Note

Bubble size measurement and error analysis in a gas liquid ejector

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Bubble size in a gas liquid ejector has been measured using the image technique and analysed for estimation of Sauter mean diameter. The individual bubble diameter is estimated by considering the two dimensional contour of the ellipse, for the actual three dimensional ellipsoid in the system by equating the volume of the ellipsoid to that of the sphere. It is observed that the bubbles are of oblate and prolate shaped ellipsoid in this air water system. The bubble diameter is calculated based on this concept and the Sauter mean diameter is estimated. The error between these considerations is reported. The bubble size at different locations from the nozzle of the ejector is presented along with their percentage error which is around 18%.

Characteristics of the gas-liquid reaction involve the knowledge of physico-chemical phenomena such as mass transfer, reaction kinetics, hydrodynamics, bubble formation, break-up and coalescence. These parameters further depend on the geometric design of the equipment or reactor. Ejector is one of the contactors which offers high interfacial area, adjustable time of contact and a co-current device where the liquid is the continuous phase and the gas is the dispersed phase. Richardson and Coulson [1] have clearly stated that the interfacial area generated in the ejector is much higher compared to the usual contactors like spray column, plate column and agitated vessels. Ejectors have no moving parts in it and fluid-fluid contact is brought immediately with high degree of turbulence. The flow phenomena of the gas-liquid system vary based on the geometry of the ejector. Many correlations have been proposed in the past, where they are partially dependent on the experimental conditions. Experimental investigations by Bhutada and Pangarkar [2] indicated that there are different flow regimes with varying hydrodynamic characteristics and that too depend on the bubble size variation in each of the flow regime.

In the ejector, the liquid phase is introduced in the form of a jet. The other phase, gas can either be sucked by the liquid or can be introduced under slight pressure. The latter method gives a higher degree of control over the gas liquid flow ratios. The bubble size generated in this ejector has high influence on the interfacial area generated. The phenomenon of bubble generation and its growth is a complex process, involving intense mixing of two phases. Continuous process of breakage and coalescence of bubbles ultimately lead in attaining a steady value. Hence, the bubble size in the ejector plays an important role and this has to be measured for further calculations of the interfacial area, mass transfer, etc. Rocio *et al.*[3] have followed shooting a film with a high-speed digital video camera (Sony-DCR-TRV9E) in a carbon dioxide absorption column in order to extract selected snapshots using Studio Version 7 software. The two dimensional measurement of the bubbles was done using Uthscsa Image Tool software. With this information, the bubble diameter associated with an equivalent diameter of a sphere with the same volume as the ellipsoid was calculated.

While investigating the effect of solution on mass transfer coefficient in columns, Alvarez *et al.*[4] measured the bubble size using a photographic method based on taking images of the bubbles. Sony (DCR-TRV9E) video camera was used to obtain the images. A minimum number of 80 well-defined bubbles along the bubble column were used to evaluate the size distribution of bubbles in the liquid phase employed, using Image Tool v2.0 software. Lehr and Mewes[5] evaluated the bubble sizes in two-phase flow. They predicted the bubble size distribution in bubble columns including the formation of large bubbles at high superficial gas velocities. In recent years, studies on bubble characteristics in ejector or venturi type bubble column are increasing as they offer distinct advantages over other conventional bubble columns in their ability to generate fine bubbles and a high gas–liquid interfacial transfer area.

