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A comprehensive investigation of predictive models for the flow regime transition in bubble columns

Vitor Augusto Regert dos Santos[1], Nicolò Varallo[1], Giorgio Besagni[1,2]
[1]*Politecnico di Milano, Department of Energy, Milan, Italy*
[2] *Helmholtz-Zentrum Dresden – Rossendorf, Institute of Fluid Dynamics, Dresden, Germany*
**vitoraugusto.regert@polimi.it*

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Introduction. Bubble columns are widely used multiphase reactors due to their excellent heat and mass transfer characteristics, simple design, and low operating and maintenance costs [1], making them particularly attractive for CO_2 absorption applications. Despite their structural simplicity, the fluid dynamics involve complex multiscale interactions [2] that give rise to distinct flow regimes, ranging from homogeneous flow with uniform mono or poly-dispersed bubble size distributions to heterogeneous flow dominated by large structures with a pronounced effect of coalescence and breakup. The fluid dynamics in bubble columns can be interpreted through a general relationship between drift flux and gas holdup, constructed based on flow regime transitions and applicable regardless of the specific system considered [3]. In this context, the theoretical framework proposed by [3] provides a comprehensive way to characterize flow regime transitions, identifying six distinct flow regimes and five transition points, along with mathematical criteria to determine these transitions directly from global gas holdup and drift flux data. While this approach represents a significant advancement in identifying and characterizing flow regimes, it relies on the availability of experimental data, consequently, the a priori prediction of flow regime transitions remains an open challenge. The present work addresses this gap by evaluating predictive models from the literature against an extensive experimental database of global gas holdup–drift flux curves. In this first step, the analysis focuses on the transition marking the end of the homogeneous regime (T_2), namely the transition from polydisperse homogeneous flow to the transition regime (or directly to heterogeneous flow in the case of large-orifice distributors), as this is the primary target of most existing predictive models.

Implementation Methods. The investigated models can be classified into three main categories. Empirical correlations that compute transition coordinates based on superficial velocities and bulk properties. Semi-empirical formulations that combine theoretical approaches with empirical closures. Finally, models based on linear stability which predict the transition from the growth of disturbances in the homogeneous regime and are derived from mechanistic theory. A comprehensive literature database was compiled, covering varied column and sparger geometries and over thirty gas–liquid mixtures, in which all the transition points were identified according to [3]. The obtained database was used as comparison benchmark for the empirical correlations of [4] and [5], semi-empirical models of [6] and [7], and the linear stability analysis of [8].

Results and Discussion. A preliminary analysis was performed, and the results are shown in Figure 1, by comparing the gas holdup predictions of the mentioned models with respect to the experimental data. The sorted experimental critical gas holdup (maximum gas holdup where homogeneous flow may exist) shows that while most of the models predict values in a determined range, without large changing according to experimental data, the stability criteria proposed by Joshi, the analysis indicates that predictions follow the trend of experimental data with a visible underprediction for most points. Moreover, the models of [8], [6] and [5] present the

best predictions overall in comparison to [7] and [4], presenting lower meaning absolute relative error and root mean square error.

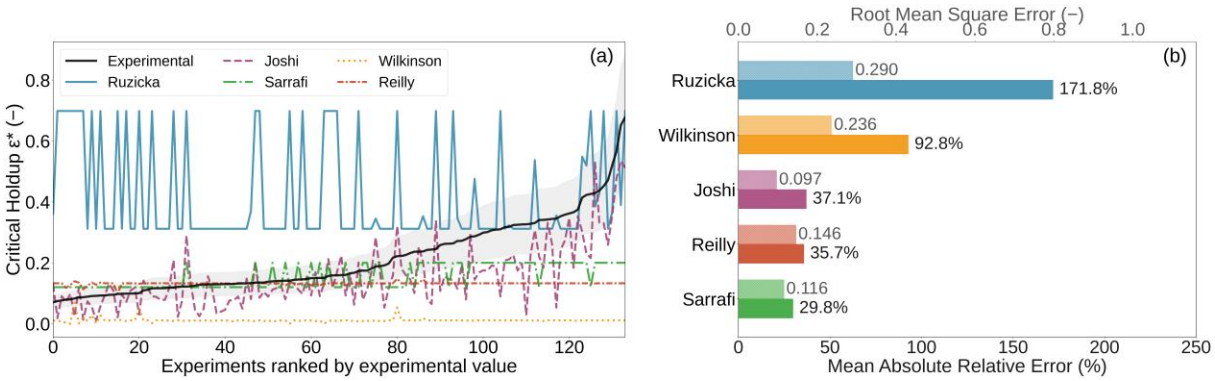

Figure 1: Model predictions vs. experimental critical holdup ε* at transition T_2. (a) Predictions overlaid on experimental values (sorted from smallest to largest); grey band: ±30% error. (b) Model ranking by Mean Absolute Relative Error (solid bars) and Root Mean Square Error (hatched bars).

Conclusions. The linear stability criteria of [8] show the best performance at capturing the experimental trend of critical gas holdup, meaning that it tends to change its prediction when the actual experimental value is different, while other approaches show limited sensitivity to factors affecting flow regime transitions, such as fluid properties, column geometry, and sparger design. Closure selection also proves critical, significantly impacting results across all models, since all the studies models require some sort of predictive correlation for different parameters. Future studies should focus on a thorough investigation of the closure relations employed in the models, as this is essential for developing predictive approaches for flow regime transitions. Furthermore, the methodologies explored in this work may be extended and adapted to predict other flow regime transitions.

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