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Buoyancy driven bubbly flows: meso-scale structures and relative motion

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Abstract

The hydrodynamics of bubble columns is revisited with a focus on the increase of the apparent relative velocity observed in the heterogeneous regime. We report experiments in an air-water bubble column of diameter 0.4m using a new Doppler probe that gives access to bubble velocities conditioned by the void fraction. First, meso-scale structures corresponding to high (clusters), low (voids) and intermediate gas concentrations relative to the mean gas hold-up are unambiguously identified using Voronoï tessellations built from the phase indicator function. Second, conditional bubble velocity data demonstrate that meso-scale structures drive the transport of both phases in the heterogeneous regime. Finally, the unconditional relative velocity is recovered from conditional relative velocities weighted by the probability of presence of bubbles in a given structure. These results provide a physical origin for swarm factors introduced in simulations. They also offer a way to connect the relative velocity enhancement with meso-scale structures characteristics, and to advance our understanding of scaling rules.

Introduction

Former experiments in bubble columns indicate that, despite the presence of complex unsteady structures (De Nevers, 1968), a self-organization of the flow prevails in the heterogeneous regime. Such a structuration arises from an equilibrium between buoyancy and inertia: the latter leads to mean and fluctuating phasic velocities scaling as $v \sim (gD\varepsilon)^{1/2}$ where g is gravity, D the column diameter and ε the gas hold-up (Cartellier, 2019). Beside, strong spatial heterogeneities in void fraction (and thus in mixture density) were detected and quantified in a $D=1\text{m}$ column (Maximiano Raimundo et al., 2019). We anticipated a link between these in-homogeneities and the relative motion between phases. Hereafter, we analyze that connection using new experimental results on bubble velocities conditioned by the local concentration.

Experimental Facility

Experiments were performed in a 3m high, $D=0.4\text{m}$ internal diameter bubble column. Air was injected through 352 orifices (1mm internal diameter, 10mm long) uniformly distributed over the cross-section. The column was filled with tap water (surface tension 67mN/m , conductivity $390\pm 60\mu\text{S/cm}$ due to solid content presence) at a static height $H_0=2.02\text{m}$. Measurements were taken in the quasi fully developed region at $H/D=3.625$. The superficial velocity V_{sg} was varied from 0.6cm/s to 26cm/s . The bubble size was almost constant (equivalent diameter from 6.6mm to 7.3mm) so that there was no significant coalescence.

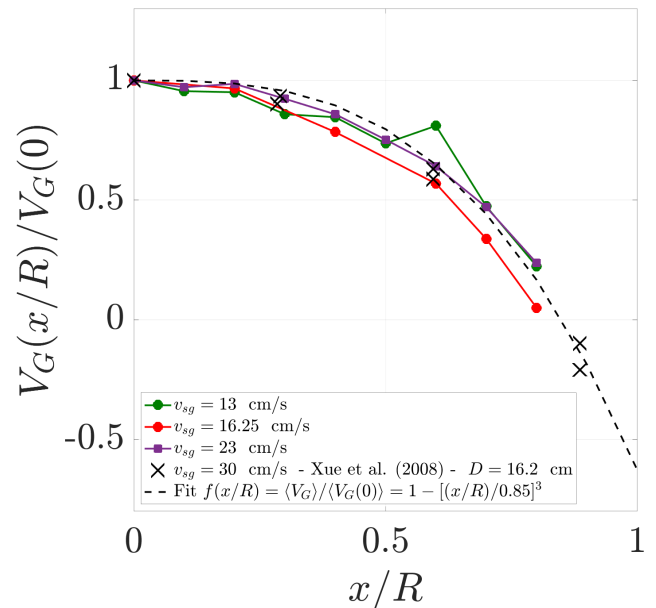


Figure 1: Mean vertical bubble velocity $V_G(x/R)$ measured with a Doppler probe scaled by its value on the axis $V_G(0)$ versus the radial distance x/R in the heterogeneous regime and proposed fit. Data from Xue et al., 2008 acquired with a four tips probe are also shown.

