Dancing Bubbles in Turbulent Flows: PIV Measurements and Analysis

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Two-phase bubbly flows are widely applied in engineering and environmental processes. The interaction of the dispersed phase with the continuous phase has a great effect on transfer processes between the phases. The interstitial relative velocities between the phases and the interfacial area and the shape of the dispersed phase are the key dependent parameters in the drag, heat and mass transfer between the phases. Although the physical understanding of bubbles rise in a liquid is a significant practical importance in many areas of engineering, neither the interactions between bubbles in clusters nor the bubble-induced pseudo-turbulence (i.e., the generation of velocity fluctuations by bubbles and their wakes in a laminar flow) are fully understood. The modeling of bubbly flows with the Computational Fluid Dynamics (CFD) codes requires detailed information about the full field velocity close to the bubble and its wake. Such information is not widely available. Experimental data exist mainly from point measurement techniques, which offer the advantage of having high time resolution, but their spatial resolution is poor, and information about the vorticity field is lacking. Many investigations have been carried out over the past three decades using hot-film and hot-wire anemometry. However, the use of hot film anemometry in two-phase flows, raise many questions that remain unanswered. In particular, the interactions between the sensors as X-probe, liquid and bubbles are not well known and can lead to errors in the determination of correct turbulence parameters. The deformation of the bubble surface is caused by sensor penetration through the bubble. Recently, interesting number of direct numerical simulation studies of bubbly flows have cast considerable light on the evolution of bubbly flow (Esamaeeli &Tryggvason, 1998, 1999; Burner & Tryggvason, 2002).

This communication is to present results of an optical technique known as particle image velocimetry (PIV) utilized in multiphase flow investigations. PIV provides instantaneous velocity fields in a 2-D plane and it can be extended to 3-D situations. Recently, increasing numbers of successful investigations are reported. In this brief PIV is applied to study bubbly flows and the component phases are separated during analysis. With the improvement of digital imaging technology in recent years, PIV measurement techniques are now capable of capturing high-resolution digital images of gas/liquid two-phase flows, in which the continuous liquid phase and the dispersed gas phase are unsteady and multi-dimensional.

A schematic of the current facility is illustrated in Fig. 1. The apparatus can achieve Reynolds Numbers for the liquid phase up to 25,000 and volumetric gas flow rate from 0 to 0.5 l/min. The flow regime can range from single-phase liquid to dispersed bubbly flow to the slug flow regime with small cap bubbles and bubble coalescence pattern. The bubbly flow is generated at the bottom of the glass pipe of an inner diameter of 5 cm. Connected to the pipe are the bubble generator, two pumps and one reservoir tank. The main liquid flow enters above the bubble generator, which is located at the bottom end of the pipe. A secondary liquid flow is injected through the lower side of the bubble generator. This secondary flow is used to control the air bubble sizes. Air is injected into the chamber between the inside of the cylinder, and the outside wall of the sintered metal tube. The secondary pump draws the water from the reservoir tank and passes it through a flow gauge and then into the centre of the bubble generator, where the air passes through the sintered metal tube. The main flow pump draws water from the reservoir, passes it through a flow gauge, and then injects it below the test section. The test section is approximately at *L*/*D* of 30, where *L* is the length from the bottom of the pipe, and *D* the pipe inlet diameter.

