Validation of the twoPhaseEulerFoam solver for jet inlet fluidized bed

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Introduction

Gas solid fluidized beds operating in the bubbling regime have been widely used in various fields of chemical engineering and of the power industry due to the highest contact efficiency between the phases, which leads to a higher conversion and to a better heat distribution [1]. Two different approaches are possible to simulate gas solid flows. The Lagrangian approach, where each particle trajectory is calculated individually, and the Eulerian approach, where the particulate phase is described as a continuum, reciprocally interpenetrating the fluid phase. The numerical modelling of bubbling fluidized beds presents particular difficulties due to the high number of particles involved in the system, which makes the adoption of Lagrangian models impossible due to their high computational cost. As a consequence, the Eulerian-Eulerian two-phase approach is the choice to simulate these systems. This approach has been implemented in an ever widely adopted open source solver twoPhaseEulerFoam written by using the OpenFOAM libraries. However no validation seems available in the open literature to the author's best knowledge. This paper aims to contribute to this task.

Mathematical Model

In the Eulerian-Eulerian two-phase approach the continuity, momentum, energy, and species conservation equations are employed to describe the spatio-temporal evolutions of all phases. The conservation equations are presented in Table 1. The closure model for h_{gs} is the Ranz-Marshall heat transfer model. The Fourier's law is used for $\mathbf{q}_g$. For k_{sg} different models are used among those available [1]. According to Gidaspow [1] the properties of the dispersed phase, being of a granular type, are computed as a function of the granular energy Θ_s. In this way the interaction between the particles are modelled according to the Kinetic Theory for Granular Flow (KTGF).

Experimental Set-Up

The bubbling fluidized bed with a central jet used in the experimental investigation of Kuipers et al. [2], was chosen as test case to compare the predictive capabilities of the solver with experimental measurements. To approximate true two-dimensional behavior and to reduce any severe restriction of solids flow by the wall effect, the bed thickness was chosen to be 0.015 m. The experimental system had a height of 1 m and a width of 0.57 m. At the center of the bottom section, a rectangular orifice, 0.015 m wide, allows a central air jet stream to be introduced in the bed, while the remaining section is uniformly fed by air at the minimum fluidization velocity.

Table 1. Conservation equations

<table>
<tr>
<td>Continuity
$$\frac{\partial \alpha_g \rho_g}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g) = 0$$
$$\frac{\partial \alpha_s \rho_s}{\partial t} + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s) = 0$$</td>
<td rowspan="3">Subscript s for solid phase
Subscript g for gas phase
$\alpha_{s,g}$ phases volume fractions
$\rho_{s,g}$ phase material density
$\mathbf{u}_{s,g}$ phase velocity
$\boldsymbol{\tau}_g = \mu_g \left[\nabla \mathbf{u}_g - \nabla^T \mathbf{u}_g - \frac{2}{3} \nabla \cdot \mathbf{u}_g \; \mathbf{I} \right]$
$\boldsymbol{\tau}_S = \mu_S (\nabla \mathbf{u}_S + \nabla^T \mathbf{u}_S) + \left(\lambda_S - \frac{2}{3} \mu_S \right) (\nabla \cdot \mathbf{u}_S) \mathbf{I}$
p shared pressure
p_s particle pressure
g gravitational acceleration
k_{sg} drag coefficient
$\mu_{s,g}$ dynamic viscosity of the phase
λ_s solid bulk viscosity
$T_{s,g}$ temperature
$C_{ps,g}$ heat capacity
h_{gs} interphase heat transfer coefficient
$\mathbf{q}_{s,g}$ conductive heat flux</td>
</tr>
<tr>
<td>Momentum
$$\frac{\partial (\alpha_g \rho_g \mathbf{u}_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g \mathbf{u}_g) = $$
$$= \nabla \cdot (\alpha_g \boldsymbol{\tau}_g) - \alpha_g \nabla p + k_{sg} (\mathbf{u}_s - \mathbf{u}_g) + \alpha_g \rho_g \mathbf{g}$$
$$\frac{\partial (\alpha_s \rho_s \mathbf{u}_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s \mathbf{u}_s) = $$
$$= \nabla \cdot \alpha_s \boldsymbol{\tau}_s - \alpha_s \nabla p - \nabla p_s + k_{sg} (\mathbf{u}_g - \mathbf{u}_s) + \alpha_s \rho_s \mathbf{g}$$</td>
</tr>
<tr>
<td>Energy
$$\frac{\partial (\alpha_g \rho_g C_{pg} T_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g C_{pg} T_g \mathbf{u}_g) = $$
$$= \nabla \cdot \mathbf{q_g} + h_{gs} (T_s - T_g)$$
$$\frac{\partial (\alpha_s \rho_s C_{ps} T_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s C_{ps} T_s \mathbf{u}_s) = $$
$$= \nabla \cdot \mathbf{q}_s + h_{gs} (T_g - T_s)$$</td>
</tr>
</table>