Measuring techniques

Statistics on liquid were gathered with a Pavlov tube consisting of two 0.5mm orifices drilled into two 6mm parallel tubes. The orifices were aligned along a vertical and faced opposite directions. The pressure transducer ensured a $\pm 5.48\text{m/s}$ dynamics in velocity with a $\pm 0.14\text{m/s}$ resolution. Its frequency response was about 8Hz . Note that the 12mm

distance between the orifices also filters velocity fluctuations. For bubbles, we used a recently developed Doppler probe (Lefebvre et al., 2022). This is an optical probe with the ability to measure the interface velocity using interferometry. Data collected in the D=0.4m column are shown Fig.1. They indicate that the radial profiles of the mean bubble velocity are self-similar in the heterogeneous regime. Interestingly, Xue et al. (2008) data collected with a four tips probe in a D=0.162m column at $V_{sg}=30\text{cm/s}$ are consistent with the proposed fit.

Conditional bubble velocities

One-dimensional Voronoï tessellations were built from phase indicator functions as shown Fig.2-left (Maximiano Raimundo et al., 2019). The normalized Voronoï cell width in the abscissa is proportional to the local (at the scale of the bubble) void fraction ε_k divided by the mean gas hold-up ε . In the heterogeneous regime, both dense ($\varepsilon_k/\varepsilon \approx 10$) and dilute ($\varepsilon_k/\varepsilon \approx 0.1$) regions are more probable than for a Random Poisson Process (RPP). The crossings with RPP delineate three populations: clusters (dense), voids (dilute) and intermediate regions in between.

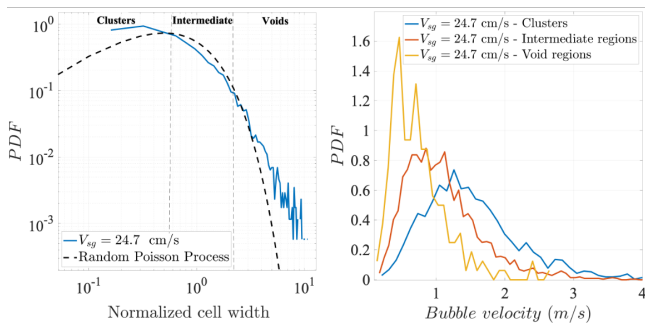


Figure 2: Measured distribution of Voronoï cell widths for $V_{sg}=24.7\text{cm/s}$. The dash line represents the Voronoï distribution for an RPP (left). Bubble velocity pdfs conditioned by the structure they belong to (right).

As each Voronoï cell is centered on a bubble, one can build statistics on bubble velocity conditional upon the structure they belong to. As shown Fig.2-right, in the heterogeneous regime, when shifting from void regions to intermediate regions and to clusters, the minimum velocities are about the same but the most probable velocity neatly increases. More, the difference between clusters and voids amounts to ≈ 3.5 times the bubble terminal velocity. These behaviors were observed at all V_{sg} in the heterogeneous regime. These results confirm our expectation that, in average, high void fraction regions are moving up must faster than low void fraction regions.

To relate these findings with the increase in the relative velocity U_R that characterizes the heterogeneous regime, we measured the proportion of bubbles in meso-scale structures. Typically, in the heterogeneous regime, 38% of bubbles pertain to clusters, 57% to intermediate regions and 5% to void regions. Then U_R was estimated from eq.(1) where each meso-scale structure contribution $V_b(\text{structure})-V_L$ is weighted by the appropriate fraction of bubbles $N(\text{structure})$.

$$U_R = N(\text{clusters})(V_b(\text{clusters}) - V_L) + N(\text{int})(V_b(\text{int}) - V_L) + N(\text{voids})(V_b(\text{voids}) - V_L) \quad (1)$$

Using all the seven data sets gathered for V_{sg} between 9cm/s and 25cm/s, U_R deduced from eq.(1) equals 0.49m/s to be compared with 0.52m/s obtained from direct measurements. The excellent agreement between the relative velocity predicted from eq.(1) using conditional velocities and that directly measured demonstrates that the relative motion of bubbles with respect to the mean liquid is driven by the presence of clusters, voids and intermediate regions. These meso-scale structures are key contributors to the swarm factor that is often injected in simulations to enforce a reduction of the drag coefficient when the local void fraction becomes large (Eterkin et al. 2021).

Conclusion

In absence of coalescence, the higher probabilities to find both clusters and void regions compared with a random Poisson process are shown to be at the origin of the enhancement in relative velocity observed in the heterogeneous regime. The next step consists in relating the relative motions between meso-scale structures due to buoyancy contrasts with their characteristics, and notably with the size and the gas fraction of these structures. Some preliminary results in that direction will be presented that open the way to identify how the relative velocity evolves with D and V_{sg} .

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