Development of water - air bubble grid turbulence

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Abstract

The evolution of the structure of a grid generated water - air bubble turbulent flow field in a vertical channel of rectangular cross section has been investigated experimentally. Distributions of the mean and statistical flow characteristics at different stages of flow development are presented for varying air flow rates. Monitored parameters include local void fraction along with continuous phase mean velocity, turbulence intensity, skewness and flatness factors. The obtained results indicate that close to the grid the void fraction and mean velocity distributions are dictated by the bubble injectors’ location on the grid. Further downstream these distributions gradually change to a double peak pattern measured at a 40 mesh distance from the grid. Corresponding autocorrelation and spectra measurements at the center of the channel exhibit a decrease in flow scales at low void fraction, which is gradually alleviated as the air flow rate increases.

1 Introduction

Bubble motion is influenced by several effects such as deformation and oscillation of bubble surface, buoyancy forces, forces resulting from bubble-continuous phase flow field and bubble-bubble interactions. Besides, the relative significance of these effects may vary considerably within the same flow field. The consequent randomness of the motion of a swarm of bubbles combined with the randomness of turbulence result to very complex flow fields. However, despite these difficulties bubble flow research seems to grow exponentially during the last two decades. Besides the technological significance of two phase flows this trend is based on significant advances in the computational and experimental tools now available. Computational fluid dynamics and especially Direct Numerical Simulation are now capable, based on simple flow analysis, to provide information on the physical aspects of the flow as well as the influence of specific parameters hardly obtainable by other means. Instrumentation such as hot wire anemometry, Laser Doppler and Phase Doppler anemometry as well as particle image velocimetry
supported by highly developed equipment and sophisticated data processing is now available for providing information on complex bubble flows.

Several investigators have performed measurements in liquid-gas bubble two-phase flows. The patterns of these studies follow closely the corresponding investigations on single phase flows. Thus most of the conducted experiments pertain to up- flows in vertical tubes as indicated in Table 1 in which those experiments and their measured experimental parameters are summarized. Prerequisite for the effective use of such measurements is the detailed monitoring of the initial and boundary conditions of the flow domain including phase distribution, the turbulence structure and the developing wall shear. The main conclusions derived from these experiments are briefly discussed in the following.

A "void peaking" phenomenon indicating that bubbles tend to concentrate in the vicinity of the walls has been observed. The velocity profile exhibits a wider flat region for low void fraction than the corresponding single phase profile, while for higher void fraction values becomes "dome" shaped. Turbulence intensity measurements show different trends. According to Serizawa (1974), Serizawa et al. (1975), and Wang et al. (1987), the turbulence intensity for low void fraction can become even lower than that of the corresponding single phase flow at specific locations of the cross section. More important, they found that isotropy is destroyed as longitudinal and transverse intensity values diverge. Contrary to the above, Theofanous and Sullivan (1982) found that, except in the vicinity of the wall, measurements of longitudinal and radial intensity are similar and remain higher than the corresponding single phase values. They concluded that the flow remains

