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Generation and control of monodisperse bubble suspensions in microgravity

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A B S T R A C T

A new experimental setup for the generation of homogeneous, monodisperse bubble suspensions in turbulent duct flows in microgravity has been designed and tested in drop tower experiments. The setup provides independent control of bubble size, void fraction and degree of turbulence. The device combines several slug-flow injectors that produce monodisperse bubble jets, with a turbulent co-flow that ensures homogeneous spatial spreading. Bubble separation in the scale of the most energetic eddies of the flow, and bubble size sufficiently smaller, ensure that turbulence is most efficient as a mechanism for spatial spreading of bubbles while preventing coalescence, thus optimizing the homogeneous and monodisperse character of the suspension. The setup works in a regime for which bubbles are spherical, but sufficiently large compared to the turbulent dissipative scales to allow for two-way coupling between bubbles and carrying flow. The volume fraction is kept relatively small to facilitate particle tracking techniques. To illustrate the potential uses of the method we characterize the statistics of bubble velocity fluctuations in steady regimes and we characterize the transient relaxation of the buoyancy-driven pseudo-turbulence when gravity is switched-off.

1. Introduction

Dispersed multiphase turbulent flows are common in many engineering applications, but pose formidable challenges to fundamental theory due to the complex interplay between the inherent fluctuations of the carrier and the random distribution of the dispersed phase, together with the presence of break-up and coalescence phenomena [1–5]. In particular the physics of bubbles in a liquid carrier [6–8] is widely recognized as crucial for a variety of space technologies. These include for instance power generation and propulsion [9], thermal management [10,11], or life support systems and environmental control for life in space [12–14]. Given that the presence or absence of buoyancy forces affects crucially the physics of bubbly flows, the fundamental understanding of gas dispersions in microgravity conditions becomes strategic for space technology. In addition, the study of bubbly flows in weightlessness poses important challenges of management and control [15,16] for its study and for practical applications. In this context, the capacity to generate monodisperse bubble suspensions in the absence of buoyancy forces, with good control of parameters such as bubble size and void fraction, becomes a very promising but challenging technical problem. Technical solutions to this problem may have direct relevance to specific technologies but at the same time they will provide the means to generate adequate testing grounds for fundamental research on turbulent bubble dispersions in microgravity.

Homogeneous bubbly flows have been largely studied in the past for the case of normal gravity [17–19]. Unfortunately, there is a lack of high quality data for this kind of flows in microgravity due to the obvious limited access to microgravity environments but in particular to the technical challenges of generating bubbles of uniform size with good control but without taking advantage of buoyancy forces. Previous studies have used for instance a hypodermic needle of 0.15 mm diameter to inject gas into a liquid co-flow that detached bubbles of typically 0.92 mm in diameter carried in a turbulent pipe of 4 cm in diameter [20]. Although this procedure allows to generate bubbles with a very precise and controlled size, it creates them at a very low rate. Despite the excellent bubble homogeneity reported, these conditions do not al-

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Nomenclature

ν	Kinematic viscosity
Re	Reynolds number
U_c	Characteristic flow velocity
L_c	Characteristic system size
T_c	Characteristic time of the flow
λ_k	Kolmogorov length
τ_k	Kolmogorov time
λ_{Max}	Characteristic size of most energetic eddies
τ_{Max}	Characteristic time of most energetic eddies
τ_B	Bubble response time
Q_l	Volumetric liquid flow rate
Q_g	Volumetric gas flow rate
$Q_{\text{co-flow}}$	Volumetric co-flow rate
ϑ	Void fraction
d_T	T-junction tubes diameter
d_B	Bubble size
u_i	Component of the bubble velocity in the i direction
n	Mean number of bubbles on given interval
σ_i	Standard deviation of i component of bubble velocity
a, b, τ	Fittings parameters for bubble velocities
d	Mean separation of pair of bubbles
d_{xy}	Mean separation in the plane xy between pairs of bubbles
$d_0, \nu_{\text{sep}}, \mathcal{L}$	Fittings parameters for pair separations

low one to study the interaction between large bubble ensembles and turbulence in the spirit of the present work. Similarly, in the area of microfluidics there are well known mechanisms to generate perfectly monodisperse bubbles that would perform adequately in microgravity (e.g. [21]). However, the microfluidic environment misses the turbulence component that is present in many applications and that we are interested in here. In addition, if injected in a turbulent flow, they would typically be too small compared to the relevant turbulent scales to produce a significant effect.