The properties of the system are summarized in Table 2 with a schematic representation of the experimental set-up.

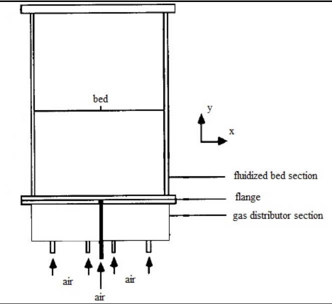
Numerical Simulations

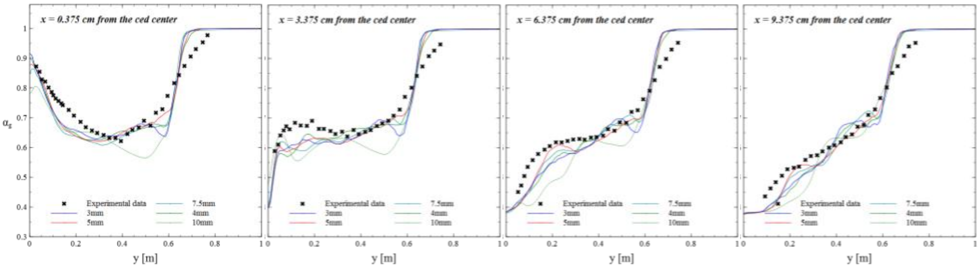
The bed configuration reported in Table 2 was reproduced with 2D numerical simulations, carried out with the open source CFD code OpenFOAM, version 2.3.x [3]. The effect of several numerical parameters and closure models is investigated: grid size, frictional stress model, interphase drag model and solid wall boundary conditions. All models analyzed are already present in the OpenFOAM library. The obtained results are related to the experimental findings of Kuipers et al. [2].

Effect of the grid size. This effect is determined by using a square mesh. Uniform and regularly structured grids provide quick convergence with minimal numerical errors. Four different grids cells size of 10, 7.5, 5, 4, 3 mm were used. Results are compared in Figure 1. The best compromise between accuracy and computational effort was found with a cell size of 5 mm. All subsequent results have been obtained adopting this cell size.

Table 2. Fluidized bed operating conditions and geometry

Bed material	ballotini
Particle diameter	500μm
Particle density	2660 kg m^{-3}
Minimum fluidization porosity	0.402
Minimum fluidization velocity	0.250m/s
Orifice velocity	5.0,10.0m/s
Initial bed height	0.500m
Temperature	293.0K





(a) **(b)** **(c)** **(d)**

Figure 1. Experimental and numerical vertical time-averaged porosity profiles at various positions from the bed center line at different grid sizes.