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Bubble size distribution of the two-phase mixture in a modified down flow bubble column was obtained using photographic method by Majumdar *et al.*[6] The photographs were taken by illuminating the flow with uniform, diffused white light and capturing the image with a digital camera. The digital photographs were processed and enhanced by using Image Processing Software (Image Pro-Plus 5.0, Media Cybernetics) that enabled to distinguish clearly the bubble boundaries. The images were taken at three axial positions for different operating conditions. The 2D picture shapes of the bubbles were approximated as spheroids,[7] where the maximum and minimum axes were automatically computed by the software program used for image analysis. The third dimension was calculated with the assumption that the bubbles are symmetric around the minimum axes. They have discussed on the bubbles that are symmetric around the minor axis, but nothing has been mentioned about those bubbles symmetric around the major axis. Experimental study on rising velocity of bubbles was done by Di Marco *et al*[8]. and the equivalent diameter of the sphere has been found. They found different regimes of terminal velocity and the viscosity dominated bubbles are spherical in nature, whereas the surface tension dominated bubbles are not spherical in shape. They concluded that the bubbles are elliptical and oscillate from the kind of oblate-to-less oblate shape and at times to prolate shape.

All these earlier literature reported the bubble size measurement considering the two dimensional elliptical contour of the bubble and computed the volume with the assumption of third axis. Thus, the volume of the ellipsoid found was equated to estimate the volume of the sphere and thereby the diameter. It is seen that only the oblate shape of the ellipsoid has been considered without giving any reason for the other possible prolate shape. The main idea of the present work is to consider both these shapes, viz oblate and prolate, of the ellipsoid and thus reporting the percentage of error involved. This will be helpful for bubble size diameter estimation that is to be used further in the mass transfer calculations. This criteria is of great importance when used in the gas-liquid reactive systems particularly. However, in the present work a non-reactive system is studied as first step.

Experimental Procedure

Image capturing method is used for the bubble size measurement in two phase system. Digital (video) camera picturisation and image analysis software are used. Earlier, the method was using a high speed camera and analyzing the pictures with the help of projection system. In our case, we have used the later version. However, the measurement and mathematical aspects of analyzing the bubbles are applicable commonly irrespective of the type of camera (video or high speed) used in photography.

A gas liquid ejector has been designed using the data given by Reddy and Kar[9] and is fabricated from borosilicate glass. The main features of the ejector are driving nozzle diameter 3 mm, throat diameter 3 mm, throat length 21 mm, suction tube diameter 44mm, nozzle length 21 mm and nozzle length/diameter ratio 7. Water is pumped through the nozzle of the main line. A secondary line through which air is sucked and a dispersion of air-water is generated, enhances the bubble formation, growth and its further movement downward. At the nozzle of the ejector the pressure energy is converted into kinetic energy, thereby reducing the pressure to the negative value. This enables the gas phase to enter and become dispersed into the liquid phase. The phenomenon is turbulent in nature and the dispersion moves down. As it moves down, the mixing intensity falls slowly. At the same time the bubble size increases due to coalescence and attains a steady value by the time it reaches the end of the diverging section of the ejector.

(i) High Speed Photography

Direct system of imaging, such as high speed photography is best suited for bubble size measurement in this gas liquid system. Experimental set-up for the photographic technique is shown in Fig. 1. Fastax 8000 camera is set before the ejector at a distance of 36 inches and the flow phenomenon is recorded using a 320ASA-100feet ORWO 16 mm film. The speed suitable for photographing this
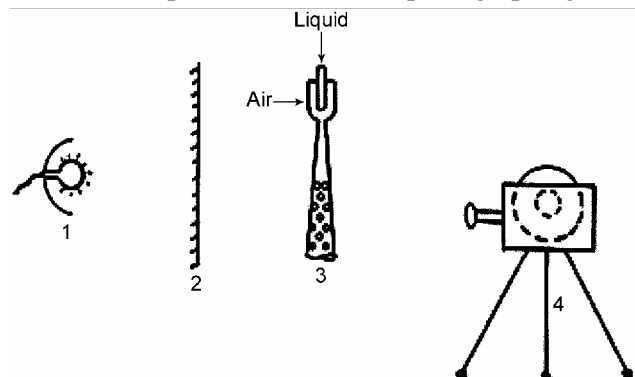

