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Some characteristics of gas–liquid two-phase flow in vertical large-diameter channels

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ABSTRACT

In engineering fields such as power generation systems (nuclear and thermal power plants), chemical processing, oil industry and so on, large-diameter channels have been extensively used to increase the mass, momentum and heat transport capability of the working fluid. Compared with small-diameter pipes, two-phase flow in the large-diameter channels shows more complicated flow characteristics. Much larger cap bubbles can exist and the interfacial instability prevents the large cap bubbles from forming large stable Taylor bubbles. So, the flow regimes and the radial void fraction profiles are different and the relative velocities between the two phases are significantly increased compared to those in small-diameter pipes. This paper reviews the recent progress in the research on two-phase flows in large-diameter channels. Recent progress on the state-of-the-art tool of four-sensor probe is explained and the necessary two-group bubbles can be classified through the measured bubble diameter, instead of the present method using bubble chord length, in 3-dimensional two-phase flow. The databases on the flows in large-diameter channels are presented and their typical multi-dimensional characteristics are discussed in detail. The most updated constitutive equations covering flow regime transition criteria, drift-flux correlations, interfacial area concentration (IAC) correlations and one- and two-group interfacial area transport equation(s) (IATE(s)) are summarized and their merits and drawbacks are analyzed. The important assumption that the area-averaged interfacial velocity weighted by IAC is equal to the area-averaged gas velocity weighted by void fraction in the 1D IATE has been confirmed by the present newly-obtained experimental data. The 1D numerical simulations of multi-dimensional two-phase flows in large-diameter channel are reviewed. Finally, the future research directions are suggested.

1. Introduction

Two phase flows in large-diameter channels have great importance in efficiently and safely transferring mass and energy from one location to another and from one phase to the other in a wide variety of industrial systems and processes including nuclear power plants and oil refineries. The large-diameter channels are defined as the channels whose diameters are greater than the maximum possible stable slug bubble size (Kocamustafaogullari et al., 1984). The two-phase flows in vertical large-diameter channels show much more complex multi-dimensional nature than two-phase flows in small diameter channels (Ohnuki and Akimoto, 2000; Schlegel et al., 2012; Shen et al., 2005a). Due to the complex nature and the resultant difficulties in measurements, much less experimental and numerical studies have been performed in vertical large-diameter channels than those in vertical small-diameter channels. However, detailed understanding of the multi-dimensional characteristics of gas-liquid two-phase flow in vertical large-diameter channels is of importance to secure the safety of nuclear power plants (NPPs), since the large-diameter channels are widely utilized in the NPPs.

The two-fluid model (Ishii and Hibiki, 2010) has been extensively used in safety analysis codes of nuclear reactor systems such as TRACE (USNRC, 2008), RELAP5 (Thermal Hydraulics Group, 1998), and TRAC-PF1 (Spore et al., 1993) to simulate the steady and transient heat transfer processes in NPPs. Starting from the issue of the revised rule on the acceptance of emergency core cooling system performance for light water reactors (USNRC, 1988), the best estimate and uncertainty evaluation (BEPU) methodologies which can deal with multi-physics and multi-scale issues have been proposed to explain the simulation accuracy and uncertainty. In the predictions of complex two-phase flows