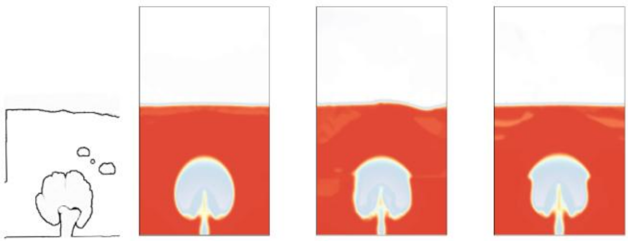
Influence of Frictional stress models. In the two fluid model the frictional stresses, which arise due to multi-particle contact, are simply added to the solids stresses from KTGF when the solids volume fraction exceeds a certain value, $\alpha_{s;fr,\min}$, which is termed the friction packing limit (FPL). The frictional stress models available in OpenFOAM 2.3.x are those proposed by Johnson and Jackson [4] (JJ) and Syamlal et al. [5] (SY). Figure 2 shows the first bubble formation in the experimental system and the numerical modelling. A too low value of $\alpha_{s;fr,\min}$ = 0.5, the suggested value for the JJ model, is clearly inadequate to reproduce the correct size of the bubble. Instead, no convergence was obtained using the suggested value for the SY, $\alpha_{s;fr,\min} = 0.63$.

Influence of Solid-wall boundary conditions. The no-slip, free-slip and partial-slip solid-wall boundary conditions, proposed by Johnson and Jackson [4], have been used in the following simulations. Figure 3 reports the simulated bubble formation compared with the experimental ones. The influence of the boundary conditions on the bubble shape becomes evident: where the particle phase is allowed to slip at the wall, Figure 3d, the bubble presents a rounded shape; instead, when a no-slip or partial-slip condition, Fig. 3b and 3c, is imposed at the wall, bubble's shape is afflicted by the wall, becoming not so rounded as before.

Experimental and numerical time-averaged porosity distributions are compared in Figures 4. Moving toward a full slip condition, figures 4c and 4d, averaged porosity isolines tend to match experimental data.

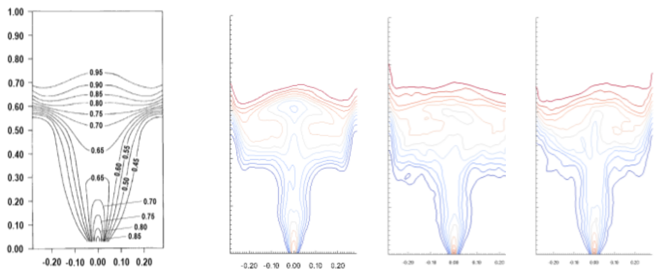
(a) (b) (c) (d)

Figure 2. Bubble shape at t = 0.3 s in experimental and numerical configuration for different frictional stress models and different value of $\alpha_{s;fr,\min}$: (a) JJ with $\alpha_{s;fr,\min} = 0.5$, (b) JJ with $\alpha_{s;fr,\min} = 0.6$, (c) SY with $\alpha_{s;fr,\min} = 0.6$.



(a) (b) (c) (d)

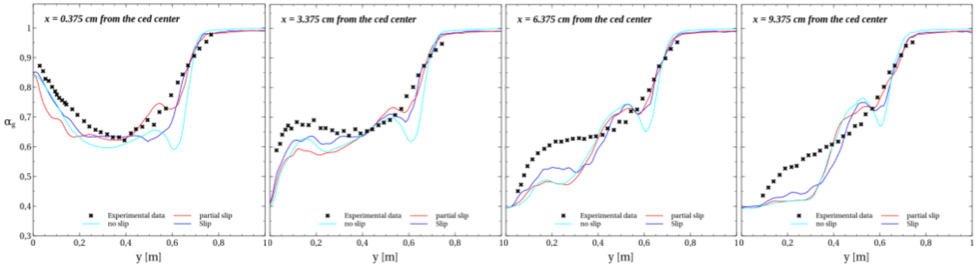
Figure 3. Bubble shape in experimental system and numerical system for different boundary conditions for the solid phase: (a) experimental, (b) no slip condition, (c) partial slip condition, (d) slip condition.