<table>
<thead>
<tr>
<th>Flow type</th>
<th>Work</th>
<th>Test section</th>
<th>Void fraction</th>
<th>Bubble diameter</th>
<th>Water velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe flow</td>
<td>Serizawa (1974), Serizawa et al. (1975)</td>
<td>∅60 mm, L=2.10 m</td>
<td>5-70 %</td>
<td>4 mm</td>
<td>0.3-1.03 m/s</td>
</tr>
<tr>
<td></td>
<td>Nakoryakov et al. (1981)</td>
<td>∅86 mm, L=6.5 m</td>
<td>50-80 %</td>
<td>Bubble to slug</td>
<td>0.22-2.05 m/s</td>
</tr>
<tr>
<td></td>
<td>Theofanous and Sullivan (1982)</td>
<td>∅57 mm</td>
<td>3-20%</td>
<td>3-4 mm</td>
<td>0.23-0.62 m/s</td>
</tr>
<tr>
<td></td>
<td>Michiyoshi and Serizawa (1986)</td>
<td>∅60 mm, L=2.15 m</td>
<td>4-27%</td>
<td>3 mm</td>
<td>0.45-0.77 m/s</td>
</tr>
<tr>
<td></td>
<td>Wang et al. (1987)</td>
<td>∅57 mm</td>
<td>10-50%</td>
<td>Bubble to slug</td>
<td>0.43-0.94 m/s</td>
</tr>
<tr>
<td></td>
<td>Liu (1997)</td>
<td>∅57 mm, L=8 m</td>
<td>3-28%</td>
<td>1-20 mm</td>
<td>0.5-3.0 m/s</td>
</tr>
<tr>
<td>Triangular conduit</td>
<td>Sim and Lahey (1986)</td>
<td>L=91 cm, base 50.8 mm, height 98.4 mm</td>
<td>66-90%</td>
<td>0.65-1.0 m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lopez de Bertodano et al (1994)</td>
<td>L=70 D, base 50.8 mm, height 100 mm</td>
<td>10-35%</td>
<td>0.5-1.0 m/s</td>
<td></td>
</tr>
<tr>
<td>Boundary layer</td>
<td>Moursali et al. (1995), Marie et al. (1997)</td>
<td>2.5x0.4x0.4 m³</td>
<td>0-5.5%</td>
<td>3.5-6.0 mm</td>
<td>&lt;1.5 m/s</td>
</tr>
<tr>
<td>Grid turbulence</td>
<td>Lance and Bataille (1982, 1991), Marie (1983)</td>
<td>2x0.45x0.45 mm³, M=40 mm, rods 8 mm</td>
<td>0-5%</td>
<td>5 mm</td>
<td>&lt;1.2 m/s</td>
</tr>
<tr>
<td></td>
<td>Panidis and Papailiou (1993, 2000) Present Work</td>
<td>1.2x0.3x0.3 mm³, M=30 mm, rods 5 mm</td>
<td>0-5%</td>
<td>3 mm</td>
<td>0.25 m/s</td>
</tr>
</tbody>
</table>
isotropic and also, that bubble turbulence is essentially additive to wall turbulence. More recent studies (Liu, 1997, Sim and Lahey, 1986, Lopez de Bertodano et al., 1994) have significantly extended the information on pipe and duct flows revealing specific properties of bubble flows.

Following the single phase research historical trends a significant amount of information regarding the interaction of bubbles with the turbulence structure of simple flow fields has been compiled. Moursali et al. (1995) and Marie et al. (1997) provided information on the development of the boundary layer in a bubbly flow investigating bubble dynamics near the wall and proposed a modified law of the wall for bubbly flows.

The experiments of Lance and Bataille (1982, 1991) and Marie (1983) on water-air bubble grid turbulence, will be discussed rather extensively since they are pertinent to the present work. Their measurements were obtained mostly at the center of the test section in a facility similar to that of the present work, with the underlying idea of “simulating” as closely as possible the highly idealized situation of a statistically uniform array of bubbles interacting with an isotropic turbulent flow field. They found the existence of two regions, namely, "one for low void fraction where hydrodynamic interactions between bubbles are negligible, and a second for high void fraction in which, due to their mutual interaction, the bubbles transfer a significant amount of kinetic energy to the flow". Although values of skewness and flatness factors indicate significant departure from normal probability distribution, they concluded on the basis of measurements of turbulence intensity and Reynolds stresses that, the structure of turbulence remains isotropic, and that bubble turbulence is additive to grid turbulence. The autocorrelation measurements presented in their work indicate a decrease of turbulent scales with increasing void fraction to a final pattern which remains unaltered for further increase of void fraction. The measured power spectra in this work exhibit a −8/3 power form.

In a similar experimental facility but with different objectives the authors of the present work provided information regarding the interaction of a swarm of bubbles with grid generated turbulence with constant initial conditions (Panidis and Papailiou, 1993, 2000). These measurements were conducted at a distance from the grid at which in the corresponding single phase flow, a fully developed, isotropic turbulent structure is expected. In these experiments a double peak void distribution prevailed in the channel influencing accordingly the velocity distribution. Higher moments of the velocity components’ distributions indicate significant changes from single phase flow which inevitably destroy isotropy. Different trends for low and high void fractions are also observed in these measurements, in which differences between the mechanisms influencing the flow structure in the central part of the channel and close to the wall are identified. Autocorrelation measurements reveal a reduction of the flow scales for low void fraction, which is gradually alleviated for higher void fraction. Spectra retained a −2 power form and the scale changes affected mostly the low frequency region of the spectrum.

In the present work the scope of the above mentioned investigation is extended to study the accumulating effect of the dispersed phase on the structure and transport processes of the nearly isotropic single phase grid turbulence during the development stages of the flow. Thus the aim of the present experimental study is to provide information regarding the void distribution and the turbulence structure development resulting from the interaction of the dispersed phase with evolving grid turbulence as influenced by the channel’s constraining walls under constant initial
conditions. Also to address the important question of self preservation which could possibly be attained by the turbulence structure. The void fraction was kept low so that a dispersed flow is obtained. A low value corresponding single phase Reynolds number was chosen so that the buoyancy induced turbulent energy was significant as compared to the corresponding single phase flow.

