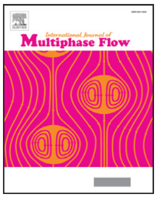
International Journal of Multiphase Flow 88 (2017) 238–250

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



Development of the droplet-capable conductivity probe for measurement of liquid-dispersed two-phase flow

Yang Liu[a], Xiaohong Yang[b], Qingzi Zhu[b], Peng Ju[b], Mamoru Ishii[b,*], J.R. Buchanan Jr[c]

[a] Nuclear Engineering Program, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[b] School of Nuclear Engineering, Purdue University, West Lafayette, IN 47907, USA
[c] Bechtel Marine Propulsion Corporation, Bettis Laboratory, West Mifflin, PA 15122, USA

ARTICLE INFO

Article history:
Received 21 August 2015
Revised 6 June 2016
Accepted 7 June 2016
Available online 18 October 2016

Keywords:
Conductivity probe
Droplets
Two-phase flow measurement
Interfacial area concentration

ABSTRACT

A new conductivity probe design has been developed in order to measure dispersed liquid particles in churn-turbulent and annular flows which cannot be detected by the conventional conductivity probes. The probe incorporates a common sensor near the measurement point to detect the local conductance signals between two sensor tips that are 150 μm apart. Once fully developed, the probe is capable of measuring local two-phase parameters of various fields including small and large bubbles, large liquid droplets and a continuous liquid field. Preliminary benchmarking studies of the probe have been performed with a specially designed droplet dispensing setup. A high speed imaging system is used to provide benchmarking data such as droplet diameter, velocity, and chord length, for individual droplets, and the time-averaged data such as droplet volume fraction, volumetric flux and interfacial area concentration. Reasonable agreement has been obtained by comparing individual droplets with a diameter range of 1.4–4.0 mm, and a velocity range of 1.6–4.8 m/s. For time- and area-averaged parameters, the results from two test runs show that the maximum absolute relative errors are 6.42%, 7.43% and 5.72% for droplet volume fraction, interfacial area concentration and volumetric flux, respectively. The error is within 5% compared with the global droplet flow rate measurement.

1. Introduction

Accurate measurement of two-phase flow interfacial structure plays a crucial role in understanding the fundamental flow dynamics as well as in providing database for the development of physics-based two-phase flow models. The conductivity needle probe, whose measuring principle is based on the significant difference of electrical conductivity between the gas and liquid phase, has been developed and applied to two-phase flow measurement over many decades. To date, it is still one of the few options that are capable of measuring local two-phase flow parameters needed for the validation of two-phase Computational Fluid Dynamics (CFD) codes (Lee et al., 2013). In particular, it has a higher spatial resolution and smaller flow disturbance compared with wire-mesh sensors (Manera et al., 2009), and has a much wider applicable range compared with optically based methods which are limited to low void fraction bubbly flows (Honkanen et al., 2005).

Neal and Bankoff (1963) were among the first who demonstrated the capability of the conductivity probe for two-phase flow measurement. They measured the local time-averaged void fraction and bubble frequency with a single-sensor probe. Later the double-sensor probe was proposed to measure bubble size and interfacial velocity by Burgess and Calderbank (1975), and Herringe and Davis (1978). Realizing the importance of the interfacial area concentration in two-phase flow modeling, Kataoka et al. (1986) developed a rigorous mathematical formulation which allows a double-sensor probe to measure the interfacial area concentration of bubbly flows consisting of small, nearly spherical bubbles. The accuracy and reliability of the double-sensor conductivity probe has been studied both experimentally (Revankar and Ishii, 1992) and numerically (Wu and Ishii, 1999).

While measuring the interfacial area concentration, the double-sensor conductivity probe assumes that all bubbles are spherical in shape, which might be a reasonable assumption for bubbly flows. For other flow regimes, this assumption may not hold since Taylor and churn bubbles start to dominate the gas phase in cap-bubbly, slug and churn-turbulent flows. The four-sensor probe is proposed to measure these larger, non-spherical bubbles (Kataoka et al., 1986) . A four-sensor probe has two additional sensors compared with a double-sensor probe, enabling it to directly measure

---

[*] Corresponding author.
E-mail address: ishii@purdue.edu (M. Ishii).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.06.012

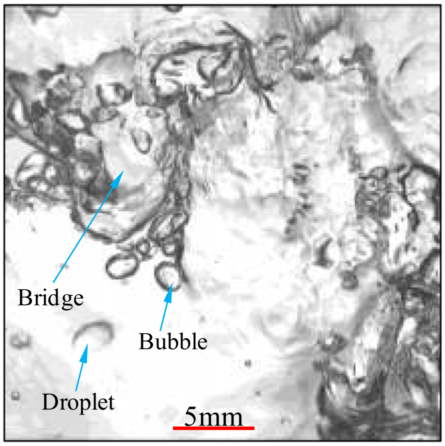


Fig. 1. Typical two-phase flow structure in churn-turbulent flow regime in a 200 mm x 10 mm rectangular test channel, $j_g = 4.5$ m/s, $j_f = 0.3$ m/s.

the normal component of the interfacial velocity, hence the interfacial area concentration for any bubble shapes. Use of the four-sensor probe was limited due to its relatively large probe size (Kataoka et al., 1994). To overcome this challenge, Kim et al. (2000) developed a miniaturized four-sensor conductivity probe which considerably reduced the probe size and the disturbance to the surrounding flow. The measurement accuracy is further improved due to the reduced "missing bubble" effect, namely, more bubbles are detected by all four sensors of a probe. This probe design has been used extensively in various experimental studies ranging from bubbly flow to churn-turbulent flow conditions. Systematic benchmarking studies of four-sensor conductivity probe has been performed in the past (Kim et al., 2000; Le Corre et al., 2003; Le Corre and Ishii, 2002).

