Measurement of Coaxial Swirling Bubble Jet Flow by Interferometric Laser Imaging

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ABSTRACT

Spatial measurements of the size and velocity distributions of air bubbles carried in swirling water flow have been conducted using Interferometric Laser Imaging (ILI). The bubbles were introduced in a pipe from a nozzle and were subsequently entrained at swirling flow, created via two side-inlets that were tangentially placed to the pipe around the bubble nozzle. Measurements with ILI and Laser Doppler Velocimetry (LDV) under these conditions proved to be challenging due the optical distortion caused by the pipe’s curvature and the out-of-focus imaging principle of ILI. To minimize said distortions, a new test section was designed; a cylindrical tube with three added thin plate windows for the needs of the measurements. Measurements were conducted 125 mm, 375 mm downstream of the bubble nozzle exit and involved the out-of-focus imaging of the interference light emanating from the illuminated bubbles. A special optical assembly containing a pair of cylindrical lenses was used to optically compress the light signal of each bubble so that measurements in bubble-dense areas can be realised. As a consequence, the acquired images contained “line” fringe patterns whose internal frequency was dependent on the bubble size, while tracking the patterns in consequent images provided the velocity of each bubble. The water velocity was measured using Laser Doppler Velocimetry. The Swirl number, which represents the swirl intensity, was calculated by the measured axial and tangential velocity profiles and was 0.58, 0.81 one pipe diameter downstream of the swirling jet outlet. The results indicate that the bubble size distribution shifted towards smaller diameters and while their radial velocity increased as the swirl intensity increased. Additionally, it could be confirmed that the swirling flow induced the attraction of bubbles toward the pipe centre away from pipe wall and this tendency was weakened further downstream of the nozzle exit for the case of Swe=0.58 compared to that of Swe=0.81. The interaction between bubble behaviour and swirling flow was successfully measured. Therefore, the applicability of the ILI method has been evaluated to be viable for the characterisation of bubble size and velocity distributions in swirling bubbly flows.

1. Introduction

Swirling bubble jet flow is widely used in a range of industrial processes, including devices such as microbubble generators, gas-liquid separators, etc. A number of studies have been previously performed on such swirling flows and methodologies to predict the characteristics of such
devices have been proposed (Y. Tanaka et al. 2001; K. Tabei et al. 2007). However, the relationship between the bubble movement and the swirling flow has not been investigated. For the further enhancement of such devices, the bubble size and velocity distributions in the resulting swirling flow are required, since this information enables us to understand the unsteady behaviour of the bubbles and the structure of their surrounding flow.

Many instruments have been proposed for the measurement of these parameters. One of the most common measurement techniques is Phase Doppler Anemometer (PDA). This technique provides the particle size and velocity by extracting information from the scattered light the particle is emanating. The main disadvantage of PDA is that many measurements are required for the analysis of the flow dynamics in a large measurement volume due to its point measurement nature. Due to this, flow visualization is not as easy as with imaging techniques that are capable to instantly visualize a relatively large area of the flow.

Interferometric laser imaging (ILI) is an advanced measurement technique for multiphase flows employed for the extraction of the size and velocity distributions of micron-sized spherical particles, as they are carried by the continuous phase. This optical technique was originally suggested for droplet measurements by König et al. (1986) and Glover et al. (1995) but can be readily applied to bubble measurements (e.g. Kawaguchi et al. 2002, Kawaguchi and Maeda 2005, Lacagnina et al. 2011). The measurement procedure for ILI involves the illumination of each bubble in the measurement area by a laser sheet, which produces an interference (fringe) pattern due to the reflected and first-order internally-refracted rays originating from the bubble surface. The pattern is subsequently captured in the far-field from a camera focused on a plane located between the measurement area and the camera’s photo-sensitive imaging sensor. It is important to note that the number of fringes is directly proportional to the bubble diameter and is independent of the absolute light intensity (Hasselbacher et al. 1991). A special optical assembly containing a pair of cylindrical lenses manipulates the focusing distance, along with a rectangular aperture which “compresses” the light signal of each bubble so that measurements in bubble-dense areas can be realised. As a consequence, the acquired images contain “line” fringe patterns whose internal frequency is dependent on the bubble size, while tracking the patterns in consequent images provides the velocity of each bubble.

