

Numerical Simulation of Flow Characteristics in Horizontal Pipe

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Abstract

The purpose of this study is to study the state of gas-solid two-phase transportation process in different types of pipelines, so as to find out the cause of pipeline blockage. The horizontal pipe is the most common arrangement in the pneumatic conveying pipeline, and the gravity direction of particles in the horizontal pipe pneumatic conveying is perpendicular to the flow direction, which makes the flow of oil well cement particles in the horizontal pipe more complex, so it is very necessary to study the pneumatic conveying process of the horizontal pipe.

Keywords

Horizontal Tube; Gas-solid Two-Phase; Pneumatic Conveying.

1. Introduction

In the process of pneumatic conveying of solid particles, due to the high gas velocity, low viscosity and high Reynolds number, it belongs to gas-solid two-phase turbulence. In this flow state, the turbulent flow of gas will have a great impact on the movement of small solid particles, and the movement of solid particles will also affect the flow of gas. There is the transfer and exchange of momentum and energy between the gas and solid phases. In addition, when the volume fraction of solid particles is large, the effect of the interaction between particles on gas flow should also be considered. Therefore, it is necessary to analyze the basic theory of gas-solid two-phase flow in pipes and the forces on solid particles. In this simulation, we use the discrete particle model (DPM) to simulate the particle flow, and use the particle random trajectory model to track the particle trajectory, so as to observe the movement of particles and fluid.

In the process of pneumatic conveying, there is the exchange of momentum and energy between gas and solid phases, and the force between gas and solid phases is the key to establish the basic equations of gas and solid phases. In the process of pneumatic conveying, the movement of solid particles in the pipeline is very complex. The force analysis of solid particles is the key to study the movement of solid particles in the process of pneumatic conveying, and also the basis for analyzing the flow mechanism of pneumatic conveying.

2. Theory and Numerical Simulation Method of Pneumatic Conveying

In the process of gas transportation, the forces on solid particles are very complex. It is mainly affected by the following forces: the gravity of particles, the buoyancy generated by gas, the virtual mass force, the drag force generated by gas, the force generated by pressure gradient, the Basset force, the Saffman force, the Magnus lift force, and various resistances. Although the forces on particles are very complex, not every force should be considered. Some forces that have little effect on particle motion can be ignored during the research.

(1) Drag force

Solid particles move along the pipeline under the action of gas, which indicates that there is a drag between gas and solid particles. This force is called drag force, which describes the interaction between gas and solid phases and the transfer of momentum. The drag force of gas

on particles depends on the velocity difference between gas and solid. In dense phase pneumatic conveying, the drag force is the dominant force between the gas and solid phases, expressed in F_{sg} .

$$F_{sg} = \beta(v_g - v_s) \quad (1)$$

Where: β is the drag coefficient. Domestic and foreign scholars have proposed many different models for the drag coefficient, but the drag coefficient model proposed by Gidaspow is widely used. Gidaspow pointed out that when the gas volume concentration is ≤ 0.8 , it uses Ergun's drag force model:

$$\beta_{ergun} = 150 \frac{\varphi_s (1 - \varphi_s) \mu_g}{\varphi_g d_s^2} + 1.75 \frac{\rho_g \varphi_s}{d_s} |v_s - v_g| \quad (2)$$

Where: μ_g is the gas viscosity coefficient; d_s is the particle diameter.

When $\varphi_g > 0.8$, β adopts Wen's drag force model:

$$\beta_{wen\&yu} = \frac{3}{4} C_D \frac{\varphi_s \varphi_g \rho_g |v_s - v_g|}{d_s} \varphi_g^{-2.65} \quad (3)$$

Where: C_D is the fluid resistance coefficient.

However, it can be seen from the above formula that the model is not continuous when $\mu_g = 0.8$, which will affect the numerical simulation results, and $\mu_g > 0.8$ is not necessarily a dilute phase pneumatic transport, so this study uses the Huilin-Gidaspow model, which is modified by LUN and others:

$$\beta = \begin{cases} \psi \beta_{ergun} + (1 - \psi) \beta_{wen\&yu} & \varphi_g > 0.8 \\ \beta_{ergun} & \varphi_g \leq 0.8 \end{cases} \quad (4)$$

$$\text{Where: } \psi = 0.5 + \frac{\arctan[262.5(\varphi_s - 0.2)]}{\pi}$$

(2) Virtual mass force

The acceleration of solid particles in the flow field will lead to the acceleration of the gas movement around the particles. Due to the inertia of the fluid, the gas will have a reaction force on the particles. Due to the effect of this force, the force that drives the particle motion will be greater than the inertia force of the particle itself. At this time, the particle is like adding a part of the virtual mass. This part of the additional mass force greater than the inertia force of the particle itself is called the virtual mass force, expressed by F_m :

$$F_m = \frac{2}{3} \pi r_s^3 \rho_g \frac{d(v_s - v_g)}{dt} \quad (5)$$

Where: r_s is the particle radius.