Fig. 1— Experimental set-up of the photographic method [1–GE bulb 750 W, 2–Ground glass, 3–Ejector, 4-FASTAX camera]

system is 700 frames per second using a lens diaphragm setting from 5.6 to 8.0. For the present work, the best suited is back lighting passing through a ground glass sheet kept between the ejector and the lighting. Two electric bulbs of 750 W and 110 V (GE make) are used for illumination purpose. A known length of reference marking is made on the ejector (by a thin metal wire of known diameter) and this is also recorded in the photograph together with the two-phase system. The magnification factor for the image of the bubbles is considered by taking the ratio of image size of the reference marking to its actual size. The details on the photographic assembly can be seen in the work reported by Raghuram *et al.*[10,11]. The film is processed in the *Fastax* continuous film processor and developer.

(ii) Analysis

The film is projected on a centimeter graph grid and the contour of the clear bubbles are marked. The bubble being ellipsoidal, their elliptical boundaries are traced and analysed. The major and minor axes of the ellipse are measured and the volume of the ellipsoid found. This is equated to the volume of a sphere and bubble diameter is calculated. It is observed from the literature that most of the work has been carried out by considering the volume equating basis and the Eq. (1) has been followed by many authors, without describing the reasons. In an actual two phase flow, the bubbles are of varying shape like ellipsoid, spheroid and sphere. Many authors have assumed only the oblate shape of the ellipsoid for this, without giving any details on the prolate shape. All these aspects are of importance in estimating the Sauter mean diameter value of the bubbles. This can be done more accurately provided the individual bubble diameter is more correctly estimated. In other words, the error embedded in the estimation is not highlighted. That means the reported bubble values may not give the correct bubble size. This seems to be a major drawback and attention has to be paid to rectify and to report more accountable value of the bubble. As a result, we can infer the possible error in the estimation of the bubble diameter. This paper will mainly focus on the following two important aspects:

Bubble diameter (*estimation by volume consideration basis*)

Sotiniedu *et al.*[12] conducted experiments with air water and their findings considered that majority of the bubble are ellipsoidal in nature. This matches in our present case and the same equations are followed.

Considering the major and minor axis of the ellipse in two dimensional contour as d_1 and d_2, the equivalent diameter of the individual bubble is expressed as:

$$d_O = (d_1{}^2 \times d_2)^{1/3} \qquad \qquad \ldots (1)$$

where d_O is the diameter for the oblate shape.

In this case, the shape of the ellipsoid will be oblate in nature (disk shaped).

The above equation cannot be true for all the ellipsoids. It all depends on the actual shape of the ellipsoid. We have observed the ellipsoid shape being prolate (like rugby ball) also and therefore the governing equation for this will be

$$d_P = (d_1 \times d_2{}^2)^{1/3} \qquad \qquad \ldots (2)$$

where d_P is the diameter for the prolate shape.

Sauter mean diameter

In each frame of film, the ejector is divided into many segment of one cm height. For each segment, a number of frames about 30 at the same location are analysed and the individual bubble diameter (d_i) is calculated using any of the Eqs (1) or (2) for d_O or d_P Then the Sauter mean diameter (d_{32}) is calculated for the number of bubbles (n), using the following formula:

$$d_{32} = \sum_{i=i}^{n} (N_i d_i^3) \Big/ \sum_{i=i}^{n} (N_i d_i^2) \qquad \qquad \ldots (3)$$

where $d_i = d_O$ for oblate and $d_i = d_P$ for prolate.

Results and Discussion

The image capturing method has both advantages and disadvantages of picturisation. The merits being that any individual bubble can be examined carefully and clearly (even the distorted bubble), generation and growth phenomenon of bubbles followed, the recorded information can be repeatedly projected for further analysis at any time. On the other hand, the demerits being that bubble volume is not directly found, but only the contours of the bubble in a single plane (two dimensional) are obtained. The position and intensity of light is crucial and the hidden bubbles have to be measured with difficulty due to less clarity. Most of the bubbles are elliptical in shape and sometime distorted in shape too. The bubbles present in the front portion gets picturised clearly, whereas the bubble present in the middle and backside are not clear. As a result, the available useful information

from such bubbles is either difficult to use or not made use of. It is extremely difficult to picturise any particular bubble from orthogonal positioning using even two cameras at the same time, since the bubble is fast moving in a stream of bubbles.

