Novel Method for the Characterization of Bubble Size Distribution

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Abstract

Bubble size measurement using imaging technique is commonly used when visualization is possible. However, overlapped bubble images are commonly found. The absence of internal separating line in overlapped bubble images creates difficulty in automatic algorithm development for accurate bubble size measurement. Common methodologies such as manipulation of pixel connectivity, segmentation by morphological watersheds, and morphological approach such as granulometry, etc are unable to give accurate treatment to overlapped bubble images when there is high degree of overlapping. This work is aimed to propose a generalized method to determine the bubble size distribution of spherical, elliptical as well as irregular shape bubbles based on bubble images. A computer automated analysis is performed by converting overlapped bubbles into segmented arcs to represent individual bubbles. The segmented arcs are then used directly for size measurement without the need to reconstruct the contours of overlapped bubbles. With the elimination of the curve fitting step, no prior assumption of the bubble shape is needed and the computation time can be greatly reduced. A probabilistic model is also developed for the transformation of bubble size distribution measured using a fixed calibration scale into the actual bubble size distribution without the information of horizontal locations from the imaging device.

Introduction

Bubble column reactors are commonly used in chemical, petrochemical and biochemical industries. The measurement of the bubble size distribution has always been a challenge. Methods such as direct visualization, dynamic gas disengagement, and other intrusive probe measurement techniques are developed to measure the bubble size distribution [1]. However, direct visualization is limited to transparent walls or windows and it can only be applicable to low gas holdup and low solid concentration conditions. Dynamic gas disengagement makes use of the pressure fluctuation signals during the gas disengagement process to correlate the bubble rise velocity with the size but the accuracy is relatively low when the system is operated in the churn-turbulent regime. Optical probe, conductivity probe and hot-film anemometry are some of the commonly used intrusive probe techniques. These intrusive probe techniques give a measure of the bubble cord-length distribution which needs to be converted into bubble size distribution by a prior assumption of a bubble shape.

A borescope is an optical inspection device that can be inserted into a bubble column to capture the bubble images at various conditions. The bubble size can be measured based on the bubble images and a calibration scale. The development of an automatic size determination

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algorithm would be important if a large amount of images need to be processed. In image analysis, it is a challenge to treat overlapped bubbles because of the absence of internal separating lines. In addition, due to the nature of 2-dimensional imaging, the horizontal distance between the bubble and the measurement device cannot be determined and therefore, it is impossible to select the appropriate calibration scale. In this study, it is attempted to develop a generalized algorithm to obtain the bubble size from bubble images without prior assumption of bubble shapes. A probabilistic model is also developed to convert the bubble size distribution measured using a fixed calibration scale to the actual bubble size distribution.

Methodology

The overall methodology can be divided into three steps: (1) Capture of bubble images; (2) Determination of bubble size distribution from borescope images using a fixed calibration scale; (3) Transformation of the bubble size distribution based on a fixed calibration scale into the actual size distribution.

Bubble images are first captured using a borescope integrated with a high speed video recording camera. Overlapped bubbles are commonly found in the images. The absence of internal separating line in overlapped bubble images creates difficulty in image analysis. Hence, the image analysis algorithm developed needs to be capable of treating both individual and overlapped bubble images. There are four key steps needed in the algorithm, namely image enhancement, identification of bubbles, identification of overlapped bubbles and bubble size determination. Each of the steps will be described briefly in the following:

Image Enhancement

Bubble images taken with the borescope are sharpened at the edge of the gas-liquid interface using high-pass Gaussian filtering. Light reflection from curved bubble surface may generate noise at the edge. Hence, high frequency noises are removed by median filtering and the background is equalized by adaptive histogram equalization.

Identification of bubbles

Bubbles are identified by employing Canny's edge detection method [2, 3]. Blurry and out-of-focus images may cause discontinuation in the perimeters during the edge detection as shown in Fig. 1(a). Hence, the perimeters are further dilated using linear structuring element to close the perimeters. The areas enclosed by the closed perimeters are then filled to represent the bubbles in a binary scale as shown in Fig. 1(b). Coordinates of the pixels on perimeter, length of the perimeter, and area of the identified bubble images are determined by assuming an 8-pixel-connectivity in a binary image. The results obtained in this operation are then used for subsequent identification of overlapped bubbles.

Identification of overlapped bubbles

Overlapped bubbles are identified based on the shape factor. The shape factor is defined as $4\pi A/P^2$, where A is the area and P is the perimeter of the detected bubble. Overlapped bubbles will have a much larger perimeter than spherical, elliptical and slightly deformed individual bubbles for a specific area. An arbitrary threshold value of 0.80 is found to give a reasonable detection of overlapped bubbles. The results after overlapped bubbles identification is shown in Fig. 1(c).

