



Modeling of void fraction covariance in two-phase flows with phase change



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ABSTRACT

The void fraction covariance, which accounts for non-uniformity in the void fraction distribution in the one-dimensional two-fluid model, has been shown to be critical for accurate prediction of the area-averaged interfacial drag force. Defined as the ratio of area-averaged square of void fraction to the square of the area-averaged void fraction, the void fraction covariance, which historically has been treated as unity, is analyzed for gas-dispersed flows undergoing phase change. The covariance is shown to be very large in subcooled boiling where the void fraction is highly non-uniform, which highlights the benefit of the bubble layer thickness averaged two-fluid model. In condensing and flashing flow the void fraction covariance is shown to be significant, having a very large impact on the interfacial drag force as the void fraction increases. The void fraction covariance is studied for its impact on the classical area-averaged two-fluid model, bubble-layer averaged two-fluid model, and area-averaged multiple bubble group two-fluid model. A simple set of correlations are proposed for easy implementation into the existing drag equations, and are shown to agree very well with experimental data.

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1. Introduction

Two-phase flows are found commonly in nature as well as a wide range of engineering applications and have, therefore, been studied extensively. Due to the complexity of the flow fields and phase interactions, two-phase flow is notoriously difficult to simulate and requires either very large computational resources or significant simplifying assumptions. Often, complete three dimensional simulation of the flow field is impractical and an area-averaged set of balance equations is used to describe the transport of mass, momentum and energy. The flow properties, when averaged over the flow cross-sectional area, reduce the study to a single spatial dimension. However, the process of area-averaging makes the information within the cross-section of the flow largely unavailable. Using proper averaging techniques, the distribution effect of the transport properties within the cross-section become absorbed into covariances. In many instances the variation of the properties in the cross-section are small and, therefore, can be simply given by their average values. However, between properties where the distribution is highly non-uniform there can be a large covariance between the averages. One classical

example of covariance in two-phase flow is the distribution parameter [1] which accounts for the difference in the product of the average void fraction and volumetric flux, and the average of the product of void fraction and volumetric flux. The distribution parameter essentially accounts for the non-uniformity of the flow properties (i.e. void fraction and volumetric flux) when area-averaging the flow field to find the proper average gas velocity. The distribution parameter was derived by applying proper averaging laws to the flow field [1], and this simple covariance term has proved to be instrumental in one-dimensional two-phase flows [2,3]. It is this same fundamental concept that necessitates the study of the void fraction covariance.

The area-averaged two-fluid model [4] is relied upon for many engineering applications and most widely used in the analysis of two-phase flows in nuclear reactor systems. The two-fluid model treats each phase separately with their own mass, momentum, and energy balance equations unlike the more simplified homogeneous, slip flow, or drift-flux models. The two velocity fields allow accurate modeling of the two phases, including weakly coupled conditions. However, complexity of the governing equations increases significantly [5]. Interfacial transfer terms (i.e. net vapor generation, interfacial drag, interfacial shear, interfacial heat transfer, etc.) couple the balance of mass, momentum, and energy at the interface between the phases and largely determine the accuracy of the two-fluid model. In order to improve the modeling of the

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Nomenclature

a_i	interfacial area concentration
C_α	covariance factor
C_0	distribution parameter
C_D	drag coefficient
C_α	void fraction covariance
M_{ig}^D	interfacial drag force
R	outer radius of annulus
R_0	inner radius of annulus
v_r	relative velocity
x_{BL}	bubble layer thickness

Greek symbols

α	void fraction
ψ_{sf}	drag shape factor
ρ	density

Mathematical symbols

$\langle \langle \rangle \rangle$	void fraction weighted area-averaged quantity
$\langle \rangle$	area-averaged quantity
$\langle \rangle_{BL}$	bubble layer averaged quantity
$ $	magnitude of quantity

Subscripts

1	group-1 bubbles
2	group-2 bubbles
12	inter-group
∞	asymptotic value
BL	bubble layer
f	liquid phase
g	gas phase

interfacial transfer terms, the two-fluid model has also been expanded to consider multiple bubble groups due to the dependence on bubble shape [6].

