Analysis of flow in fluidized bed of particles

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Abstract: The paper presents a study of the flow in a fluidized bed. The analysis is based on measurements made on an experimental stand and computer simulations. Free software packages have been used for simulations. Simulation is done using the most common model for this kind of problem. The first type of model is the Eulerian-Eulerian type and have as their first approximation, the assimilation of the solid phase with a continuous environment. The second category of models is Eulerian-Lagrangian type, they treat the fluid phase as continuous and the solid phase as individual particles or groups of particles “parcels” with similar characteristics. The results of the simulations were compared with the measurements performed on an experimental stand. The experimental stand is composed of a glass column with a diameter of 75mm and a height of 500mm and allows the study of flow in a fluidized bed containing spherical glass beads of 250–500μm in diameter. The results of the simulation were in good agreement with measured data and in accordance with the result presented in other specialized studies.

1. Introduction
The problems related to the multiphase flow and the turbulent fluidized bed reactors are frequently encountered in industrial practice, solving them is a very difficult one. Their analytical approach is not satisfactory and the numerical approach is difficult to solve. The models currently used have limited applicability due to the multitude of simplifying assumptions or are high consuming of computing resources, which greatly limits their area of use for practical problem [1-3]. In the last years three main categories of models have been imposed: two-fluid model (TFM, Eulerian-Eulerian) [4], discrete particle method (DPM Eulerian-Lagrangean) [5], and direct numerical simulation (DNS) [6], of course, multiple hybrid models have been developed to use the advantages offered by the first mentioned ones, to increase the accuracy and reduce the computational effort required.

That study presents simulations result for gas-solid flows in a fluidized bed using only TFM and DPM models, due to the limitations imposed by the available computing resources. The software used is MFiX v. 19.3 [7] offered for free by the National Energy Technology Laboratory (NETL) a U.S. Department of Energy (DOE). The program can do simulation with both models, with different formulations for calculating the moment equation and the drag coefficient. In the software are implemented more models derived from that, hybrid method, but these are not fully documented and tested.

In the end, comparative studies have been made to highlight the strengths and weaknesses of each method. The results of the simulations were compared with the measurements performed on an experimental stand.
2. Theoretical background

2.1. Two-fluid model
The TFM models are Eulerian-Eulerian type and have as their first approximation, the assimilation of the solid phase with a continuous environment. This approximation allows the use of the same set of equations for the solid phase as for the fluid phase but with modified properties. These types of models are the simplest and offer the fastest results, but require high performance models for solid phase simulation, mainly for its transport properties and fluid-solid phases interaction (drag coefficient).

In the TFM model the gas phase dynamics for two components is described by the mass (1), (3) and momentum conservation equations (2) and (4) [8]:

\[
\frac{\partial}{\partial t}(\varepsilon_f\rho_f) + \nabla \cdot (\varepsilon_f \rho_f u_f) = 0, \tag{1}
\]

\[
\frac{\partial}{\partial t}(\varepsilon_s\rho_s) + \nabla \cdot (\varepsilon_s \rho_s u_s) = -\varepsilon_f \nabla P_f - (\nabla \cdot \varepsilon_f \tau_f) - I_p + \varepsilon_f \rho_f g, \tag{2}
\]

\[
\frac{\partial}{\partial t}(\varepsilon_f\rho_f u_f) + \nabla \cdot (\varepsilon_f \rho_f u_f u_f) = 0, \tag{3}
\]

\[
\frac{\partial}{\partial t}(\varepsilon_s\rho_s u_s) + \nabla \cdot (\varepsilon_s \rho_s u_s u_s) = -\varepsilon_s \nabla P_s - (\nabla \cdot \varepsilon_s \tau_s) - I_p + \varepsilon_s \rho_s g, \tag{4}
\]

where \(\varepsilon\) is the volume fraction, \(\rho\) is the density, \(\mu\) is the shear viscosity, \(\lambda\) is bulk viscosity, \(u\) is the velocity, \(g\) gravitational acceleration, and \(P\) pressure tensor. These variables have two variants, one for the fluid phase and other for the solid phase noted with the subscript "f" and "s".

