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One-group interfacial area transport equation and its sink and source terms in narrow rectangular channel

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ABSTRACT

The characteristics of two-phase flow in a narrow rectangular channel are expected to be different from those in other channel geometries, because of the significant restriction of the bubble shape which, consequently, may affect the heat removal by boiling under various operating conditions. The objective of this study is to develop an interfacial area transport equation with the sink and source terms being properly modeled for the gas–liquid two-phase flow in a narrow rectangular channel. By taking into account the crushed characteristics of the bubbles a new one-group interfacial area transport equation was derived for the two-phase flow in a narrow rectangular channel. The random collisions between bubbles and the impacts of turbulent eddies with bubbles were modeled for the bubble coalescence and breakup respectively in the two-phase flow in a narrow rectangular channel. The newly-developed one-group interfacial area transport equation with the derived sink and source terms was evaluated by using the area-averaged flow parameters of vertical upwardly-moving adiabatic air–water two-phase flows measured in a narrow rectangular channel with the gap of 0.993 mm and the width of 40.0 mm. The flow conditions of the data set covered spherical bubbly, crushed pancake bubbly, crushed cap-bubbly and crushed slug flow regimes and their superficial liquid velocity and the void fraction ranged from 0.214 m/s to 2.08 m/s and from 3.92% to 42.6%, respectively. Good agreement with the average relative deviation of 9.98% was obtained between the predicted and measured interfacial area concentrations in this study.

1. Introduction

In the analysis of two-phase flow, the two-fluid model is the most detailed and accurate model. Its two-phase mass, momentum and energy conservation equations are obtained from a proper averaging of local instantaneous balance equations, which results in the two-phase interaction terms appearing in each of the averaged balance equation. These terms specify the important mass, momentum and energy transfers through the interface between the two phases. Therefore, it is indispensable to develop accurate closure relations for the interfacial transfer terms in the two-fluid model.

All of the interfacial transfer terms in conservation equations can be given in terms of the interfacial area concentration (IAC), a_i, and driving force (Ishii and Hibiki, 2006):

$$(\text{Interfacial transfer}) = a_i \times (\text{Driving force}). \tag{1}$$

The interfacial area concentration is defined as the total interfacial area of the bubbles per unit mixture volume. It specifies the geometric capability of the interfacial transfer. The driving forces for the interfacial transport characterize the local transport mechanisms such as the turbulence, molecular transport properties and driving potentials. Since the interfacial area concentration is an essential property for the internal structure of two-phase flow, it changes with the evolution of the flow due to physical processes. Kocamustafaogullari and Ishii (1995) recommended an introduction of the interfacial area transport equation (IATE) to describe the change of IAC in a two-phase flow. The two-group approach to treat bubbles in two groups has been proposed to accommodate the IATE in a practical CFD simulation (Ishii and Hibiki, 2006). In the two-group approach, spherical and distorted bubbles are considered as the group one bubbles and cap, slug and churn-turbulent bubbles are considered as the group two bubbles.

Since each bubble has an approximate spherical shape in a bubbly flow, these bubbles can be classified into one bubble group. Wu et al. (1998) and Hibiki and Ishii (2000a) accordingly deduced the one-group IATE given by

