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Review

Databases of interfacial area concentration in gas–liquid two-phase flow

Chih-Hung Lin [a], [*], Takashi Hibiki [b]

[a] Center for Energy and Environment Research, National Tsing-Hua University, No. 101, Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan, ROC
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, USA

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ABSTRACT

Extensive literature review has been performed to provide the most updated information on local interfacial area measurements. The review begins with a brief introduction of various available experimental techniques which have been utilized for interfacial area measurement. Since the local sensor probe method is the most widely utilized technique, the basic concepts of this method are discussed. A deficiency in the mathematical formulation converting interfacial velocity information into interfacial area concentration information is pointed out. The correct mathematical formulation is properly introduced and some pre-cautions are recommended for when measured interfacial area concentration is utilized for benchmarking the interfacial area transport equations and 1D and 3D thermo-fluid dynamic simulation codes. Extensive literature review has been conducted to identify available interfacial area data. The flow conditions of the available data include adiabatic and diabatic conditions, various channel geometries such as round channel, annulus channel, rectangular channel, subchannel, and rod bundles, elevated pressure conditions, various channel size conditions, wide-range flow regime conditions, and normal gravity and microgravity conditions. In spite of tremendous efforts devoted in the past 30 years, further systematic experimental effort is essential to establish solid experimental databases for benchmarking the interfacial area transport equations and 1D and 3D thermo-fluid dynamic codes.

1. Introduction

The two-fluid model (Ishii and Hibiki, 2010) which considers phases separately is widely utilized in 1D nuclear-thermal hydraulics system analysis codes such as TRACE (TRACEV5.0 User's Manual – Volume 2: Modeling Guidelines, 2008) and RELAP (RELAP5/MOD3.3, 2001) and 3D Computational Fluid Dynamics codes such as CFX and Fluent. Various closure relations are required to mathematically close the two-fluid model. Among them, interfacial transfer terms are some of the most important terms in the two-fluid model. The interfacial transfer terms are commonly represented as the product of the interfacial area concentration and a driving force. The interfacial area concentration in a 1D code has been given by an empirical correlation which is not capable of predicting the interfacial area concentration dynamically and depends on the flow regime. The interfacial area transport equation has been proposed to overcome such problems (Kocamustafaogullari and Ishii, 1995). The initial focus of the interfacial area transport equation was bubbly flow and the one-group bubble approach which was successfully applied to the bubbly flow regime (Wu et al., 1998; Hibiki and Ishii, 2000). The two-group approach treating bubbles was utilized to extend the applicable range of the interfacial area transport equation to non-bubbly flow regimes (Hibiki and Ishii, 2000). The modeling efforts of source and sink terms in the interfacial area transport equation were reviewed extensively in (Hibiki and Ishii, 2009). The accuracy of these interfacial area transport models which determines the fidelity of computational codes should be validated by extensive experimental data taken in various test conditions.

The verification and validation (V & V) process is indispensable in demonstrating the fidelity of computational codes (Oberkampf and Trucano, 2008). In V & V, validation experiments are expected to play a vital role to ensure the accuracy of computational codes. Oberkampf and Trucano (2008) classified traditional experiments into three classical categories and one additional category for V & V. They are (1) scientific discovery experiments, (2) model

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[*] Corresponding author. Fax: +886 3 5715131x42859.
E-mail addresses: chihhunglin@mx.nthu.edu.tw, gp6ej3@gmail.com (C.-H. Lin).

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calibration experiments, (3) proof tests or system performance tests, and (4) validation experiments. The validation experiments are performed to determine the predictive accuracy of a computational model. Measurements of interfacial area concentration have traditionally been conducted in the category of (1) to secure the originality of research. The local sensor probe method has often been utilized to measure the interfacial area concentration. The key to this method is to translate measured interfacial velocities into interfacial area concentrations through a mathematical formula. The validity of the mathematical formula is essential to the interfacial area measurement but has not been systematically discussed in the past. Before migrating our experimental endeavor towards the category of (4), the experimental efforts extensively performed in the past 30 years are to be reviewed and summarized.

The purpose of this paper is two-fold. The first objective is to provide an extensive review of existing techniques for measuring interfacial area concentration and to discuss a mathematical formula to convert measured interfacial velocities into interfacial area concentrations. The second objective is to provide a comprehensive review of existing databases of interfacial area concentration measurements. Those databases are expected to be used for the development or validation of an interfacial area transport equation which reflects the true transfer mechanisms in two-phase flow.

2. Measurement techniques of interfacial area concentration

2.1. Available techniques to measure interfacial area concentration

Various measurement techniques are available to measure interfacial area concentration. In this section available measurement techniques are briefly reviewed.

