Project Outcomes Report

Use of Multiphase CFD to Improve the Closure Relations of Mechanistic Model Codes for Oil and Gas Applications

Here we provide a summary of the main project results and findings at both universities:

MIT

- First, through sensitivity analysis of three different models (Orell and Rembrand, 1986; Ansari et al., 1994; Petalas and Aziz, 2000) it was determined that the dominant closure relation with respect to the models' figures of merit, i.e. the void fraction (or liquid holdup) and the pressure drop, is the Taylor bubble velocity. Thus the focus became study of Taylor bubble's dynamics. The finite-volume CMFD code used in this study, Transat®, was validated with a series of Taylor bubble test cases, which built enough confidence on the CMFD code to employ it, to develop a new and broad numerical database from which one can study the dynamics of Taylor bubbles in inclined pipes. However, two main assumptions were made in the numerical simulations: (i) a lubricating film exists between the Taylor bubble and the pipe wall at all inclinations, and (ii) the Taylor bubble length does not affect its dynamics in inclined pipes. To verify the robustness of the first assumption, an analytical model predicting the gravity-induced drainage of the thin film was presented, and from it, a new criterion to avoid the film breakup was derived: $\bar{t}_{bubble} = t_{bubble}/\tau < 0.01$, where t_{bubble} is the Taylor bubble's passage time and τ is the characteristic drainage time. The model was experimentally validated through Taylor bubbles in inclined pipes with stagnant liquids (Lizarraga-Garcia et al., 2016). The second assumption was justified through experiments performed in the laboratory and simulations.

- In the literature, the Taylor bubble velocity is modeled based on two different contributions: (i) the drift velocity, i.e., the velocity of propagation of a Taylor bubble in stagnant liquid, and (ii) the liquid flow contribution. Here, we first analyzed the dynamics of Taylor bubbles in stagnant liquid by generating a large numerical database that covers the most ample range of fluid properties and pipe inclination angles explored to date: $Eo \in [10,700]$, $Mo \in [1 \cdot 10^{-6}, 5 \cdot 10^{3}]$, and $\theta \in [0°, 90°]$. A new unified Taylor bubble velocity correlation, proposed for use as a slug flow closure relation in the mechanistic model, was derived from that database employing logistic dose-response curves. The new correlation clearly outperformed current correlations when tested against both the numerical database and experimental data: the absolute average relative error is 8.6% and 13.0%, while the coefficient of determination R^2 is 0.97 and 0.84, respectively. The second best correlation reported absolute average relative errors of 120% and 37%, and $R^2 = 0.40$ and 0.17, respectively. Furthermore, other hydrodynamic features were reported. Of particular importance in slug flow are the perturbed distances upstream and downstream the bubble, Z' and L_{min}, respectively, as they represent the area of influence of the Taylor bubble, which is relevant for coalescence phenomena in transient slug flow. Z' was determined to not vary significantly with Eo, Mo or θ, as its maximum value is approximately $Z' \approx d$ for inclined pipes. On the other hand, the value of L_{min} changed significantly with respect to the vertical pipe over the numerical database, and can reach up to 11 times that value for cases with $Mo = 5{,}000$.

- Finally, simulations of Taylor bubbles in inclined pipes with upward and downward flow were performed. As of now, a model with $C_0 = 2$ in the model of Nicklin et al. (1962) seems to behave the best for upward flow. However, for downward flow the bubble terminal velocity is ill-predicted by this approximation, especially when Taylor bubbles become non-axisymmetric beyond certain liquid flow values in vertical pipes. Furthermore, a Taylor bubble breakup mechanism for lower than expected liquid velocities was observed, where a liquid jet penetrates the bubble from its bottom.

- Some important questions remain. First, the bubble volume beyond which the bubble becomes a Taylor bubble. Based on our simulations, the volume needed to obtain a bubble terminal velocity independent of the volume itself increases with decreasing inclination angle with respect to the horizontal, θ. Furthermore, it is still unknown the maximum Eo at which Taylor bubbles exist in inclined pipes. Similarly to the previous trend, this critical Eo increases as θ decreases. Another instability mechanism that still needs to be further evaluated is the breakup mechanism observed in Taylor bubbles in vertical pipes with liquid flow where the Taylor bubble bottom cannot sustain the stagnant pressure built on it and a liquid jet breaks it. We think that this breakup mechanism will correlate to the Weber number.

Kuwait University

- We defined reference pipe geometrical parameters, fluid properties, and operating conditions (gas, oil and water flow rates) to develop reasonable number of cases for the CFD simulation runs. These reference conditions represent a wide range of Kuwaiti reservoirs conditions (p and T).

- We coded, tested, and validated Ansari *et al*. (1994) two-phase upward vertical slug flow model, using VBA (Visual Basic in Excel) language. Later Ansari *et al*. model was modified for inclined upward flow since the developed closure relationship is applicable for vertical and inclined flow. Furthermore, the model was expanded to include Black-Oil and Compositional fluid models using Kartoatmodjo and Schmidt correlation (1991), and Peng Robinson (1976) Equation of State, respectively.

- Using the developed code, we conducted a sensitivity study to identify the most sensitive closure relationships on pressure gradient and average liquid holdup. To carry out the sensitivity analysis, the five closure relationships in the Ansari *et al*. slug flow models, namely the gas velocity in liquid slugs (Harmathy, 1960), the liquid velocity in Taylor bubble region (Brotz, 1954), the slug liquid holdup (Selvester *et al*., 1987), the slug translational velocity (Bendiksen, 1984) and the average slug length (L_s=16d) were identified and tested. Two methods were used in the sensitivity study, namely the perturbation method, and Taylor Series Expansion method.

- We developed (collect, processed, filtered) a large data base of drift velocity from the open literature and from other resources to be used for the validation study of the CFD based unified closure relationship of drift velocity. The collected databases are as follows: Zukoski (1996), Weber (1985), Felizola (1994), Moreiras (2012), Shosho (2001), and Gockal *et al*. (2010).

- We developed (collect, processed, filtered) a large data base of pressure gradient and average liquid holdup for vertical and inclined two-phase flow in pipes to be used for validation study of pressure gradient and liquid holdup.

- We validated the developed closure relationship of drift velocity with the experimental data database using six statistical validation parameters.

- We compared the developed closure relationship of drift velocity with six of the currently existing drift velocity closure relationship.

- We incorporated the newly developed drift velocity closure relationship into the Ansari *et al*. model, which was then validated (with the new closure relationship) against the collected pressure gradient and average liquid holdup database.

The main beneficiaries of the work performed in this project are the engineers and practitioners in the oil/gas industry, who use mechanistic-model codes to predict the performance of multi-phase flow systems in oil/gas plants. The greater fluid dynamics community benefits from deeper understanding of slug flow characteristics.

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