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Review

Constitutive equations for vertical upward two-phase flow in rod bundle

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ABSTRACT

In view of the quality assurance of two-phase flow simulations, CSAU (Code Scalability, Applicability, and Uncertainty) methodology and code V & V (Verification and Validation) have been proposed. The estimation of simulation uncertainty is indispensable in using best-estimate computational codes. A key of successful two-phase flow simulations is to use the state-of-the-art constitutive equations to close the mathematical system used in two-phase flow analyses. The advanced constitutive equations should be developed based on "physics" behind phenomena and should consider scaling parameters which enable their application beyond test conditions used for a code validation. Two-phase flow simulations in a rod bundle is important in various industrial apparatuses such as heat exchangers and nuclear reactors. Constitutive equations for two-phase flows in a vertical rod bundles have been advanced in recent five years. In view of this, this paper provides a comprehensive review of most advanced constitutive equations for two-phase flow analyses in a vertical rod bundle. The constitutive equations of two-phase flow parameters reviewed in this paper are flow regime map, void fraction, void fraction covariance and relative velocity covariance, interfacial area concentration and wall friction. In addition, an exact formulation of one-dimensional momentum equation in two-fluid model considering void fraction distribution is discussed.

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Nomenclature

a	coefficient
a_i	interfacial area concentration
b	coefficient
C	Chisholm's parameter
C_0	distribution parameter
C_{wf}	wall drag coefficient of liquid phase
C_{wg}	wall drag coefficient of gas phase
C_α	void fraction covariance
C'_α	relative velocity covariance
C_∞	asymptotic distribution parameter
d_B	bubble departure diameter
D_H	hydraulic equivalent diameter
D_{Sm}	Sauter mean diameter
f	Fanning friction factor
g	gravitational acceleration
g_1	factor
G	mass flux
j	mixture volumetric flux
j_f	superficial liquid velocity
j_g	superficial gas velocity
La	Laplace length
M_{ik}	interfacial drag force
$M_{\tau k}$	viscous and turbulent shear stress
n	exponent
N_{a_i}	non-dimensional interfacial area concentration
N_{La}	non-dimensional Laplace length
N_{Re_b}	bubble Reynolds number
$N_{\mu f}$	viscosity number
N_ρ	density ratio
p	pressure
p_c	critical pressure
Re	Reynolds number
$Re_{2\phi,f}$	liquid phase Reynolds number
t	time
v	velocity
v_{gj}	drift velocity
V_{gj}^+	non-dimensional drift velocity
X	Martinelli's parameter
z	axial position

Greek symbols

α	void fraction
$\Delta\rho$	density difference
ε	energy dissipation rate per unit mass
ε_w	wall surface roughness
ϕ^2	two-phase wall friction multiplier
ϕ_S	correction factor
$\Phi_{Phase\ Change}$	sink/source term of interfacial area concentration due to phase change
$\Phi_{Pressure\ Change}$	sink/source term of interfacial area concentration due to pressure change
Φ_{sink}	sink term of interfacial area concentration due to bubble coalescence
Φ_{source}	source term of interfacial area concentration due to bubble breakup
η	factor
μ	viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ_w	wall shear stress

Subscripts

B	bubbly flow condition
BB	bulk boiling condition
$crit$	critical value
f	liquid phase
$film$	liquid film
g	gas phase
k	liquid or gas phase
L	laminar region
$L-T$	transition region between laminar and turbulent regions
max	maximum value
P	pool condition
SB	subcooled boiling condition
T	turbulent region
w	wall

Superscript

$+$	non-dimensional value

Mathematical symbols

$\langle\rangle$	area-averaged quantity
$\langle\langle\rangle\rangle$	void-fraction-weighted mean quantity

1. Introduction

Two-phase flows are encountered in various industrial apparatuses such as chemical reactors, boilers, heat exchangers and nuclear reactors. Detailed three-dimensional two-phase flow analyses using two-phase computational fluid dynamics (two-phase flow CFD) codes have been advanced for design and performance analyses of industrial apparatuses [1]. However, the prediction accuracy of the two-phase flow CFD does not reach sufficient level for these purposes due to the difficulty of modeling in interfacial area concentration, two-phase flow turbulence, non-drag force and wall nucleation source [2,3] as well as lack of local two-phase flow data to be used for validating the two-phase flow CFD [4].

In a practical use of two-phase flow analyses, one-dimensional analyses are common. For example, a nuclear reactor system is composed of many components such as reactor core, piping and safety components which make the system complicated. In order to simulate some accident scenario, the nuclear system behavior is the focus. A flow channel in each component is area-averaged and one-dimensional formulation is used in a nuclear thermal-hydraulic system analysis code. In the nuclear thermal-hydraulic system analysis code, the two-fluid model is often utilized as modeled two-phase conservation equations [5]. The one-dimensional