Numerical Simulation on Gas-Solid Two-Phase Flow in Horizontal Pneumatic Conveying Pipe Based on DPM Model

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Abstract. The determination of pipe deposition and optimum conveying velocity in pneumatic conveying has an important impact on conveying efficiency. The Euler-Lagrange method DPM model is used to analyse five different particle sizes and densities of small particles, and the flow pattern in the horizontal pipeline at different particle sizes and densities is derived from the graphs of the maximum discrete phase concentration, particle trajectory and discrete phase concentration distribution for each working condition. The simulation results show that the deposition increases with particle size and density, the optimum conveying speed increases with particle size and density, the larger the deposition, the larger the required conveying velocity. The velocity of 2 m/s can make the particles below 20\,\mu m suspended transport, the velocity of 4 m/s allows particles with a particle size of 30\,\mu m and a density of 1000 kg/m\textsuperscript{3} or less to be transported in suspension and 6 m/s allows particles with a density of 2000 kg/m\textsuperscript{3} or less to be transported in suspension. The aim is to provide a reference for the design of pneumatic conveying systems and the selection of the optimum conveying velocity.

Keywords. Pneumatic conveying, DPM model, gas-solid two-phase flow, numerical simulation.

1. Introduction
Pneumatic conveying is a method used to transport loose particles, powders etc., from one location to another via closed pipes [1]. Compared to traditional material conveying methods, pneumatic conveying has the advantages of simple structure, small footprint, clean and environmental protection, and flexible arrangement. Pneumatic conveying has been widely used in food, chemical and energy [2-4]. Pneumatic conveying systems consist mainly of horizontal, vertical and bent pipes. Due to the limitations of the measuring equipment, numerical simulations are often used as a necessary complement to the flow analysis. Pneumatic conveying is a gas-solid two-phase flow category, and computational fluid dynamics (CFD) provides a more convenient and efficient method for complex models [5], and Fluent is used as reliable simulation software for pipeline science research. In the operation of pneumatic conveying systems, pipe deposition is an important factor affecting the conveying efficiency, and determining the optimum conveying velocity is its main problem. In recent years, scholars have done a lot of researches on pneumatic conveying pipeline deposition. Li et al. [6] established a pneumatic conveying experimental bench and used Eulerian method to analyze the flow characteristics of sand in the horizontal pipeline of pneumatic conveying, and obtained the...
characteristics of pressure drop and particle concentration in the horizontal pipeline, and agreed with the experimental results, which laid a foundation for the engineering design of pneumatic conveying system. Miao Z et al. [7] carried out numerical simulation of powder dense phase pneumatic conveying by CFD to obtain the influencing factors of different flow pattern conversion in horizontal pipeline. Qin et al. [8] studied the flow law of micron particles in horizontal pipeline under the influence of different particle size, shape, lift force and other factors by DPM model, analyzed the number of particle deposition under different conditions, and obtained the main factors affecting horizontal pipeline pneumatic conveying. However, the current studies on deposition using CFD methods have mainly focused on Eulerian methods, and relatively few studies of deposition using the Fluent sub-model Lagrange discrete phase model (DPM), which provides a model basis for gas-solid two-phase flows with solid phase volume fraction less than 10% and without consideration of collisions, and which provides a visual observation of the particle trajectory motion compared to Eulerian methods, and is important for the optimal running velocity. The model can be used to visualise the particle trajectory motion compared to the Eulerian method.

In this paper, we start from the study of pneumatic conveying horizontal pipe, and use DPM model to analyse the maximum discrete phase concentration, particle trajectory, outlet discrete phase concentration distribution to analyse the flow state and optimum conveying velocity under different particle sizes and densities. Fluent software is used to simulate and analyse the flow phenomena in the horizontal pipeline for pneumatic conveying.

