Influence of Bubble Release Mechanism on the Rise Velocity and Deformation of Single Bubbles in Aqueous Ionic Liquid Solutions

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Bubble columns are widely used in chemical and biochemical processes, where reactor performance depends on bubble fluid dynamics governing gas holdup, mixing, and mass transfer. Since these multi-scale phenomena originate from individual bubble behavior, including rise velocity and deformation, accurate characterization of single-bubble dynamics is essential for developing predictive gas–liquid fluid dynamic models [1,2].

A dedicated experimental facility (Figure 1) was set-up to investigate single-bubble dynamics under ambient conditions. Bubbles with equivalent diameters of 3–10 mm were generated using two methods (Figure 1): freely injected bubbles produced directly from capillary injections, and bubbles accumulated in a rotating dumping cup and subsequently released under controlled conditions. The dumping cup was operated at rotational speeds of 5, 20, 60, and 100 rpm. Bubble dynamics was recorded using a Phantom Miro C321 high-speed camera equipped with a 50 mm Kowa LM50JC10M C-mount lens, positioned perpendicular to the observation section approximately 50 cm above the injection point, with a resolution of 1920 × 1080 px and backlighting for high-contrast detection. Bubble dynamics were quantified using automated image processing based on contour reconstruction and centroid tracking (Figure 2), enabling determination of equivalent diameter, aspect ratio, trajectory, and velocity for non-spherical bubbles.

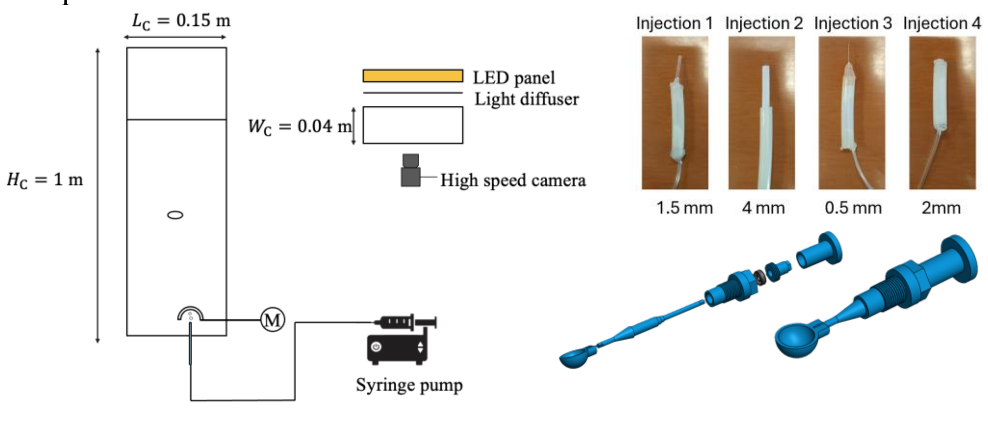

Figure 1: Experimental set-up, bubble injection configurations, and rotating dumping cup mechanism used for single-bubble generation.

Experiments were conducted in distilled water and aqueous solutions of 1-butyl-3-methylimidazolium tetrafluoroborate (BMIM-BF_4) at 0.1, 10, and 20 wt%, corresponding to $\log_{10}$(Mo) values of -10.78, -10.00, and -9.57, respectively, to evaluate the influence of release dynamics and liquid properties on bubble dynamics and deformation.

Freely injected bubbles exhibited consistently higher terminal velocities than dumping-cup bubbles across all tested liquid systems. In distilled water, freely injected bubbles reached 0.232-0.261 m/s, compared with 0.200-0.225 m/s for dumping-cup release. At 0.1 wt% BMIM-

BF$_4$, freely injected bubbles exhibited velocities of 0.210-0.216 m/s, compared with 0.164-0.201 m/s for dumping-cup bubbles (Figure 3). At higher ionic liquid concentrations, freely injected bubbles in 10 wt% BMIM-BF$_4$ reached approximately 0.210-0.216 m/s, while dumping-cup bubbles ranged from 0.164-0.201 m/s; in 20 wt% BMIM-BF$_4$, freely injected bubbles maintained higher velocities than dumping-cup bubbles, reaching approximately 0.220-0.232 m/s compared with 0.182-0.218 m/s. This difference was accompanied by greater bubble deformation for freely injected bubbles, whereas dumping-cup bubbles remained closer to spherical geometry. These observations indicate that the release mechanism influences the initial bubble shape and detachment dynamics, thereby modifying the fluid dynamic drag, consistent with theoretical predictions for the surface-tension-dominant regime [3].

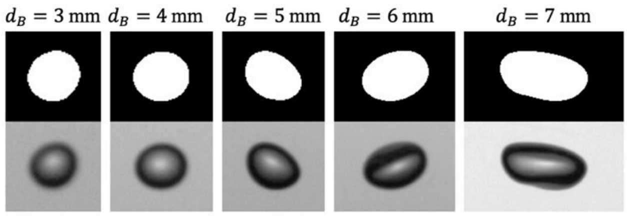

Figure 2: Example of bubble detection image processing: original (bottom) and binarized images (top), corresponding to $\log_{10}$(Mo) = -10.00.

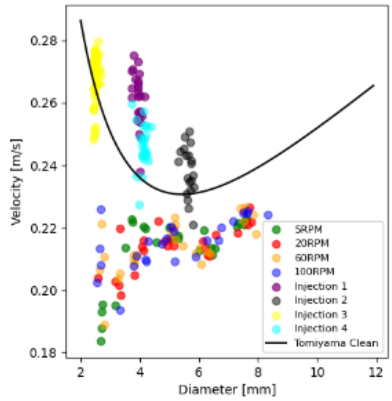

Figure 3: Representative bubble velocity–aspect ratio data (0.1 wt% BMIM-BF$_4$).

The presence of BMIM-BF$_4$ modified bubble behavior through interfacial effects associated with surface-active species [4]. At higher BMIM-BF$_4$ concentrations, Marangoni stresses suppressed deformation by reducing interfacial mobility [4], leading to similar aspect ratios for bubbles generated by both injection methods. However, the results demonstrate that the bubble generation method consistently influences rise velocity across all tested liquid systems. In distilled water and 0.1 wt% BMIM-BF$_4$, freely injected bubbles were more deformed and exhibited higher terminal velocities than dumping-cup bubbles, whereas at higher BMIM-BF$_4$ concentrations (10 and 20 wt%), dumping-cup bubbles still exhibited lower terminal velocities despite similar bubble shapes, indicating that the detachment conditions imposed by the dumping cup continue to influence fluid dynamic behavior beyond the initial formation stage.

References

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