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Development of interfacial area concentration correlations for small and large bubbles in gas-liquid two-phase flows

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ABSTRACT

The design and safety analysis of various equipment and systems in energy and aerospace industries present the need for a better understanding and modeling of two-phase flows. The interfacial area concentration (IAC) defined as the interfacial area per unit volume of the mixture is one of the key parameters to determine the interfacial interaction and transfer terms coupling the transport of mass, momentum and energy across the interfaces between two phases in two-phase flows. The IAC changes are usually modeled by developing constitutive relations based on the physical transport mechanisms. In the past several decades, the drag-based two group bubble categorization (group 1 small bubbles: spherical and distorted bubbles, group 2 large bubbles: cap, slug and churn-turbulent bubbles) has been extensively and effectively utilized in the analysis of bubbly-to-slug flow transition, slug flow and churn flow. This study performed an extensive survey on existing correlations for two-group bubble IAC prediction and collected the IAC database (390 data points) taken under the experimental conditions such as channel diameters from 0.00194 m to 0. 1016 m, channel length-to-diameter ratios from 2 to 829, channel shapes from round pipe, annulus, narrow rectangular channel to rod bundle channel, superficial liquid velocities from 0.018 m/s to 5.1 m/s, superficial gas velocities from 0.0148 m/s to 8.79 m/s and void fraction from 1.31% to 85.6%. The existing two-group bubble IAC correlations were found to hold under some flow and channel geometrical conditions and to produce relatively large prediction deviations under the other conditions in the range of the presently-collected database. So this study presented a systematic way to predict the IAC for bubbly, slug and churn flows in small diameter pipes by using the two group bubble categorization. New correlations were developed to predict the group 1 and 2 bubble void fractions from total void fraction of all bubbles by utilizing the rapidly-increasing feature of group 2 bubbles in bubbly-to-slug flow regime transition. The IAC contribution from group 1 bubbles was modeled by using the drag coefficients of distorted bubbles from Ishii and Zuber (1979) and Tomiyama et al. (1995). The typical slug flow pattern and the slug bubble length model of Sakaguchi et al. (2001) were utilized to develop the correlations of IAC and bubble diameter for group 2 bubbles. The developed two-group bubble IAC correlations to estimate the IAC were compared with all of the collected database. The mean absolute relative deviations are ± 41.2%, ± 73.7% and ± 27.4% and the root mean square errors are 94.7 1/m, 27.2 1/m and 124 1/m for group 1, group 2 and all bubbles respectively.

1. Introduction

Two-phase flow provides a way for engineers and scientists to effectively monitor, control and optimize the chemical and physical transport processes in nuclear reactors, space-rockets, steam boilers and so on. The accomplishment of these tasks requires the people to overcome the difficulties in dealing with the discontinuity induced by the existence of phase-separating interfaces and to establish reliable two-phase flow models. The two-fluid model proposed by Wallis (1969) and Ishii (1975) is a widely-used valuable tool in analyzing general two-phase flow transport problems. The model properly describes the two phases based on a set of conservative equations for each phase. The spatial distribution and temporal development of each phase have been sufficiently depicted and reflected in the averaging of its local instantaneous balance equations of mass, momentum and energy. Due to the averaging processing, the interfacial interaction/transfer terms appear in each of the averaged balance equations in the model. These terms