2. Mathematical Calculation Equation

2.1. Gas Phase Control Equation [9]
In this paper, the volume fraction of solid phase is less than 10%, so the DPM model can be used. It is assumed that both gas-solid phase temperatures are the same as the atmospheric temperature, so the energy equation is not considered. In the DPM model, the gas phase is treated as a continuous phase, and the controlling equation for the solid phase according to Newton's second law is

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0
\]  

(1)

\[
\begin{align*}
\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho uu) + \frac{\partial}{\partial y}(\rho uv) + \frac{\partial}{\partial z}(\rho uw) & = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} - \frac{\partial p}{\partial x} + F_x \\
\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho vu) + \frac{\partial}{\partial y}(\rho vv) + \frac{\partial}{\partial z}(\rho vw) & = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} - \frac{\partial p}{\partial y} + F_y \\
\frac{\partial}{\partial t}(\rho w) + \frac{\partial}{\partial x}(\rho wu) + \frac{\partial}{\partial y}(\rho vw) + \frac{\partial}{\partial z}(\rho ww) & = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} - \frac{\partial p}{\partial z} + F_z
\end{align*}
\]

(2)

where \( \rho \) is the density of the fluid, \( p \) is pressure, \( F_x, F_y, F_z \) are volume forces acting on the micro-element, respectively, \( u, v, w \) are velocity components along \( x, y, z \) axes, respectively.

2.2. Solid Phase Control Equations
Considering the solid phase as a discrete phase and using the Lagrangian method for particle tracking, the controlling equation for the solid phase according to Newton’s second law can be obtained as [9-10]

\[
\frac{du_p}{dt} = F_p(u - u_p) + \frac{g_s(\rho_p - \rho)}{\rho_p} + F_x
\]  

(3)

\[
F_D = \frac{18 \mu}{\rho_p d_p^2} \frac{C_D Re}{24}
\]  

(4)

\[
Re = \frac{\rho_d |u - u_p|}{\mu}
\]  

(5)
\[ C_D = \frac{24}{Re} f(Re) \]  

(6)

where \( \rho_p \) is the density of the particle, \( F_D \) is fluid drag forces on particles, \( \mu \) is fluid dynamic viscosity for gas phase, \( d_p \) is particle diameter, \( u, u_p \) are fluid and particle velocities, respectively. In different flow regions, there are different equations for \( f(Re) \). \( f(Re) = 1 \) in the Stokes zone, \( f(Re) = 1 + 3/16 Re \) in the Oseen zone and \( f(Re) = 1 + 1/6 Re^2/3 \) for the standard resistance.

2.3. Turbulence Models

The two-equation k-\( \varepsilon \) model is widely used in the calculation of turbulence parameters, which includes the standard k-\( \varepsilon \), RNG k-\( \varepsilon \), and Realizable k-\( \varepsilon \) models. In this paper, the flow in the tube is a typical turbulent flow, so the standard k-\( \varepsilon \) model is used. The standard k-\( \varepsilon \) model equation is:

\[
\frac{\partial \left( \rho \varepsilon \right)}{\partial t} + \nabla \cdot \left( \rho \varepsilon \mathbf{u} \right) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \mathcal{G}_k + \mathcal{G}_b - \rho \varepsilon - Y_m + S_k
\]

(7)

\[
\frac{\partial \rho k}{\partial t} + \nabla \cdot \left( \rho u_i \right) = \frac{\partial}{\partial x_j} \left( \mu \frac{\partial k}{\partial x_j} \right) + \frac{\varepsilon}{\sigma_k} \left( \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \right) - \frac{C_{1k}}{k} \rho \varepsilon^2 + S_k
\]

(8)

where \( \mu_t \) is viscosity factor, \( Y_m \) is contribution of pulsational expansion in compressible turbulence, \( \sigma_\varepsilon \), \( \sigma_k \) are prandtl number against turbulent energy and turbulent dissipation rate, respectively, \( \mathcal{G}_k \), \( \mathcal{G}_b \) are turbulent kinetic energy due to mean velocity gradient and buoyancy, respectively, \( S_k \). \( \mathcal{S}_\varepsilon \) are user-defined source term, respectively. \( C_{1k}=0.09 \), \( C_{1\varepsilon}=1.44 \), \( C_{\alpha_k}=1.92 \), \( C_{\alpha_\varepsilon}=0.09 \) are standard empirical values and the turbulent kinetic energy \( k \) and turbulent dissipation rate \( \varepsilon \) are defaulted to 1.0 and 1.3 in the Fluent software.