(a) (b) (c) (d)

Figure 4. Experimental and numerically time-averaged porosity distributions for : (a) experimental, (b) no slip condition, (c) partial slip condition, (d) slip condition.

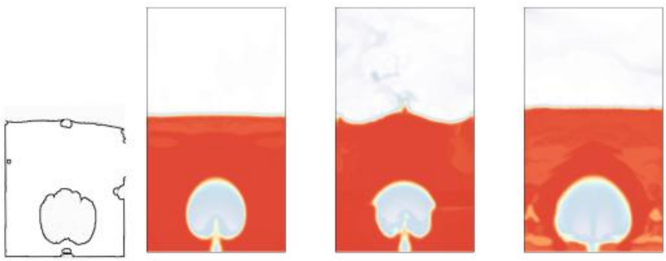
Figure 5 reports vertical time-averaged porosity profiles at various positions from the bed center line. Increasing the distance from the bed center line, Figures 5c and 5d, results obtained for partial slip conditions are closer than the other simulations to the experimental data because, moving from the center to the walls, the influence of boundary conditions become more evident.



(a) **(b)** **(c)** **(d)**

Figure 5. Vertical time-averaged porosity profiles at various positions from the bed centre line for different boundary conditions.

Influence of Interphase drag coefficient models. In the TFM the two phases are coupled through the interphase momentum transfer, one of the most important and dominant forces in fluidized bed modeling. The intherphase drag coefficient models compared in this work are: the model GidaspowErgunWenYu [5] (GEWY), the model SyamlalOBrien [5] (SyOB) and the model GidaspowSchillerNaumann [6] (GiSN), all available in OpenFOAM 2.3.x. In Figure 6 the simulated bubble formation are compared with the experimental one. The bubble shape is almost the same with simulations adopting the GEWY model, Fig. 6b and the GiSN model, Fig. 6d. With the SyOB model the shape is not so rounded and the bubble is smaller, with an irregular free bed surface. Simulations with model GiSN are closer to the experimental data than the other simulations, both for the bubble shape and for bubble dimension.

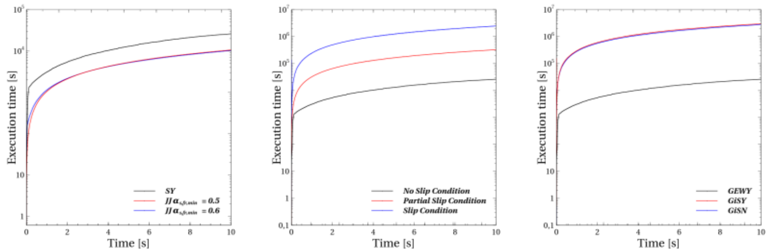


(a) **(b)** **(c)** **(d)**

Figure 6. Bubble shape in experimental and numerical system for different inter-phase drag coefficient models: (a) experimental, (b) GEWY, (c) SyOB, (d) GiSN.

Conclusions

Numerical simulations of bubble formation in 2D gas solid fluidized bed using the Eulerian-Eulerian approach were performed. The simulation results were validated against experimental data obtained by [2]. The results indicate the best solver setup that gives results closer to the experimental data: the SY FSM model [5], the JJ partial-slip boundary conditions for solid phase [4], and the GiSN model for the interphase drag coefficient. This configuration, on the other hand, gives numerical problem in terms of stability: numerical convergence was obtained using a fixed time step of 10^{-6} s. Accepting less accurate results, the use of GEWY model for the interphase drag model and the no-slip conditions for the solid phase at the wall significantly decreases the computational time. This latter configurations gives a rapid convergence. The different execution times required to simulate 10 s of real flow for the different simulations are shown in Figures 7.



(a) **(b)** **(c)**

Figure 7. Effects of model setup on the execution time: (a) frictional stress models, (b) boundary wall conditions, (c) interphase drag model.

References

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