Simulation of Polydisperse Bubbly Flows with CFD and PBM: Importance of Interfacial Forces

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Abstract: Developing reliable Computational Fluid Dynamics Population Balance Model (CFD-PBM) is beneficial for studying the behavior of any industrial-scale polydisperse mixing system. Overall performance of this method relies on the closure relations employed in the averaged field equations. This work focuses on the relations proposed for the lift and wall lubrication forces used in the momentum balance equation. The selected relations are assessed using the experimental data of a polydisperse bubbly flow. Following this, the necessity of adjusting lift coefficient for improving the results is illustrated. Finally, the evolution of the bubble size distribution predicted by the CFD-PBM is evaluated against the experimental data.

Keywords: Polydispersity, Population balance model, Two-fluid model, Interfacial forces.

Introduction

Modelling the polydispersity features, e.g. size distribution, of the disperse phase is one of the crucial aspects of multiphase mixing simulations. Knowledge of the properties of the disperse phase is essential for accurate estimation of the interfacial heat and mass transfer occurring in practical and industrial mixing applications. In this regard, the population balance model coupled with the computational fluid dynamics, namely CFD-PBM, is a powerful tool for studying the evolution of the properties of the disperse phase and its interactions with the continuous phase. Concerning the CFD, adopting the Eulerian-Eulerian framework, called Two-fluid model, is currently the only viable choice if the simulation target is an industrial-scale equipment. However, the performance of the two-fluid model depends strongly on the relations required to close the averaged field equations. The closure relations relevant to the momentum balance equation are termed as interfacial forces including mainly drag, lift, turbulent dispersion and wall lubrication forces. However, these models were mostly developed through simplistic theoretical/experimental methods that limits their applicability. Among the mentioned forces, lift and wall lubrication forces have been provoking ongoing debate over their physical explanation and corresponding suggested models. In this work, the performance of two recent combinations of models proposed for the lift and wall lubrication forces are compared with each other using monodisperse approach in a bubbly air/water two-phase system for which experimental data are available. Moreover, the potential for improving the results through adjustment of the lift coefficient is demonstrated. In the second part, the evolution of the bubble size distribution (BSD) is studied by employing the PBM coupled with the Two-fluid model using the best setting for the interfacial forces. Finally, the results are validated using the available experimental data.

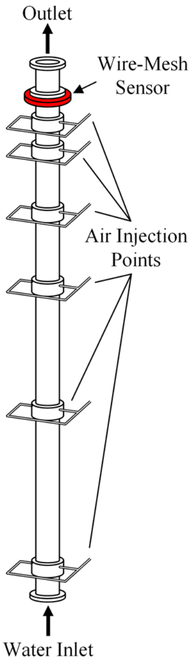
Methods and Experiment

Experimental Setup

The investigated experimental setup is an 8 (m) vertical pipe with inner diameter of 0.1953 (m) in which air and water flow upward cocurrently, see Figure 1. The data used in the present study was obtained by Bayer and co-workers [1]. The setup works adiabatically at constant temperature of 30 (ºC). The air is introduced into the pipe through the injection points on the wall, while the water enters from the bottom. This way of air injection creates a sort of developing flow that provides useful experimental data for evaluating the interfacial forces. A wire-mesh sensor placed at the top of the pipe measures air volume fraction, air velocity and bubble size distribution for several combinations of air and water inlet flow rates. To follow the evolution of the properties along the axial direction, several air injection points are embedded at specific heights, each one operates at a time. It is worth noting that the operating pressure is set to 2.5 (bar) at the active injection point that makes it possible to assemble the data corresponding to different injection points and therefore follow the evolution of the measured profiles. Lastly, it should be mentioned that all the simulated experimental cases operate in the bubbly flow regime.

Simulation Approach

As explained before, the two-phase flow behavior was simulated by employing the Two-fluid model in which two separate momentum equations are solved for the continuous and disperse phases under the assumption of interpenetrating continua. Taking advantage of the axial symmetry, only a quarter portion of the pipe was discretized using structured O-grid mesh. The gas inlet is modeled by a circular ring. Moreover, only the first 5-meter portion of the column was simulated due to the high computational demand of simulating the entire column. The calculations were performed using a modified version of twoPhaseEulerFoam solver of OpenFOAM v4.1. The modifications include addition of the new interfacial forces and coupling the PBM with the Two-fluid model. The PBM implementation aims at following the evolution of the BSD due to the pressure change, and the coalescence and breakage phenomena by employing the Quadrature Method of Moments (QMOM). Once the moments are calculated, the average bubble size required by the Two-fluid model can be updated accordingly. Further details of the implementation is described by Buffo and co-workers [2].



