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Characteristics of two-phase flows in large diameter channels

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ABSTRACT

Two-phase flows in large diameter channels have a great deal of importance in a wide variety of industrial applications. Nuclear systems, petroleum refineries, and chemical processes make extensive use of larger systems. Flows in such channels have very different properties from flows in smaller channels which are typically used in experimental research. In this paper, the various differences between flows in large and small channels are highlighted using the results of previous experimental and analytical research. This review is followed by a review of recent experiments in and model development for flows in large diameter channels performed by the authors. The topics of these research efforts range from void fraction and interfacial area concentration measurement to flow regime identification and modeling, drift-flux modeling for high void fraction conditions, and evaluation of interfacial area transport models for large diameter channels.

1. Introduction

Two-phase flows in large diameter channels play key roles in a number of industrial systems and processes. Oil pipelines and refineries, bubble column reactors, nuclear energy systems, and many other industrial efforts make extensive use of gas-liquid flows to for various applications including to promote chemical reactions between gases and dissolved reactants and to promote effective cooling through boiling and natural circulation.

These large diameter systems are defined as systems where stable slug bubbles are unable to form. Slug bubbles occupy the entire cross-section of the flow channel. In large diameter channels such bubbles quickly collapse due to Rayleigh-Taylor and Kelvin-Helmholtz instabilities on the upper surface. This instability and a lack of stable slug bubbles means that flows in large diameter channels behave much differently than flows in small diameter channels. A detailed review of the unique properties of flows in large diameter channels can be found in the work of Shen et al. (2014).

The instability in the bubble surface results in the collapse of the upper surface of the bubble, leading to breakup. This limits the ability of bubbles to continue to grow. The defining feature of large diameter channels is that the channel size is larger than this maximum bubble diameter. As discussed by Kataoka and Ishii (1987) and Hibiki and Ishii (2003), this results in the relative velocity between the gas and liquid phases being insensitive to the channel diameter in large diameter systems.

These effects have a strong effect on the flow regimes present in large diameter channels (Ohnuki and Akimoto, 2000; Schlegel et al., 2013). While the terminology varies depending on the researcher, the 'slug flow' regime in small diameter channels is replaced by a 'cap-turbulent' transition region which represents a transition between dispersed bubbly flow and fully-churn turbulent flow. These flow regime transitions are much more gradual than in small diameter channels, where the transition to slug flow can occur very abruptly.

Another key difference between large and small diameter channels is the behavior of turbulence. Turbulence is produced at much larger length scales in large diameter channels, which can result in bubbles being carried along in groups and enhancing the turbulent mixing of the two phases (Ohnuki and Akimoto, 2001). The existence of a large number of cap bubbles rather than a small number of slug bubbles can also significantly increase the turbulence induced by the relative velocity between the phases (Serizawa and Kataoka, 1990). Turbulence is a key parameter in determining the interfacial area concentration, and significant increases in turbulence can act to increase the interfacial area concentration (and reduce the average bubble size) (Akita and Yoshida, 1974). As the strength of turbulent eddies increases, they impart more energy to the interface when they interact with bubbles. This increases the likelihood that the interface will deform sufficiently to result in the breakup of a bubble into two smaller bubbles. The bubble-induced turbulence is extremely important in large diameter

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Nomenclature

$\langle a_i \rangle$	interfacial area concentration [1/m]
C	constant in the IATE [–]
D	diameter [m]
$\langle j_f \rangle$	liquid superficial velocity [m/s]
$\langle j_g \rangle$	gas superficial velocity [m/s]
z	axial position [m]
$\langle \alpha \rangle$	void fraction [–]

channels, as shear-induced turbulence decreases with increasing diameter and may be insignificant for very large flow channels.

The distribution of the phases is also very different in large diameter channels. Because the channel diameter is larger, the velocity gradients near the wall are generally smaller. This leads to reduced lift force on the gas phase. Combined with turbulent mixing, this tends to flatten the void fraction profile and reduce or eliminate the near-wall void peak noted in small diameter channels (Hibiki and Ishii, 2001; Shen et al., 2005; Smith et al., 2012a).

Finally, the tendency of large cap bubbles to concentrate in the center region of the pipe can enhance the local liquid and gas velocities in the center of the pipe. When the total liquid flow rate is small, this can require negative liquid velocities near the channel wall in order to maintain the total liquid flux (Ohnuki and Akimoto, 2000; Smith et al., 2012a; Ohnuki et al., 1995). This local or secondary recirculation can result in extremely large variations in the liquid and gas velocity near the wall, making near-wall measurement of bubble properties difficult.

