Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Void fraction measurement of bubble and slug flow in a small channel using the multivision technique

Huajun Li, Xiaohu Zheng, Haifeng Ji*, Zhiyao Huang, Baoliang Wang, Haiqing Li

State Key Laboratory of Industrial Control Technology, College of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 25 October 2016
Accepted 23 November 2016
Available online xxx

Keywords:
Gas–liquid two-phase flow
Void fraction
Bubble flow
Slug flow
Multivision technique

ABSTRACT

Using the multivision technique, a new void fraction measurement method was developed for bubble and slug flow in a small channel. The multivision system was developed to obtain images of the two-phase flow in two perpendicular directions. The obtained images were processed—using image segmentation, image subtraction, Canny edge detection, binarization, and hole filling—to extract the phase boundaries and information about the bubble or slug parameters. With the extracted information, a new void fraction measurement model was developed and used to determine the void fraction of the two-phase flow. The proposed method was validated experimentally in horizontal and vertical channels with different inner diameters of 2.1, 2.9, and 4.0 mm. The proposed method of measuring the void fraction has better performance than the methods that use images acquired in only one direction, with a maximum absolute difference between the measured and reference values of less than 6%.

Introduction

Investigation of gas–liquid two-phase flow in small channels has become increasingly important because of the rapid development of micrometer-scale devices, which are used in chemical reactors, heat exchangers, refrigeration processes, and micro-evaporators, among other applications (Crowe, 2005; Kandlikar, Garimella, Li, Colin, & King, 2005; Tibiriçá & Ribatski, 2013). The void fraction is one of the most important parameters that determines the two-phase flow behavior, and is therefore a key determinant of the heat and mass transfer efficiency. This parameter is also important for estimating the pressure drop and other parameters (Hetsroni, 1982; Mehendale, Jacobi, & Shah, 2000; Mishima & Hibiki, 1996; Tibiriçá & Ribatski, 2013). However, in channels with small diameters which are generally in the range of 1.0–6.0 mm (Mishima & Hibiki, 1996; Winkler, Killion, Garimella, & Fronk, 2012; Zeguai, Chikh, & Tadrist, 2013), two-phase flow differs from that in larger channels, which makes conventional methods of measuring the void fraction unsuitable (Mehendale et al., 2000; Mishima & Hibiki, 1996; Saisorn & Wongsises, 2008; Winkler, Killion, Garimella, Fronk, 2012; Winkler, Killion, & Garimella, 2012). Therefore, new methods of estimating the void fraction in small channels are required.

Different methods have been applied for measuring the void fraction in two-phase flow in a small channel, including high-speed-camera methods, tomographic methods, and methods based on electrical measurement (Saisorn & Wongwises, 2008; Serizawa, Feng, & Kawara, 2002; Triplett, Ghiaasiaan, Abdel-Khalik, & Sadowski, 1999; Triplett, Ghiaasiaan, Abdel-Khalik, Lemouel, & Mccord, 1999; Winkler, Killion, Garimella, Fronk, 2012; Winkler, Killion, Garimella, 2012). In contrast to other measurement methods, which usually provide indirect information, high-speed-camera methods provide direct information relating to the two-phase flow inside the channel. The images can also be analyzed to obtain valuable information about the flow structure and phase distribution of the gas and liquid phases. In addition, high-speed-camera methods are more suitable than other methods for channels with small diameters (Clarke & Rezkallah, 1996; Kawahara, Chung, & Kawaji, 2002; Triplett, Ghiaasiaan, Abdel-Khalik, Lemouel et al., 1999; Serizawa et al., 2002; Winkler, Killion, Garimella, Fronk, 2012). Triplett, Ghiaasiaan, Abdel-Khalik, Lemouel et al. (1999) analyzed images of air–water flow in circular tubes with diameters of 1.1 and 1.45 mm by measuring the diameters of the bubbles. They assumed that the bubbles had spherical caps or an elliptical form, that the elongated bubbles in the slug flow were cylinders with spherical caps, and that churn flow could be represented by a mean fraction of about 0.5. Serizawa et al. (2002)

---

* Corresponding author.
E-mail addresses: hfji@iipc.zju.edu.cn, hfji@zju.edu.cn (H. Ji).

http://dx.doi.org/10.1016/j.partic.2016.11.004

Please cite this article in press as: Li, H., et al. Void fraction measurement of bubble and slug flow in a small channel using the multivision technique. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2016.11.004

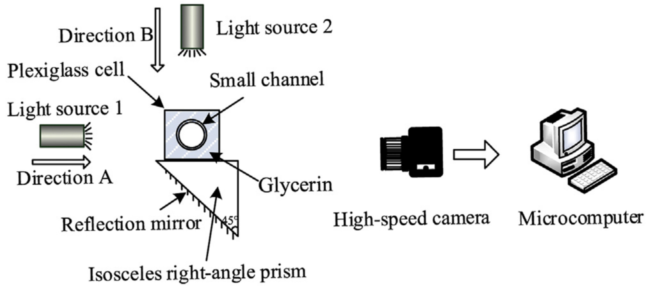
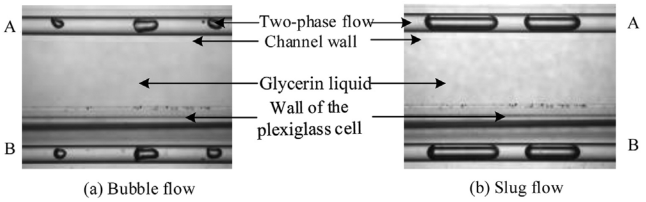


Fig. 1. Construction of the multivision system.