In this paper we build on the previous development of a device for the injection of monodisperse bubble jets in a quiescent liquid [22–28], to design, construct and test a gravity-insensitive method that generates monodisperse, homogeneous bubble suspensions, with good and independent control on the degree of turbulence, the bubble size and the bubble density. The system is tested in microgravity by means of a series of free-fall experiments conducted in the ZARM Drop Tower at Bremen. We discuss and demonstrate the practical use of this procedure and we illustrate its functionality and performance to acquire valuable data in different situations. The set-up was designed to allow a separate control of the bubble characteristics and of the turbulent flow. The idea is to combine several injectors where a slug flow with monodisperse bubbles has been created in a capillary T-junction of liquid and gas mixing, prior to injection. The bubble diameter is close to that of the junction tubes, typically of the order of one millimeter, but can be fine-tuned through the week dependence on Weber number taking advantage of the control of the volume injection rates of both gas and liquid [22]. The Weber numbers used are sufficiently small so that bubbles are essentially spherical once injected in the carrying co-flow. However, bubbles are relatively large compared to the turbulent dissipation scale, so they may have an active coupling with the flow. The latter is a duct flow with a side of 100 mm allowing for eddies much larger than the bubble size. The bubble densities here considered are such that the void fraction is small, typically of a few percent, to facilitate particle tracking techniques and to avoid coalescence, but the method is not limited to these small values. In our experiments, the typical bubble-bubble distance is comparable to the size of the most energetic eddies, thus favoring efficient spatial dispersion while avoiding coalescence phenomena. The void fraction can also be changed by tuning the volume rates of gas and liquid injection at the capillary T-junctions that produce the slug flows injected in the carrying co-flow, as described in [22–24]. Changing the number of such injectors, which we keep at four in all our experiments, gives additional freedom to increase the void fraction further. Finally, the degree of turbulence of the carrying flow can be changed by controlling the total liquid flow rate pumped into the duct.

For illustrative purposes and to demonstrate the applicability of the set-up, we address two situations of interest. First, we use particle-tracking techniques to characterize the statistics of bubble velocities and to discuss their interaction with the flow in nearly stationary conditions. Second, we study the decay of pseudo turbulence caused by buoyancy forces in normal gravity [29–31], when gravity is switched off. In normal gravity, the decay of pseudo turbulence has been measured in the region left behind by a bubble swarm [32]. In our case we can directly visualize the process using the bubbles themselves as tracers.

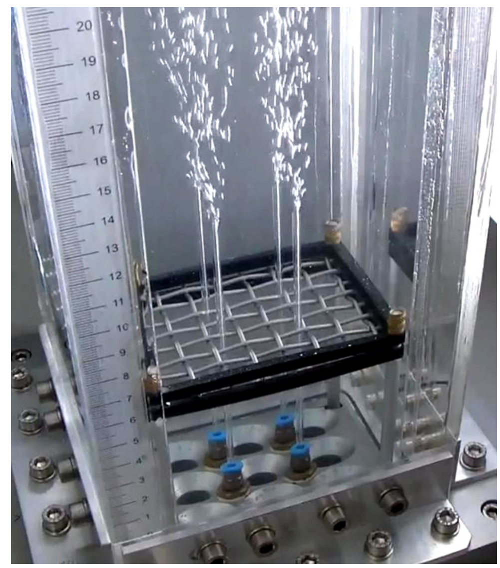

Fig. 1. Snapshot of the experimental channel while injecting bubbles from the 4 injectors.

The method proposed is sufficiently versatile and accurate to open many possibilities of acquiring systematic data in a variety of situations, that in turn may provide new insights into the fundamental physics of turbulent bubbly flows.

2. Experimental generation of turbulent bubble suspensions

2.1. Description of the apparatus and the protocol

To achieve a controlled homogeneous distribution of monodisperse bubbles within a turbulent flow we use a vertical duct of square section and dimensions $800 \times 100 \times 100$ mm^3. At the base of the channel we inject the carrying co-flow from nine evenly-spaced inlets (separated 30 mm between centers) with 14.5 mm inner diameter and with a final nozzle of 90° opening up to 26.9 mm diameter. Those inlets surround four bubble injectors (see Figs. 1, 2) of 1.6 mm inner diameter also separated distances of 30 mm between centers. The co-flow is provided by a main wa-