In the present study, the interferometric laser imaging technique was applied for measurements in a coaxial swirling bubble jet flow. The objective of this study is to experimentally investigate the interaction between rising bubbles and their surrounding swirling flow using ILI. In the present contribution, we describe the effect of the swirl intensity on the bubble behaviour using
the local distribution of bubble size and velocity provided in a variety of downstream measurement locations and discuss the applicability of the ILI method for such measurements.

2. Measurement Technique

When imaging with ILI, each bubble is illuminated by a laser sheet and the interference pattern that is formed from the reflected and first-order refracted rays on the bubble surface is imaged in the far-field from an out-of-focus camera. The pattern for each individual bubble is recorded at an angle \( \theta \) in relation to the light forward propagation direction, for a certain angular range \( \alpha \) (i.e. the collection angle). The number of fringes \( N \) contained in this pattern relates to the bubble size by the relation

\[
d = \frac{2\lambda N}{\alpha} \left[ m \cos(\theta/2) - \frac{m \sin(\theta/2)}{\sqrt{m^2 - 2m \cos(\theta/2)+1}} \right]^{-1},
\]

where \( m \) is the relative refractive index and \( \lambda \) the light illumination wavelength.

In Fig. 1, a typical ILI optical arrangement is shown, depicting the propagation of the scattered and refracted light rays and the formation of the interference pattern. The pattern propagates to the CCD camera and is captured in the shape of a line due to the rectangular aperture, and is lengthened or shortened transversely by the pair of cylindrical lenses. The orientation of the cylindrical lenses is set to vertical and they hence have no influence longitudinally. A typical ILI image is depicted in Fig. 2. The evaluation of bubble size is realised by isolating the individual fringe patterns, performing Fourier analysis and determining the number of fringes \( N \) via subpixel interpolation; Kawaguchi et al. 2002 details the procedure in detail.

The velocity of each bubble is obtained from the displacement of the interference pattern between two consecutive images, which are captured by the camera using the illumination provided by a double-pulsed laser at a set time interval. As a result, ILI can provide both the size and velocity of each bubble spatially.

Fig. 3 shows an instantaneous bubble flow field depicting both the bubble velocity vector and diameter in the measurement area. The particular flow field was produced by two consequent images. The diameter of each circle and the length of each line represent the diameter and corresponding velocity, respectively, of each detected bubble.
3. Experimental Setup

The experimental setup used for the measurements is given in Fig. 4. Spatial measurements of the size and velocity distributions of air bubbles carried in swirling water flow have been conducted using ILI. The bubbles were jetted from a stainless pipe nozzle exit and were
subsequently entrained in the swirling water flow, created via two side-inlets that were tangentially inserted to the pipe around the bubble nozzle. Fig. 5 shows the bubble generation and swirling compartment details. Additional swirling water flow was imposed around the coaxial swirling bubble jet flow via four inlets to prevent stagnation of the bubbles in the pipe. The pipe geometry must be taken into account to minimize optical distortions introduced by the pipe curvature and its out-of-focus imaging principle. Thus, two planar windows were introduced for the entrance of the laser light in the pipe, and for the camera view. The arrangement of the windows was set such as that the scattering angle $\theta$ was 45°. This pipe had a diameter of 88 mm, with tangentially inserted planar sections acting as the viewing and light entrance windows whose length was 39 mm and run along the length of the pipe (as shown in Fig. 6).

The ILI measurements were conducted 125 mm downstream of the bubble nozzle exit, with 2,000 image pairs captured at the plane of the pipe axis with a time difference of 150 $\mu$s. The optical equipment consisted of an double-pulsed Nd:YLF pulsed laser at a wavelength of 527 nm along with a 2456×2058 pixel CCD imaging receiver. The optical arrangement resulted to a measurement area of 14.0x10 mm$^2$. The laser pulse energy was 10 mJ while the thickness of the laser sheet was measured to be approximately 1.5 mm.
4. Results and Discussion

4.1 The velocity distribution of liquid phase

The velocity of the liquid phase, which was water, was measured using Laser Doppler Velocimetry. The flow rate via the four inlets was $Q = 0.0050 \text{ m}^3/\text{min}$ constantly, for swirling flow rates $Q = 0.0085, 0.0220 \text{ m}^3/\text{min}$. Fig. 7 shows the velocity distribution of the liquid phase along the pipe. The results confirmed the presence of qualitative swirling flow. The Swirl number $Sw$ was defined by using the equation

$$Sw = \frac{G_\theta}{G_z R}$$

which express the proportionality between the angular ($G_\theta$) and axial direction momentum ($G_z R$). The Swirl number was evaluated to being $Sw=0.58$ and $0.81, 80 \text{ mm downstream of the bubble nozzle exit.}$
4.2 Bubble size, velocity and number density distributions
The spatial distributions of the bubble position, size and velocity in the swirling flow were measured by ILI. Measurements were conducted at two locations where the axial locations were \( z = 125 \text{mm}, 375 \text{mm} \) for when \( Sw = 0.58, 0.81 \). Both experiments took place with 200 ppm 3-pentanol dissolved in the water. At each measuring location, 2000 images were taken to obtain the information of bubbles that exist in the 14mm \( \times \) 10mm measuring area.