Interfacial momentum exchange term \(I_p\) stress tensor \(\tau\) and kinetic pressure tensor for solid phase \(P_s\) and \(\beta\) interphase drag coefficient are determinate from the kinetic theory of granular flow.

\[
\tau_f = -\mu_f (\nabla u_f + \nabla u_f^T) + 2/3 \mu_f (\nabla \cdot u_f), \tag{5}
\]

\[
\tau_s = -\mu_s (\nabla u_s + \nabla u_s^T) - (\lambda_s - 2/3 \mu_s) (\nabla \cdot u_s), \tag{6}
\]

\[
I_p = \beta(u_f - u_s). \tag{7}
\]

For interphase drag coefficient \(\beta\), exist in the speciality literature, many expressions. These formulations are in principal a function of Reynolds number \(Re\), solid volume fraction \(\varepsilon_s\) and diameter of particles in the solid phase \(d_p\). Two of the most used are presented in the next equation:

- Syamlal and O’Brien [9]:

\[
\beta = \frac{3}{4} C_D \frac{\rho_f \varepsilon_f}{d_p} \frac{u_f - u_s}{V_r^2}, \tag{8}
\]

\[
C_D = \left(0.63 + 4.8 \sqrt{\frac{\varepsilon_f V_r}{Re}}\right), \tag{9}
\]

\[
V_r = \frac{1}{2} (A - 0.06 \frac{Re}{\varepsilon_f} + \sqrt{\left(0.06 \frac{Re}{\varepsilon_f}\right)^2 + 0.12 \frac{Re}{\varepsilon_f} (2B - A) + A^2}, \tag{10}
\]
\[ A = e_j^{1.14}, \quad B = \begin{cases} 
0.8e_j^{1.28} & e_j \leq 0.85 \\
2.65 & e_j > 0.85 
\end{cases} \]  \quad (11)

- Gidaspow [10]:

\[ \beta = \begin{cases} 
\frac{3}{4}C_D \rho_c e_j \frac{\mu_f - u_i}{d_p} e_j^{-2.65} & e_j \leq 0.2 \\
150 \frac{e_j \mu_f}{e_j d_p} + 1.75 \frac{\rho_c e_j \mu_f - u_i}{d_p} e_j > 0.2 
\end{cases} \]  \quad (12)

2.2. Discrete particle model

DPM category of models is Eulerian-Lagrangean type, they treat the fluid phase as continuous and the solid phase as individual particles or groups of particles “parcels” with similar characteristics. That type of model offers results closer to reality for a wide variety of flow regimes, but uses important computing resources.

The DPM model use for fluid phase dynamics the same equations (1) and (2) like TFM but \( I_p \) is calculated using the expression for equation (13) [11]:

\[ I_p = \frac{1}{V_c} \sum_{i=1}^{N_p} \beta (u_f - u_i) \delta (r - r_i), \]  \quad (13)

where \( V_c \) is the volume of calculation cell, \( u_i \) is particle speed, \( \delta (r - r_i) \) is a discrete representation of a Dirac delta function that distributes the reaction force, \( r_i \) is the positional vector of particle and \( N_p \) is the total number of particle or “parcels”.

For solid phase the motion of every individual particle in the system is calculated from Newton’s second law [11]:

\[ m_i \frac{dv}{dt} = -V_c \nabla p + V_c \beta \left( u - u_i \right) + m_i g + F_{ip} + F_{iw}, \]  \quad (14)

where \( -V_c \nabla p \) is the force due to pressure, \( V_c \beta \left( u - u_i \right) \) is the force due to drag, \( m_i g \) is the gravity force, \( F_{ip} \) is particle-particle interaction force and \( F_{iw} \) is particle-wall interaction force. The contact forces are caused by collisions with walls or other particles. A soft-sphere approach is used for collisions evaluation with a linear spring/dash-pot model. The velocities, positions and collision forces of the particles are calculated at every time step using a first order time integration.

3. Experimental data

The experimental stand presented in figure 1 is composed of a glass column with a diameter of 75mm and a height of 500mm and allows the study of flow in a fluidized bed containing spherical glass beads of 250–500μm in diameter.