(a) Bubble flow (b) Slug flow

Fig. 2. Original image of the gas–liquid two-phase flow.

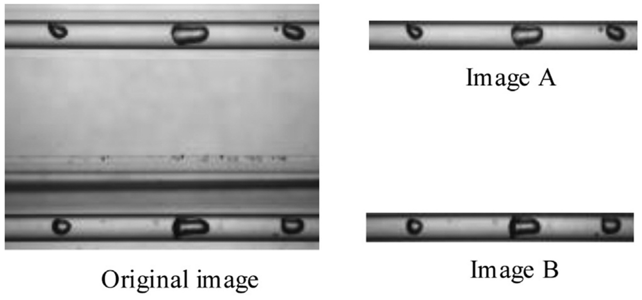


Fig. 3. Image segmentation.

investigated the two-phase flow of air–water and steam–water in microchannels. They used images captured by a high-speed video camera mounted on a microscope to calculate the volumetric void fraction for bubble and slug flow by assuming that the bubbles had an axisymmetric shape. Kawahara et al. (2002) used a similar method to that of Serizawa et al. (2002) to record videos of the two-phase flow. They assigned each frame a void fraction value and the void fraction was taken as the time-averaged values of these frames. Clarke and Rezkallah (1996) studied two-phase flow in a 9.53-mm vertical tube. They digitized the images, assumed that the bubble had a cylindrical body with two semi-spherical caps, and then calculated the volumetric void fraction. However, these methods mentioned above are based on image acquisition in only one direction, and use 2D information to study the characteristics of a 3D object. The information extracted from these 2D images is limited and the obtained information does not fully reflect the whole flow characteristics of the two-phase flow and may cause inaccuracy in measuring the void fraction (Winkler, Killion, Garimella, Fronk, 2012).

The multivision technique is an emerging technique that could overcome the mentioned shortcomings of existing methods that image only in one direction. Using the multivision technique, an object can be imaged from different directions (Hossain, Lu, & Yan, 2012). Enabled by the rapid advancement of image-capturing technology and computer science, the multivision technique has been applied in many industrial fields, for example, defect detection of object surfaces, reconstruction of burner flames, and point positioning in computer vision (Cai, Qin, Liu, & Zhang, 2010; Hossain et al., 2012; He, Hu, Liu, & Meng, 2010; Ishino, Takeuchi, Shiga, & Ohiwa, 2009; Xue, Chen, & Ge, 2013). With images captured from different directions, more detailed and accurate information of the two-phase flow can be obtained. However, to date, there has been very little research on the application of the multivision technique to void-fraction measurements of two-phase flow (Fu et al., 2009).

In this work, we develop a new method of measuring the void fraction using the multivision technique, in which images of the two-phase flow are obtained simultaneously in two perpendicular directions. After processing and analyzing the images, we determined the void fraction using a new model. Experiments in small channels with different inner diameters (2.1, 2.9, and 4.0 mm) were carried out to verify the effectiveness of the proposed method.

The multivision system

Fig. 1 shows the multivision system, which consists of an isosceles right-angle prism, two light-emitting diodes (LED), a small channel, a transparent Plexiglas cell, a high-speed camera, and a microcomputer. The LEDs are used to supply back lighting. The isosceles right-angle prism is arranged with one of its right-angle edges close to the Plexiglas cell. The small channel is arranged inside the Plexiglas cell and is surrounded by glycerin. Images of the two-phase flow are captured using the high-speed camera and are transmitted to the microcomputer.

In contrast to other multivision systems, we introduced the Plexiglas cell and the glycerin (which has a refractive index close to that of the channel wall) to decrease image distortion (Kawahara et al., 2002) and improve the measurement accuracy. The single high-speed camera was used to obtain the images of the two-phase flow simultaneously in two directions. As shown in Fig. 1, in direction A, the front view of the two-phase flow is directly captured by the camera; by contrast, indirection B, the side view of the two-phase flow is reflected by the oblique plane of the right-angle prism, which can be considered as a reflection mirror, and then captured by the camera (Fu et al., 2009).

Two examples of the original images obtained from bubble and slug flow in a horizontal channel are shown in Fig. 2(a) and (b), respectively. The two-phase flow, channel wall, glycerin, and the wall of the Plexiglas cell are indicated in the images. Each image contains the front view (A) and the side view (B) of the two-phase flow. It can be observed that the flow has different shapes in the two directions. This indicates that two-phase flow in the small channel is complex, and this behavior should be considered in the void-fraction measurement. Owing to the effect of glycerin, image distortion caused by the channel wall was effectively reduced, allowing higher-quality images to be obtained (Kawahara et al., 2002; Lim et al., 2013; Zeguai et al., 2013).

Image processing

Image processing for void-fraction measurement in this work included image segmentation, image subtraction, edge detection, binarization, and hole filling (Gonzalez & Woods, 2001; Nishino, Kato, & Torii, 2000; Okawa, Ishida, Kataoka, & Mori, 2005; Valecillos, Romero, Márquez, & Vergara, 2012; Winkler, Killion, Garimella, Fronk, 2012).

Image segmentation and image subtraction

The purpose of image segmentation is to extract the useful information and remove the background from the original images (Gonzalez & Woods, 2001). A typical example of image segmentation is shown in Fig. 3. After image segmentation, two useful parts of

Please cite this article in press as: Li, H., et al. Void fraction measurement of bubble and slug flow in a small channel using the multivision technique. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2016.11.004