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A correlation for interfacial area concentration in high void fraction flows in large diameter channels

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HIGHLIGHTS

- An algebraic correlation for interfacial area concentration is derived.
- Correlation is applicable beyond bubbly flow in large diameter pipes.
- Includes models for Sauter mean diameter for two groups of bubbles.
- Data of Schlegel et al. (2012, 2014) is predicted with 22.6% error.

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ABSTRACT

Two phase flows exist as a part of many industrial processes, including chemical processes, nuclear reactor systems, and heat exchangers. In all of these applications the interfacial area concentration is an important parameter for evaluating the interactions between the phases, including drag forces, heat transfer or chemical reaction rates. Many models for interfacial area concentration exist for dispersed bubbly flows; however this type of flow only exists at relatively low void fractions. Very few correlations exist for the prediction of cap-turbulent, slug, or churn-turbulent flows. In this paper a new correlation for predicting the interfacial area concentration beyond bubbly flows in large diameter pipes is derived using a two-bubble-group method (spherical and distorted bubbles as Group-1 bubbles and cap and churn-turbulent bubbles as Group-2 bubbles) and the two-group interfacial area transport equation. The derivation assumes steady state and fully developed flow, and is based on interfacial area transport source and sink terms for large diameter pipes developed by Smith et al., 2012a. Int. J. Heat Fluid Flow 33, 156–167. The resulting equations can be used to predict the void fraction for each group of bubbles and the Sauter mean diameter for each group of bubbles in addition to the total interfacial area concentration. The model is then benchmarked based on the data collected by Schlegel et al., 2012. Exp. Therm. Fluid Sci. 41, 12–22; Schlegel et al., 2014. Int. J. Heat Fluid Flow 47, 42–56. It is found that the correlation predicts the data for Sauter mean diameter of Group 1 bubbles with RMS error of 23.3% and bias of +1.83%. For Group 2 bubbles the RMS error is 24.0% and the bias is +5.35%. This indicates that the correlation somewhat over-predicts the bubble sizes. In spite of this the prediction error remains reasonable compared to the accuracy of previous correlations, and given that the experimental uncertainty can be as high as 15% for some flow conditions. The RMS error and bias in the total interfacial area concentration are 22.6% and −4.29%, respectively. This is consistent with the over-prediction of the Sauter mean diameters, but again is reasonable considering the experimental uncertainty and the prediction error of previous correlations. The model is also able to predict the trends found in the experimental data with varied liquid and gas velocities, representing a large improvement over previous modeling efforts. An expanded database of accurate interfacial area concentration measurements at higher pressures would allow further improvement of the model benchmark and expansion of the range of applicability of the model.

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1. Introduction

Two-phase flows exist as part of industrial processes in many fields. In chemical processing or cooling applications, two-phase flows easily provide a large surface area for efficient chemical reactions or heat transfer. The amount of surface area available for heat or mass transfer, or interfacial geometry, is described quantitatively by the interfacial area concentration. This makes the interfacial area concentration one of the key parameters necessary for predicting the performance of such systems. This importance has been known for decades and has been investigated a great deal.

For chemical reaction processes and for heat transfer properties, low void fraction bubbly flow systems have been frequently used (Akita and Yoshida, 1974). For chemical reaction processes this region provides the highest interfacial area concentration, and due to the small bubble sizes in this flow regime the gas phase can react more completely before leaving the system. For heat transfer systems this region allows nucleate boiling, which allows for very high heat transfer rates. Thus most of the work for developing interfacial area concentration models has focused on this region (Hibiki and Ishii, 2001a, 2002; Hibiki et al., 2006; Lin and Hibiki, 2014). However high void fraction churn-turbulent and annular flows are also important in many industrial processes. Phase separation, such as separation of gas and oil in the petrochemical industry, typically occurs in the churn-turbulent flow regime and can be strongly affected by the fluid particle size and shape distribution. Churn-turbulent and annular flows are also commonly found in heat transfer applications such as nuclear reactor systems or industrial boilers. These types of flows have not been investigated or modeled as thoroughly (Hazuku et al., 2007). This is largely due to their complex behavior and the associated modeling challenges.