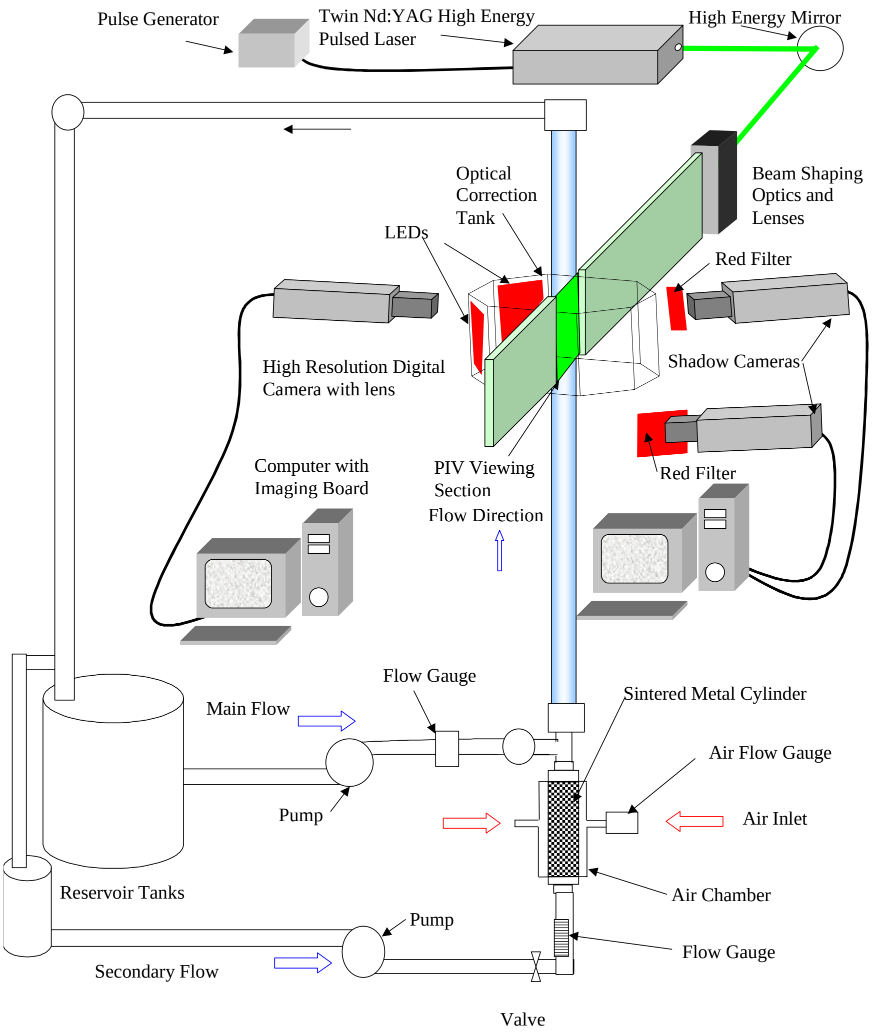

Fig. 1 Two-phase flow test facility

A twin Nd:YAG high energy (400 mJ) pulsed laser (9.0 ns pulse width) is used as illumination source. Typical high-energy optics is used to manipulate the laser beam and form the laser sheet necessary for PIV measurements. The synchronization signals originate from the cameras and are passed through a pulse generator and trigger the laser. The high-resolution (1016×1016 pixel) digital camera and associated frame grabber boards have two modes of operation. The normal, continuous, mode has a 30 frame per second (fps or Hz) framing rate. The 'triggered' mode enables the cameras to capture two consecutive frames with a very small time delay controlled by the user, while the system has a capture rate of 15 Hz. Two other digital cameras are used for shadow PIV. The cameras are capable of capturing frames at 30 Hz with a resolution of 640x480. Illumination is supplied by two red light emitting diodes (LEDs), which oppose each of the cameras within the measurement volume. A screen diffuses the LED light and filters are attached to each camera to remove any reflected laser light and permit only red light. A 3-D bubble shape is reconstructed from the two shadow cameras (Ortiz, 2001; Todd, 2002). An optical correction tank encloses a portion of the pipe where the PIV measurement volume is located. This tank is filled with oil to reduce the optical refraction effects of the cylindrical pipe. The laser sheet, optical correction tank, and camera positions are indicated in Fig. 2.

The flow tracer size that can be used in a PIV system is a function of the laser power and camera resolution. A tracer size of 4 μm has been found to be very suitable for this system. The tracer particles are neutrally buoyant, chemically compatible, and optically reflectable and have diameters of few micrometers. Since the tracer particles are small, high-energy lasers are commonly used as illumination source.