Several studies have been performed to measure two-phase flows in large diameter channels. A very thorough review of these efforts can be found in the work of Shen et al. (2014). Recent measurements to identify flow regime, measure the area averaged void fraction, and measure the interfacial area transport properties for air-water two-phase flows have been performed by Schlegel et al. (2013, 2009, 2012, 2014a) and Smith et al. (2012a). These experiments were performed in test facilities ranging in diameter from 0.101 m to 0.304 m, with measured void fractions ranging from 0.1 to 0.9. Area-averaged void fraction was measured using electrical impedance void meters. Using a self-organized neural network, the impedance void meter signals were used to classify each flow condition as bubbly, cap-turbulent, or churn-turbulent flow. Local void fraction and interfacial area concentration profiles were measured using four-sensor electrical resistivity probes.

This paper will review recent research on various topics important for modeling flows in large diameter channels, including:

- The modeling of flow regime and the evaluation of flow regime models for large diameter channels using experimental observations.
- An evaluation of drift-flux correlations for large diameter channels and recent improvements to improve the performance of the drift-flux model at elevated void fractions in large diameter channels.
- A review of recent contributions of interfacial area concentration data at relatively high void fractions for evaluation of interfacial area concentration models.
- A summary of minor modifications to the interfacial area concentration models that must be made to account for new data at high void fractions, which was not available when the models were initially developed.

2. Flow regimes in large channels

2.1. Modeling flow regime

Schlegel et al. (2009) recommended simple models for the flow regime boundaries for large diameter channels. For the transition from bubbly to cap-turbulent flow, a constant void fraction of 0.3 was recommended. This value was determined from the packing of spheres with a pitch of two bubble diameters in a tetrahedral lattice. For the transition from cap-turbulent to churn-turbulent flow a constant void fraction of 0.51 was recommended. Again, this value is based on the packing of cap-shaped bubbles with a pitch of two bubble diameters in addition to the packing of small spherical bubbles. The entrainment condition for the transition from churn-turbulent to annular flow given by Mishima and Ishii (1984) is recommended for large diameter channels, as no liquid film exists to allow the flow reversal mechanism.

2.2. Evaluation with experimental data

These flow regime boundaries are shown in Figs. 1–3 (Shen et al., 2014) along with the data of Schlegel et al. (2013), Ohnuki and Akimoto (2000) and Smith et al. (2012a). It can be seen that the model given by Schlegel et al. (2009) performs reasonably well at predicting the flow regime transitions determined by a neural network (Schlegel et al., 2013; Smith et al., 2012a). Fig. 1 shows that the data of Schlegel et al. (2013) agrees very well with the proposed flow regime transitions. This figure includes flow conditions for pipe diameters from 0.152 m to 0.304 m and axial locations representing z/D values from 8 to 34. Some overlap between the identified flow regimes is shown, however this is due to the gradual transition between flow regimes. In this figure, the flow regimes are given as *Flow Regime 1*, *Flow Regime 2*, and *Flow Regime 3* rather than using the traditional flow regime names. This is because the data was evaluated using a self-organized neural network. Because a self-organized network was used, no desired flow characteristics for each group were input during the classification process. The resulting categories are based only on internal similarities in the measured data. Because of this, there is no a priori knowledge of the flow regime. Including a name and description of the resulting flow classifications would be a construct of the authors – discussion and evaluation – rather than a reflection of

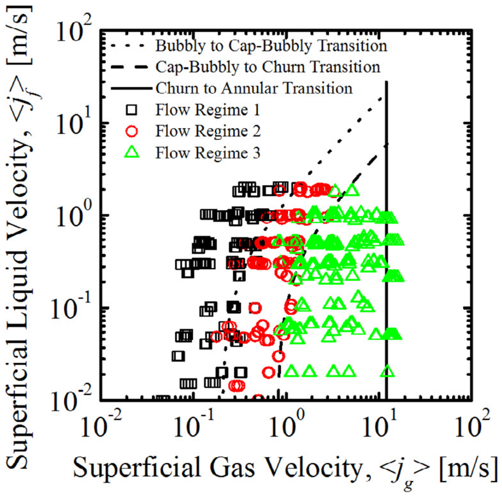

Fig. 1. Experimental flow regime identification of Schlegel et al. (2013).

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