Investigation on velocity distribution of TFM and DEM phase in hybrid model of CBFB in mining

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Abstract. As a novel model for gas solid flow simulation, the investigation of TFM-DEM hybrid model is far from completely, including mutual interaction of TFM and DEM phase, selection of DEM portion and coherence of the predicted results from both phases. Therefore, in present study, the consistency of velocity distribution between TFM and DEM phase is investigated. The correlation of instantaneous and time-averaged velocity distribution of TFM and DEM phase in specific area in CBFB for mining is studied. And the differences of the axial and radial velocity between the particles of different sizes are discussed. The influence of particle diameter and the ratio of DEM and TFM phase on the correlation of velocity, both instantaneous and time-averaged, are taken into consideration.

1. Introduction

Gas-solid flow is widely used in various industrial applications, such as pharmacy, chemical industry, food processing, energy and environment [1]. Therefore, gas-solid flow has drawn the attention of great number of researchers on its interaction between gas and particle, rate of reaction and the dynamic characters of flow field, which can provide the basic theory for prediction and control of gas-solid flow process [2].

There are two methods of simulation in gas solid flow: Euler-Euler and Euler-Lagrange method. Due to the assumption of taking particles as continuous media, the Euler-Euler method can provide relatively reliable prediction with less computational consumption. However, Euler-Euler method traces particles from the meshing level, failing to capture the detailed information of individual particle. On the contrary, Euler-Lagrange method (namely Discrete Element Method) can trace particles by particle level. But the computational cost increases sharply as the number of particles increases, limiting its applications in industrial process [3].

Under the premise mentioned above, the concept of TFM-DEM hybrid model is brought up. As shown in Fig. 1, the solid is divided into two phases for calculating and post-processing, namely TFM and DEM phase. The solids solved by TFM model is called TFM phase, so is DEM phase. The TFM model can significantly reduce the consumption in computation and DEM model can capture the information (location, velocity and force) from particle level. However, hybrid model is still in its infancy whose parameters and applications have not been fully studied [4].
2. Governing equations

Based on statement above, the main focus lies on interaction between gas, TFM and DEM phase, which should be defined explicitly. Since separate TFM model and DEM model have already been elaborated fully, only TFM and DEM momentum equations are listed.

\[
\frac{D}{Dt} (\varepsilon_{cs} \rho_{cs} \nu_{cs}) = \nabla S_{cs} + \varepsilon_{cs} \rho_{cs} g + I_{ge} - I_{cd} \tag{1}
\]

Where \( S_{cs} \) —— stress tensor in continuous phase (Pa);
\( I_{ge} \) —— momentum exchange term between gas and continuous phase;
\( I_{cd} \) —— momentum exchange term between continuous phase and discrete phase;

\[
\frac{dx^{(i)}(t)}{dt} = v^{(i)}(t) \tag{2}
\]

\[
m^{(i)} \frac{dv^{(i)}(t)}{dt} = F_{T}^{(i)} = m^{(i)} g + F_{gd}^{(i)}(t) + F_{cd}^{(i)}(t) + F_{c}^{(i)}(t) \tag{3}
\]

\[
I^{(i)} \frac{dw^{(i)}(t)}{dt} = T^{(i)} \tag{4}
\]

Where \( m^{(i)}, I^{(i)} \) —— particle’s mass (kg) and moment of inertia (kg·m²);
\( T^{(i)}, F_{T}^{(i)} \) —— total moment of force (N·m) and external force on the particle (N);
\( F_{gd}^{(i)} \) —— drag force exerted on particle \( i \) in its meshing, including pressure item and viscous item (N);
\( F_{cd}^{(i)} \) —— force exerted on particle \( i \) by continuous phase (N);
\( F_{c}^{(i)} \) —— interaction between the DEM particles

The drag force model is used to calculate the interaction in momentum between the gas and TFM phase. Take Gidaspow model for instance, actually it is a combination of Wen-Yu drag model and Ergun equation with the formula below.
\[ \beta = 150 \varepsilon_g^2 (1 - \varepsilon_g) \mu_g \varepsilon_g d_g^2 + 1.75 \rho_g \varepsilon_g |v_g - v_s| \varepsilon_g \leq 0.8 \]

\[ = \frac{3 C_d \varepsilon_g \rho_g |v_s - v_g|}{4d} \varepsilon_g^{2.65} \quad \varepsilon_g > 0.8 \quad (5) \]