(3) Basset force

Basset force is considered as an instantaneous flow resistance, which takes into account the acceleration process of solid particles. When the particle is in an accelerated state, the force has a great influence on the particle movement. Basset force exists only when particles are in viscous fluid, and it is related to the instability of fluid flow. Basset force is expressed by F_B , then there is:

$$F_B = 6r_s^2 \sqrt{\pi\mu\rho_g} \int_{t_0}^t (t-\tau)^{\frac{1}{2}} \frac{d(v_g - v_s)}{dt} d\tau \quad (6)$$

Where τ is a time variable, integrating the whole movement process of particles from the start time t_0 to t , and only when the acceleration of solid particles in the flow field is very large will the effect of this force be considered.

(4) Saffinan force

When solid particles move in the flow field with velocity gradient, there is a pressure difference on both sides of the particles due to the velocity difference on both sides of the vertical particle mainstream direction. Under the effect of this pressure difference, the solid particles will be subject to a lift force, which is called Saffinan force, expressed by F_s :

$$F_s = 6.46r_s^2 (\rho_g \mu)^{\frac{1}{2}} k^{\frac{1}{2}} (v_s - v_g) \quad (7)$$

Because the velocity gradient is very small in the general flow field, the Saffinan force is often ignored.

(5) Magnus force

In the pneumatic conveying pipeline, the solid particles move with the air flow and rotate at high speed, and the irregular solid particles rotate faster than the spherical solid particles. Due to the existence of velocity gradient on both sides of particles in the flow field, the force on solid particles is uneven, which leads to the rotation of solid particles due to the effect of shear torque. The rotation of solid particles will produce a force perpendicular to the flow direction of the fluid, which is called Magnus force, expressed in F_M . This force can generally be ignored in the flow field analysis.

3. Numerical Simulation of Flow Characteristics in Horizontal Pipe

In this paper, ICEM grid division software is used for grid division, and commercial CFD software Fluent is used for numerical simulation of the pneumatic conveying process of oil well cement particles in horizontal pipes. This chapter mainly simulates the pressure drop rule of horizontal pipe pneumatic conveying with oil well cement particles and the influence of gas flow velocity, oil well cement particle size, pipe diameter, oil well cement particle mass flow and other factors on the flow characteristics of horizontal pipe conveying process.

3.1. DPM Model Establishment

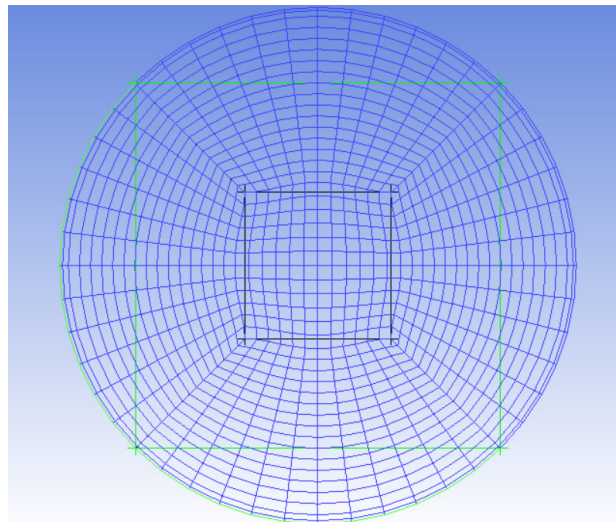


Fig 1. Face grid

First, the DPM steady state model is used to simulate the horizontal pipe with an inner diameter of 203.2 mm and a length of 5000 mm. The influence of inlet conditions on gas-solid flow field can be reduced by selecting a horizontal pipe with a length of 5000 mm. The quality of mesh has an important impact on the accuracy of simulation results. Compared with 2D mesh, 3D mesh division is more complex. In this paper, the professional grid division software ICEM is used for grid division. Considering that the horizontal tube of the research model is a circular tube, the O-type radiation grid is adopted to draw the grid concisely, which is also conducive to improving the quality of the grid. When dividing the mesh, the boundary layer mesh is densified, and the mesh quality is above 0.7, which meets the calculation requirements. There are 492000 grid nodes in total.

3.2. Solver Setup

This simulation uses ANSYS 19.0 software to simulate the model. A pressure-based solver is selected and a steady-state solution is adopted. Turbulence model selection criteria k- ϵ the turbulence model of the model takes full account of the gas-particle coupling. Pressure-velocity coupling is implemented by coupled algorithm. The main parameters of numerical simulation are shown in Table 1.

