Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Bubble size and flow characteristics of bubbly flow downstream of a ventilated cylinder

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ARTICLE INFO

Article history:
Received 21 January 2017
Received in revised form 11 April 2017
Accepted 18 April 2017
Available online 27 April 2017

Keywords:
Cylinder
Ventilation
Bubbly wake flow
Statistical analysis
Sauter mean diameter
Bubble velocity

ABSTRACT

Bubbly flows downstream of a ventilated cylinder in a water tunnel are experimentally studied. Emphasis is placed upon the relationship between bubble property and carrier flow parameters. Under no-ventilation condition, the pure-water wake flow is measured with particle image velocimetry technique. Bubbles are generated with ventilation and the bubbly flow is visualized using shadow image velocimetry. The separation and statistical treatment of bubbles in the captured images are accomplished with an in-house code. The influence of upstream flow velocity and air flow rate is examined. Sauter mean diameter of the bubbles and bubble velocity distribution are obtained. Instantaneous bubbly flow pattern is in accordance with the carrier flow characteristics. Across the high-vorticity region, bubbles experience a remarkable bubble size variation, large bubbles are annihilated. As for cross-sectional bubble size distribution, the tendency obtained with image processing agrees with the result obtained with the formula associating turbulent kinetic energy dissipation with bubble size. As upstream velocity increases, the percentage of small bubbles increases. Both bubble volume fraction and the most predominant bubble size increase with air flow rate. The percentage of large bubbles varies slightly with air flow rate.

1. Introduction

The bubbly flow is an important flow pattern in many chemical processes and enviromental engineering applications. However, the fundamental bubbly flow mechanisms such as bubble dynamics and mass transfer have not been fully elucidated so far. The relationship between bubbly flow pattern and the carrier flow characteristics is of prime importance in consideration of the bubble movement, deformation and collapse. Even with adequate carrier flow information, modeling the bubble motion process is not an easy task, since that the turbulent fluctuations residing in the carrier flow exert a complicated effect on bubbles. An overview of the treatment of such an issue has been presented by Brennen (1995). Until now, bubbly flows in pipes and columns, which share simple boundary conditions, have been studied extensively. In contrast, few studies of bubbly flows around a foil or a blunt body have been reported.

Measurement techniques for bubbly flows are exceedingly important and greatly appreciated. One branch of studies is featured by the application of intrusive probes. For instance, Xue (2004) used a four-point optical probe with a tiny probe tip to measure bubble velocity at a sampling frequency of 40 kHz; Smith et al. (2012) employed an electrical conductivity probe to measure bubble void fraction and the attainable accuracy proved to be fairly high. Another branch of studies advocate non-invasive measurement techniques. Tassin and Nikitopoulos (1995) acquired bubble velocity using phase-Doppler and video-imaging techniques and found both results were desirable. The radioactive particle tracking technique was practiced by Gupta and Roy (2013) to measure water velocity in a bubbly flow; Tayler et al. (2012) used an ultrafast magnetic resonance imaging technique to measure bubble size and bubble position simultaneously at high bubble void fraction. Overall, optical and imaging techniques yield relatively accurate and comprehensive results.

Recently, a promising experimental technique, namely shadow image velocimetry (SIV), was attempted to trace bubbles (Lee et al., 2013). The central part of such a technique lies in two aspects, high-speed photography and image processing. Consecutive bubble images are captured physically. And bubbles in the captured images, overlapped or separated, are identified and statistically manipulated through some specifically developed algorithm.

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http://dx.doi.org/10.1016/j.cherd.2017.04.019

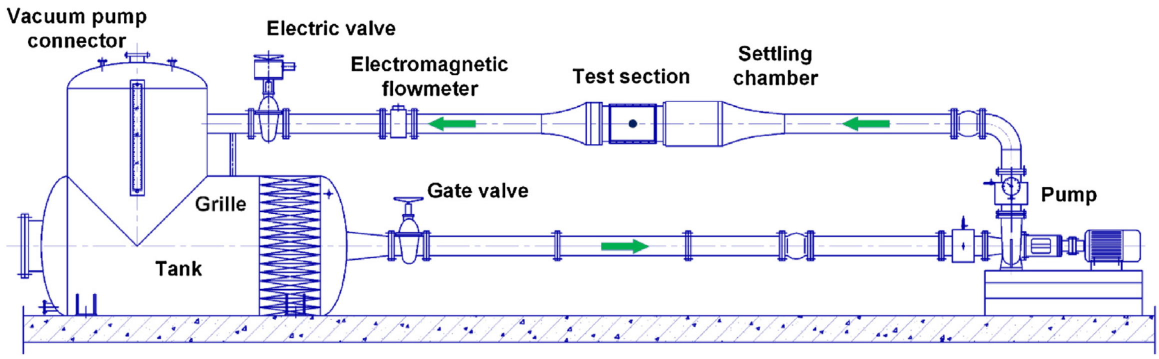

Fig. 1 – Schematic of experimental setup.

