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Interfacial area concentration in gas–liquid bubbly to churn flow regimes in large diameter pipes

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ABSTRACT

This study performed a survey on existing correlations for interfacial area concentration (IAC) prediction and collected an IAC experimental database of two-phase flows taken under various flow conditions in large diameter pipes. Although some of these existing correlations were developed by partly using the IAC databases taken in the low-void-fraction two-phase flows in large diameter pipes, no correlation can satisfactorily predict the IAC in the two-phase flows changing from bubbly, cap bubbly to churn flow in the collected database of large diameter pipes. So this study presented a systematic way to predict the IAC for the bubbly-to-churn flows in large diameter pipes by categorizing bubbles into two groups (group 1: spherical or distorted bubble, group 2: cap bubble). A correlation was developed to predict the group 1 void fraction by using the void fraction for all bubble. The group 1 bubble IAC and bubble diameter were modeled by using the key parameters such as group 1 void fraction and bubble Reynolds number based on the analysis of Hibiki and Ishii (2001, 2002) using one-dimensional bubble number density and interfacial area transport equations. The correlations of IAC and bubble diameter for group 2 cap bubbles were developed by taking into account the characteristics of the representative bubbles among the group 2 bubbles and the comparison between a newly-derived drift velocity correlation for large diameter pipes and the existing drift velocity correlation of Kataoka and Ishii (1987) for large diameter pipes. The predictions from the newly-developed two-group IAC correlation were compared with the collected experimental data in gas–liquid bubbly to churn flow regimes in large diameter pipes and their mean absolute relative deviations were obtained to be 28.1%, 54.4% and 29.6% for group 1, group 2 and all bubbles respectively.

1. Introduction

The two-fluid model (Ishii, 1975; Ishii and Hibiki, 2010) is a widely-used valuable tool in analyzing general two-phase flow transport problems. The model properly formulates the transport problems in terms of two sets of conservation equations representing the balance of mass, momentum and energy of each phase. Since these conservation equations are derived from an appropriate averaging of local instantaneous balance equations, the interfacial interaction/transfer terms appear in each of the averaged balance equations. These terms govern the mass, momentum and energy transfer at interfaces between two phases. In order to close the mathematic system of these equations, the interfacial transfer terms between two phases must be specified by either mechanistic models or correlations.

The interfacial transfer terms are strongly related to the interfacial area concentration (IAC, namely Interfacial area density), defined as the interfacial area per unit volume of the mixture, and to the local transfer mechanisms such as the degree of turbulence near interfaces and the driving potential (Ishii and Hibiki, 2010). Basically the interfacial transfer terms can be expressed by a product of the IAC and the driving force. The IAC characterizes the kinematic effects and is related to the structure of the two-phase flow. The driving forces for the inter-phase transport characterize the local transport mechanism and must be modeled separately (Kocamustafaogullari and Ishii, 1995). There are two ways to develop the constitutive relations for the IAC. The first way is to obtain the IAC from one or two interfacial area transport equation(s) which can dynamically model the interfacial transfer and the interfacial structure evolutions from the entrance and developing flow regime to the fully developed flow regime through mechanistic modeling of various fluid particle interaction processes (Hibiki and Ishii, 2000; Smith, 2002). It is no doubt that

