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Investigation of one-dimensional interfacial area transport for vertical upward air–water two-phase flow in an annular channel at elevated pressures

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HIGHLIGHTS

- Interfacial area transport equation (IATE) for a rectangular duct is modified for an annulus.
- IATE predicts interfacial area transport in bubbly-to-churn flow.
- Scalability of IATE to elevated pressure conditions is validated.
- Detailed 1D interfacial area transport data are presented.
- Detailed interfacial area transport mechanisms are discussed.

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ABSTRACT

The interfacial area transport of vertical, upward, air–water two-phase flows in an annular channel has been investigated at different system pressures. The inner and outer diameters of the annular channel were 19.1 mm and 38.1 mm, respectively. Twenty three inlet flow conditions were selected, which covered bubbly, cap-bubbly, and churn-turbulent flows. These flow conditions also overlapped with twelve conditions of a previous study for comparison. The local flow parameters, such as void fractions, interfacial area concentrations (IAC), and bubble interface velocities, were measured at nine radial positions for the three axial locations and converted into area-averaged parameters. The axial evolutions of local flow structure were interpreted in terms of bubble coalescence, breakup, expansion of the gas-phase due to pressure drop and system pressure. An assessment of interfacial area transport equation (IATE) was made and compared with the experimental data. A discussion of the comparison between model prediction and the experimental results were made.

1. Introduction

Physical problems of two-phase flow are generally represented by macroscopic field equations and constitutive relations using the continuous formulation. A detailed treatment of the two-phase motion is possible through the two-fluid model (Ishii and Hibiki, 2010). The two-fluid model is formulated by considering each phase separately in terms of two sets of conservation equations governing the mass, momentum and energy for each phase. In the two-fluid formulation, the interaction terms, which couple the transport of mass, momentum and energy of each phase across the interfaces, appear in the field equations. These interfacial transfer terms are strongly related to the interfacial area and to the local transfer mechanisms, for example, the degree of turbulence near the interfaces. Therefore, an accurate model for the interfacial area is essential for the two-fluid model formulation.

Two-fluid model is adopted in most of the nuclear analysis codes such as TRACE, RELAP5, TRAC, CATHARE, and ATHLET, or computational multi-fluid dynamic codes like CFX and FLUENT. The IAC is usually modeled based on flow regime transition criteria and regime-dependent constitutive relations in these codes. As an example, IAC is represented in terms of a geometric parameter of the flow, the phasic velocities, and the void fraction in RELAP5 and TRAC, which use various flow regime maps. The flow regime maps are based on the assumptions of steady-state and fully developed flows. These flow regime maps produce discontinuous changes in the interfacial transfer because very small changes in the state of flow condition (i.e., superficial liquid and gas velocities) can lead to a very different steady-state flow regime. The flow regime transitions represent bifurcation phenomena in the two-fluid model. Also, since the maps are static, they cannot resolve

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Nomenclature

a_i	interfacial area concentration
a_{i1}	Group-1 interfacial area concentration
a_{i2}	Group-2 interfacial area concentration
BT	inter-group transfer
C	adjustable variable or parameter
C_D	drag coefficient
CD_{c1}^{*2}	inter-group transfer coefficient
D_b	critical bubble size
D_{c1}^{*}	dimensionless diameter
$D_{d,\max}$	maximum diameter that a distorted spherical bubble can reach
D_h	hydraulic diameter
D_{Sm}	Sauter mean diameter
G	gap in a rectangular/annular channel
g	gravitational acceleration
j	total volumetric flux
j_f	liquid superficial velocity
j_g	gas superficial velocity
P	pressure
r	local radial distance to the center
R	radius of tube
R_i	inner radius of the annulus
R_o	outer radius of the annulus
RE_{ait}	relative error for the prediction of interfacial area concentration
RC	random collision
SO	shearing off
TI	turbulent impact
XP	expansion
v_g	bubble interface velocity
v_{g1}	Group-1 bubble interface velocity
v_{g2}	Group-2 bubble interface velocity
VEL	velocity effect
WE	wake entrainment
z	axial position in the flow direction

Greek letters

α	void fraction
α_1	Group-1 void fraction
α_2	Group-2 void fraction
$\Delta\rho$	density difference between liquid and gas phases
$\Delta\dot{m}_{12}$	net inter-group mass transfer rate from Group-1 to Group-2 bubbles due to bubble interactions and pressure effect
ε	turbulent kinetic energy dissipation rate per unit mixture mass
η	void fraction source/sink rate
η_{ph}	volume change rate per unit mixture volume
$\phi_{j,1}$	Group-1 source or sink term due to bubble interactions
$\phi_{j,2}$	Group-2 source or sink term due to bubble interactions
ρ	density
σ	surface tension
ϕ	interfacial area concentration source/sink rate
ϕ_k	viscous dissipation rate for each phase

Subscripts

1	Group-1 bubbles
2	Group-2 bubbles
b	bubble
C	coalescence
exp	expansion
f	liquid
g	gas
i	interface/inner
j	index
k	kth phase
$m1$	maximum in Group-1
$m2$	maximum in Group-2
RC	random collision
SI	surface instability
SO	shearing-off
TI	turbulent impact
t	total or turbulence
WN	wall nucleation
WE	wake entrainment
w, wall	wall

Superscripts

(1)	interactions with Group-1 bubbles
(11,2)	coalescence of a Group-1 bubble with another Group-1 bubble to generate a Group-2 bubble
(12,2)	coalescence of a Group-1 bubble with a Group-2 bubble to generate a Group-2 bubble
(2)	interactions within Group-2 bubbles
(2,1)	Group-1 bubbles generated from breakup of a Group-2 bubble
(2,2)	Group-2 bubbles generated from breakup of a Group-2 bubble
(2,11)	breakup of a Group-2 bubble to generate two Group-1 bubbles
(2,12)	breakup of a Group-2 bubble to generate a (or multiple) Group-1 bubble(s) and a Group-2 bubble

Mathematical symbols

$\langle\rangle$	area averaging
$\langle\langle\rangle\rangle$	void-weighted area averaging

the time scale over which flow regime transitions occur. The two-fluid model, with static flow regime transition criteria and flow regime-dependent constitutive relations, represents a conceptual inconsistency in modeling the dynamic phase interactions. To better characterize the effects of interfacial structure and regime transition, a mathematical model which can take into account the dynamic change of the interfacial structure is needed.

Recent advances in two-phase flow measurement techniques have promoted further research on interfacial area transport. Especially, the improvement of double- and four-sensor conductivity probes (Kataoka et al., 1986; Hibiki et al., 1998; Wu and Ishii, 1999; Kim et al., 2000) allowed accurate measurements of local two-phase flow parameters, such as void fraction, interfacial area concentration (IAC), interfacial velocity, etc. This, in turn, has resulted in the improvement of interfacial area transport models (Kocamustafaogullari and Ishii, 1995; Morel et al., 1999; Hibiki and Ishii, 2000; Sun et al., 2004a).

The formulation of interfacial area transport equations is based on statistical mechanics and its concept has been fully established (Ishii and Hibiki, 2010). However, bubble coalescence and breakup, which are the source and sink terms for interfacial area due to bubble interaction, are still being developed. These parameters have significant dependence on flow conditions and geometries. There are vast amount of experiments conducted in round tubes (Grosstete, 1995; Hibiki et al., 1998, 2001; Hibiki and Ishii, 1999; Ishii and Kim, 2004; Yao and Morel, 2004) and some in rectangular