3. Horizontal Pipeline Gas-Solid Two-Phase Flow Model

3.1. Model Assumptions

In this paper, the object of study are micron particles, due to the small size of the particles, so the following assumptions: (1) the gas flow itself can be compressed, but the gas flow velocity is low, Mach number below 0.3, so the gas is assumed to be incompressible. (2) The velocity of the gas is equal to the velocity of the particles. (3) The particles are all spherical and the effect of shape on flow is ignored. (4) The particles are uniformly incident on the vertical inlet surface into the calculation domain. (5) The force \( F_p \) acting on the particles by the fluid is ignored and only the effect of the field force on the particles is considered.

3.2. Pre-Processing Geometry Model

The horizontal pipe is selected as the object of study, due to the long pipe in pneumatic conveying, the calculation volume is large, so the full development of 2 m horizontal pipe is selected for analysis. The geometric model of pipe diameter 50 mm is shown in figure 1. In order to improve the mesh quality and the accuracy of the solution, ICEM-CFD was used to carry out hexahedral structured o-grid of the horizontal pipe, the geometric model of the pipe diameter 50 mm inlet mesh division is shown in figure 2, the final mesh cell number is 436872, the mesh quality is greater than 0.7.

3.3. Solver Parameter Settings

A pressure-based solver is used for the continuous phase, discrete phase steady-state simulations, and a gravity term is added. The inlet and outlet boundary conditions are velocity inlet and pressure outlet boundary conditions. In the discrete phase setup, the particles are set to inlet surface injection with a mass flow rate of 0.16 kg/s and a spherical single particle size is chosen for the particle discrete phase model. The discrete phase increases the effect of turbulence in the random wander model (RWM). The particle boundary conditions are escape conditions for inlet and outlet and reflect conditions for the wall.
4. Simulation Results and Analysis

It is essential to determine the validity of a simulation before it is carried out for a gas-solid two-phase flow, and the reliability of the simulation has been verified by a combination of simulation and experiment in references [11-12]. In a horizontal pipe with gas-solid flow, the maximum discrete phase concentration is to a certain extent representative of the deposition in the pipe. In the following, the flow pattern will be analysed by the maximum discrete phase concentration for different particle sizes and densities, and the particle trajectory diagram and the discrete phase concentration distribution at the outlet will be used to visualise the particle flow and provide reference for determining the optimum velocity under different operating conditions.

4.1. Effect of Particle Size on Flow

The maximum discrete phase concentrations were quantified for five different particle sizes (10, 20, 30, 40 and 50μm) at different velocities when the density was 1120 kg/m$^3$, and the results are shown in figure 3. As can be seen from figure 3, the maximum discrete phase concentration gradually decreases with increasing velocity and particle deposition gradually decreases. At the same velocity, the larger the particle size, the larger the maximum discrete phase concentration and the more serious the deposition, which changes more obviously with particle size at low velocity. This is because the greater the velocity, the greater the kinetic energy of the air, the easier it is for the particles to be suspended, and as the particle size increases, the more pronounced the effect of gravity, the easier it is for the particles to be deposited towards the bottom of the tube, and it is more difficult for particles of larger size to obtain larger velocities under the same conditions. In addition, smaller particles are more likely to be suspended by gas turbulence.

