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Hydrodynamics of bubble columns in the heterogeneous regime: mechanisms, scale-up and modelling

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Bubble column reactors, where gas is injected at the bottom of an initially stagnant liquid, are widely used in chemical engineering (e.g. for hydrogenation such as in Fischer-Tropsch synthetic fuels production), for bio-chemical transformations (aerobic bioreactors, algae production), waste management (wet oxidation) and flotation units (deinking of paper, extraction of rare metals). All these activities are also fundamental for the development of many recycling and renewable energies industries.

These reactors often operate in the heterogeneous regime, characterized by a strongly polydisperse distribution of bubble sizes, high gas concentrations (15 to 40%) and strong velocity fluctuations ($\approx 25\text{-}30\%$ times the mean). Owing to such flow complexity, no reliable scaling rules are available for reactor designers. This problem dramatically hampers optimization and process control. In particular, extrapolation between laboratory-scale and industrial-sized columns (diameter 5 to 10 m, height 20 to 40 m) is not controlled, and therefore the simulations lead to realistic results only via an ad-hoc adjustment depending on the size of the column (Forret et al. 2006; Rollbusch et al. 2015).

Recently, two-fluid models have been significantly improved using kinetic theory concepts (Fox 2012). They are now able to handle coalescence and break-up on a sound basis (Marchisio and Fox, 2013, Renze et al. 2014). Furthermore, the latest advances in Fox's group (Capecelatro et al. 2015) are potentially apt in representing collective effects such as those observed in experiments. The above new contributions form a solid basis for definite progress towards the understanding of bubble column hydrodynamics.

In this work, we present well-controlled experiments (Maximiano's PhD, 2015) that span the largest range of parameters ever considered: diameter from 0.15 to 3m (figure 1), void fractions up to 35%, with a fixed bubble size distribution (i.e. no coalescence). We find that, contrary to common belief (Ruzicka et al. 2013), coalescence is not a necessary condition for homogeneous/heterogeneous transition to occur. Rather than emerging by way of large bubbles, heterogeneity arises from clusters of bubbles organized at mesoscale (\approx a few tens bubble size). These clusters lead to large concentration gradients (0.1 to 10 times the mean) that generate strong shear as the relative velocity between cluster and void regions largely exceeds the terminal velocity of an isolated bubble. When accounting for this slip velocity in momentum exchange, 3D two-fluid simulations become able to reproduce scale-up within $\pm 15\%$ without any adjustment. We also confirmed the self-organization of these flows and clarified scaling laws. In particular, and contrary to intuition, the entrained liquid flow rate was shown to depend only on the column diameter and not on the injected gas flow rate (see figure 1c).

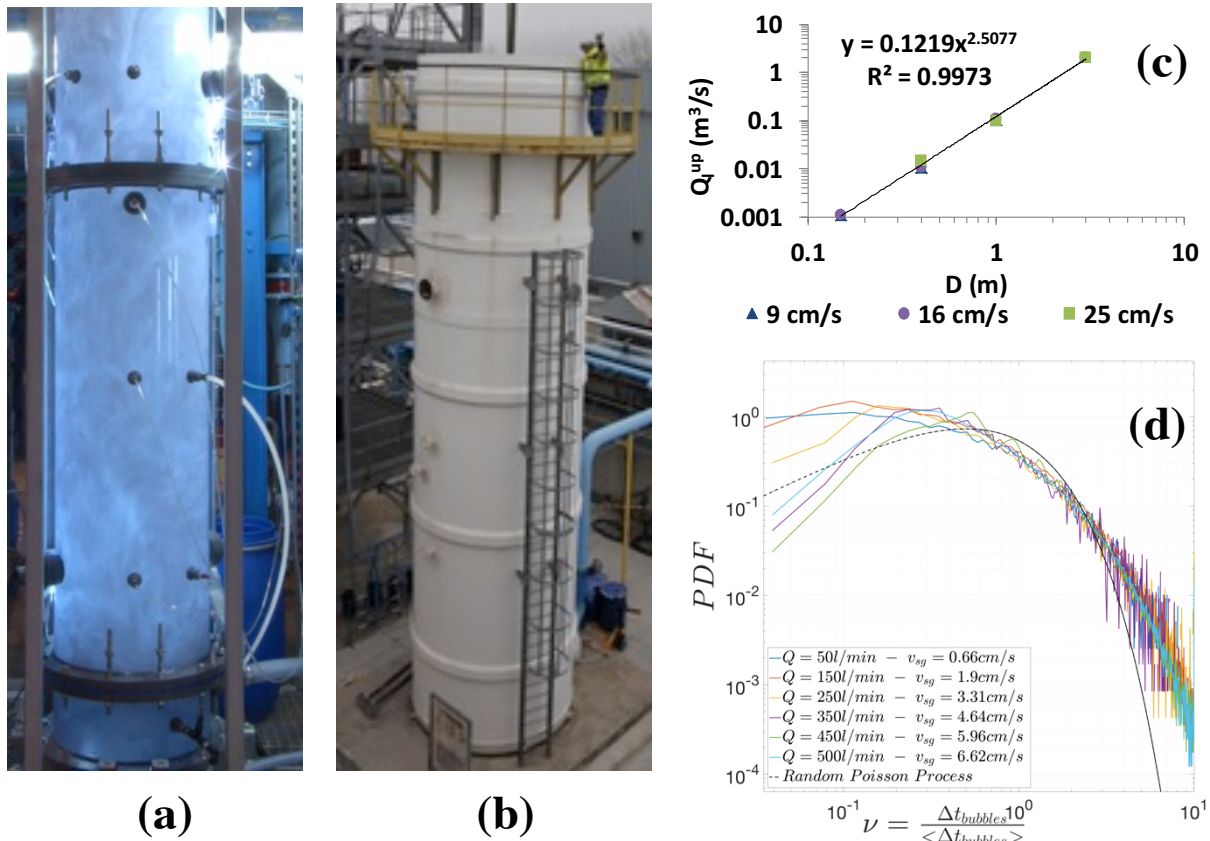


Figure 1: bubble columns of 1m and 3m in diameter, heights 5.7 (a) and 12m (b). Scaling of the entrained liquid flow rate in coalescence free conditions (c, from Maximiano PhD). Voronoï tessellations PDFs for differens values of superficial gas velocities v_{sg} (d).

Finally, we show some preliminary results from ongoing work: following recent advances in the context of particle-laden turbulent flows, joint velocity-concentration measurements based on Voronoï tessellations (Monchaux et al. 2010) have been developed to characterize clusters dynamics as well as instantaneous velocity gradients which are believed to be the key to turbulence production (figure 1d).

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