The conventional conductivity probe, either the double-sensor or the four-sensor type, is based on the basic assumption that the liquid phase is continuous. With this assumption, the probe measures the conductance between an exposed sensor tip and the probe casing which is in good contact with the continuous liquid field surrounding the casing. If the tip is covered by a gas bubble, a low conductance is detected and vice versa. However, this assumption may not hold in the churn-turbulent to annular transition and annular flows. In such flows, liquid droplets can break off from the continuous liquid field, existing as dispersed liquid phase surrounded by the gas phase. Fig. 1 shows a sample high speed image taken in the churn turbulent flow regime in a 200 mm x 10 mm rectangular test section. The superficial gas velocity is $j_g = 4.5$ m/s and the superficial liquid velocity is $j_f = 0.3$ m/s. It is clearly seen that large droplets coexist with bubbles, liquid bridges as well as continuous liquid and gas fields. Since dispersed liquid particles are not in contact with a probe casing while they pass through the probe tip, a low conductance signal will be detected by the probe circuit. In this case these droplets will be erroneously identified as gas phase. Therefore the gas void fraction will be over-estimated. The liquid-phase data will not only show some uncertainties in the volume fraction, but more so in the interfacial area concentration due to the small size of the dispersed liquid particles. Further, the data obtained in such conditions lack the information of the dispersed liquid field since dispersed liquid particles cannot be detected. Such information is indispensable to the development of the advanced two-phase flow models such as the interfacial area transport equation (Ishii and Kim, 2004) and the four-field two-fluid model (Lahey Jr and Drew, 2001), both being proposed to cover a wide range of two-phase flow regimes including the churn-turbulent and annular flows.

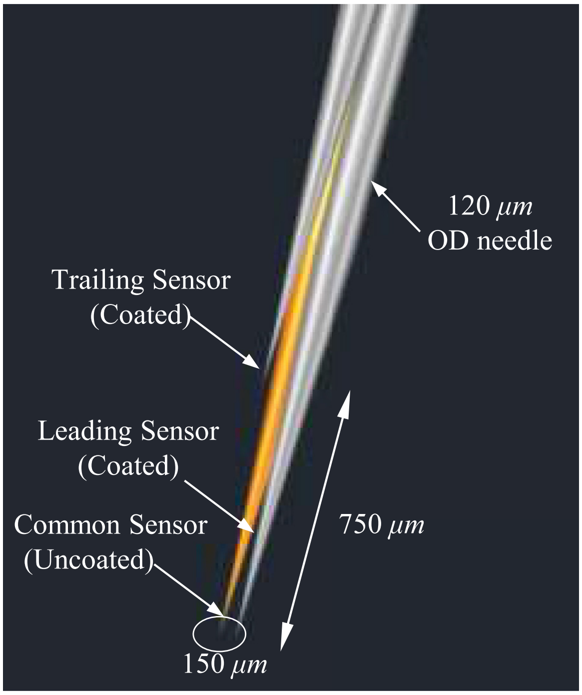


Fig. 2. Schematic of double-sensor droplet-capable conductivity probe.

A new conductivity probe design, called the double-sensor Droplet-Capable Conductivity Probe (DCCP-2) is proposed in this paper in order to overcome the above measuring challenge and to further extend the capability of the conductivity probe. In this design, a common sensor is added to the conventional double-sensor conductivity probe such that the conductance change between the common sensor and the nearby leading and trailing sensors can be detected by the probe circuit. The conductance between the casing and the ground sensor is used to indicate the connectivity between the detected liquid and the continuous liquid phase. This improvement not only makes it feasible to detect dispersed liquid particles, but also enables the DCCP-2 to distinguish them from the continuous liquid field, for example, liquid droplets from disturbance waves or ligaments. The DCCP-2 also has the capability to measure small and large bubbles as the conventional probe does. Therefore, it can be used to perform an accurate and detailed local measurement in a wide spectrum of two-phase flow regimes spanning from bubbly to annular flows. It should be noted that the optical fiber-based probes, though being able to detect dispersed droplets (Saito et al., 2009), cannot distinguish a dispersed liquid particle from a continuous liquid field. The unique feature of the DCCP-2 will further enable us to explore the complex two-phase flow structures such as those in the wispy annular flows, where very limited data and understanding is available to date (Hawkes et al., 2000).

2. Design of the DCCP-2

The DCCP-2 consists of one leading sensor, one trailing sensor and one common sensor as shown in Fig. 2. Both the leading and trailing sensors are coated with insulating material except at the tips, while the common sensor is left uncoated. One of the major changes from the conventional conductivity probe design is the addition of the common sensor. In the new design, the probe measures the electrical connection between the leading sensor (or the trailing sensor) and the common sensor which are about 150 µm apart. For liquid particles of 1 mm and bigger, it can be assumed that the common sensor is always in the liquid phase if either of