In order to evaluate phase separation or the transfer of mass, momentum and energy it is possible to use a two-fluid or drift-flux model coupled to a correlation for interfacial area concentration (Ishii and Hibiki, 2010). For these high-void-fraction processes current modeling methods utilize very simple ad-hoc models (Spore et al., 1993; Thermal Hydraulics Group, 1998). Unfortunately these models are not physically realistic and result in very high error when predicting two-phase flow systems. Recent efforts have been made to develop an interfacial area transport equation for use in various flow regimes (Hibiki and Ishii, 2000a; Fu and Ishii, 2003a,2003b; Sun et al., 2003; Smith et al., 2014) or to use various population balance approaches (Lehr and Mewes, 2001; Yao and Morel, 2004; Sari et al., 2009; Huh et al., 2006; Liao et al., 2011). However these transport equations require detailed *a priori* knowledge of the inlet conditions, either from another simulation or from experimental data, and such information may not be available for some applications. They are also computationally intensive, requiring complex computational systems and the inclusion of additional transport equations in the computational approach. This does not lend the transport equation approach to some engineering design and analysis situations where such a high degree of accuracy and detail is not necessary. Often simplified models can be used to provide more economical solutions or early in the design process to make informed decisions. To address these needs, a correlation should be developed based on physical arguments to capture the behavior of the interfacial area concentration. Some progress has been made in this area by Ozar et al. (2012), however their model is empirical and may not reflect the physical dependencies of two-phase flows completely.

There is also the issue of flow channel geometry. The analyses present in the literature have largely focused on interfacial area concentration in round tubes with small diameter (Hibiki and Ishii, 2001a, 2002; Hibiki et al., 2006). Small diameter tubes have a dimensionless diameter that satisfies the condition (Schlegel et al., 2010)

$$D_h^* = \frac{D_h}{\sqrt{\frac{\sigma}{g\Delta\rho}}} \leq 18 \tag{1}$$

This corresponds to about 5 cm for air–water flows at atmospheric pressure and temperature. These types of flow systems are characterized by the presence of a stable slug flow regime, with regularly-shaped Taylor slug bubbles. Some work has also been performed for annulus flow channels (Ozar et al., 2012), which are often used to simulate nuclear reactor rod bundles. However many industrial systems have dimensionless diameters which are much larger, ranging from 55 to as much as 500. These systems are considered to be large diameter systems (Brooks et al., 2012). Large diameter systems are characterized by the inability to sustain stable Taylor slug bubbles which occupy the entire cross-sectional area of the channel. Almost no work has been done in this area due to the complexity of analyzing such flows, despite their importance in many engineering systems. Dimensionless pipe diameters between 18 and 52 are considered a transition region between small diameter and large diameter systems.

The pipe diameter can have a significant effect on the interfacial area concentration for void fractions higher than 0.3. In small diameter pipes the slug bubble relative velocity increases as the pipe diameter increases (Ishii, 1977). This reduces the void fraction, thereby resulting in decreased interfacial area concentration. In the transition region between small and large diameter the slug bubbles begin to become unstable, resulting in a higher bubble number density and smaller cap bubbles. This leads to increased interfacial area concentration. In large diameter systems the diameter is expected to have negligible effect on the interfacial area concentration, as very little change is expected in the bubble behavior at various diameters. For dispersed bubbly flow conditions where no cap or slug bubbles are present the pipe diameter is expected to have very limited influence on the bubble diameter. This effect will be mostly through changes in turbulence behavior as described by the Reynolds number.

In order to address these challenges research has been undertaken to accomplish several major tasks:

(1) Briefly summarize some unique characteristics of large diameter pipe flows;
(2) Analyze and evaluate the performance of existing interfacial area correlations;
(3) Develop an interfacial area correlation applicable beyond bubbly flow conditions;
(4) Benchmark the correlation using data collected in large diameter channels.

2. Two-phase flows in large diameter channels

In large diameter channels, stable Taylor cap/slug bubbles are unable to occupy the entire cross-section of the flow channel. When a cap bubble approaches a certain maximum diameter the surface of the bubble is unable to support the weight of the water above it due to Taylor instability. Generally this maximum bubble size is given as a dimensionless diameter of 30 to 52 (Kataoka and Ishii, 1987; Brooks et al., 2012). If the pipe size is smaller than this value, then the bubble occupies the entire cross-section before reaching the stability limit and can form a stable slug bubble. If the pipe is larger than this limit then any bubbles formed which are larger than the stable size limit will be subject to instability and break apart. It should be noted that it is still possible to form bubbles larger than the stable size limit through coalescence of large bubbles. However the resulting bubble will be unstable and will quickly disintegrate rather than form a stable gas slug.