Due to the large number of working conditions, the trajectory diagram for five different particle sizes of 10, 20, 30, 40 and 50μm at 500 mm at the end of the horizontal pipe and the discrete phase concentration distribution at the outlet are visualised in figure 4, using a velocity of 2 m/s as an example. As can be seen from the graph, at a particle size of 10μm, the discrete phase concentration is evenly distributed and in full suspension flow, but the energy consumption is greater and the wear is more serious in the pneumatic conveying bend. When the particle size is 20μm, most of the particles are in suspension, only a small number of particles sink under the action of gravity, but can maintain the normal flow state. In industrial production, taking into account energy consumption and wear needs, often to maintain the state of the velocity as the conveying velocity. Particle size from 30μm onwards, the interaction between particles and particles, particles and the wall surface to enhance the momentum loss increased, until 50μm, the particles are completely deposited and the deposition area is concentrated at the bottom of the pipe, which no longer meets the industrial conveying requirements and requires a greater conveying velocity. Therefore, when the velocity is 2 m/s, it is possible to maintain the industrial conveying requirements for particles below 20μm.
4.2. Influence of Particle Density on Flow

Due to the large number of working conditions, the maximum discrete phase concentrations are now quantified for different particle sizes of 10, 20, 30, 40 and 50 µm at different densities of 1000, 1500, 2000, 2500 and 3000 kg/m$^3$ at a velocity of 2 m/s and the results are shown in figure 5. It can be seen from the figure that as the density increases, the maximum discrete phase concentration of the particles increases and the particles are more likely to be deposited, and the larger the particle size, the more serious the deposition. This is because as the particle density increases, the influence of gravity increases and the particles are more likely to be deposited towards the bottom of the pipe. When the particle size is 10µm, the maximum discrete phase concentration changes very little, combined with the conclusion of 3.1, it can be assumed that 2 m/s velocity can make 10µm, 3000 kg/m$^3$ below the particles remain suspended, so that 50µm, 1120 kg/m$^3$ density particles suspended need more than 10m/s speed. As there are many different particle size, the optimum flow velocity at different densities is now chosen for particles with a particle size of 30µm.

Figure 6 quantifies the maximum discrete phase concentrations of five different densities at different velocities, which shows that it is more difficult to obtain large velocities for denser particles under the same conditions. Velocity of 4m/s must enable 1000 kg/m$^3$ of particles to be transported in suspension. Therefore, to determine the optimum conveying velocity for different densities at 30µm, the simulation only needs to start with a velocity of 4 m/s and a density of 1500 kg/m$^3$. 

Figure 7 shows the 500mm trajectory at the end of the pipe for 4m/s, 30µm particles at densities of 1500, 2000, 2500 and 3000kg/m$^3$ and the discrete phase concentration distribution at the outlet,
yielding that most of the particles are still deposited at a density of 1500 kg/m$^3$ and as the density increases the deposition becomes more severe and higher velocities are required to maintain normal transport.

Figure 8 shows the 500 mm trajectory at the end of the pipe and the discrete phase concentration distribution at the outlet for the same conditions at 6 m/s. From 2500 kg/m$^3$ onwards, the particles sink and a higher velocity is required to maintain normal conveying. Therefore, a velocity of 6 m/s is sufficient for industrial conveying of particles with a density of 2000 kg/m$^3$ or less.

5. Conclusions

The determination of pipe deposition and optimum conveying velocity is an important issue in engineering design, so this paper analyses the flow characteristics of different particle sizes and densities based on the DPM model, and draws the following conclusions.

(1) Compared with the Eulerian method, the model provides an intuitive and clear observation of the particle trajectory, which provides a reference for the determination of the optimal conveying speed.

(2) The larger the particle size, the greater the effect of gravity, the more likely it is to be deposited, the less likely it is to be suspended by gas turbulence, the lower the kinetic energy of mutual collision, and the more difficult to obtain larger velocities. 2 m/s velocity can make the particles below 20 μm suspended transport.

(3) The greater the density, the greater the pipeline deposition, and the effect of density changes on deposition is more pronounced for particles of larger particle size. When the particle size is 30 μm, 4 m/s velocity can make the mainstream suspension transport of particles below 1000 kg/m$^3$, and 6 m/s velocity can make the mainstream suspension transport of particles below 2000 kg/m$^3$.

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