Injecting air into water serves as an effective measure of generating bubbles. Provided that the water flows with certain characteristics, bubbles involved might exhibit specific behavior. The present study is intended to reveal the bubbly flow pattern downstream of a cylinder. Therefore, a cylinder is deployed in the horizontally installed transparent section of a water tunnel. Particle image velocimetry technique is used to measure flow velocity downstream of the cylinder under no-ventilation condition. Air is injected into water flows through a flow passage inside the cylinder. High-speed photography, in association with LED light source, is utilized to capture consecutive images of moving bubbles downstream of the cylinder. During the experiment, the influence of upstream velocity and air flow rate is considered. In the captured images, the identification and extraction of individual bubbles are accomplished by using a specifically developed code. Primary bubble parameters of velocity, Sauter mean diameter and volume fraction are obtained statistically. Critical factors determining the bubble size distribution are anticipated to be explained. And the association between carrier flow characteristics and bubbly flow pattern is expected to be established as well.

2. Experimental setup

2.1. *Water tunnel and ventilated cylinder*

The experiment work was carried out in the water tunnel shown schematically in Fig. 1. The dimensions of the horizontally mounted test section are 0.7 × 0.05 × 0.315 m. All the four sides of the test section are transparent. A circular cylinder with the diameter and length of 0.03 m and 0.049 m, respectively, was installed in the test section. Mounted upstream of the test section, an elaborately designed settling chamber yields a homogeneous upstream flow immune to the disturbance of circulating bubbles. Meanwhile, physical properties of the carrier flow, which were specifically discussed by Akita and Yoshida (1974), can be stabilized to a desirable level.

A ventilation system with the primary components is shown in Fig. 2. The stabilization tank can provide a fairly stable air pressure. The air flow rate is read from the rotameter. There is one hole on the cylinder surface for discharging air into the water tunnel, and the hole is positioned in the middle along the cylinder axis. Such a scheme ensures a two-dimensional flow in the cross section vertical to the cylinder axis. Therefore the observation of the bubble flow patterns is performed with the same depth of view.

Xiang et al. (2011) injected gas into a downward liquid pipe flow and produced by adjusting relevant parameters a cone-shaped cavity with its size comparable to the inner diameter of the pipe. Kawakami and Arndt (2011) injected air into the water flow in a water tunnel and induced supercavity encompassing a submerged cavitator. Here, there is only one hole with the diameter of 1 mm in the cylinder, as shown in Fig. 2. And the air flow rate can be adjusted through the pressure valve; therefore, bubbles were dispersedly distributed and bubble size is small. According to the explanation of the effect of Stokes numbers made by Varaksin (2013), the collisional Stokes number in the bubbly wake flow possesses an order of magnitude of 1.

Bubbles transported by the wake flow downstream of a cylinder bear a background of well-acknowledged carrier flow features. There are several factors that are supposed to affect the bubbly flow pattern. Akbar et al. (2013) transformed a symmetric bubbly flow pattern to an asymmetric bubbly flow pattern in a rectangular column via two arrays of injecting nozzles. In the present study, the position of the injection hole is fixed and the air flow rate is adjusted.

2.2. *Optical configuration*

The pure-water wake flow was measured with a LaVision PIV system. A Nd:YAG laser with the light wavelength of 532 nm was used to illuminate the flow regions. A CCD camera of Imager Pro SX 5M, featuring an image resolution of 2456 × 2058 pixels, was used. The maximum image-capturing frequency is 14.5 fps. Hollow glass particles with diameters ranging from 20 to 50 μm were used as tracing particles. Data acquisition and processing were conducted using the Davis software. The Tecplot software was used to process acquired data and to calculate flow quantity values.

With the light source being replaced by an LED light source, the SIV technique was utilized to capture bubbly flow images. As shown in Fig. 3(a), the light source and the camera are located at the two sides of the test section. With the mode of double-frame and double-exposure, the time interval between two neighboring frames is 600 ns.

During the experiment, after each individual case, the entire loop will be emptied and then refilled with pure water. This avoided the disturbance of residual bubbles and dissolve air. The maximum upstream velocity in the experiment was 7 m/s, leaving no chance for cavitation generation. Apart from the above consideration, the experimental rig was carefully calibrated. In consideration of the manufacture and installation of the cylinder, precision manufacturing technique was used to drill hole inside the cylinder, and for the installation, calibration instruments were used to ensure that the axis of the cylinder is parallel to the streamwise direction, and the uncertainly aroused by the deviation is around 0.2%. For the uncertainty associated with PIV, since that the velocity magnitude is fairly low in the present study, and according to the specification of the PIV system used, the maximum uncertainly is less than 0.2%. Therefore, the overall uncertainty of the experiment was less than 0.5%. Along the streamwise