Non-intrusive measurements of bubble size and velocity

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Abstract A non-intrusive measuring technique based on video-imaging has been developed for the measurement of bubble size, velocity and frequency. Measurements carried out with this method have been compared to those obtained by an optimized phase-Doppler system in standard configuration, for a wide range of bubble sizes produced from single injectors in a quiescent environment. The two measuring techniques have yielded velocities and frequencies that are in very good agreement while the size of spherical bubbles was consistently measured by both methods. The phase-Doppler system was also used to size oblate-spheroidal bubbles moving with their equatorial plane parallel to the scattering plane, yielding measurements reasonably close to the average radius of curvature of the bubbles in the neighborhood of the equatorial plane, as calculated from the video-imaging data. Both methods were used for detailed velocity measurements of the bubble-stream in the neighborhood of the injector tip. The observed bubble-velocity variation with the distance from the injector tip does not always display the usual increasing trend leading into the terminal velocity. When injection conditions are near the transition from discrete to jet injection mode and the bubbles are small, the latter decelerate into a terminal velocity due to direct interaction of successive bubbles at the injector tip. The measured terminal velocities of bubble-chains for a variety of bubble sizes and injection frequencies, are successfully predicted by using a far-field wake approximation to account for the drafting effect which is responsible for bubble-chain velocities higher than those of single bubbles.

1 Introduction
Local measurements in dispersed, two-phase, liquid/gas flows have mostly been performed using intrusive techniques which involve placing probes within the flow. These intrusive techniques can introduce considerable error in the variables which are being measured by distorting flow patterns and disturbing the gas/liquid interface. Intrusive techniques may be reliable when the size of the bubbles involved is considerably larger than the characteristic size of the probe used, and the measurements are away from solid boundaries. However, if the bubble size is small (e.g. less than 2 mm for air-water), and/or inter-bubble distances are small, and/or measurements are carried out near solid boundaries, intrusive measurements can be highly unreliable. In such cases non-intrusive measurements made without the use of a physical probe are necessary to obtain accurate information on relevant flow variables such as bubble size, velocity and frequency.

Several non-intrusive techniques have been developed in recent years for obtaining local measurements in dispersed two-phase flows. Light-scattering and visualization based methods are among the most prominent ones. Among the latter, direct photography (Hawinghorst 1983), holography (Peterson et al. 1983) and video-imaging (Mueller and Hugi, 1989) techniques have been used. Holography is a rather complex and costly method which, however, can provide three-dimensional field information. Direct photography measurements can require much subjective input by the user and are quite cumbersome for velocity measurements. Video-imaging allows for easy digitization of visual images which can then be processed and analyzed in a systematic way and can easily provide two-dimensional field information on the size, velocity and frequency of a dispersed phase. Light scattering methods, such as laser-Doppler velocimetry, have been successfully used for a number of years now for the measurement of carrier fluid and particle velocities and their use has been extended to large particles or bubbles (Durst and Zarlé 1976; Durst et al. 1981, 1984, 1986). More recently further development of the work initiated by Durst and Zarlé (1976) has led to the successful use of a phase-Doppler method for simultaneous measurements of particle/bubble velocity and size (Saffman et al. 1984; Hardalupas et al. 1987; Brena de la Rosa et al. 1989; Naqvi et al. 1990). Brena de la Rosa et al. (1989) carried out bubble measurements showing good agreement between bubble size and velocity measured with the phase-Doppler method and results from direct photography. In their study they also argued that for slightly non-spherical bubbles (ellipsoidal) the phase-Doppler measurement is a directional one, in their case measuring the minor axis of the ellipsoidal bubble. Although measurements of particle/bubble...
velocity and size have been carried out successfully using the phase-Doppler method, rigorous guidelines for an optimum system configuration have only been established very recently by Naqvi and Durst (1992) and measurements based on such a system have not been reported. For instance, Brena de la Rosa et al. (1989) carried out their measurements at a scattering angle of 60°, which is well outside the optimum range.