The drag force between the gas and DEM phase (particle \(i\)) is expressed below:

Where \(P_g(x^{(i)})\) —— average gas pressure in particle \(i\) meshing (Pa);

\(v_g(x^{(i)})\) —— gas velocity in particle \(i\) meshing (m/s);

\(V^{(i)}\) —— particle volume (m\(^3\));

\(\beta_{gd}\) —— momentum exchange coefficient between gas and DEM particles

The momentum interaction terms between the TFM and DEM phases share similar form. However, the gas velocity is taken by the center of the mesh, instead of actual particle location. Meanwhile, the DEM phase particles' velocity is calculated approximately as the mesh average, not the individual. Under the premise above, the coefficient of momentum interaction between TFM and DEM phase can be referred in according literature.

In present study, \(e_{cd}\) and \(C_f\) are set as 0.9 and 1. Among the terms in the right part of Equ.9, the first term means taking consideration of momentum exchange due to the collision and sliding, and the second term indicates the influence of the existence of cluster in dense gas-solid flow.

3. Configuration and simulation

![Figure 2 Simplified configuration of furnace](image)

The simplified configuration of 10t/h furnace is shown in Fig. 2. Primary air is pumped into the furnace from bottom evenly with velocity of 3.0m/s. In order to enhance the mixing in furnace, secondary air is injected from the single side at the height 0.9m with velocity of 35m/s. The air flow ratio of primary and secondary air is 3:1. The meshing in the configuration is uniform and the size is 0.05m×0.05m.

In present simulation, the particle consists of bio-component with same density 1200kg/m\(^3\) but different diameter 1.5mm and 4.0mm, respectively. The particles are well mixed and equal in number. The initial bed height is 0.6m with void fraction 0.4. The DEM phase is homogeneously distributed in TFM phase, and other parameters are listed in Table 1.
Table 1 Configuration and parameters

| Configuration                      | Unit | Value  |
|-----------------------------------|------|--------|
| height                            | m    | 7.3    |
| width                             | m    | 2      |
| primary air velocity              | m/s  | 3.0    |
| secondary air velocity            | m/s  | 35     |
| inlet diameter of secondary air   | m    | 0.05   |
| furnace outlet diameter           | m    | 0.9    |
| the number ratio of particles 1&2 in TFM phase | —    | 1:1    |
| the number ratio of particles 1&2 in DEM phase | —    | 1:1    |
| Volume ratio of DEM and TFM phase | —    | 0.078 (1:3.2) |

In order to demonstrate the relation of TFM and DEM phase velocity, the time of 10s, 12s and 14s and height of 0.5m, 1.0m and 1.5m are picked to do the analysis and comparison, in which the TFM phase velocity is extracted from meshing level. Then the program is MATLAB is used to trace DEM particles to get the instantaneous and time-averaged velocity. Moreover, these figures below are also drawn in the environment of MATLAB.

3.1. Comparison of instantaneous velocity distribution

Figure. 3 The instantaneous radial and axial velocity distribution at different time (y=0.5m)

The figure above shows the velocity comparison of two phases (TFM phase in meshing, and DEM particle in its location). The DEM particles’ velocity is presented as spots in figure. The time point of 14s shows the same inclination, thus it is not presented in present study.

As for the instantaneous radial distribution, the TFM phase velocity varies significantly. It can also be seen that the velocity distribution curves of 1.5mm and 4.0mm are very close to each other, indicating they have similar moving state. This phenomenon also applies to DEM phase. Except for specific DEM particles, most TFM and DEM particles’ radial velocity agree well with each other, with average error of 5.6% and 1.7%, respectively.