In the estimation of bubble size for the gas - liquid system in the ejector, measurements are made from a distance of 16 cm away from the nozzle and up to the end of the diverging section, since dispersion and bubble growth stabilize in this range. An explanation to this phenomenon has been given by Panchal *et al.*[13.] Depending upon the pressure profile and mass ratio, various regimes of two - phase flow have been observed in the diverging section of the ejector. The flow regimes being coaxial and then homogeneous, bubbly flow are observed in this, which greatly influences its growth. Hence, up to a distance of 16 cm, coaxial flow occurs and there after, bubbly flow is observed in the ejector. Measurements have been done within this range and are discussed here. Four different liquid flow rates, namely 75.8, 94.7, 113.6 and 132.6×10^{-6} m^3/s with corresponding air flow rate being 65.1, 68.4, 72.6 and 79.5×10^{-6} m^3/s have been tried for the bubble size.

Bubble size

The relationship between bubble size as a function of its distance from nozzle is shown in Fig. 2. It is seen for a given flow rate of air and water that the bubble size increases as the dispersion is moving away from the nozzle, due to coalescence. The growth rate is faster initially and becomes steady by the time the dispersion reaches at the end of the divergent section of the ejector. The slope of the curves in the figure further strengthens this aspect. The trend of the graph is same for all the corresponding combination of the gas liquid flow rate, whereas the bubble size is slightly smaller in the sequential combination. It can also be seen that bubble size obtained from oblate ellipsoidal consideration is always greater than that obtained from the prolate ellipsoidal consideration, at any particular location of the ejector. This is as per expectation since the oblate volume is greater than the prolate volume, for any given axes values of an ellipsoid.

Error aspect

The shape of the ellipsoid in the two phase system is picturised as ellipse in two dimensional plane. The ellipsoid in actual system could be of oblate or prolate shape; however in both the cases the contour is same in two dimension. As a result, the volume of the

oblate ellipsoid is different from that of the prolate ellipsoid, which leads to different values of Sauter mean diameter ultimately. Hence, there could be possibility of the error in the bubble diameter. Figure 3 gives the relationship of the bubble diameter with the percentage error, due to this shape consideration. The
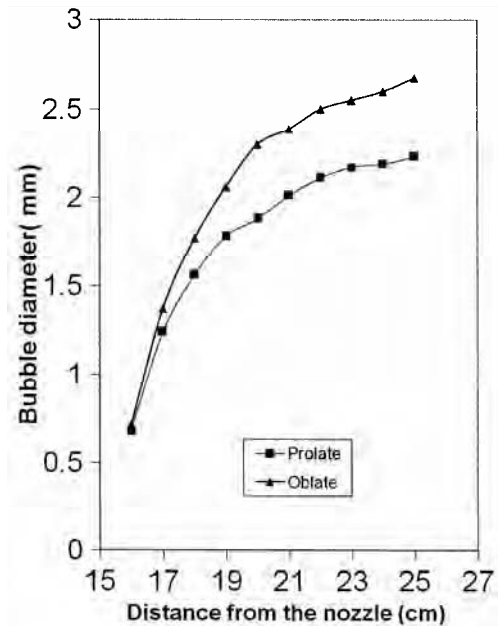

