Modeling of void fraction covariance and relative velocity covariance for upward boiling flow in vertical pipe

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ABSTRACT

Drift-flux parameters have been often used to formulate one-dimensional interfacial drag force in dispersed two-phase flow, which is one of key parameters to predict void fraction using one-dimensional thermal-hydraulic codes. This approach is called "Andersen approach", which has been widely used in one-dimensional nuclear thermal-hydraulic system analysis codes such as TRACE, RELAP5 and TRAC-BF1. However, the current formulation of one-dimensional interfacial drag force ignores important void fraction covariance and relative velocity covariance when local interfacial drag force is converted to one-dimensional interfacial drag force. The impact of neglecting void fraction covariance and relative velocity covariance on one-dimensional interfacial drag force and relative velocity has been discussed in detail. In view of the importance of the drift-flux parameters, void fraction covariance and relative velocity covariance on one-dimensional formulation of the interfacial drag force, three constitutive equations have been developed for upward boiling two-phase flow in a vertical pipe. The validity of the modeled void fraction covariance and relative velocity covariance for subcooled and bulk boiling flow in a vertical pipe has been verified by boiling R12 data taken in a vertical pipe with the diameter of 19.2 mm under the pressure simulating prototypic nuclear reactor thermal-hydraulic conditions. The correlation of void fraction covariance agrees with the boiling flow data in the vertical pipe with the mean absolute error, standard deviation, mean relative deviation and mean absolute relative deviation being 0.828, 3.43, 10.3% and 33.5%, respectively. The correlation of relative velocity covariance agrees with the boiling flow data in the vertical pipe with the mean absolute error, standard deviation, mean relative deviation and mean absolute relative deviation being −0.00394, 0.0663, −0.184% and 5.11%, respectively. Due to the great importance of the void fraction covariance and relative velocity covariance on one-dimensional interfacial drag force formulation, it is highly recommended to include the void fraction covariance and relative velocity covariance in the one-dimensional formulation of the interfacial drag force used in nuclear thermal-hydraulic system analysis codes.

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1. Introduction

In two-phase flow analyses, mass, momentum and energy balances are often formulated by two-fluid model [1]. The two-fluid model is composed of mass, momentum and energy conservation equations for each phase, and is capable of simulating dynamic and non-equilibrium two-phase flow provided accurate interfacial area transfer terms are given. Several one-dimensional and three-dimensional computational fluid dynamics (CFD) codes have been developed based on the two-fluid model. The formulations of non-drag forces and interfacial area concentration are keys for developing successful three-dimensional CFD codes [2], whereas the interfacial drag force is one of most important terms for one-dimensional codes [3].

Due to the limited availability of the interfacial area constitutive correlations [4–8], one-dimensional nuclear thermal-hydraulic system analysis codes such as TRACE [9], RELAP5 [10] and TRAC-BF1 [11] have formulated the interfacial drag force in dispersed two-phase flow with the aid of drift-flux parameters such as distribution parameter and drift velocity, which is known as "Andersen approach". In view of this, extensive researches have been performed for developing reliable drift-flux correlations [12–20]. Recent extensive review of the interfacial drag force in one-dimensional two-fluid model [21] pointed out a vital role of "void fraction covariance", which has not been considered for the current formulation of the interfacial drag force in one-dimensional system analysis codes. The void fraction covariance

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Nomenclature

a_i	interfacial area concentration
C_0	distribution parameter
C_i	drag coefficient
C_α	void fraction covariance
C'_α	relative velocity covariance
g	gravitational acceleration
j	mixture volumetric flux
M_{ig}^D	interfacial drag force
m_d	mean absolute error
m_j	exponent in assumed mixture volumetric flux distribution
m_{rel}	mean relative deviation
$m_{rel.ab}$	mean absolute relative deviation
m_α	exponent in assumed void fraction distribution
N	number of sample
R	pipe radius
R_i	radius of inner pipe for annulus
R_o	radius of outer pipe for annulus
R_p	radial position where local void fraction becomes zero
r	radial coordinate from pipe center
s_d	standard deviation
v	velocity
v_{gj}	drift velocity
v_r	relative velocity between phases
$\overline{v_r}$	difference between void fraction weighted mean velocities
x_{WP}	bubble-layer thickness