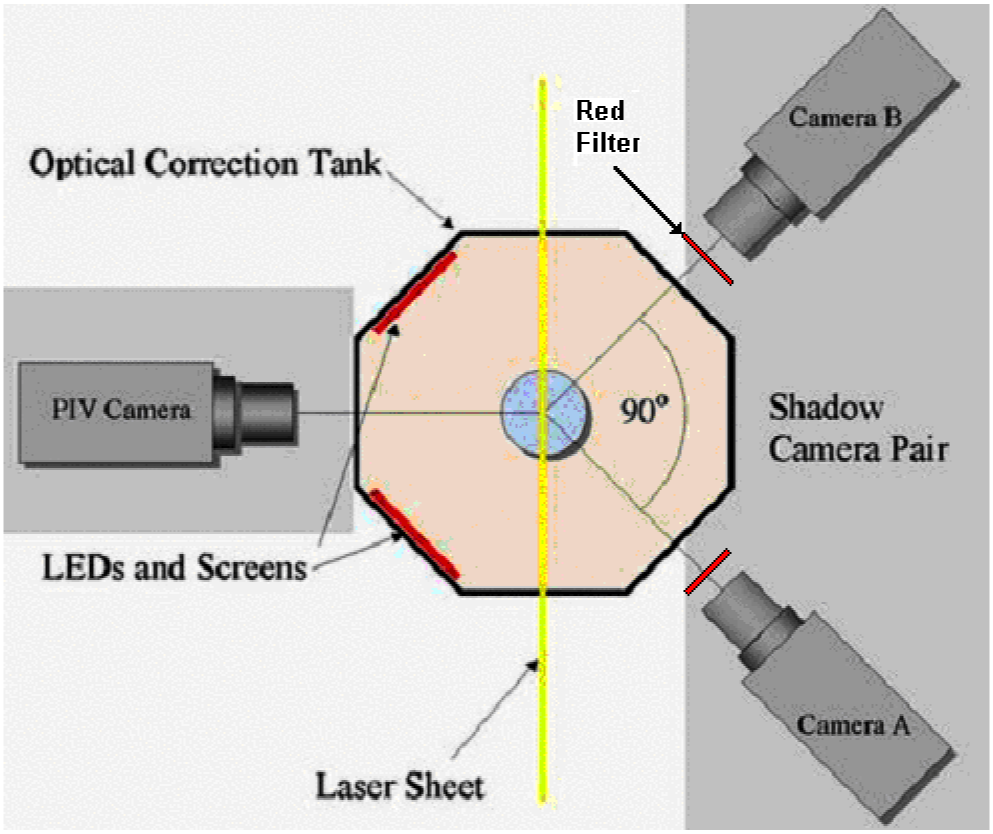

Fig. 2 Measurement System Layout

The process of the image analysis involves several steps to produce a sequence of frames into a series of vector maps. The first step involves thresholding each frame to remove the background and highlight the flow tracer images. The next step is to locate the centroid of each tracer image and create a data file for each frame containing all the centroid information, tracer image area, and average tracer image intensity. Finally, the data files are input into the particle-tracking algorithm to determine the tracer path from frame to frame. Several tracking algorithms are used for the tracking process: cross correlation, a neural network using a Hough Transform and Spring Model.

