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An integrative image measurement technique for dense bubbly flows with a wide size distribution

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HIGHLIGHTS

- A robust image analysis approach for highly turbulent bubbly flows is proposed.
- It can resolve both in-focus and out-of focus bubbles over a wide size range.
- It can segment individual bubble from large clusters in high void fraction images.
- The approach was validated using both synthetic bubble images and experimental data.
- It allows real time analysis of two-phase flows in many industrial applications.

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ABSTRACT

The measurements of bubble size distribution are ubiquitous in many industrial applications in chemical engineering. The conventional methods using image analysis to measure bubble size are limited in their robustness and applicability in highly turbulent bubbly flows. These flows usually impose significant challenges for image processing such as a wide range of bubble size distribution, spatial and temporal inhomogeneity of image background including in-focus and out-of-focus bubbles, as well as the excessive presence of bubble clusters. This article introduces a multi-level image analysis approach to detect a wide size range of bubbles and resolve bubble clusters from images obtained in a turbulent bubbly wake of a ventilated hydrofoil. The proposed approach was implemented to derive bubble size and air ventilation rate from the synthetic images and the experiments, respectively. The results show a great promise in its applicability for online monitoring of bubbly flows in a number of industrial applications.

1. Introduction

Bubbly flows occur frequently in natural systems and are also used for different applications in petroleum, energy-producing and chemical industries. Some of the common applications involve bubble columns which are used as reactors in a variety of chemical and biochemical processes, e.g. the Fischer–Tropsch process for hydrocarbon synthesis, hydrogenation of unsaturated oil, coal liquefaction, fermentation, waste water treatment etc. (Smith et al., 1996; Lau et al., 2013). Bubbly flows are also ubiquitously found in flotation cells (Sadr-Kazemi and Cilliers, 1997), aeration studies (Roesler and Lefebvre, 1989) and spargers (Geary and Rice, 1991) etc. In many of such processes, the accurate prediction of pressure drop and wall heat transfer is necessary, both of which are strongly dependent upon the concentration, spatial distribution and morphology of the bubbles (Kamp et al., 2001). Similarly, in many liquid–gas systems, gases are dispersed in liquids to obtain large interfacial area available for chemical reactions, heat and mass transfer processes. The rate of such processes is characterized by bubble surface area flux which is closely associated with the bubble size distribution (Junker, 2006).

Different techniques have been employed to measure bubble size distributions. Broadly, it can be divided into two categories – intrusive and non-intrusive techniques. Both these methods have been extensively reported in the literature – some of the intrusive methods employ capillary suction probes (Laakkonen et al., 2005), conductivity probes (Liu and Bankoff, 1993), optical fiber probes (Saberi et al., 1995) and wire-mesh sensors (Prasser, 2008), etc. The non-intrusive methods include interferometric particle imaging (Glover et al., 1995), laser Doppler velocimetry (Mudde et al., 1998), extinction and scattering activity measurement (Zaidi, 1998), phase Doppler anemometry (Laakkonen et al., 2005) and other particle-imaging techniques (Tayali and Bates, 1990; Adrian, 1991; Grant, 1997), etc. In general, non-intrusive methods are

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preferred over intrusive methods which disturb the local flow fields because of the placement of the probes.

Digital image analysis offers many advantages in terms of flexibility, relative insensitivity to the optical properties of the dispersed phase, easier optics alignment as compared to laser-diffraction methods, as well as the capability of providing the velocity and size information of the dispersed phase simultaneously. Thus, it is very convenient and time efficient for online monitoring and analysis of a large number of images. However, to implement this technique for real-time analysis of the bubbly flow images from different engineering applications pose multifarious challenges. These challenges include, for instance, the computational speed for real-time image processing, the ability to cope with the poor quality of images caused by varying intensity characteristics of the background and out-of-focus objects, and the robustness of the technique especially in its capability to resolve overlapped clusters in the high void-fraction flows.

The optical image analysis have been used recently for quantifying the bubble size distribution (e.g. Honkanen et al., 2010; Ferreira et al., 2012; do Amaral et al., 2013; Kracht et al., 2013; Lau et al., 2013). Generally, due to the excessive coalescence and breakup of bubbles, most of the proposed techniques for bubble image processing produce considerable errors when applied to flows with high superficial gas and liquid velocities. These errors are closely related to the challenge of extracting accurate bubble information from large clusters due to the coalescence of bubbles. A brief review of these techniques is presented in Section 3.1. Overall, these techniques are still limited in their robustness to resolve large bubble clusters particularly under highly unsteady flows with large void fractions of bubbles. Another limitation of the reported techniques is related to their ability to deal with a wide range of bubble size distribution. In addition, algorithms with significant improvements in computational speed are needed for fast processing of a large number of images and online monitoring of bubble concentration and distribution.

