# Development of a robust image processing technique for bubbly flow measurement in a narrow rectangular channel

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**ABSTRACT**

This paper presents a robust image processing technique for bubbly flow measurement over a wide range of void fractions. The proposed algorithm combines geometrical, optical and topological information recorded with high speed cameras to separate and reconstruct the overlapping bubbles. The common difficulties such as overlapping, irregular bubble shape, surface deformation and large clustering in digital image processing are solved by combining different information based on a preset decision table and flow chart. Test with synthetic bubble images is performed to evaluate the reliability of the algorithm and quantify the uncertainty of the data. The result shows that the proposed algorithm can accurately measure bubbly flows with void fraction up to 18% for large bubbles. Four runs of bubbly flow images in a 30 mm $\times$ 10 mm rectangular channel are then recorded by three high speed cameras. The area-averaged void fraction of these test runs range from 2.4% to 9.1%. The axial and lateral distributions of bubble number density are obtained by the present algorithm for studying the characteristics of these flows.

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## 1. Introduction

Bubbly flow measurement is one important but challenging task in studying two-phase flows. Bubbles and surrounding liquid flow form a four-way coupling system which involves complex hydrodynamic forces between two phases and various bubble interaction mechanisms. Commonly used engineering models employ certain averaging algorithm to simplify the mathematical description of the complex bubbly flow phenomena (Ishii and Hibiki, 2011). Measurement of averaged quantities including bubble number density, void fraction, interfacial area concentration are of practical interest to provide database for the development and benchmarking of various two-phase flow models. In multiphase computational fluid dynamics (CFD), the initial distribution and boundary conditions from measurement are also necessary to meet the modern validation experiment requirements (Oberkampf and Smith, 2014).

Techniques used for bubbly flow measurement can be largely classified into two groups, namely, intrusive and non-intrusive methods. Typical intrusive methods applied in bubbly flow measurement include fiber optic probe (De Lasa et al., 1984), conductivity probe (Leung et al., 1995; Kim et al., 2000), sampling probe (Alves et al., 2002), phase-sensitive constant temperature anemometry (Mercado et al., 2010) and wire-mesh sensors (Prasser et al., 1998). Non-intrusive methods include X-ray or $\gamma$-ray computed tomography (Kumar et al., 1995; Schmitz et al., 1997), laser Doppler anemometry (Kulkarni et al., 2001) and image processing technique (Honkanen et al., 2005; Colombet et al., 2011; Bouche et al., 2012). The intrusive methods require direct contact of the sensor/probe with the flow during the measurement. This may cause undesired disturbance to the flow field. The spatial resolution of intrusive methods is usually not very high since a probe or a wire-mesh sensor can measure one or a limited number of discrete points at a time. Increased number of measurement points will increase flow disturbance and consequently the uncertainty of the data. Non-intrusive methods do not require direct contact with the flow field, thus can achieve a higher spatial and temporal resolution. With the major development of digital imaging technique in recent years, image processing combined with high speed cameras has become an attractive technique for its capability in obtaining high spatial and temporal resolution bubbly flow data.

Several technical challenges will be encountered while using the image processing technique, and they are summarized in Fig. 1. Take images with parallel background light as example, an ideal spherical bubble usually results in a circular shape with dark edge and bright center in the image. In reality, the bubbly flow images are much more complicated. The disturbances introduced by bubbles and liquid turbulence may affect the shape and motion

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(a) Overlapping  (b) Irregular Shape  (c) Surface Deformation  (d) Large Clustering
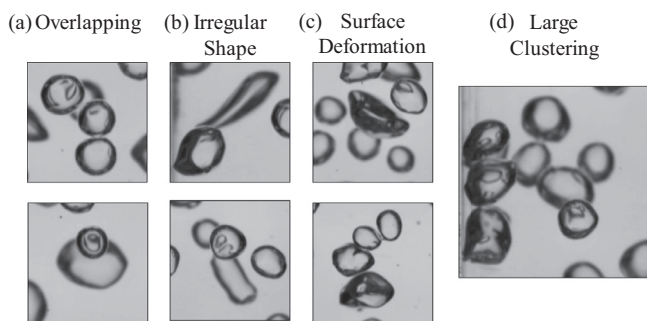
**Fig. 1.** Sample bubbly flow images showing various technical difficulties in image processing (a) bubble overlapping along camera axis, (b) irregular shape bubble formed by liquid turbulence and/or during bubble coalescence and breakup, (c) large bubble appeared in a dark solid shape due to surface deformation, (d) large cluster of bubbles in high void fraction condition.

of nearby bubbles. Large bubble surface tends to be more unstable due to increased inertia effect. If a bubble is disturbed by surrounding flow, or becoming unstable, or going through coalescence/breakup process, its surface can be distorted and take arbitrary shape. When projected to the image plane, these bubbles may be elongated or appear darker with edges become thicker than normal spherical or ellipsoidal bubbles. At high void fraction, bubble overlapping becomes another challenging issue in image processing. In a cluster of overlapping bubbles, part of the bubble information is missing in the image. It may be difficult to accurately identify each bubble and reconstruct their actual boundaries. If not handled properly, the result such as bubble number density, void fraction will contain significant errors. For a large cluster of bubbles, how to correctly group the separated arcs that belong to the same bubble is another problem. Some bubbles in the middle of the cluster may have three or four separated arcs. If these arcs are not classified correctly, the bubble number and the final reconstructed bubble shape will be incorrect.