In the present study we have developed a technique based on video-imaging for the measurement of bubble size and velocity using a rather inexpensive system. Measurements obtained by this method from a well controlled bubble-injection experiment have been compared to simultaneous measurements using a phase-Doppler system optimized according to the theoretical guidelines of Naqvi and Durst (1992). A wide range of bubble sizes has been examined well into the ellipsoidal regime. Both methods have been used to measure the near-injector velocity distribution and the terminal velocity of the generated bubble-streams for a variety of injection conditions. The motion of bubble streams in the neighborhood of the injector is of particular interest to applications related to a wide range of phase-contacting equipment such as bubble columns and fermentation vessels.

2 Experimental facilities

The experimental setup is such that a single stream of mono-disperse air bubbles is formed in a tank of quiescent water. This controlled environment provides for an effective comparison of the two methods and for measurements in the bubble injection region. The water tank is made from Plexiglas to allow optical access for the measurements. It is 28 cm high with a 10 cm by 10 cm base. The tank is filled with contaminant-free, distilled water and fully sealed except for the bubble injector and an air exhaust port. Saturated, particle-free air is supplied to a single injector from a pressurized tank through a pressure regulator, Teflon tubing, saturator, a shut-off needle valve and a micrometer flow-regulating valve. The injector is connected after the regulating valve. A variety of injectors have been used in order to generate a wide range of bubble sizes. The majority of these injectors are made from glass capillary tubing which has been locally heated and pulled to a sharp point. Injector sizes range from 0.6–100 μm as measured by a scanning electron microscope. Thus, bubbles ranging from 250 μm to over 3 mm have been generated. The exhaust port of the tank is connected to a soap-film flow meter to monitor the injection air-flow-rate. A schematic portraying the containment tank, injector and the measuring systems used during the present experiments is shown in Fig. 1.

3 Video-imaging technique

The system used for the video-imaging method is based on an interlaced CCD camera with a 512 × 512 sensor array equipped with a 50 mm lens. Magnifications of up to 70 times have been accomplished with the use of extension tubes placed between the camera body and the lens. As shown in Fig. 1 the CCD camera is connected to a monitor and a Super-VHS video cassette recorder (S-VHS VCR) where the image within the field of view of the camera can be recorded to be analyzed at a later date. Both the camera and the S-VHS VCR can be connected to a video frame-grabbing and digitizing board (512 × 512 pixel resolution) installed inside a personal computer. The digitizing board transforms the analog image coming from the VCR or the camera to a digital image with 400 × 490 or 512 × 512 picture elements (pixels) respectively. Each pixel has one out of a possible 256 gray-level intensities assigned to it. Once the image is digitized, it can be analyzed to gather the required information using the appropriate image processing and analysis algorithms. The images can be viewed on the monitor before and after digitization as may be desired.

The bubbles injected in the tank are lit from behind, as viewed through the camera lens, to ensure well-focused images. Such lighting produces a dark bubble image on a bright background. When the bubble is within focus, a bright spot appears in the center of the bubble. This bright spot corresponds to light rays which pass through the bubble without being considerably deflected by the successive refractions. When the bright spot is minimized and the edges are well-defined, the bubble is in focus. This focusing method is described in more detail by Mueller and Hugi (1989).

The video-imaging technique is based on images provided by the CCD camera. These images are interlaced. A frame resulting from an interlaced video image is composed of two fields, each of which occupies every other horizontal row of pixels (horizontal lines) in the frame. The fields are not gathered from the camera at the same time. The exposure time for each field is limited by the shutter speed which can be 1/60, 1/1000, or 1/2000 seconds for the camera used in this experiment. Regardless of the shutter speed, each field is transmitted from the camera every 1/60 second, so it takes 1/30 second to gather one full frame. When a live image is viewed on a monitor, interlacing gives the effect of smooth and continuous motion. To "freeze" a moving bubble on the video image, field exposure times should be less than the time scale of the bubble motion. This can be achieved by either using one of the three available shutter speeds on the camera or with a field-synchronized strobe light, if the bubbles are moving faster than what the highest shutter speed can handle. A strobe light with flash duration of 0.8 μs has been used in such cases.

As a result of interlacing, a moving bubble occupies different positions on each field of the same frame. Thus each frame can