Fig. 2— Bubble size at different places from the nozzle. [Air 65.1×10^{-6} m^3/s with liquid 75.8×10^{-6} m^3/s]
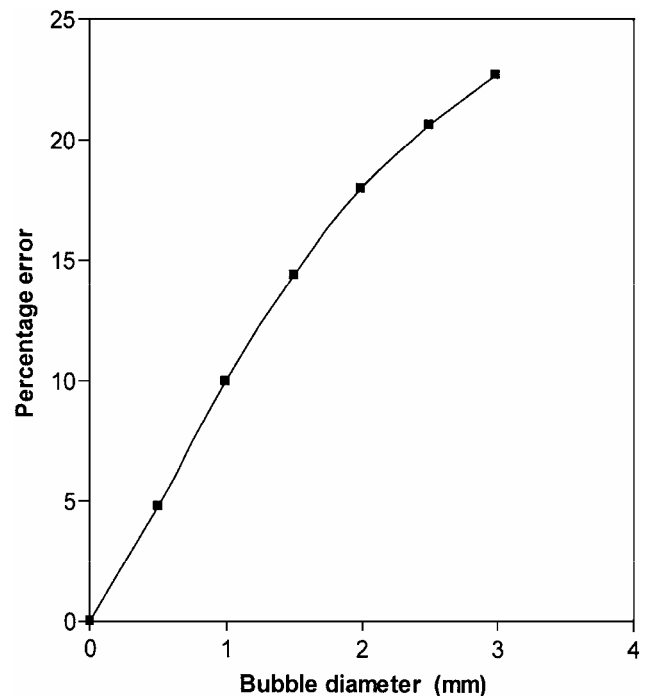

Fig. 3— Percentage error of bubble diameter due to shape consideration

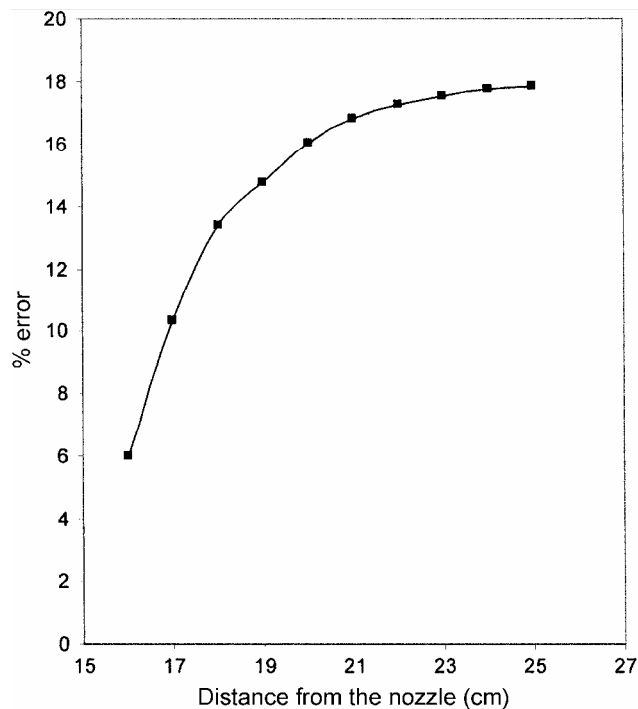Fig. 4— Percentage error in the bubble size at different distance from the nozzle.

Conclusion

Bubble size measurement has been carried out with photography technique. Individual bubble diameter is estimated considering the bubble being oblate and prolate in shape, based on volume equating basis. Sauter mean diameter has been calculated in the conventional way. The possible error between these two consideration is presented in this paper. The bubble growth with respect to the distance away from the nozzle of the ejector has also been reported. Closer look into this error consideration will pave the way for more accurate estimation of bubble size in any gas- liquid column.

percentage error is calculated as the difference between the diameters of the oblate and prolate to the diameter of the oblate.

$$\text{Percentage error} = (d_O - d_P)/d_O \qquad \qquad ... (4)$$

The four sets of experimental values are used to calculate the error and the average value is taken (Fig. 4). As the bubble size increases the percentage error also increases. This shows the percentage error of the bubble at various distances from the nozzle of the ejector. The error increases slowly as it is farther from the nozzle and reaches a steady value by the time the dispersion comes out the ejector, during which time the bubble size stabilises.

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