In the area-averaged two-fluid model, the interfacial drag force remains the most critical constitutive model as it couples the momentum of each phase [5,7]. Recent work has presented the correct area-averaged interfacial drag force for the traditional two-fluid model and multi-group two-fluid model [8]. It has been shown that the area-averaged interfacial drag force is dependent on the covariance stemming from the average of the squared void fraction, through the area-averaged relative velocity. This covariance accounting for the non-uniform distribution in void fraction within the averaging plane is the void fraction covariance. Recent work [9,10] has shown that the traditional approach of assuming the void fraction covariance of unity [11], can lead to significant under-prediction of the interfacial drag force and, therefore, void fraction covariance must be characterized for various two-phase flow conditions.

The void fraction covariance has been studied for adiabatic vertical gas-dispersed flows in a pipe and annulus under upward and downward flow conditions for a wide range of liquid and gas flow rates. The effect of the void fraction covariance on the area-averaged relative velocity was shown to be significant across flow regimes and particularly large in conditions where the void fraction distribution within the flow area is significantly non-uniform [10]. In adiabatic air–water flows the distribution of the phases within the averaging plane is determined by the lateral forces acting at the interface between the phases. These forces, including the lift force, turbulent dispersion force, and wall force, can lead to significant non-uniformity in the void fraction profile such as wall-peaking in bubbly flows and center-peaking in cap/slug/churn-flows [12,13]. However, in flows with phase change, the non-uniformity in the void fraction can be enhanced by mass transfer between the phases. The bubble layer thickness model [14] was specifically developed to reduce the covariance in area-averaging the two-fluid model in subcooled boiling. In subcooled boiling the gas phase is produced and can only exist near heated surface, resulting in a drastic wall peaked profile. By defining the two-phase region from the subcooled single phase liquid region, the bubble layer thickness model provides the proper averaging domain for the two-fluid model.

Considering the impact of phase change on the distribution of void fraction within the flow cross-section, it is expected that these flows will have a significant void fraction covariance which must be accounted for in order to properly simulate the flow with the area-averaged two-fluid model. Therefore, a new model for void

fraction covariance in phase-change flows is proposed. The new model is intended to significantly reduce the error in the estimation of void fraction covariance which would consequently reduce the error in the estimation of relative velocity and interfacial drag force. The model includes boiling, condensing, and flashing flows and can be easily implemented in the modeling of the area-averaged interfacial drag force.

2. Background

2.1. Void fraction covariances

In the area-averaged two-fluid model, interfacial drag force is the most critical model as it accounts for momentum coupling between the phases [5,7]. The interfacial drag force is given by [4,8],

$$\langle M_{ig}^D \rangle = -\frac{1}{8} C_D \rho_f \psi_{sf} \langle a_i \rangle | \langle v_r \rangle | \langle v_r \rangle \quad (1)$$

where C_D is the drag coefficient, ρ_f is the density of liquid phase, ψ_{sf} is the drag shape factor, $\langle a_i \rangle$ is the area-averaged interfacial area concentration, $\langle v_r \rangle$ is the area-averaged relative velocity and $| \langle v_r \rangle |$ is the absolute value of area-averaged relative velocity. Therefore, the area-averaged local relative velocity is critical for one-dimensional drag force. Even small error in the relative velocity can have large impact on interfacial drag.

Area-averaged local relative velocity was recently shown [9] to be,

$$\langle v_r \rangle = C_\alpha \left(\frac{1 - C_0 \langle \alpha \rangle}{1 - \langle \alpha \rangle} \langle \langle v_g \rangle \rangle - C_0 \langle \langle v_f \rangle \rangle \right) \quad (2)$$

where C_0 is the distribution parameter, $\langle \alpha \rangle$ is the area-averaged void fraction, and $\langle \langle v_g \rangle \rangle$ and $\langle \langle v_f \rangle \rangle$ are void fraction weighted area-averaged gas and liquid velocities respectively. The covariance factor, C_α , is given by,

$$C_\alpha \equiv \frac{1 - \langle \alpha \rangle}{1 - C_\alpha \langle \alpha \rangle} \quad (3)$$

Here, the term C_α is called void fraction covariance and is given by,

$$C_\alpha \equiv \frac{\langle \alpha^2 \rangle}{\langle \alpha \rangle^2} \quad (4)$$

where $\langle \alpha^2 \rangle$ is area-average of square of void fraction. Through analogy to the well established distribution parameter [10], the covariance is related to physical parameters in a form of an asymptotic

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