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Nomenclature

A_0	four-sensor probe basic determinant (–)
$A_{01,l}$	four-sensor probe's basic determinant with the l-th interface's velocity-reciprocal (–)
$A_{02,l}$	four-sensor probe's basic determinant with the l-th interface's velocity-reciprocal (–)
$A_{03,l}$	four-sensor probe's basic determinant with the l-th interface's velocity-reciprocal (–)
$A_{01,h}$	four-sensor probe's basic determinant with the h-th bubble's velocity-reciprocal (–)
$A_{02,h}$	four-sensor probe's basic determinant with the h-th bubble's velocity-reciprocal (–)
$A_{03,h}$	four-sensor probe's basic determinant with the h-th bubble's velocity-reciprocal (–)
a_i	all bubble IAC (1/m)
a_{i1}	group 1 bubble IAC (1/m)
a_{i2}	group 2 bubble IAC (1/m)
$B_{01,l}$	four-sensor probe's bubble distance determinant calculated from the l-th ($l = 2h$ or $2h + 1$) interface side (–)
$B_{02,l}$	four-sensor probe's bubble distance determinant calculated from the l-th ($l = 2h$ or $2h + 1$) interface side(–)
$B_{03,l}$	four-sensor probe's bubble distance determinant calculated from the l-th ($l = 2h$ or $2h + 1$) interface side(–)
C	constant (–)
C_0	distribution parameter (–)
$C_{0,Ishii}$	distribution parameter calculated from the C_0 equation of Ishii (1977) (–)
C_1	variable in the correlation of Schlegel and Hibiki (2015) (–)
C_2	variable in the correlation of Schlegel and Hibiki (2015) (–)
C_3	variable in the correlation of Schlegel and Hibiki (2015) (–)
C_{D1}	leading group 1 bubble drag coefficient (–)
C_{dv}	aspheric shape factor of a bubble (–)
$C_{dv,crit}$	critical aspheric shape factor between the spherical and non-spherical bubble (–)
D_{av}	bubble average diameter (m)
D_{c1}^{*}	ratio of the critical bubble diameter at the two-group bubble boundary to group 1 Sauter mean diameter (–)
D_{c2}^{*}	ratio of the critical bubble diameter at the two-group bubble boundary to group 2 Sauter mean diameter (–)
D_h	hydraulic equivalent diameter (m)
D_h^{*}	non-dimensional hydraulic equivalent diameter (–)
$D_{h,l}$	the h-th bubble's diameter calculated from the l-th ($l = 2h$ or $2h + 1$) interface side (m)
D_{Sm1}	group 1 Sauter mean diameter (m)
D_{Sm2}	group 2 Sauter mean diameter (m)
g	acceleration of gravity (m/s^2)
j	mixture volumetric flux (m/s)
j_f	superficial velocity for liquid phase (m/s)
j_g	superficial velocity for gas phase (m/s)
Lo	Laplace length (m)
$N_{\mu f}$	liquid phase viscosity number (–)
$N_{Re\varepsilon}$	dissipation Reynolds number (–)
N_{vr}	relative velocity ratio (–)
N_{We} or We	Weber number (–)
P	probability (–) or pressure (MPa)
R	radius, m
r	radial distance from the pipe center, m
R_{Bj}	change rate of bubble number density caused by the j-th bubble breakup (1/(m^3 s))
R_{Ck}	change rate of bubble number density caused by the k-th bubble coalescence (1/(m^3 s))
R_{ph}	change rate of bubble number density caused by phase change (1/(m^3 s))
T	temperature, °C
u_{r1}	preceding group 1 bubble's relative velocity (m/s)
$\bar{u}_{rw2}$	bubble average velocity in wake region (m/s)
$\bar{u}_{w12}$	group 1 entrained bubble's local wake velocity (m/s)
$\mathbf{V}_{b,h}$	the h-th bubble velocity (m/s)
v_f	liquid phase velocity (m/s)
$\tilde{v}_f$	variation of liquid phase velocity (m/s)
$\mathbf{v}_g$	velocity for gas phase (m/s)
v_{g2}	velocity of group 2 bubbles (m/s)
V_{gj}	drift velocity in two-phase flow (m/s)
V_{gj}^{+}	non-dimensional drift velocity (–)
$V_{gj,\ B}$	bubbly flow drift velocity used in correlation of Hibiki and Ishii (2003b) (m/s)
V_{gj_B}	bubbly flow drift velocity used in correlation of Shen et al. (2010b) (m/s)
$V_{gj,\ P}$	drift velocity of pool boiling flow used in correlation of Hibiki and Ishii (2003b) (m/s)
V_{gj_S}	slug flow drift velocity used in correlation of Shen et al. (2010b) (m/s)
v_{gx}	component of gas phase velocity in x direction (m/s)
v_{gy}	component of gas phase velocity in y direction (m/s)
v_{gz}	component of gas phase velocity in z direction (m/s)
v_{gz1}	z directional component of group 1 bubble velocity (m/s)
v_{gz2}	z directional component of group 2 bubble velocity (m/s)
$\mathbf{v}_i$	interfacial velocity (m/s)
v_{iz}	component of interfacial velocity in z direction (m/s)
$\mathbf{V}_{i,l}$	velocity vector of the l-th interface (m/s)
We_1	Weber number of group 1 bubbles (–)
We_2	Weber number of group 2 bubbles (–)
We_{cr1}	critical Weber number of group 1 bubbles (–)
We_{cr2}	critical Weber number of group 2 bubbles (–)
z	height (m)

Greek letters

α	void fraction (–)
α_1	group 1 bubble void fraction (–)
$\alpha_{1,max}$	the maximum possible group 1 bubble void fraction (–)
α_2	group 2 bubble void fraction (–)
α_{gs}	average void fraction in liquid slug and film in slug and churn flows (–)
$\Delta\rho$	two-phase density difference (kg/m^3)
ε	all bubble energy dissipation rate per unit mass (m^2/s^3)
ε_1	group 1 bubble energy dissipation rate per unit mass (m^2/s^3)
ε_2	group 2 bubble energy dissipation rate per unit mass (m^2/s^3)
ϕ	IAC source or sink (1/(ms))
ϕ_B	IAC change rates caused by bubble breakup (1/(ms))
ϕ_C	IAC change rates caused by bubble coalescence (1/(ms))
ϕ_E	IAC change rates caused by gas expansion (1/(ms))
ϕ_{ph}	IAC change rates caused by phase change (1/(ms))
λ	interaction efficiency (–)
ν_f	liquid kinematic viscosity (m^2/s)
$\theta_{i,2h}$	angle between bubble velocity and interfacial normal direction at the probe touching point on the $2h$-th interface (–)
$\theta_{i,2h+1}$	angle between bubble velocity and interfacial normal direction at the probe touching point on the $2h$ + 1-th interface (–)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ψ	bubble shape factor (–)