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Nomenclature

A_1	a coefficient (-)
A_2	a coefficient (-)
A_3	a coefficient (-)
A_4	a coefficient (-)
a_i	interfacial area concentration of all bubbles (1/m)
a_{i1}	interfacial area concentration of group 1 bubbles (1/m)
a_{i2}	interfacial area concentration of group 2 bubbles (1/m)
$a_{i,mea}$	measured interfacial area concentration (1/m)
$a_{i,pre}$	predicted interfacial area concentration (1/m)
b	equatorial radius of an oblate spheroidal bubble (m)
B_1	a coefficient (-)
B_2	a coefficient (-)
B_3	a coefficient (-)
B_4	a coefficient (-)
c	polar radius of an oblate spheroidal bubble (m)
C_{ct}	a factor taking into account for the wavy interfaces in slug (C_{ct}=1) and churn-turbulent (C_{ct}>1) flows (-)
C_D	drag coefficient of the distorted particle (-)
d_{bs}	average diameter of the small bubbles (namely group 1 bubbles) (m)
$d_{d,max}$	the maximum distorted bubble diameter, (m)
D_H	hydraulic equivalent diameter of flow channel (m)
D_H^+	dimensionless pipe diameter (-)
d_S	diameter of a slug bubble (m)
d_{Sm1}	Sauter mean diameter of group 1 bubbles (m)
d_{Sm2}	Sauter mean diameter of group 2 bubbles (m)
d_{v1}	volume equivalent diameter of group 1 bubbles (m)
d_{v2}	volume equivalent diameter of group 2bubbles (m)
Eo	Eotvos number (-)
E_{rms}	Root mean square error for IAC (1/m)
G	mass flux of the two-phase flow mixture (kg/(m^2.s))
g	gravitational acceleration (m/s^2)
j	mixture volumetric flux (m/s)
j_f	superficial liquid velocity (m/s)
j_g	superficial gas velocity (m/s)
k	steepness of the sigmoid curve (-)
l	the lth data number (-)
L_S	length of a slug bubble (m)
$m_{rel,ab}$	mean absolute relative deviation (%)
N	total data number (-)
n_1	group 1 bubble number density (1/m^3)
P	Pressure (MPa)
Re	Reynolds number (-)
R_{Err}	predicted relative error (-)
S_{obl}	surface area of an oblate spheroidal bubble (m^2)
v_f	velocity of liquid phase (m/s)
v_g	velocity of gas phase (m/s)
V_{obl}	volume of an oblate spheroidal bubble (m^3)
V_{Slug}	volume of a slug bubble (m^3)
z	height (m)

Greek Letters

α	void fraction of all bubbles (-)
α_1	void fraction of group 1 bubbles (-)
$\alpha_{1,\text{base}}$	base group 1 bubble void fraction in the IAC correlation of Ozar et al. (2012) (-)
$\alpha_{1,\max}$	maximum group 1 bubble void fraction, namely total void fraction at the bubbly-to-slug flow transition (-)
α_2	void fraction of group 2 bubbles (-)
α_{BS}	void fraction at bubbly-to-slug flow transition (-)
α_{crit}	critical total void fraction in the IAC correlation of Ozar et al. (2012) (-)
α_{gs}	average void fraction in the liquid slug and film in slug and churn flows (-)
α_L	lower void fraction in the IAC model of Thermal Hydraulics Group (1998) (-)
α_{mid}	midpoint void fraction of the sigmoid curve (-)
α_{SA}	void fraction at slug-to-annular-mist flow transition (-)
β	angular eccentricity of an oblate spheroid (-)
ε	energy dissipation rate per unit mass (m^2/s^3)
ϕ_1	shape factor of group 1 bubbles (-)
ϕ_2	shape factor of group 2 bubbles (-)
μ	viscosity (Pa s)
μ_1	aspect ratio (=c/b) of an oblate spheroidal bubble (group 1 bubble) (-)
μ_2	aspect ratio (=L_S/d_S) of a slug bubble (group 2 bubble) (-)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

f	liquid phase
g	gas phase
sph	a spherical bubble

Mathematical symbols

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

couple the transport of mass, momentum and energy across the interfaces between two phases. In order to get over the weakest link in the model, the important interfacial transfer terms between two phases must be modeled reliably. The interfacial transfer terms are proportional to the interfacial area concentration (IAC) defined as the interfacial area per unit volume of the mixture and the driving force characterizing the local transport mechanism (Ishii and Mishima, 1980). They should be modeled separately.

In view of the great importance of IAC in the two-fluid model and two-phase flows, a number of experimental and modeling studies (Ishii and Mishima, 1980; Kocamustafaogullari et al., 1994; Kocamustafaogullari and Ishii, 1995; Wu et al., 1998; Hibiki and Ishii, 2000, 2001, 2002; Fu and Ishii, 2002a,b; Sun et al., 2004; Shen et al., 2005a, 2006, 2010a,b, 2011, 2012a, 2016; Ishii and Hibiki, 2010; Schlegel et al., 2012; Shen and Nakamura, 2013, 2014; Sun et al., 2014; Shen and Hibiki, 2015; Schlegel and Hibiki, 2015) on the IAC have been performed to understand and predict its characteristics. According to the difference in modeling the IAC, these studies are classified into two types. The first is to obtain the IAC from one or two interfacial area transport equation(s) (IATE) 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. It is no doubt that this way is promising. However, this way 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 is to develop static flow-regime dependent correlations and models based on physical mechanisms and existing experimental data in the two-phase flows. 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.