Greek

α	void fraction
$\langle \alpha_{BB} \rangle$	area-averaged void fraction when distribution parameter reaches unity
$\langle \alpha_{crit} \rangle$	critical area-averaged void fraction
$\langle \alpha_{SB} \rangle$	area-averaged void fraction at transition between subcooled boiling and bulk boiling regions
ε	quantity of a specific parameter
$\Delta\rho$	density difference between phases
ρ	density
σ	surface tension
ω	weighting factor

Subscript

0	value at pipe center
BB	bulk boiling
SB	subcooled boiling
f	liquid phase
g	gas phase
$I - M$	Ishii and Mishima's model
$RELAP5$	RELAP5 formulation
$TRACE$	TRACE formulation
W	value at wall

Mathematical symbols

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

appears when local relative velocity is area-averaged but due to the lack of sufficient local void fraction data at the early stage of the one-dimensional interfacial drag force formulation, the void fraction covariance was ignored [22]. Such insufficient formulation of the one-dimensional interfacial drag force in dispersed two-phase flow has been utilized until now.

From a viewpoint of the great importance of the void fraction covariance, Brooks et al. [23] collected local void fraction data taken for upward and downward adiabatic air-water flows in vertical pipes and annulus. The extensive database covers the channel diameter from 1.27 to 15.2 cm and the pressure from 0.1 to 0.603 MPa. Based on the data, Brooks et al. [23] developed empirical correlations of the void fraction covariance for adiabatic two-phase flow in a vertical pipe and a vertical annulus. Dandekar and Brooks [24] collected local void fraction data taken for upward boiling water and R113 two-phase flows in vertical annuli and upward adiabatic condensing/flashing steam-water flows in a vertical annulus. The extensive database covers 3 different flow channel dimensions and the pressure from 0.1 to 0.953 MPa. Based on the data, Dandekar and Brooks [24] developed empirical correlations of the void fraction covariance for boiling flow in a vertical annulus. These systematic researches clearly indicate that neglecting void fraction covariance causes significant underestimation of relative velocity between phases.

One-dimensional nuclear thermal-hydraulic system analysis codes have been used to simulate thermal-hydraulic behaviors in various flow channels including a rod bundle and a pipe. This requires accurate constitutive equations to predict the void fraction covariance in a rod bundle and a pipe. In view of the above, this study is aiming at developing a reliable constitutive equation of the void fraction covariance and relative velocity covariance for upward subcooled and bulk boiling flows in a vertical pipe under prototypic nuclear reactor pressure condition. This study is

expected to provide the important constitutive equation to be implemented in one-dimensional nuclear thermal-hydraulic system analysis codes.

2. Existing work of void fraction covariance and relative velocity covariance

2.1. Definition of void fraction covariance and relative velocity covariance in dispersed two-phase flow

Brooks et al. [21,23] have provided a detailed introduction of void fraction covariance and relative velocity covariance. The interfacial drag force formulation in one-dimensional nuclear thermal-hydraulic system analysis codes should include the void fraction covariance and relative velocity covariance. In what follows, some detailed explanations are given for the formulation of the interfacial drag force for dispersed two-phase flow, and the definitions of "void fraction covariance" and "relative velocity covariance" are given in the process of the formulation.

Under a steady-state condition, the interfacial drag force, M_{ig}^D, is locally balanced with the buoyancy force as:

$$M_{ig}^D = -\alpha(1 - \alpha)\Delta\rho g, \tag{1}$$

where α, $\Delta\rho$, and g are, respectively, the void fraction, density difference between phases, and gravitational acceleration. Under the steady-state condition, the general form of the interfacial drag force is given as:

$$M_{ig}^D = -C_i|v_r|v_r, \tag{2}$$

where C_i and v_r are, respectively, the drag coefficient and relative velocity between phases. The one-dimensional form of Eq. (1) is represented by: