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The development of the structure of water – air bubble grid turbulence

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ABSTRACT

The development of the turbulent flow field generated due to the interaction of grid turbulence with a swarm of bubbles is investigated experimentally, in a vertical channel of rectangular cross section. Void fraction and streamwise mean and rms velocity distributions have been measured at several distances from the grid, with an optical probe and Laser Doppler Velocimetry, in relation to the air flow rate ratio. The obtained results indicate that close to the grid the void fraction and velocity distributions are dictated by the bubble injectors' location on the grid. Downstream the void fraction distribution changes to a double peak pattern. The velocity distribution is characterized by a shear layer between the wall area and the central area of the channel. The extend of this shear layer is increasing as the distance from the grid and the gas flow rate ratio are increasing, and is associated with a corresponding increase of the turbulence fluctuations. Autocorrelation and spectra measurements at the centre of the channel show a reduction of the flow scales for low void fraction. Consistently, power spectra distributions indicate that bubbles cause a redistribution of energy manifested by the relative enhancement of the intermediate scales' energy content and a consequent reduction in the larger scales. These trends are gradually alleviated and reversed at large distances from the grid, as the air flow rate is increased.

1. Introduction

Bubble flow research has grown exponentially during the last decades. Besides the scientific and technological significance of two-phase flows, this trend has been achieved thanks to contemporary, significant advances of computational and experimental research tools. 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 on the influence of specific mechanisms (e.g. lift force, bubble–bubble interactions etc.) hardly obtainable by other means. On the other hand instrumentation such as Hot Wire Anemometry (HWA), Laser Doppler (LDA) and Phase Doppler Anemometry (PDA), as well as Particle Image (PIV) and Particle Tracking Velocimetry (PTV), supported by highly developed equipment and sophisticated data processing, is now available for providing detailed information on complex bubble flows. Despite all this progress, two phase flow theory and especially bubble flow theory, but also our capability to solve particular practical problems in engineering applications, are still lagging considerably behind single phase fluid mechanics.

Bubble motion is influenced by several effects, such as deformation and oscillation of bubble surface, buoyancy forces, and forces resulting from bubble-continuous phase and bubble–bubble interactions. Besides, the relative significance of these effects may vary considerably within the same flow field. The consequent complexity of the motion of a swarm of bubbles, and its interaction with the turbulence of the continuous phase, along with the dependence of the flow field on (usually unknown) details of the initial and boundary conditions, result in flow fields whose stability and evolution in most of the practical cases defy our analytical or numerical capabilities. Therefore, although deterministic in principle, these flow fields have to be often faced as random turbulent or pseudoturbulent processes.

Several investigators have performed measurements in liquid–gas bubble two-phase flows. The pattern of bubble flow research has been largely influenced by the corresponding investigations in single phase flows, deviating from this line to accommodate bubble specific effects. Taking into account the preferential direction of bubble motion due to buoyancy, as well as the flow characteristics in related applications, most of the conducted experiments pertain to up - flows in vertical tubes (Serizawa et al., 1975; Nakoryakov et al., 1981; Theofanous and Sullivan, 1982; Michiyoshi and Serizawa, 1986; Wang et al., 1987; Liu, 1997; Ohnuki and Akimoto, 2000; Shawkat et al., 2007) or grid turbulence channels (Lance and Bataille, 1982, 1991; Marie, 1983; Panidis and Papailiou, 1993, 2000), although down flow cases have been also considered (Moghaddas et al., 2004; Rensen et al., 2005, see also Table 1). Several investigations focus on specific cross section effects (Sim and Lahey, 1986; Lopez de Bertodano et al., 1994),

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Table 1
Experiments in bubbly flows.

Flow type	Work	Test section	Void fraction (%)	Bubble diameter	Water velocity (m/s)
Pipe flow	Serizawa (1974), Serizawa et al. (1975)	∅60 mm, L = 2.10 m	5–70	4 mm	0.3–1.03
	Nakoryakov et al. (1981)	∅86 mm, L = 6.5 m	50–80	Bubble to slug	0.22–2.05
	Theofanous and Sullivan (1982)	∅57 mm	3–20	3–4 mm	0.23–0.62
	Michiyoshi and Serizawa (1986)	∅60 mm, L = 2.15 m	4–27	3 mm	0.45–0.77
	Wang et al. (1987)	∅57 mm	10–50	Bubble to slug	0.43–0.94
	Liu (1997)	∅57 mm, L = 8 m	3–28	1–20 mm	0.5–3.0
	Ohnuki and Akimoto (2000)	∅200 mm, L = 12.3 m			0.06–1.06
	Shawkat et al. (2007)	∅200 mm, L = 9.56 (8.4) m	1.2–13.6	3–6.5 mm	0.20–0.68
	Hosokawa and Tomiyama (2004)	∅30 mm, L = 10 m (∅20 mm, L = 2 m)	1.5–3.0	4.7–4.9 mm	0.5–1.0
	Hosokawa and Tomiyama (2009)	∅25 mm, L = 2 m	1.46–3.99	3.21–4.25 mm	0.5–1.0
Duct flow	Hosokawa et al. (2009)	$800 \times 50 \times 50$ mm^3	1	0.47 mm	0.06
Triangular conduit	Sim and Lahey (1986)	L = 91 cm, base 50.8 mm, height 98.4 mm	66–90		0.65–1.0
	Lopez de Bertodano et al. (1994)	L = 70 D, base 50.8 mm, height 100 mm	10–35		0.5–1.0
Shear flow	Rightley and Lasheras (2000)				
Boundary layer	Moursali et al. (1995), Marie et al. (1997)	$2.5 \times 0.4 \times 0.4$ m^3	0–5.5	3.5–6.0 mm	<1.5
Grid turbulence	Lance and Bataille (1982, 1991), Marie (1983)	$2 \times 0.45 \times 0.45$ mm^3 M = 40 mm, rods 8 mm	0–5	5 mm	<1.2
	Moghaddas et al.(2004) (down flow)	∅75 mm, L = 0.75 m M = 2 mm	2.4	2.27–2.50 mm	1.3
	Rensen et al. (2005) (down flow)	$2 \times 0.45 \times 0.45$ m^3 Active grid	0.5–2.9	1–2 mm	0.20
	Panidis and Papailiou (1993, 2000) present work	$1.2 \times 0.3 \times 0.3$ mm^3 M = 30 mm, rods 5 mm	0–5	3 mm	0.25

or on detailed monitoring of the flow characteristics in shear or boundary layers (Moursali et al., 1995; Marie et al., 1997; Rightley and Lasheras, 2000). Prerequisite for the effective use of such measurements is the detailed monitoring of the initial and boundary conditions of the flow domain besides phase distribution, turbulence structure and developing wall shear.

These studies provide information regarding specific attributes of the flow field, in most of the cases in relation to the void fraction (or the gas flow rate ratio). In general it can be stated that results indicate 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" (Lance and Bataille, 1991).

The void distribution and the associated distribution of the streamwise mean velocity have been considered in most of the previous studies. Close to the channel's boundary a "wall peaking" phenomenon, indicating that bubbles tend to concentrate in the vicinity of the walls, has been observed which is probably associated with the effect of the lift force and the development of large flow structures (e.g. Serizawa et al., 1975; Lance and Bataille, 1991; Shawkat et al., 2007 for the lowest void fraction). In the central part of the channel the same effects, in several cases (large tubes or grid turbulence channels – low void fractions), result in more or less uniform void and velocity distributions across large areas of the cross section (Lance and Bataille, 1991; Panidis and Papailiou, 2000), whereas (usually for larger void fractions) dome shaped profiles have been also observed (Serizawa et al., 1975; Wang et al., 1987; Shawkat et al., 2007 for higher void fractions).

The turbulence characteristics of bubble flows have attracted the interest of several investigators. Turbulence intensity measurements show different trends. In low void fraction flows the turbulence intensity may become even lower than that of the corresponding single phase flow at specific locations of the cross section (Serizawa et al., 1975; Wang et al., 1987; Shawkat et al., 2007; Hosokawa et al., 2009). In general an increase of turbulence intensity is observed, and several investigators assumed that, bubble turbulence is essentially additive to that of the corresponding single phase flow (Theofanous and Sullivan, 1982; Lance and Bataille, 1991) whereas Hosokawa and Tomiyama (2004, 2009, 2010) and Hosokawa et al. (2010) related attenuation or enhancement of turbulence with the eddy viscosity ratio between dispersed phase and shear induced turbulence and the associated length and velocity ratios. Different trends have also been observed regarding the influence of the bubbles on the isotropy of the flow, since several investigations indicate isotropic fields (Theofanous and Sullivan, 1982; Lance and Bataille, 1991) whereas in others the isotropy is destroyed as streamwise and transverse intensity values diverge (Serizawa et al., 1975; Wang et al., 1987; Panidis and Papailiou 2000).

The spectral energy distribution in turbulence and the associated issues of energy cascade and flow scales is also an open research issue in bubble flows. A decrease of the turbulence length scales for low void fractions has been observed by several investigators (Panidis and Papailiou, 2000; Shawkat et al., 2007). This behaviour is consistent with power spectral distributions measured by several investigators indicating energy enhancement at intermediate or small scales and small energy reduction at large scales due to the presence of bubbles (Lance and Bataille, 1991; Panidis and Papailiou, 2000; Rensen et al., 2005; Hosokawa and Tomiyama, 2010). On the other hand, previous results show different trends regarding the scaling exponent of the power spectrum. In several investigations the Kolmogorov energy spectrum exponent $-5/3$ is progressively substituted by $-8/3$ as the void fraction is increased (Lance and Bataille, 1991; Michiyoshi and Serizawa, 1986; Wang et al., 1987), whereas in others the exponent remains close or a little steeper than $-5/3$ (Panidis and Papailiou, 2000; Rensen et al., 2005; Hosokawa and Tomiyama, 2010).

The present work is a follow up of a previous investigation on the interaction of grid generated turbulence with a swarm of bubbles. The previous measurements were conducted at a distance from the grid at which, in the corresponding single phase flow, a