Many image processing algorithms have been proposed to deal with the aforementioned issues in the past. The related works are summarized in Table 1. In general, there are two major steps to process bubbly flow images. The first step is bubble segmentation, namely, to separate overlapping bubbles in a cluster and identify the right number of bubbles. The second step is to reconstruct the missing part of each individual bubble and correct any arti-

facts if necessary. For bubble segmentation, Hough transform (Pei and Horng, 1995), breakpoint method (Freeman and Davis, 1977; Teh and Chin, 1989) and watershed method (Meyer and Beucher, 1990; Bleau and Leon, 2000) are the most used techniques. The Hough transform is good for detecting circular shape objects as shown by Hosokawa et al. (2009) in micro-bubble measurement, by Prakash et al. (2012) in bubbles affected by turbulence, and by Yu et al. (2009) and Mathai et al. (2015) in solid particle measurement. It has a good accuracy for small spherical bubbles or solid spheres. The result becomes less accurate for large size bubbles with irregular shapes. For non-spherical bubble cluster, Honkanen et al. (2005) and Honkanen (2009) used the breakpoint method to separate overlapped bubble boundaries in the cluster. The unoccluded edges for each bubble can be obtained by this method. The watershed method is used by Lau et al. (2013) and Karn et al. (2015) to separate the clustered bubble groups consisting of various sizes. Optical properties such as the intensity difference between bubbles and background are used by Bröder and Sommerfeld (2007) to detect bubble outline for nonclustered bubbles. Ferreira et al. (2012) proposed to use the shape complexity to classify solitude and clustered bubbles. For bubble reconstruction, the most used method is to connect the missing section on bubble boundary with a straight line, or to fit an ellipse based on the extracted outline arcs for the bubble. Considering the complexity of the bubbly flow, using one method for cluster separation and bubble reconstruction will have very limited applicability. For watershed method, the over- and under- segmentation are common problems found in the past studies. One single bubble can be divided into several separated objects if the shape is elongated. If two bubbles are too close to each other, they can be grouped as one object in the image. To detect bubble boundary based on intensity gradient may result in different recognition rate for in-focus and out-of-focus bubbles with a certain threshold. For the breakpoint method, using one threshold is not always robust to correctly identify all breakpoints. Deformed bubbles can cause oversegmentation problem. The breakpoint may not be detected if two bubbles are too close and are smoothly overlapping in the image. With these difficulties, most existing studies attempting to extract all the bubbles in the image are limited to void fraction less than 7%. Note that Ferreira et al. (2012) applied their algorithm to void fraction up to 11%. However, their algorithm did not separate the overlapping bubbles. The uncertainty in bubble number density and void fraction data may need further assessment. For bubbly

**Table 1**
Summary of image processing schemes for bubbly flow available in the literature.

| Reference | Test section | Void fraction | Bubble size | Bubble segmentation | Bubble reconstruction |
|---|---|---|---|---|---|
| (Honkanen et al., 2005; Honkanen, 2009) | Round pipe $D = 105$ mm | ≤ 2% | 0.01–2 mm | Breakpoint | Ellipse fitting |
| (Zaruba et al., 2005) | Rectangular channel 100 mm × 20 mm | ≤ 4% | 1–4 mm | N/A | N/A |
| (Bröder and Sommerfeld, 2007) | Rectangular channel 300 mm × 100 mm | 0.5–5% | 2–4 mm | Edge intensity gradient | Use bubble with 85% contour detected |
| (Hosokawa et al., 2009) | Round pipe | N/A | 0.08–1 mm | Hough transform | N/A |
| (Yu et al., 2009) | Round pipe $D = 9$ mm | N/A | 2.38 mm | Hough transform | Ellipse fitting |
| (Lelouvetel et al., 2011) | Round pipe $D = 44$ mm | 0.5–1% | 1.18–2.87 mm | N/A | N/A |
| (Ferreira et al., 2012) | Rectangular channel 140 mm × 20 mm | ≤ 11% | 4.5–7.5 mm | Shape complexity* | N/A |
| (Prakash et al., 2012) | Rectangular channel 0.45 m × 0.45 m | N/A | 2.5–3.15 mm | Hough transform | N/A |
| (Lau et al., 2013) | Rectangular channel 200 mm × 30 mm | 6.8% | 2–6 mm | Watershed | Ellipse fitting |
| (Karn et al., 2015) | Rectangular channel 1 m × 0.19 m | N/A | 0.1–1 mm | Watershed; morphological characters | N/A |

* The shape complexity method is used to classify different types of bubble clusters. No actual segmentation is carried out in this method.