As for the instantaneous axial velocity distribution, the small particles are more prone to be influenced by gas flow, leading to a large velocity value in both TFM and DEM phase. As is in radial velocity distribution, the error in axial is small as well: 5.4% and 3.5%. In addition, in the scope investigated, the diameter does not make great difference on the velocity coherence. The comparison results show though the solids are divided into two phases, hybrid model can give similar instantaneous result.
3.2. The influence of height on the velocity comparison

As shown above, the studied region lies at the height of y=1m, above the secondary air inlet, thus the flow condition is much influenced by secondary air, leading to higher maximum velocity compared with y=0.5m in general. Because the secondary is pumped into the furnace from single side, the velocity distribution appears the inclination of ‘one side high, the other low’. As for the difference in radial and axial velocity, no matter TFM and DEM phase, the velocity of 1.5mm and 4mm particles are close to each other at same velocity, with average error of 18% and 16.1% at 10s. Compared with y=1m, the error in y=0.5 is less, indicating the lower the studied region is, the more coherent TFM and DEM phase is. Probable reasons are:

1. In the meshing of y=1m, the DEM particles are less than in y=0.5m. Take 10s for instance, the numbers are 23 and 102, respectively. The decrease of particles results in the declination in regulation.

2. The error in simulation calculation also makes contribution to some extent.

However, in the scope investigated, the velocity distribution of TFM and DEM phase shows good agreement. Furthermore, the phenomenon of no DEM particle in y=1.5m meshing validates the conclusion that in such apparatus, the solid concentration is close to 0 above the height of 1.5m. Therefore, no discuss and analysis is made in such condition.

3.3. Comparison of time-averaged velocity distribution

The time-averaged velocity can significantly make the conclusion more applicable. Therefore, the program in the environment of MATLAB is coded to do the time-averaging of velocity of both TFM and DEM phase with formula. The axial time-averaged velocity shares the same.

After time-averaged processing, the velocity distribution of TFM and DEM phase is shown:

We can clearly conclude that the 1.5mm and 4.0mm particles have same moving inclination in radial direction, as it is in instantaneous case. As for axial direction, 1.5mm particle velocity is more than 4.0mm, which leads to stratification fluidization in bed. Compare y=0.5m with y=1.0m, the coherence in velocity distribution is better, and the reason is stated above, namely more particles cluster at the lower part.

The identical point of instantaneous and time-averaged velocity distribution lies on (1) radial velocity of different particles is nearly the same; as for axial velocity, small particles are more prone to
move upwards than big ones. (2) With the increase of height, the coherence in velocity distribution gets worse both in instantaneous and time-averaged. The diverse point: the fluctuation in instantaneous velocity distribution is violent while in time-averaged it is stable.

However, we can also observe there exists some error between the TFM and DEM phase velocity distribution. It is mainly because:

1. The hybrid model only takes consideration of the drag force between TFM and DEM phase, neglecting the equivalent collision.

2. The particles number of DEM is relatively small, failing to occupy every meshing at every time point. These data in ‘empty’ meshing will lead to curve interruption in time, thus causes fluctuation in curve in the figure.

3.4. The influence of ratio of DEM phase on velocity distribution

Keep other parameters constant, only change the ratio of DEM and TFM phase to 1:12.8, then redo the simulation and results are shown below:

![Figure 6](image)

**Figure. 6** The time-averaged axial velocity distribution after decrease in DEM phase

As shown above, with the decrease of DEM phase particles, more error between the two curves can be obviously observed, which means in the scope investigated, the increase in DEM phase ratio can help improve the velocity distribution coherence to some degree. It can also indicate that the trace of DEM particles and their other information can represent all particles in the flow filed, aiming to figure out the flow, mixing and mass transfer phenomenon with less computation cost.

4. Conclusion

This present research investigates the gas solid flow in furnace with the help of TFM-DEM hybrid model. The velocity distribution coherence of TFM and DEM phase is studied.

1. In instantaneous velocity distribution, the velocity in radial and axial direction shows good agreement with small error. In the scope investigated, diameters do not have conspicuous effect on the distribution relation. With increase in height, the coherence condition gets worse due to particle concentration begins to fall.

2. In time-averaged velocity distribution, good agreement in velocity distribution can also be evidently observed, but with little fluctuation.

3. Under the premise of constant simulation condition, the increase in ratio of DEM can help enhance the velocity coherence. Meanwhile, the simulation result obtained in such condition can be more representative.

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