The bubble size distributions at \( z = 125 \text{mm} \) for each Swirl number are shown in Fig. 8; it is apparent that the size distribution shifted towards smaller diameters as the swirl intensity increased. From ILI measurement of the bubble jet, for the case of \( Sw = 0.81 \), the number of the 250 \( \mu \text{m} \)-sized bubbles reduced, while the number of 150 \( \mu \text{m} \)-size bubbles increased by approximately 30% compared to the case of \( Sw = 0.58 \).

Fig. 9 shows the mean flow field for all measured bubbles, over the contour of the spatial distribution of the measured average bubble number, as obtained by the captured images for \( Sw = 0.58 \).

Fig. 10 shows the mean local radial velocity of the bubbles obtained by averaging for each radial position for the two swirling conditions. It can be deduced that the swirl led to radial velocity and velocity gradients of bubbles to differ according to their sizes and the swirling intensity of the water. The velocity gradients for the case of \( Sw = 0.81 \) were about three times as that of \( Sw = 0.58 \). This means that the bubbles gravitated to the center of the pipe in the swirling flow. With the swirl increase, this tendency was more pronounced.
Figs. 11 and 12 show the number of bubbles on a set averaging volume in space at each radial position. The peak positions in the distributions were significantly different on their magnitude. Additionally, it can be confirmed that the swirling flow induced the attraction of bubbles toward the pipe centre away from pipe wall. This tendency was weakened far downstream of the nozzle exit for the case of $Sw = 0.58$ comparing to that of $Sw = 0.81$. This is a result of weakening of the swirling component further downstream of the flow, causing bubbles to be transported radially outwards for the case of $Sw = 0.58$.

Fig. 8 Probability density distribution of the bubble diameter.
Fig. 9 Spatial distribution of the measured bubbles with velocity vectors ($Sw = 0.58$)

$Sw = 0.58$

$Sw = 0.81$

Fig. 10 Local radial velocity profile of the bubbles for two Swirl numbers along the radial direction of the measurement area.
Fig. 11 Number density distribution downstream of the bubble nozzle exit ($Sw = 0.58$).

![Image](image_url)

$Sw = 0.81$

Measuring area ($z = 375$mm)

Measuring area ($z = 125$mm)

Nd-YLF Laser

Fig. 12 Bubble number density profile downstream of the bubble nozzle exit ($Sw = 0.81$).

5. Conclusion

In order to investigate the relationship between bubble dynamics in a swirling flow, spatial measurements of the size and velocity distributions of air bubbles carried in swirling water flow have been conducted using Interferometric Laser Imaging. Measurement using ILI under these conditions proved to be challenging due to errors introduced by the optical distortion present due to the pipe curvature and the out-of-focus imaging principle of ILI. To minimize said distortions, a new test section whose shape was an acrylic cylindrical tube with three added thin plate windows for the needs of the measurements was introduced. Two flow conditions, namely $Sw = 0.58, 0.81$ were compared for the distributions of bubble position, sizing and velocity. The main conclusions of the study are summarized as follows:
The bubble size distribution shifted towards smaller diameters as the swirl intensity increased.

The swirl led to the radial velocity and velocity gradients of the bubbles to differ, depending on their sizes and the swirl intensity of the water.

The swirling intensity of the continuous phase flow and affected the number density of bubbles at each radial position. The swirling flow induced the attraction of bubbles toward the pipe centre away from pipe wall and this tendency was weakened far downstream of the nozzle exit for the case of $Sw = 0.58$ comparing to that of $Sw = 0.81$.

Following the above, it can be concluded that the applicability of the ILI method has been proven to be viable for the characterisation of bubble size and velocity distributions. In future work, the alteration of the bubble size distribution due to the swirling flow for various initial void fractions will be performed.

6. References


