Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
International Journal of Multiphase Flow 31 (2005) 593–617
International Journal of Multiphase Flow
www.elsevier.com/locate/ijmulflow

Methodological improvement of an intrusive four-sensor probe for the multi-dimensional two-phase flow measurement

Xiuzhong Shen [a], Yasushi Saito [a], Kaichiro Mishima [a,*], Hideo Nakamura [b]

[a] *Research Reactor Institute, Kyoto University, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan*
[b] *Tokai Establishment, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan*

Received 11 June 2004; received in revised form 1 February 2005

Abstract

This paper aimed to improve the four-sensor probe methodology for the multi-dimensional two-phase flow measurement. We theoretically derived the interfacial measurement theorem relating the local instantaneous interfacial velocity to local measurable velocities of the multi-sensor probe in the improvement. Based on this theorem, theoretical measurement methods for the local instantaneous interfacial normal direction and the local time-averaged interfacial area concentration (IAC) using the four-sensor probe were presented. An interface-pairing signal-processing scheme was proposed to identify the same interfaces from the sequential signals detected by different sensors. The practical application of the improved IAC methodology to the two-phase flow in a vertical large diameter pipe showed that the four-sensor probes (together with the interface-pairing signal-processing scheme) could effectively measure the local time-averaged IACs with high effective interface percentages not only in the one-dimensional two-phase flow but also in the multi-dimensional two-phase flow. The measurement error analysis indicated that the errors from the bubble deformation and velocity variation due to the sensor piecing were negligible if we only applied the multi-sensor probe to the two-phase flow with the bubbles having much larger size than the sensor diameter. The total error from both the escaped and missing bubbles in the void fraction and IAC measurements was estimated at about 15.75% in the two-phase flow in a pool.

* Corresponding author. Tel.: +81 724 51 2449; fax: +81 724 51 2637.
E-mail address: mishima@rri.kyoto-u.ac.jp (K. Mishima).

0301-9322/$ - see front matter
doi:10.1016/j.ijmultiphaseflow.2005.02.003

Keywords: Interfacial measurement theorem; Interfacial normal direction; Interfacial area concentration; Four-sensor probe; Two-phase flow measurement

1. Introduction

One of the most characteristic features of two-phase flow is the existence of a multi-dimensionally moving interface between two phases that make theoretical predictions of flow parameters immensely more difficult than in single-phase flow. Thus, experimental measurements play a key role in providing information for design, and supporting analyses of system behavior. Since there is no effective ways for the multi-dimensional two-phase flow measurement up to now, it is very important to develop a method to measure the characteristics of the multi-dimensional two-phase flow.

Delhaye and Bricard (1994) pointed out that the geometric structure of a bubbly two-phase flow can be characterized by two of the three following parameters: the interfacial area concentration (IAC), the void fraction and the Sauter mean diameter. The IAC (a) is defined by the total interfacial area per unit mixture volume. According to Ishii (Ishii, 1975), the local time-averaged IAC at a fixed position in space $\mathbf{x}_0$ is given by

$$\bar{a}^t = \frac{1}{\Omega}\sum_l \frac{1}{|\mathbf{V}_{il}\cdot\mathbf{n}_{il}|}, \tag{1}$$

where Ω, l, $\mathbf{V}_{il}$ and $\mathbf{n}_{il}$ denote the time interval for averaging, the lth interface, the velocity vector of the lth interface, the surface normal unit vector of the lth interface at $\mathbf{x}_0$ when it passes through $\mathbf{x}_0$, respectively. The void fraction (α) is defined by the total gas phase volume per unit mixture volume. The Sauter mean diameter (d_{SM}) is given by the ratio of the volume and surface area of a typical bubble. There exists a classical expression for the three parameters, given by

$$\mathrm{d}_{SM} = \frac{6\alpha}{a}. \tag{2}$$

The intrusive multi-sensor resistance or optical probe methods for both the IAC and the void fraction measurements have been studied extensively in the past few decades. But the IAC measurement was developed from the void fraction measurement by taking advantage of the phase change signals and was much more complicated in methodology than the void fraction measurement. The basic principle for the IAC measurement with a multi-sensor probe was originally proposed by Kataoka et al. (1986). Numerous researchers showed their efforts to improve this original method in various ways. All of these IAC measurement studies using multi-sensor probes can be classified into two types, the double-sensor probe method (Kataoka et al., 1986; Hibiki et al., 1998; Wu and Ishii, 1999) and the four-sensor probe method (Kataoka et al., 1986; Revankar and Ishii, 1993; Kim et al., 2001; Euh et al., 2001). The former double-sensor probe method adopted several assumptions for bubble shape and bubble motion to enable the measurements and analyses of IAC. However, at the same time, these assumptions impose certain limitations on the application of the method. The most important and problematic assumptions are the following two ones. The first is that the bubble is spherical and the second is that the interfacial velocity can be approxi-