The most common and straightforward technique is the **photographic method**. To use this method, some device to correct the reflection effect at a test channel wall should be installed and some geometrical assumption of a bubble shape such as ellipsoidal bubbles should be made to compute interfacial area concentration from a one-directional image. Stereo-imaging using two simultaneous images taken with different angles provides a much more accurate measurement of interfacial area concentration (Takamasa et al., 2003a,b). However, the applicable range of the photographic method is limited to relatively low void fraction. In order to apply this method to high void fraction, bubble size near the wall is assumed to be uniform along the test channel and total interfacial area concentration is computed by the bubble size and void fraction, measured by another method, through $a_i = 6\alpha/D_{Sm}$. This approach is often utilized to measure interfacial area concentration in bubble column.

The **chemical absorption method** is also common in chemical engineering research. This technique is developed based on the fact that mass transfer rate is proportional to interfacial area concentration (Radhkrishnan and Mitra, 1984). The applicability of this method is limited to measurement of volume averaged interfacial area concentration.

The **dynamic gas disengagement method** utilizes bubble rising velocity characteristics (Hean et al., 1996). The bubble rising velocities in some bubble shape regimes are expressed as a function of bubble size. Measuring bubble rising velocity yields the bubble size. The bubble rising velocity is often measured by high-speed video. Interfacial area concentration is computed by the bubble size and void fraction measured by another method.

The **light attenuation method** is based on scattering gas bubbles in liquids. Several researchers have performed experiments to measure interfacial area concentration using this technique (Calderbank, 1958). Ultrasound attenuation and scattering techniques are also utilized to measure interfacial area concentration (Bensler, 1990). These methods are applied to line-averaged or area-averaged interfacial area concentration measurement.

A much more sophisticated technique is available to measure local instantaneous interfacial area concentration using **high-speed X-ray tomography** (Misawa et al., 2003). Unfortunately, the temporal and spatial resolutions may not be sufficient to capture small bubble behavior. **Neutron radiography** can be utilized to visualize and measure gas–liquid two-phase flow in a metallic conduit or liquid metal two-phase flow. The neutron radiography method has been applied to measure interfacial area concentration of annular flow in a narrow rectangular channel (Hibiki et al., 1995).

A **Laser focus displacement meter** is available to measure the liquid film in annular flow (Hazuku et al., 2007). The measured liquid film thickness can be converted into interfacial area concentration. This technique is applicable to measure interfacial area concentration for a relatively smooth interface.

The **Wire-mesh sensor technique** was developed to measure local interfacial area concentration (Prasser, 2007). This technique uses a wire-mesh installed in a flow channel. Unfortunately, the installed wire-mesh acts as a flow obstacle and thus this technique may not be applicable to measurement in a secondary flow dominated flow such as two-phase flow in pool conditions.

Conductivity and optical probe techniques are widely utilized to measure local time-averaged interfacial area concentration (Hibiki et al., 1998; Kim et al., 2000; Shen et al., 2012a,b). These techniques utilize single-sensor probes (Mizushima et al., 2013), double-sensor probes (Hibiki et al., 1998), four-sensor probes (Kim et al., 2000) and sometimes five-sensor probes (Euh et al., 2001). These techniques measure bubble interface velocity and convert it into interfacial area concentration through some mathematical relations (Kataoka et al., 1986).

The above techniques of interfacial area concentration measurement have both advantages and disadvantages. The double-sensor probe and four-sensor probe methods are widely utilized to measure local time-averaged interfacial area concentrations in the bubbly flow regime and beyond bubbly flow regimes, respectively, which provide excellent database to benchmark current 1D nuclear system analysis codes as well as 3D CFD simulation codes. Therefore, a mathematical background on the double-sensor probe method and four-sensor probe method is briefly reviewed.

2.2. Theoretical foundation of interfacial area concentration measurement using probe method

2.2.1. Mathematical relationship between bubble rising velocity and interfacial area concentration for simplified case

Consider spherical bubbles rising through the same distance in the vertical upward direction to simplify the problem, see Fig. 1. The bubble rising velocity and measurement time are denoted by v_g and Δt, respectively. Bubbles within a distance L from the needle can hit the needle for a time Δt and the distance is given by

$$L = v_g \Delta t. \tag{1}$$

The void fraction within a distance L is expressed as

$$\alpha = N\frac{(2/3)D_b}{L}, \tag{2}$$

where N and D_b are the bubble number and bubble diameter respectively. $2/3D_b$ in Eq. (2) is the average bubble chord length of a bubble with the diameter of D_b. Here it is assumed that a portion of the vertically rising spherical bubbles hit the probe with equal probability. Using the geometrical relationship of $a_i = 6\alpha/D_{Sm}$, the following equation can be obtained as (Herringe and Davis, 1976; Wu and Ishii, 1999)