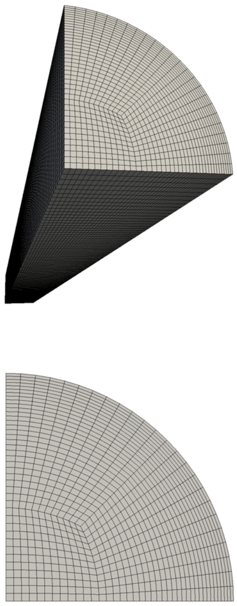


Figure 1: Left) Schematic diagram of the TOPFLOW experimental setup. Right) Designed mesh.

Closure Models

As mentioned previously, closure expressions are required for modelling the turbulence and the interfacial forces. In this work, only the turbulence in the continuous phase is considered due to the low global gas holdup of the investigated experimental cases. The turbulence properties were estimated by employing the single-phase k-ε model scaled by the continuous phase volume fraction. Concerning the interfacial forces, firstly, a set of preliminary simulations were conducted to examine the effects of each force, namely drag, turbulent dispersion, lift and wall lubrication forces. The first two forces are not problematic as the common available models give similar predictions. In this work, these forces are estimated using Tomiyama Correlation [3] and Burns expression [4] respectively. In contrast, there is no consensus on the lift and wall lubrication forces, which are the subject of this study. We aim at comparing two different combinations of lift and wall lubrication expressions. The first combination consists of Tomiyama model [5] for lift coefficient, which is based on the experiments in laminar shear flow, and Hosokawa model [6] for wall lubrication force. On the other hand, the second combination comprises Sugrue model [7] for the lift coefficient, which takes into account the flow turbulence, and the geometrical approach proposed by Lubchenko [8] to consider the presence of the wall. It should be noted that the Lubchenko approach needs a damping function that brings the lift coefficient down to zero near the wall. Thus, in this work, the damping function proposed by Shaver and Podowski [9] is applied on the lift coefficient near the wall.

As regards PBM, expressions to estimate breakage and coalescence of the bubbles are required. It is known that several factors contribute to breakage and coalescence phenomena. However, it is evident that, in a turbulent condition, the first contribution to be taken into account is the turbulent fluctuation. For this purpose, the coalescence frequency is calculated via the expression proposed by Coulaloglou and Tavlarides [10] and the coalescence efficiency is estimated by the Chesters' expression [11]. Moreover, the breakage phenomenon is expressed using Laakkonen et al. [12] model for estimating both the frequency and the daughter distribution.

Results and Discussion

Monodisperse simulations

As indicated previously, the first part of the work focuses on the interfacial forces, specifically lift force and wall lubrication force. Figure 2 depicts the radial profiles of the air volume fraction at three heights obtained by employing three different set of models for a selected experimental case.

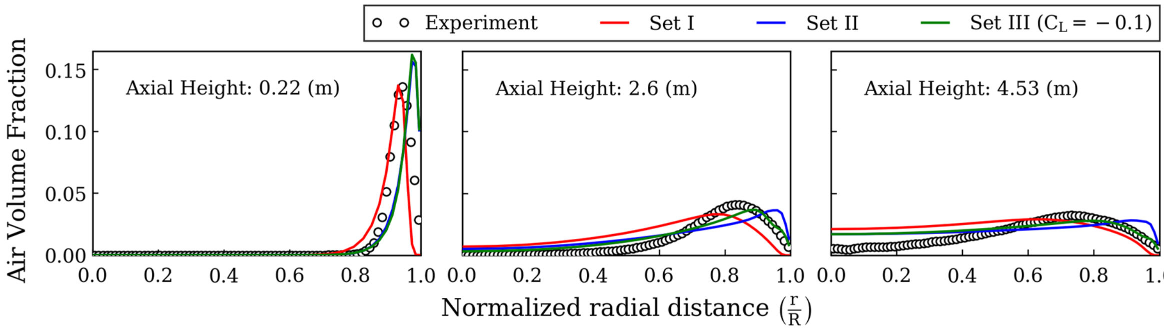


Figure 2: Radial profile of air volume fraction for experimental case with U_g=0.0235 m/s and U_l=1.017 m/s

The radial profiles of the same colour were obtained by employing one of the three sets of models that differ in the expressions for the lift coefficient and/or the wall lubrication force. Table 1 summarizes the difference between the employed sets of models. It should be noted that Set III is the same as Set II except that a constant lift coefficient is used instead of estimating it by the Sugrue model. The reason for using constant lift coefficient will be clarified later.