2 Experimental apparatus and equipment

The experiments have been conducted in the two-phase water channel operating in the Laboratory of Thermodynamics shown in Fig. 1. The test section is 1200 mm long with a square cross section of width, \( B = 300 \text{ mm} \). It is positioned vertically with the mean flow of water directed upwards. Two transparent facing walls allow Laser Doppler Velocimetry (LDV), and visualization techniques to be used. Probes can be inserted in the flow through openings at 100 mm intervals on the third wall. The grid placed at the test section entrance forms a biplane square, consisting of copper tubes with outside diameter of 5 mm, crossed at mesh spacing \( M = 30 \text{ mm} \). It is also used for the injection of the bubbles, through hypodermic needles of inside diameter 0.2 mm, located at the copper tube crossings. The volumetric air flow rate is regulated by a pressure reducer and measured with a variable area flowmeter. The water velocity field is monitored with a dual beam forward scatter LDV system, the transmitting and the receiving optics of which were mounted on a carrying table capable of moving in three directions. Local void fraction measurements were conducted with an Optoflow fiber optics probe. Bubble

![Diagram of experimental facility](image-url)
measurements were conducted with double-exposure photography. Bubble mean diameter was found to be 3 mm and bubble mean slip velocity, at low void fraction, was approximately 250 mm/s. Extensive reference to the experimental apparatus, instrumentation and the measuring and data interpretation techniques used in this work can be found in Panidis and Papailiou (2000).

The water flow rate was kept constant during all the experiments. The corresponding single phase Reynolds number based on grid mesh was low (7,000) so that the turbulence energy introduced to the flow due to buoyancy was significant as compared to the single phase flow turbulence. The measured quantities comprise local void fraction as well as water mean velocity, turbulence intensity, skewness, and flatness factors profiles at six locations downstream of the grid for varying void fraction. Autocorrelation and spectra at the center of the channel are also presented. In the following the main findings of this work are outlined and briefly discussed.

3 Experimental results

3.1 Void fraction distribution

Close to grid the void fraction distribution is dictated by the bubble injection pattern as it is clearly indicated by the peak values measured above the injectors’ locations (Fig. 2, \( H = 2.3 \) M). At a distance of 7 M from the grid, a pattern of two distinct regions prevails in the void distribution. At this location one region extending over the central part of the channel can be identified, where the influence of the injector's location is still present and a second region develops close to the wall where the

Fig. 2. Development of the local void fraction profile along the channel for varying gas flow rate ratios, \( \beta \) (see Fig. 3 for legend).
void appears redistributed to the effect that the initially two peaks close to the wall have been merged to form a wider peak. Further downstream the void distribution exhibits two separate regions forming two peaks located between the wall and the central line of the channel. At larger distance from the grid a one peak distribution is observed which appears to prevail thereafter.

![Graph showing distribution of longitudinal mean velocity along the channel for varying gas flow rate ratios, $\beta$](image1)

![Graph showing distribution of longitudinal turbulence intensity along the channel for varying gas flow rate ratios, $\beta$](image2)

Fig. 3. Distribution of the longitudinal mean velocity along the channel for varying gas flow rate ratios, $\beta$

Fig. 4. Distribution of the longitudinal turbulence intensity along the channel for varying gas flow rate ratios, $\beta$ (see Fig. 3 for legend).
3.2 Distribution of mean velocity and higher moments statistics

The mean velocity distribution appears to be closely related to that of the void fraction as they follow the same pattern. As shown in Fig. 3 close to the grid the influence of the injectors is

Fig. 5. Distribution of the longitudinal skewness factor along the channel for varying gas flow rate ratios, $\beta$ (see Fig. 3 for legend)

Fig. 6. Distribution of the longitudinal flatness factor along the channel for varying gas flow rate ratios, $\beta$ (see Fig. 3 for legend)
obvious and a similar to the void distribution merging pattern evolves in the following stages although in a less pronounced way. The influence of the bubble-wall interaction is strong in all stages extending to considerable distance from the wall, which increases further from the grid and for higher void fraction. These findings are in agreement with the results in Panidis and Papailiou (2000) complementing and clarifying the evolution of the flow mean structure in the channel. The related experiments of Lance and Bataille (1991) were deliberately designed to avoid these effects.

