory of gases to deduce the coalescence rate; while Yao and Morel (2004) proposed a new model following the work of Prince and Blanch (1990) and noted that both the free traveling time and the interaction time in the whole coalescence processes should be addressed separately. Furthermore, in the source term of TI, Wu et al. (1998) used a simplified momentum balance approach to derive the bubble breakup rate; and Hibiki and Ishii (2000a) still assumed that both the bubbles and eddies behave like the gas molecules, and used the kinetic theory of gases to deduce the breakup rate; whereas Yao and Morel (2004) pointed out that the bubble breakup also occurs in low Weber number conditions due to the resonance of bubble oscillations with turbulent eddies, and hence such mechanism was taken into account in their model. On the other hand, calculation results of Ishii and Kim (2001) indicated that the gas expansion term, which was previously ignored by Wu et al. (1998), may contribute significantly to the total variation of IAC. Thus, the model of Wu et al. (1998) was reexamined and improved based on more detailed experimental data in a wide range of bubbly flow conditions in 25.4, 50.8 and 101.6 mm diameter pipes (Ishii and Kim, 2001; Sun et al., 2002). Hibiki and Ishii (2002) also refined the source and sink terms developed in their previous study (Hibiki and Ishii, 2000a) and proposed two correlations for the adjustable variables, which were assumed to be constants in their original coalescence and breakup models. Additionally, based on the work of Yao and Morel (2004), Nguyen et al. (2013) proposed new mechanistic bubble coalescence and breakup models considering turbulent suppression phenomena.

As discussed above on the one-group IATE, various theoretical models (see Table 1) of bubble coalescence and breakup mechanisms were developed and improved by several researchers (Wu et al., 1998; Ishii and Kim, 2001; Hibiki and Ishii, 2000a, 2002; Yao and Morel, 2004; Nguyen et al., 2013). However, they were mainly focus on small pipes with the diameter that covers from