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CFD Simulations of Bubble Columns in the Heterogeneous Flow Regime

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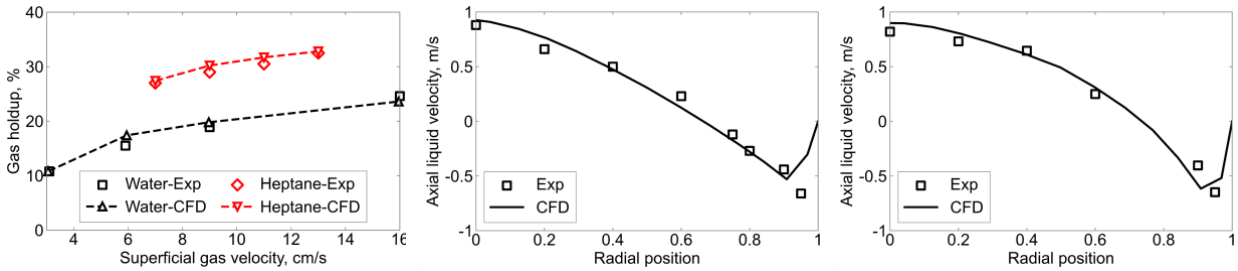
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Introduction. Bubble columns are gas–liquid reactors widely used in industrial processes such as oxidation, hydrogenation, and Fischer–Tropsch synthesis, as well as in wastewater treatment and biotechnological applications [1]. Despite their simple design, their fluid dynamics are highly complex and depend on geometry, flow rates, and fluid properties. Industrially, they often operate in the heterogeneous churn-turbulent regime, characterized by high gas volume fractions and strong liquid recirculation [2]. Experimental investigations alone are often insufficient to characterize these conditions at large scale, where measurements are very challenging. Therefore, computational fluid dynamics (CFD) has become an essential tool for scale-up and reactor design. In this study, a CFD model for bubble columns in the homogeneous regime is developed and validated against experimental data for air–water systems in columns with diameters of 0.4 m and 1 m and further evaluated for a nitrogen–heptane system, addressing a gap in the literature, where such systems are still scarcely explored.

Numerical Method. The numerical model is based on the two-fluid model and implemented in the multiphase code developed at *HZDR* [3], extending the OpenFOAM Foundation software. In the two-fluid framework, the Navier–Stokes equations for each phase are ensemble-averaged, and the effects of turbulence and interfacial phenomena are accounted for through closure models. For the momentum exchange between phases, drag and virtual mass are considered. The single bubble drag coefficient proposed in [4] is modified with a swarm correction factor to account for the influence of neighboring bubbles [5]. For the virtual mass force, a constant coefficient of 0.5 is used [6]. The $k-\omega$ SST model, augmented with source terms from [8], is employed to model turbulence in the liquid phase, while the gas phase is treated as laminar. The three-dimensional transient simulations were performed on a structured hexahedral mesh for a total duration of 60 s. Data were sampled after the initial transient phase had ended.

Results. The numerical model was validated against experimental data for global gas holdup, as well as for radial profiles of void fraction and axial liquid velocity. Two bubble columns were considered, with internal diameters of 0.4 m and 1 m, both operating under air–water conditions. Additional validation was carried out for a nitrogen–heptane system in the 0.4 m column. The results for the air–water and nitrogen–heptane systems in the 0.4 m column, together with the radial profiles of axial liquid velocity, are presented in Figure 1. Overall, the model predicts both global and local flow properties with good accuracy across all the cases investigated. Its capability to handle different fluid systems is confirmed by the comparison between air–water and nitrogen–heptane conditions. As shown in Figure 1a, the gas holdup increases with superficial gas velocity for both systems, and the numerical results are in close agreement with the experimental data. In addition, the model captures the systematically higher gas holdup observed in the nitrogen–heptane system, reflecting its ability to account for variations in fluid properties.



(a) Comparison between experimental and CFD-predicted gas holdup for air-water and nitrogen-heptane systems.

(b) Comparison of experimental and CFD-predicted axial liquid velocity profiles for the air–water system at a superficial gas velocity of 16 cm/s.

(b) Comparison of experimental and CFD-predicted axial liquid velocity profiles for the nitrogen–heptane system at a superficial gas velocity of 13 cm/s.

Figure 1: Comparison between experimental data and CFD predictions for gas holdup and axial liquid velocity.

Conclusions. We presented a CFD model to simulate the heterogeneous flow regime in industrial-scale bubble columns. The model has been validated against experimental data for different column dimensions and phases. Overall, the numerical results are in good agreement with the experimental data for both local and global flow properties, demonstrating the model's ability to accurately predict system behavior across different fluids.

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