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Nomenclature

A_{V0}	inlet void fraction at $z/D_H = 0$
A_{V1}	a fitting coefficient for void fraction
A_{V2}	a fitting coefficient for void fraction
A_i	surface area of a spherical-edged pancake bubble (m^2)
A_{iFilm}	surface area of a rectangular-edged pancake bubble considering a finite thickness for the liquid film between the channel wall and the bubble (m^2)
A_{iR}	surface area of a rectangular-edged pancake bubble (m^2)
a_i	interfacial area concentration (1/m)
a_{iFilm}	interfacial area concentration considering a finite thickness for the liquid film between the channel wall and the bubble (1/m)
a_{iR}	interfacial area concentration considering the rectangular-edged pancake bubble (1/m)
c	ratio of the rectangular-edged pancake eddy diameter to the spherical-edged pancake bubble diameter
d	diameter of a spherical-edged pancake bubble body (m)
$d\theta$	a small angle step
$d_e + s$	diameter of a rectangular-edged pancake eddy (m)
D_H	hydraulic equivalent diameter (m)
dl	a small circumferential step on $S_{c,h}$ (m)
$\left(\frac{dp}{dz}\right)_F$	frictional pressure loss gradient of two-phase flow (Pa/m)
d_{sm}	Sauter mean bubble diameter (mm)
dt	a small time step (s)
e	average energy of a single eddy (J)
E_B	energy required for a pancake bubble breakup into two equal-volume pancake bubbles (J)
f_B	bubble–eddy collision frequency (1/s)
f_C	bubble random collision frequency (1/s)
F_S	a function of c
F_V	a function of c
j	mixture volumetric flux (m/s)
j_g	superficial gas velocity (m/s)
j_f	superficial liquid velocity (m/s)
K_C	a constant
L	height of a rectangular channel (m)
Lo^*	non-dimensional Laplace constant
m_e	mass of a single eddy (kg)
N_b	number of the bubbles in a narrow rectangular control volume
N_e	eddy number per fluid volume ($1/m^3$)
n	particle number density ($1/m^3$)
n_e	number of eddies of wave number per two-phase mixture volume ($1/m^3$)
P	pressure (Pa)
P_0	inlet pressure at $z/D_H = 0$ (Pa)
P_A	a fitting coefficient for pressure (Pa)
R_B	bubble number density (n) change rate due to bubble breakup, namely bubble breakup rate ($1/(m^3s)$)
R_C	bubble number density (n) change rate due to bubble coalescence, namely bubble coalescence rate ($1/(m^3s)$)
R_j	bubble number density (n) change rate due to the jth bubble breakup and coalescence ($1/(m^3s)$)
R_{ph}	bubble number density (n) change rate due to phase change ($1/(m^3s)$)
r_R	radius of a rectangular-edged pancake bubble (m)
s	gap size of the rectangular channel (m)
S_B	surface available to collision (m^2)
S_C	surface available to collision (m^2)
$S_{C,h}$	edge surface area of the hth bubble for collision (m^2)
t	time (s)
U_B	volume available to collision (m^3)
u_B	eddy velocity (m/s)
U_C	volume available to collision (m^3)
u_C	speed of the hth pancake bubble or average bubble velocity (m/s)
U_{C2}	volume outside the hth bubble in the control volume (m^3)
u_e	velocity of a single eddy (m/s)
V	volume of a narrow rectangular control volume (m^3)
V_b	volume of a spherical-edged pancake bubble (m^3)
V_{bFilm}	volume of a spherical-edged pancake bubble considering a finite thickness for the liquid film between the channel wall and the bubble (m^3)
V_{bR}	volume of a rectangular-edged pancake bubble (m^3)
$\mathbf{v}_g$	velocity of gas phase (m/s)
$\mathbf{v}_{gz\ z}$	directional component of gas phase velocity (m/s)
$\mathbf{v}_{pm}$	average local particle velocity weighted by the particle number (m/s)
w	width of a rectangular channel (m)
x	liquid film thickness (m)
z	height from the inlet of the rectangular channel (m)

Greek letters

α	void fraction
α_{iFilm}	void fraction considering a finite thickness for the liquid film between the channel wall and the bubble
α_{max}	maximum allowable void fraction
ΔA_i	surface area change due to the unit change of the bubble number density change rate, namely the surface area change due to each bubble number change in a unit volume and a unit time step (m^2)
Δa_i	interfacial area concentration change due to the void fraction change (1/m)
ε	energy dissipation rate per unit mass (m^2/s^3)
γ_B	a function of c
γ_C	a constant
γ'_B	a function of c
γ'_C	an adjustable valuable
η	a constant
Φ_B	interfacial area concentration change rates due to bubble breakup (1/(ms))
Φ_C	interfacial area concentration change rates due to bubble coalescence (1/(ms))
Φ_E	interfacial area concentration change rates due to gas expansion (1/(ms))
Φ_{ph}	interfacial area concentration change rates due to phase change (1/(ms))
Φ_T	total interfacial area concentration change rate due to bubble coalescence, breakup and expansion (1/(ms))
Γ_C	an adjustable valuable
λ_B	bubble breakup efficiency
λ_C	bubble coalescence efficiency
θ	an angle between the velocity of the hth pancake bubble and the normal direction of an element on $S_{c,h}$
ρ_f	liquid phase density (kg/m^3)
ρ_g	gas phase density (kg/m^3)
σ	surface tension (N/m)
ψ	factor depending on the shape of the bubbles

Subscripts

0	inlet value at $z/D_H = 0$
g	gas phase
f	liquid phase

Mathematical symbols

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