Table 1: Summary of the set of models employed in the simulations

	Lift Coefficient	Wall Lubrication Force
Set I	Tomiyama Model	Hosokawa Model
Set II	Sugrue Model + near wall damping function	Lubchenko Geometrical Approach
Set III	Constant Coefficient + near wall damping function	Lubchenko Geometrical Approach

Starting with Set I, it is evident that its performance is inferior to those of the other sets for this test case except for the region very close to the injection point. The main reason is the Hosokawa wall lubrication force since it results in an unphysically large force near the wall that essentially pushes away all the gas from the wall. Therefore, the gas phase spreads towards the centre of the column much more than what is expected according to the experimental data. Furthermore, another major drawback is having some computational cells near the wall with virtually no gas, which is not physical. On the other hand, Sets II and III do not empty the region near the wall out of gas which is the advantage of using Lubchenko approach. Regarding the lift coefficients, Tomiyama model results in a large negative lift coefficient (-0.16) whereas Sugrue model estimates a small positive average lift coefficient for this test case. As the total performance of the models depends also on the employed wall lubrication force, it is difficult to comment on the sign of the lift coefficient in advance. However, it is possible to vary the lift coefficient and observe the change in the results. Since the Lubchenko approach does not yield unphysical profiles, a new set of models (named as Set III) including constant lift coefficient and Lubchenko approach was considered. The green profile in Figure 2 shows how using a negative lift coefficient (-0.1) yields more satisfactory results for this test case, particularly in the higher sections. It should be noted that the same improvements were achieved for the other experimental cases by adjusting the lift coefficient. Thus, Set III was chosen to be used in polydisperse simulations whose lift coefficient is constant and subject to change for each experimental case.

Polydisperse simulations

The last set of simulations aimed at predicting the bubble size distribution by employing PBM coupled with the Two-Fluid model. Figure 3 shows the axial profile of the surface-averaged mean Sauter diameter (d_{32}) predicted by the PBM in comparison with the experimental measurements for three experimental test cases. The most interesting result is the green profile corresponding to Case 3 where the entire model, including the selected coalescence and breakage kernels, performs well in predicting the decrease of the d_{32} due to the breakage dominancy in the lower part of the column and then reaching a sort of equilibrium between breakage and coalescence. On the other hand, Cases 1 and 2 (red and blue profiles) are different than Case 3 in the sense that their average d_{32} remain almost constant along the axial direction. Again, the predicted profiles show good agreement with the experimental data for Case 1 (red profile) whereas a discrepancy can be observed for Case 2 (blue profile). It can be associated with the fact that other coalescence/breakage mechanisms might play role in the system. More studies are following in this direction to identify the effect of other mechanisms in this particular system.

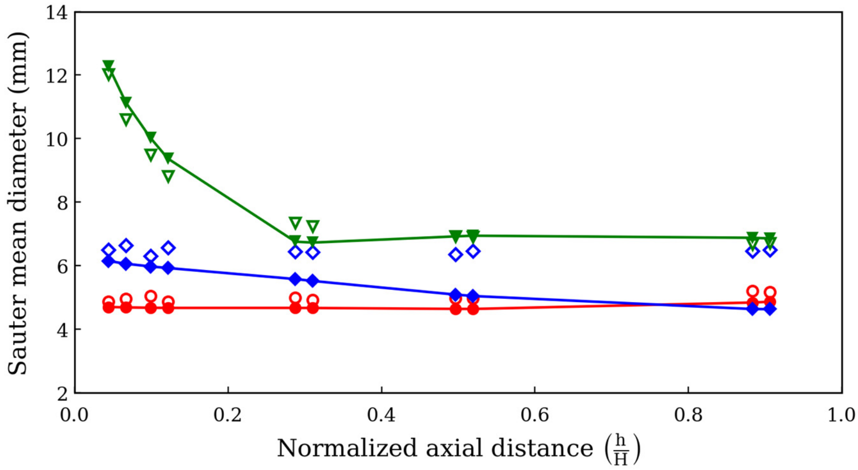


Figure 3: Axial profiles of the surface-averaged d_{32} obtained by PBM (solid line + marker) compared with the experimental measurements (hollow marker); red colour (Case 1): U_L ,U_G=0.641, 0.0096(m/s); blue colour (Case 2): U_L ,U_G=1.017, 0.0235(m/s); green colour (Case 3): U_L ,U_G=0.405, 0.0368(m/s)

Conclusions

The performance of two different combinations of models for lift and wall lubrication forces were assessed through Eulerian-Eulerian CFD simulations of a set of bubbly air/water experiments. It was concluded that adopting Lubchenko geometrical approach to consider the presence of the wall yields more realistic results in contrast to those achieved by the Hosokawa model, particularly in regions close to the wall. Regarding the lift models, it was shown that using an adjusted lift coefficient, instead of the one estimated by either the Tomiyama correlation or the Sugrue expression, can improve the predicted results for the investigated test cases. Finally, the predictions of the mean Sauter diameter confirms that the PBM coupled with the Two-fluid model is a reliable choice for estimating the properties of the polydisperse flows provided that the hydrodynamics of the system are simulated appropriately. In this respect, future works will focus on examining the effects of different coalescence/breakage mechanisms and extending the Two-fluid approach to Multi-fluid one where the bubbles (entities of the disperse phase) are allowed to move with different velocities.

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