The length of the test section does not allow a final conclusion regarding attainment of full development and establishment of self preservation in the flow structure. However, for low void fraction there is some indication that convergence to a fully developed state might have been
reached at the end of the test section.

The characteristic pattern of the phase distribution evolution and the accompanying velocity
distribution are closely related to the sensitivity of the lift force to the local shear and the shape of
the bubbles as well as to the development of large eddies entraining the bubbles. Moreover it is
plausible to suggest that the final result of the above described phenomena is the development of a
two distinct regions flow pattern downstream of the grid namely, one close to the wall region
strongly affected by the dispersed phase and a second region extending over the central part of the
channel in which the effect of the dispersed phase is less pronounced as already has been
discussed by Panidis and Papailiou (2000).

Fig. 8. Longitudinal power spectra for varying $\beta$
(thin lines represent the corresponding single phase spectrum).
Further information regarding the processes involved in the dynamics of the flow as reflected in the turbulence structure can be obtained from the measured turbulence statistics. The distributions of turbulence intensity, as well as those of skewness and flatness factors (Figs. 4, 5, 6) confirm the strong influence of the bubble presence on the turbulent flow field near the wall resulting to the continuous thickening of the boundary layer and the formation of a two region flow pattern. Considering the physical meaning of the skewness and flatness factors as discussed by Townsend (1976) and Papaïliou (1980) it is evident that the dynamic development of the turbulent flow field of the continuous phase is accomplished through the action of turbulence as dictated by the interaction processes between the two phases, as discussed in the following.

A homogeneous turbulent flow field is characterized by a joint-normal probability distribution function of the fluctuating velocity corresponding to the values of zero for skewness and three for flatness (Townsend, 1976). In general, deviations of the flatness factor from the value of three are related to the presence of inhomogeneities in the turbulence structure while abnormally high values of this factor are indicative of a spotty turbulence intensity character. Furthermore, the physical meaning of the skewness factor is associated with convection of turbulent energy from regions of high intensity to regions of lower intensity. Accordingly as the obtained distributions of flatness and skewness clearly indicate the main mechanism by which the flow field is modified is the presence of the bubbles. More specifically the significant deviation from the value of three characterizing the flatness distribution of the single phase grid turbulence (Fig. 6) close to the wall in the presence of the bubbles indicates the creation of strong inhomogeneities in this boundary layer region. Inspection of the skewness distribution (Fig. 5) appears to exhibit corresponding deviations in this factor in the presence of the bubbles indicating convection of turbulent energy from high intensity to low intensity regions.

In conclusion, the obtained measurements indicate that the observed distributions of the two phase field are the result of turbulent action initiated near the wall by the interaction processes between the two phases.

3.3 Autocorrelation and spectra

Further information regarding the nature of the physical phenomena involved in the interaction and energy exchange processes between the two phases are expected to be gained from the study of statistical characteristics such as turbulent correlations and the spectral distribution of turbulent kinetic energy.

Autocorrelation and spectra measurements at the center of the channel provide information on the energy transfer processes and the scales of the turbulent field (Figs. 7, 8). A general remark for the autocorrelation diagrams at all locations is that for low void fraction the autocorrelation is decreasing much faster than the corresponding single phase curve. This behavior consistent with the findings of Lance and Bataille (1982, 1991) and Panidis and Papaïliou (2000) indicates that even for the lowest void fraction the integral scale and the microscale are significantly decreased as related to the single phase magnitudes. This trend is reversed as the air flow rate ratio increases, more notably at the further downstream locations, a feature not present in Lance and Bataille flow. A small secondary hump at low void fraction indicative of a double turbulence structure is
also present in most of the low void fraction autocorrelation diagrams.

Complimentary information about the structure of the flow can be obtained from the spectra measurements. The reduction of the turbulence scales for low void fraction is manifested in the low frequency part of the spectrum while there is no visible difference in the higher frequency part where a $-2$ power form is retained for all the measurements. As the void fraction increases the low frequency part of the spectrum is increased indicating the development of larger turbulent structures in the flow more notable at the locations close to the end of the test section. All two phase flow spectra present small peaks in a rather large region around 10 Hz. These peaks which are also present in the previous work measurements may be indicative of the bubble-turbulence interaction scales. This notion is compatible with the development of an inverse cascade as proposed Panidis and Papailiou (2000). As related to Lance and Bataille (1982, 1991) measurements the differences in the autocorrelation evolution and the corresponding $-8/3$ power form found in this work should be attributed to the different scales of turbulence and bubble forcing in the two experiments.

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**References**