Figure 3 presents a few frames of the snapshots of reconstructed results from the two shadow cameras images at several transient times. From these two images the three-dimensional positions of the bubbles can be determined. It is also clear that the bubble size varies from bubble to another and the bubble shape is not spherical. The bubble sizes were between 0.8 to 2 mm. The liquid velocity field and vorticity obtained from the PIV image are added to the figure. This plot is accompanied by a view down the axis of the pipe. Assembling the entire sequence of the plots into a movie provides an informative structure of the flow. For instance, the vortical structure embedded within the flow due to the passage of bubbles is delineated. It is noted that the bubble interaction can take place by drafting, kissing and tumbling where a bubble is drawn into the wake of a bubble in front. Similar behavior is also obtained by direct numerical simulation of Tryggvason group. It is interesting to note that at the injection location, the bubbles are uniformly distributed. Later and at the measurement zone, the flow pattern is irregular and non-uniformly distributed. There are regions with relatively high bubble concentrations and other regions are free of bubbles. Direct numerical simulations with PIV measurements offer the opportunity to reveal the complex structure of bubbly flow and the interactions of small motion with the large scales. Closure constitutive relations for engineering applications would be best estimated.

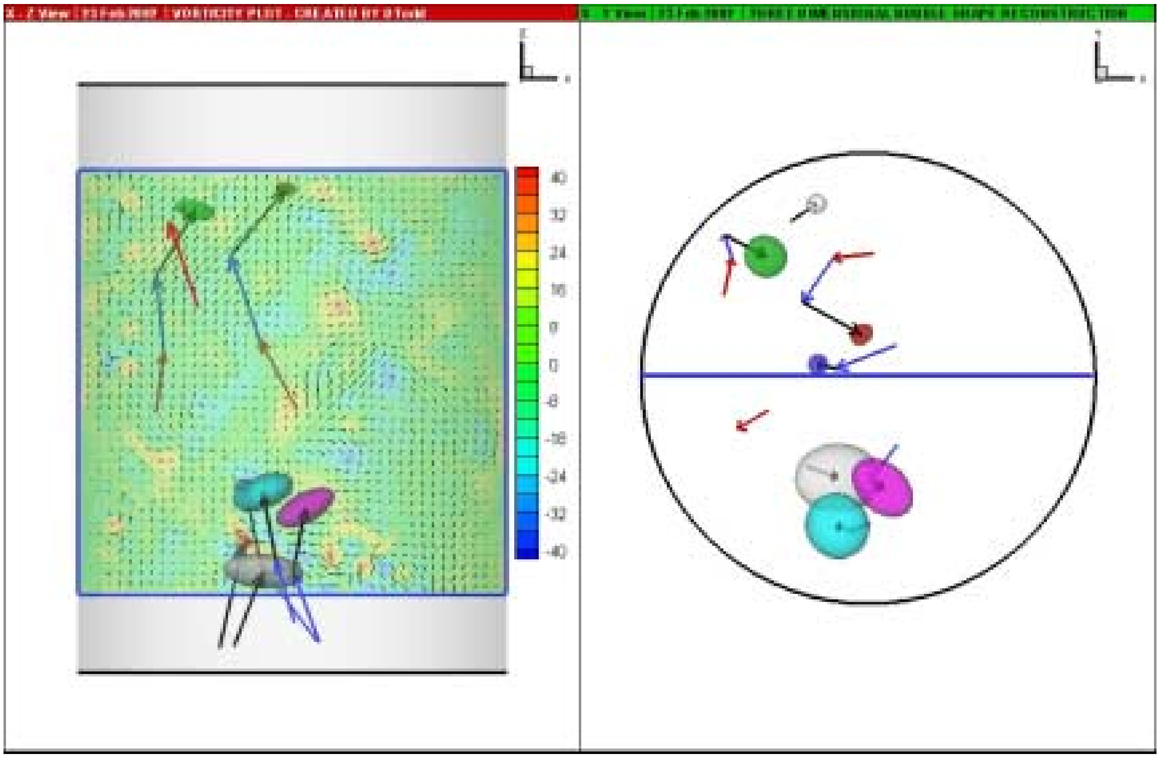

Fig. 3.a

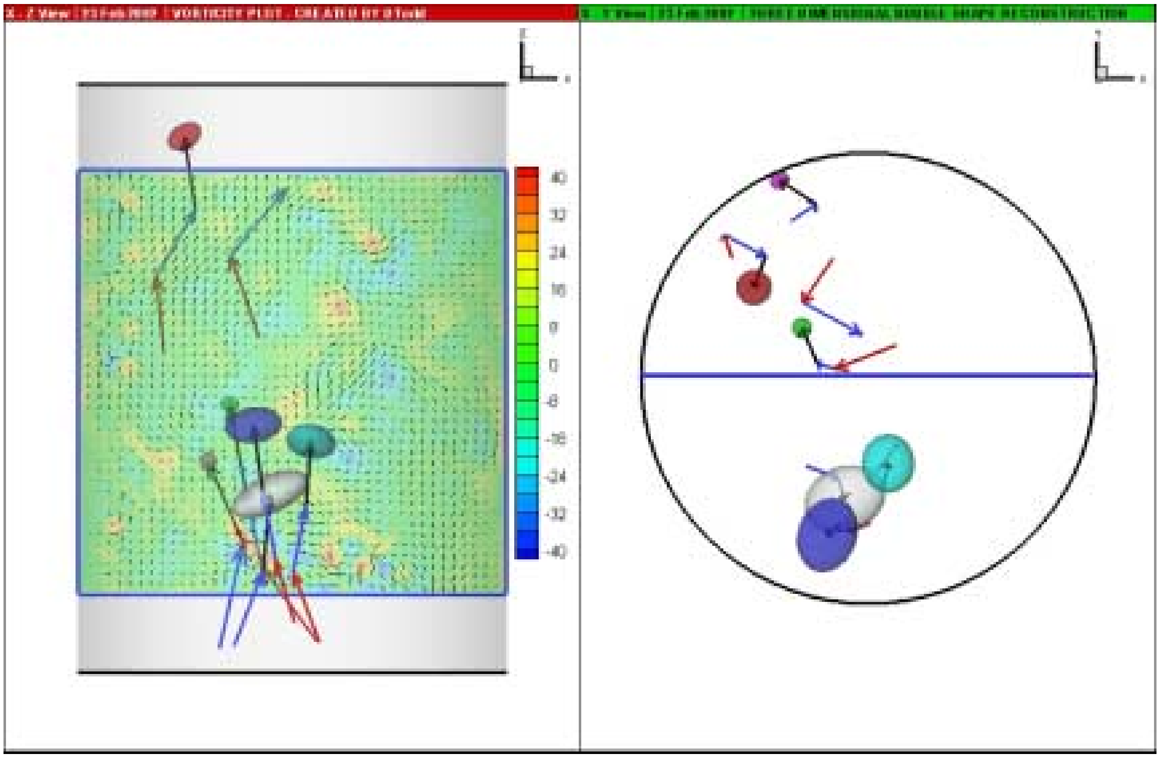

Fig. 3.b

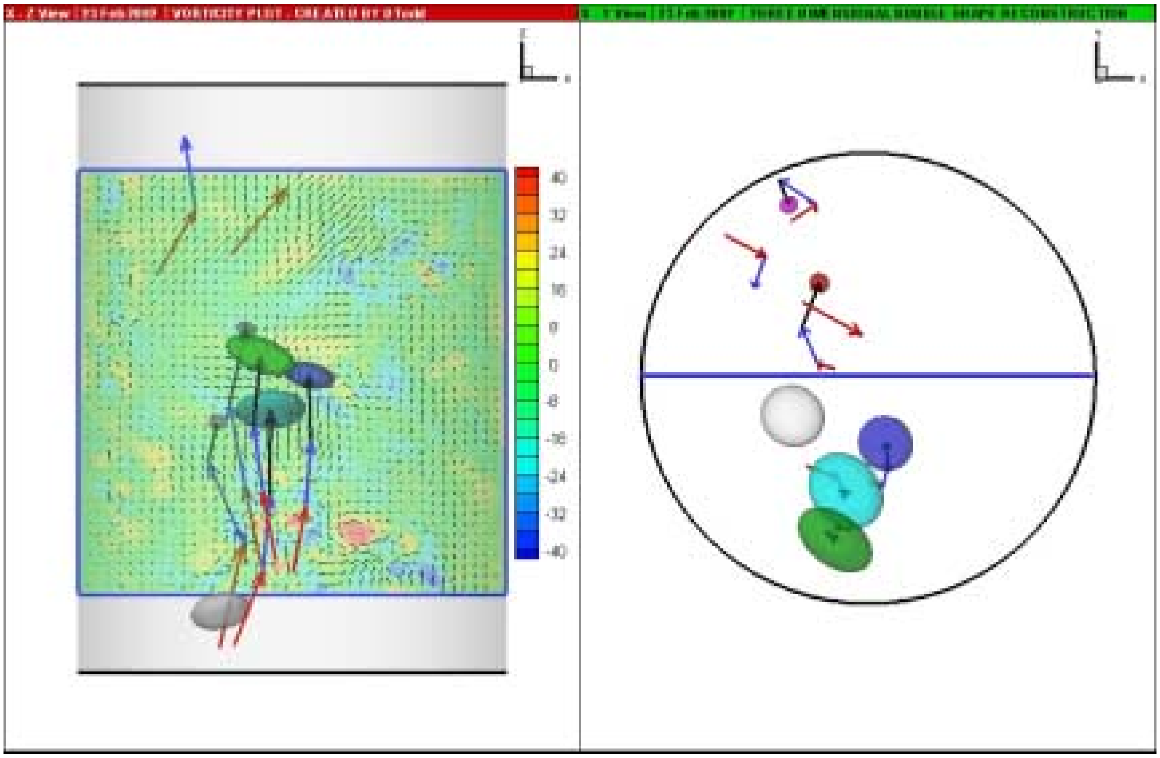

Fig. 3.c

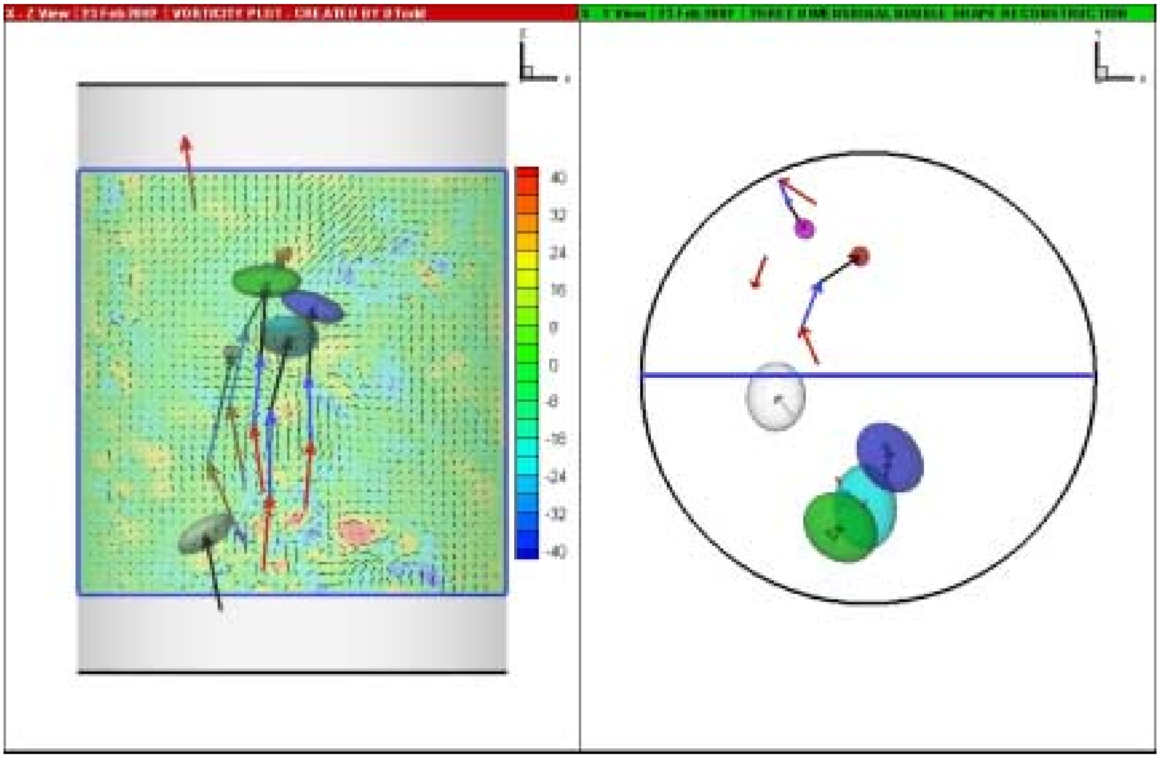

Fig. 3.d

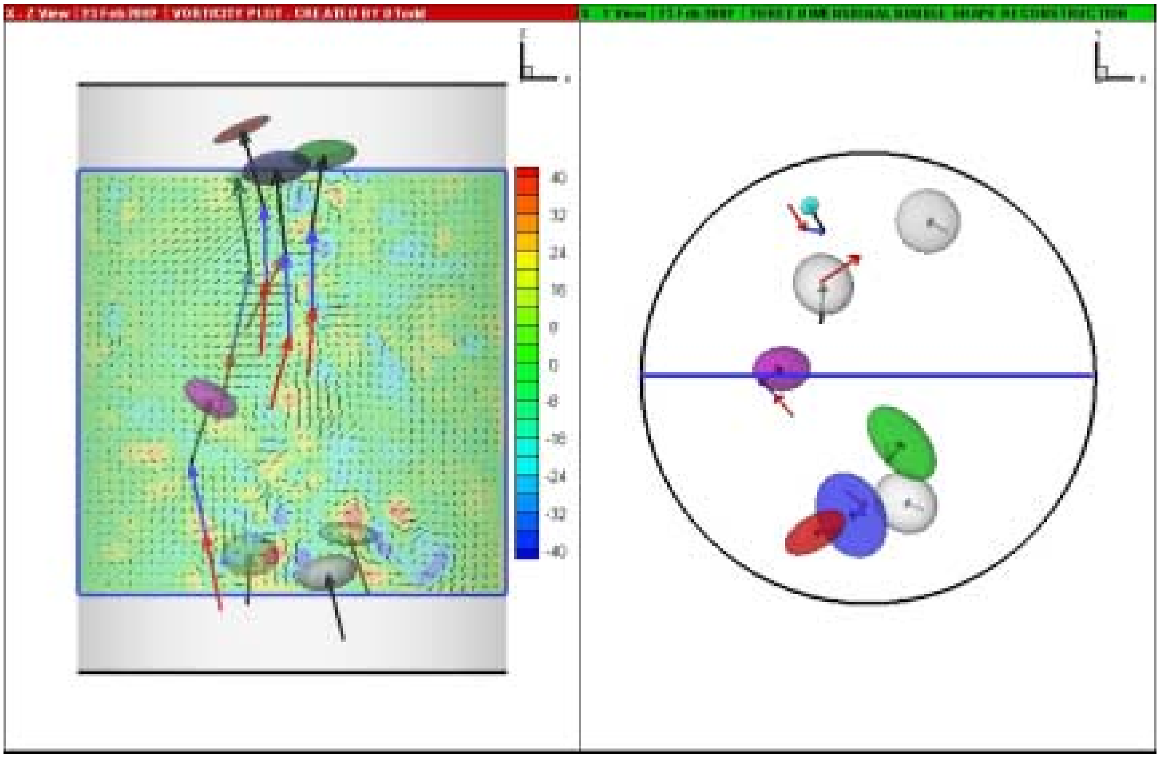

Fig. 3.e Selected snapshots of interactions of the bubbles with the flow

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