Thus, in the present study, we introduce an integrative image measurement technique to analyze high void fraction bubbly flows with a wide dynamic size range of bubble size. The development of this technique is driven by our recent study on the bubbly wake flows of aerated hydrofoils. This research is focused on developing a test-bed through conducting physical water-tunnel experiments to quantify the dissolved oxygen transfer across bubbles under various flow conditions. The experiments result in a large quantity of varying quality of bubble images with significant clustering due to highly unsteady and complex flows and coalescence of bubbles. These images make it unfeasible to implement prior measurement techniques to achieve fast and accurate image analysis.

This paper is structured as follows: Section 2 provides the details for the experimental facility, setup and the optical approach used to capture digital images. The proposed image analysis algorithm is described in Section 3. Subsequently in Section 4, we present validation of our image analysis technique through both simulation and experimental approaches, which is followed by a final conclusion in Section 5.

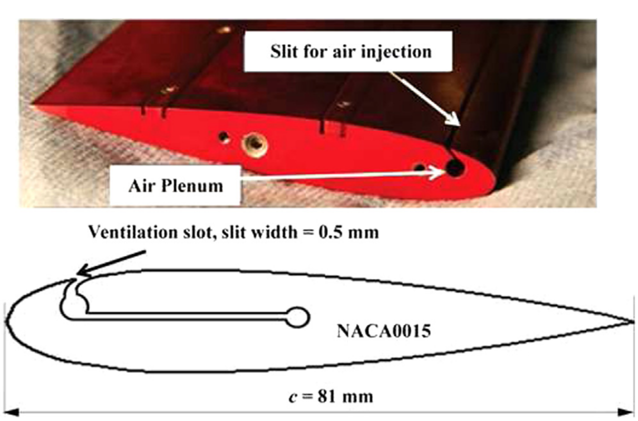

Fig. 1. Details of the ventilated foil.

2. Description of experimental setup

The experiments were conducted in the high-speed water tunnel at Saint Anthony Falls Laboratory (SAFL) of the University of Minnesota. The tunnel has a horizontal test section of 1 m (Length) × 0.19 m (Width) × 0.19 m (Height) with three sides having plexiglass wall for optical access. The tunnel is designed for cavitation and air ventilation studies and is capable of operating with velocity in excess of 20 m/s. A special design feature of the tunnel provides for fast removal of large quantities of air bubbles generated during cavitation and ventilation experiments, allowing us to conduct bubbly flow experiments for extended periods of time with little effect on test section conditions.

During the experiments, a NACA0015 hydrofoil was installed in the test section with angle of attack (α) of 0°, 4° and 8°. The hydrofoil was 190 mm in span and 81 mm in chord. As shown in Fig. 1, a narrow spanwise slot allows air to be injected into the flow over the hydrofoil. The full width of the injection slot is used for measurements of oxygen uptake. This results in a dense spanwise bubbly wake. However, in order to make bubble measurements, ventilation was limited to a narrow 9.6 mm slot at the center of the span. This configuration ensured that bubbles remain mostly within a narrow distance away from the center. Considerable thought was given to obtain a reasonable representative sample of the bubble population that exists when the full span is ventilated. Under this scheme, 45 different experiments were conducted at different water speeds, ventilation gas flow, angles of attack of hydrofoil and the bubbly wake images were obtained at three different axial locations, i.e. 109, 243 and 377 mm from the hydrofoil center. 90,000 bubble images were captured using the SIV technique.

Shadow Image Velocimetry technique (SIV) is most suited for analysis of bubbly flows. It employs direct in-line volume illumination using low power sources such as LED and an optical setup to produce a narrow depth-of-field for 2D plane imaging (Goss et al., 2007; Bröder and Sommerfeld, 2007). Fig. 2 shows a schematic of the experimental setup. A custom-made pulsed LED light source from Innovative Scientific Solutions Inc. was used to illuminate the flow. The pulsed LED array has flash rates up to 10 kHz with a 5 μs pulse width and rise and fall times ~200 ns. To ensure uniform back-lighting in the images, a light shaping diffuser is placed between the light source and the flow, which eliminates noise generated by non-uniform lighting. A 1 K × 1 K pixel Photron APX-RS camera (capable of 3000 frames/s at full resolution) with a 60 mm lens was used to obtain images.

In the SIV technique, two LED light pulses separated by a short time are synchronized with camera exposure in order to obtain two consecutive images (or, double frames). The first pulse is fired at the end of the first exposure and the next at the beginning of the following exposure. In our experiments, the time duration between two pulses was kept 100–230 μs depending on free stream velocity. Using the obtained image pairs, the instantaneous velocity field of the bubbles was obtained using commercially available Particle Image Velocimetry (PIV) software (DaVis 7.2 from LaVision). The image pairs were captured at a frame rate of 25 image-pairs per second and the exposure time for individual images was kept 15 μs to prevent any blurring in the images. A data set consisted of 1000 image-pairs taken over 40 s. The field of view of the captured images was approximately 60 mm × 60 mm.