The stand is equipped with a PC-controlled data acquisition and control system. The installed sensors allow the measurement of the flow and the pressure drop in the glass column reported to the atmospheric pressure for a regime. The height of the particle bed can be measured only using the graded ruler attached to the column. Variation of the air flow can be done manually from the valve on the panel or by changing the speed of the compressor, much finer. The measurements were made by changing the air flow in a step of 0.5 l/min and recording the values. In the area of minimum fluidization speed, several measurements were made at a step of 0.25 l/min, to capture the phenomenon of fluidization. Fluidization was followed visual and using the pressure drop on the
particle column. Measurements were made until the bubble fluidization regime of the particle bed was reached. The results of the measurements were carefully processed, filtered and interpolated using spline functions [11,12]. They are presented in figure 2 (a) and (b). The minimum fluidisation speed \( U_{mf} = 15.05 \text{mm/s} \), the height of fixed bed \( H_{mf} = 120 \text{mm} \), and \( \Delta p_{mf} = 182 \text{mmH}_2\text{O} \).

### 4. Simulation parameters and results

Bot simulations were done in an identical condition. The simulation conditions were chosen mainly by taking into account the DPM model, which is more restrictive than TFM and a large consumer of computing resources. In the same computing conditions, DTM consumes 3 times more computational memory and requires 10 times more processing time. And last but not least, the available computing resources were taken into account. The working cases have been dimensioned so that the program runs completely in the memory of the computer, without performing write operations on disk, only in case of saving the data.

In these conditions, the simulations were performed on a rectangular field 2D, 75X230mm, the chosen height being twice the height of the space occupied by the particle bed under initial conditions. The particle size was set as the average for the analysed granulation from bed \( d_p = 0.35 \text{mm} \) and the initial solid fraction in bed \( \varepsilon_s = 0.4 \) was chosen. The discretization network was chosen 40X80 regular and uniform but is to mentioned that TFM is very sensitive to grid resolution. The boundary conditions were chosen: non-slip on the wall; constant and uniform initial inlet velocity at the bottom side and constant atmospheric pressure \( p_0 = 101325 \text{Pa} \) at the outlets on the upper side. For the drag coefficient, the Syamlal-O'Brien model was set, in the gravitational field and isothermal conditions. The rest of the settings were chosen by default for the two models. The initial conditions were for all cases zero velocity for fluid and bed particles.
5. Results
Following the speed values, from the experimental measurements, simulations were made for all the speeds around the minimum fluidization speed $U_{mf}$. The simulated period was $t=5s$ for each case. A total of 32 simulations were performed, 16 for each model, summing approximately 200 working hours. The amount of data collected is very large, therefore only the most relevant ones have been selected and are presented in figure 3, 4 and 5 (a), (b) and (c).

The pressure drop on the particle bed was obtained by making the difference between the value of the fluid phase pressure in the middle of the bottom part of the domain and the atmospheric pressure present theoretically at the upper part of the domain. The fluidization velocity was considered the one for which the pressure drops had the maximum value. The height of the particle bed was determined qualitatively visual because the appearance of bubbles on the surface of the bed makes the delimitation of a solid-fluid separation surface difficult. The data obtained from the simulation are not eloquent sheets in the absence of velocity distribution measurement for the particles. For this reason, a
comparison was made only for the minimum fluidization velocity, the bed height and drop of pressure at that speed and the result are presented in table 1.

Table 1. Comparison of measured and simulated data.

|                  | Min. fluidisation velocity [mm/s] | Error [%] | Bed height [mm] | Error [%] | Pressure drop [mmH²O] | Error [%] |
|------------------|----------------------------------|-----------|-----------------|-----------|-----------------------|-----------|
| Experiment       | 15.05                            |           | 120             |           | 18.2                  |           |
| TFM              | 16.32                            | 15.1      | 116             | -3.75     | 19.1                  | 4.9       |
| DPM              | 19.37                            | 28.7      | 121             | 0.83      | 18.4                  | 1         |

6. Conclusions

Analysing the data obtained by measurements and the results of the simulations carried out it is found that in both cases, there is an overestimation of the speed of fluidization more important at DPM. The height of the particle bed is underestimated in the case of TFM and well approximated by the DPM, as expected considering the assimilation of the particle bed with a fluid. The pressure drop on the particle bed was fairly well approximated by both models, from which one can conclude that solving the fluid phase flow through the particle bed is well resolved by both models, the major problems being in modelling the particle bed evolution.

The phenomenon of fluidization was qualitatively surprised by both models used, and the existing complex phenomena could be simulated, but the results are not very accurate. The DPM model has a better performance and also presents a better development perspective, but it is prohibitive from the point of view of the necessary computing resources since the studied problem was very simple. For study is very important to have accurate data measurement about moving of particle in a fluidized bed because the tow type of simulations show only approximatively similar data.

7. References

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