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Nomenclature

A	a coefficient (–)
A'	a coefficient (–)
A''	a coefficient (–)
a	base radius of the representative spherical cap bubble (m)
a_i	interfacial area concentration of all bubbles (1/m)
$a_{i,mea}$	measured interfacial area concentration (1/m)
$a_{i,pre}$	predicted interfacial area concentration (1/m)
$\tilde{a}_i$	non-dimensional interfacial area concentration of all bubbles (–)
a_{i1}	interfacial area concentration of group 1 bubbles (1/m)
$\tilde{a}_{i1}$	non-dimensional interfacial area concentration of group 1 bubbles (–)
a_{i2}	interfacial area concentration of group 2 bubbles (1/m)
B	an exponent (–)
B'	an exponent (–)
B''	an exponent (–)
C	an exponent (–)
C'	an exponent (–)
C''	an exponent (–)
C_1	a coefficient (–)
D	an exponent (–)
d_{base}	base diameter of the representative spherical cap bubble (m)
$d_{d,max}$	maximum distorted bubble diameter (m)
D_H	hydraulic equivalent diameter of flow channel (m)
$D_{H,Crit}$	critical hydraulic equivalent diameter of flow channel (m)
$(-dp/dz)_F$	frictional pressure loss per unit length (Pa/m)
D_{Sm1}	Sauter mean diameter of group 1 bubbles (m)
D_{Sm2}	Sauter mean diameter of group 2 bubbles (m)
f_1	a factor (–)
f_2	a shape coefficient (–)
g	gravitational acceleration (m/s^2)
h	height of the representative spherical cap bubble (m)
j_f	superficial liquid velocity (m/s)
j_g	superficial gas velocity (m/s)
k	an index (–)
Lo	Laplace length (m)
$\widetilde{Lo}$	non-dimensional Laplace length (–)
m_d	mean absolute deviation for interfacial area concentration (1/m)
m_{rel}	mean relative deviation (–)
$m_{rel,ab}$	mean absolute relative deviation (-)
N	data number (–)
n_2	group 2 bubble number density (1/m^3)
$N_{\mu f}$	viscosity number (–)
P	Pressure (Pa)
R_{Err}	a relative error (–)
Re	Reynolds number (–)
Re_1	Reynolds number for group 1 bubbles (–)
Re_2	Reynolds number for group 2 bubbles (–)
Re_f	Reynolds number of liquid phase (–)
V_{cap}	volume of the representative spherical cap bubble (m^3)
$V_{gj,cap}$	drift velocity for large cap bubbles (m/s)
S_{cap}	surface area of the representative spherical cap bubble (m^2)
s_d	standard deviation for interfacial area concentration (1/m)
z	height (m)

Greek letters

α	void fraction of all bubbles (–)
α_1	void fraction of group 1 bubbles (–)
ε	energy dissipation rate per unit mass (m^2/s^3)
$\tilde{\varepsilon}$	non-dimensional energy dissipation rate per unit mass (–)
ε_1	energy dissipation rate per unit mass of group 1 bubbles (m^2/s^3)
ε_2	energy dissipation rate per unit mass of group 2 bubbles (m^2/s^3)
ε_B	energy production rate per unit mass due to all bubble expansion (m^2/s^3)
ε_F	energy production rate per unit mass due to wall friction (m^2/s^3)
ϕ	a shape factor of a bubble (–)
μ	aspect ratio of the representative spherical cap bubble (–)
μ_f	viscosity of liquid phase (Pa s)
ν_f	kinematic viscosity of liquid phase (m^2/s)
θ_w	wake angle of the representative spherical cap bubble (°)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

f	liquid phase
g	gas phase

Mathematical symbols

$\langle\rangle$	area-averaged quantity over cross-sectional flow area
$\langle\langle\ \rangle\rangle$	void fraction weighted cross-sectional area-averaged quantity

this way is promising. However, it is still under development due to the difficulties in correctly understanding particle coalescence and disintegration mechanisms and reliably modeling the various fluid particle interaction processes. The second way is to develop static flow-regime dependent correlations and models based on physical mechanisms in the two-phase flow and existing experimental data (Yu et al., 2002; Ozar et al., 2012). This way is a traditional and widely-used method, in which the scale effects of geometry and fluid properties are taken into account in its original physical mechanisms. Until the development of the interfacial area transport equation is complete, the static flow-regime dependent correlations and models will continue playing an important role in calculating the IAC for two-phase flows.

Two-phase flows in large diameter pipes are frequently encountered in a wide variety of industrial systems. The past experimental studies (Sun et al., 2002; Shen et al., 2005a, 2006, 2010a,b,c, 2015; Prasser, 2007; Schlegel et al., 2014; Sun et al., 2014) indicated that the two-phase flow in large diameter pipes keeps the following characteristics. (1) Slug flow observed in small diameter pipes cannot be formed in large diameter pipes due to the interfacial instability. (2) Relative to a sudden transition from bubbly to slug flow observed in small diameter pipe, a gradual transition from bubbly to cap/churn-type flow with strong local recirculation patterns takes place in large diameter pipes. (3) Radial void fraction profiles in large diameter pipes are flatter than those in small diameter pipes in the cap/slug flow regime. (4) Relative velocities between large bubbles and liquid are greatly increased relative to those in small diameter pipes due to the formation of large cap bubbles resulting from the reduced influence of the pipe wall. (5) The pipe diameter change has a negligibly small effect on the bubble