Bubble size determination

Once overlapped bubbles are identified, the intersecting points between different bubbles on the perimeters are identified using a curvature profile based method [3, 4]. The yellow crosses shown in Fig. 1(d) are the intersecting points. The perimeter of each overlapped bubble image is segmented at the identified intersecting points. Each segmented arcs corresponds to a separate bubble in an overlapped bubble image. The maximum distance between two pixels on a segmented arc is determined by iteration. This maximum distance, indicated by the straight line in Fig. 1(e) is considered as the bubble size. This definition of bubble size can eliminate the need of bubble reconstruction and give fast and reasonable estimation of the bubble size. The developed automatic image analysis algorithm is tested on bubble images obtained by borescope. Fig. 1(f) shows that the image analysis algorithm developed can successfully determine the sizes of both individual and overlapped bubbles. Further development of the algorithm is ongoing for improved edge detection and isolation of overlapped bubbles.

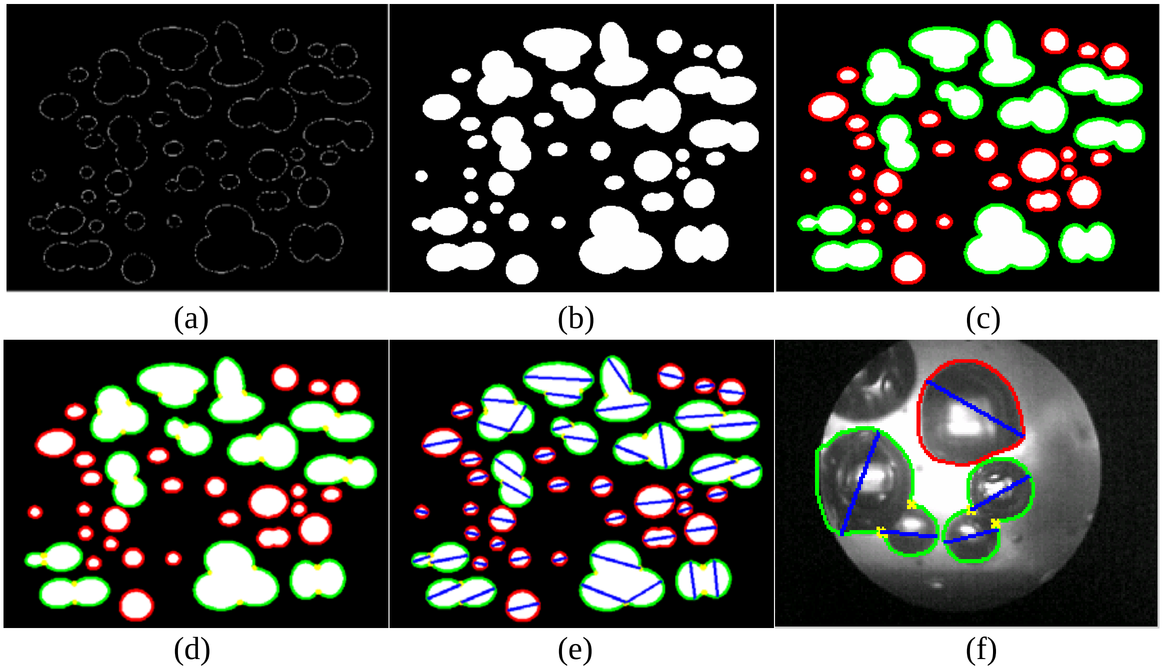

Fig. 1. Steps involved in automatic image analysis algorithm: (a) Detection of bubble edges; (b) Conversion to binary scale; (c) Identification of overlapped and individual bubbles; (d) Identification of intersecting points for overlapped bubbles; (e) Size determination; (f) Application on borescope image

Probabilistic Model

The bubble sizes determined using the image analysis algorithm is based on a fixed calibration scale. However, depending on the horizontal location of the bubble, a different calibration scale needs to be employed. For example, the bubble that is close to the borescope will appear larger than the bubble that is far from the borescope even though their actual size may be the same. Since it is impossible to determine the horizontal distance between the bubble and the borescope from the image, a probabilistic model is developed to determine the actual bubble size distribution from the bubble size distribution measured based on a fixed calibration scale.

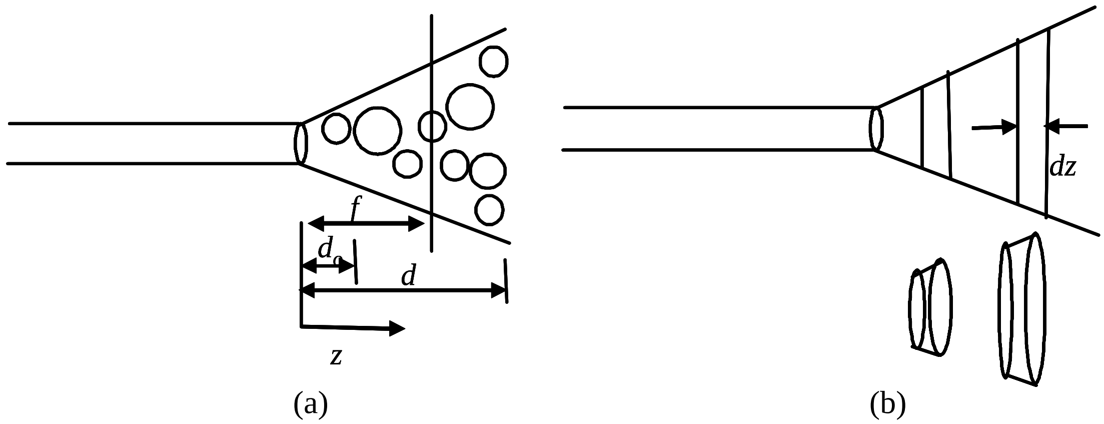

Fig.2. (a) Borescope operations and variable definition ; (b) differential measurement volume

An illustration of the borescope operation is shown in Fig. 2(a). For a borescope with a focal length, *f*, only the bubbles appearing within the depth of field (between d_o and *d* from the borescope) is visible. As shown in Fig. 2(b), for a fixed angle of view, the visible volume of width, *dz* increases with distance from the borescope, *z*. By assuming that all the bubbles are uniformly distributed in the whole measurement volume [5], the number of bubbles of a particular size within a differential volume of width, *dz* would also increase proportionally with *z*. Hence, the conditional probability density function (*pdf*) for bubbles appearing at horizontal location, *z* can be written as a linear function of *z*. The marginal *pdf* of any measured size, *y*, can be obtained from the conditional *pdf* of a bubble appearing in the differential volume at horizontal location, *z* by assuming that the probability of the finding the size contained in a differential volume of width, *dz* is the invariant of the variable change. The *pdf* of *y* is then used to derive an analytical probabilistic model to transform the measured size distribution to the actual size distribution.

The probabilistic model developed is tested theoretically. A set of bubbles with known distribution is passed through a borescope measurement volume. The bubble size distribution observed from the borescope is then simulated based on the conditional *pdf* of size, *y* with respect to the fixed calibration scale. As shown in Fig.3, the preset bubble size distribution is shown as solid circles. The simulated observed bubble size distribution is shown as thick solid line. The fixed calibration scale at the focal plane ($z = f$) is used. As the probability of observing bubbles further away from the focal plane is higher, the simulated distribution has a lower average bubble size and a wider distribution than the actual distribution. The simulated size distribution is then transformed using the probabilistic model. The thinner solid line in Fig. 3 represents the transformed bubble size distribution. The transformed size distribution is found to resemble the original size distribution. Hence the probabilistic model is capable of transforming the measured bubble size distribution with respect to a fixed calibration scale into the actual bubble size distribution without requiring any information about bubble horizontal location.

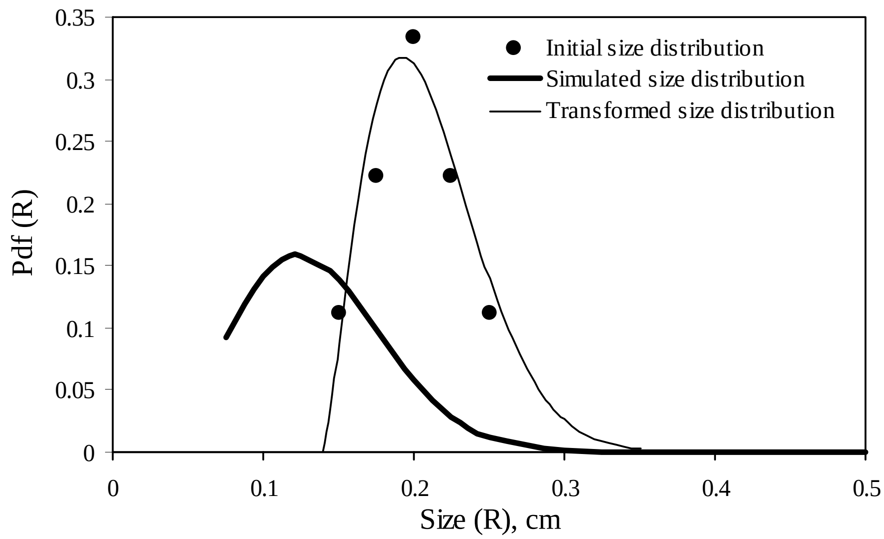

Fig. 3: Transformation of simulated size distribution into actual size distribution

Conclusions

An automatic image analysis algorithm is developed to determine the sizes of individual and overlapped bubbles borescope images. The algorithm can be applied successfully to real bubble images but further development of the algorithm is needed for improved edge detection and isolation of overlapped bubbles. A probabilistic model is also developed to solve the multiple-calibration problem in image analysis. The model is successful in transforming a measured size distribution using a fixed calibration scale into the original size distribution.

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