Table 1. Horizontal pipe simulation parameters

physical quantity	numerical value
Length of pipe (m)	10
Inner diameter of pipe (mm)	203.2,150,100
Particle mass flow rate (kg/s)	0.03,0.1,0.3,0.5
Particle density (kg/m ³)	1900
Conveying Pressure (MPa)	0.1
Particle diameter (μm)	45,60,80,100
Inlet gas velocity (m/s)	5,7.5,10,15

3.3. Calculation Results and Analysis

(1) The influence of airflow velocity

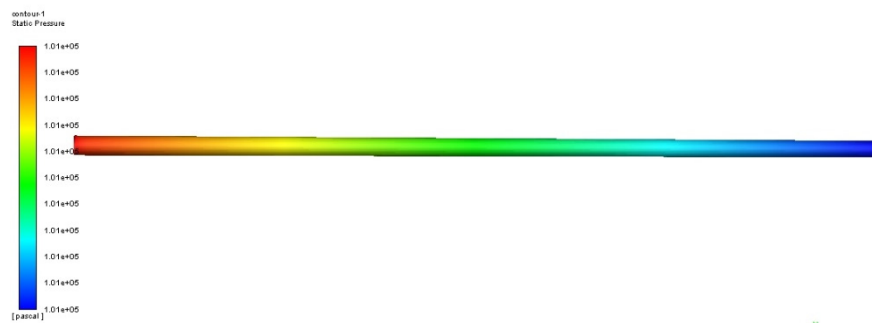


Fig 2. Horizontal pipe pressure change

The change of fluid pressure and velocity is one of the important parameters to characterize the flow characteristics of horizontal conveyor pipes, which reflects the flow level of fluid in pipes. Figures 2 and 3 show the variation trend of pressure and velocity of fluid in a horizontal pipe. Where the pressure is equal in the longitudinal section. Figure 3 shows the velocity

variation of the central section of the pipe. It can be seen from the diagram that the fluid pressure decreases evenly while the velocity increases because the wall is an insulated wall. According to Bernoulli equation, the pressure decreases and there is no gravitational potential energy in the horizontal direction, so the kinetic energy increases. In addition, it can be seen from the diagram that the flow rate in the center of the pipe is the highest and decreases as it approaches the boundary.

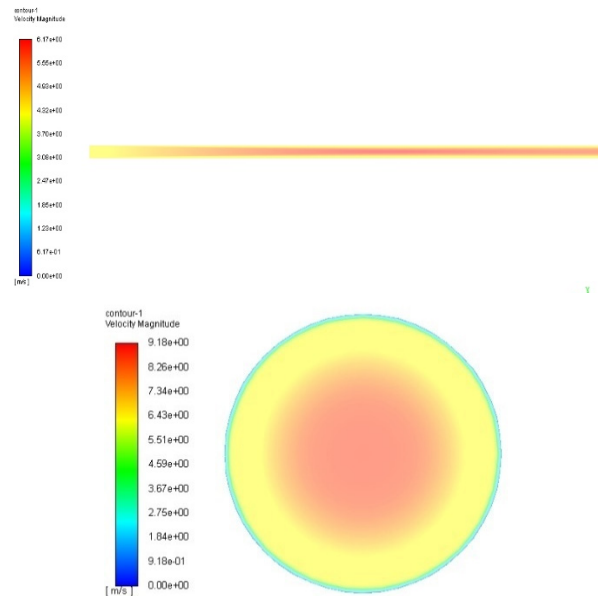


Fig 3. Horizontal Pipe Speed Variation

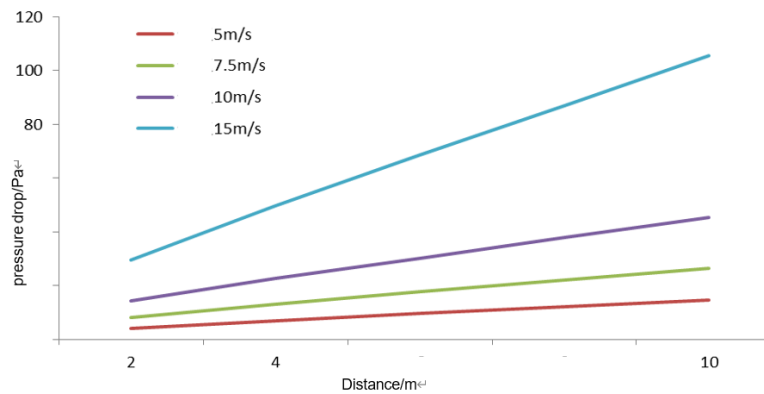


Fig 4. Variation of axial pressure along pipe at different gas velocities

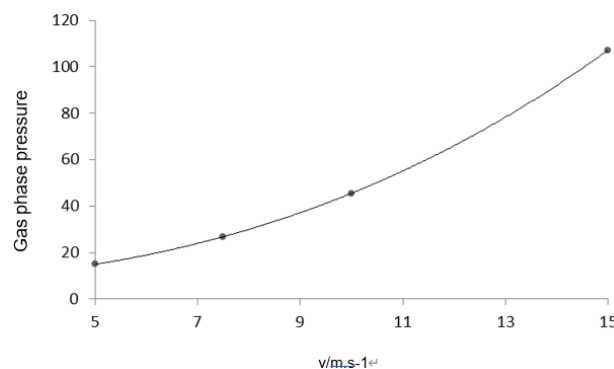
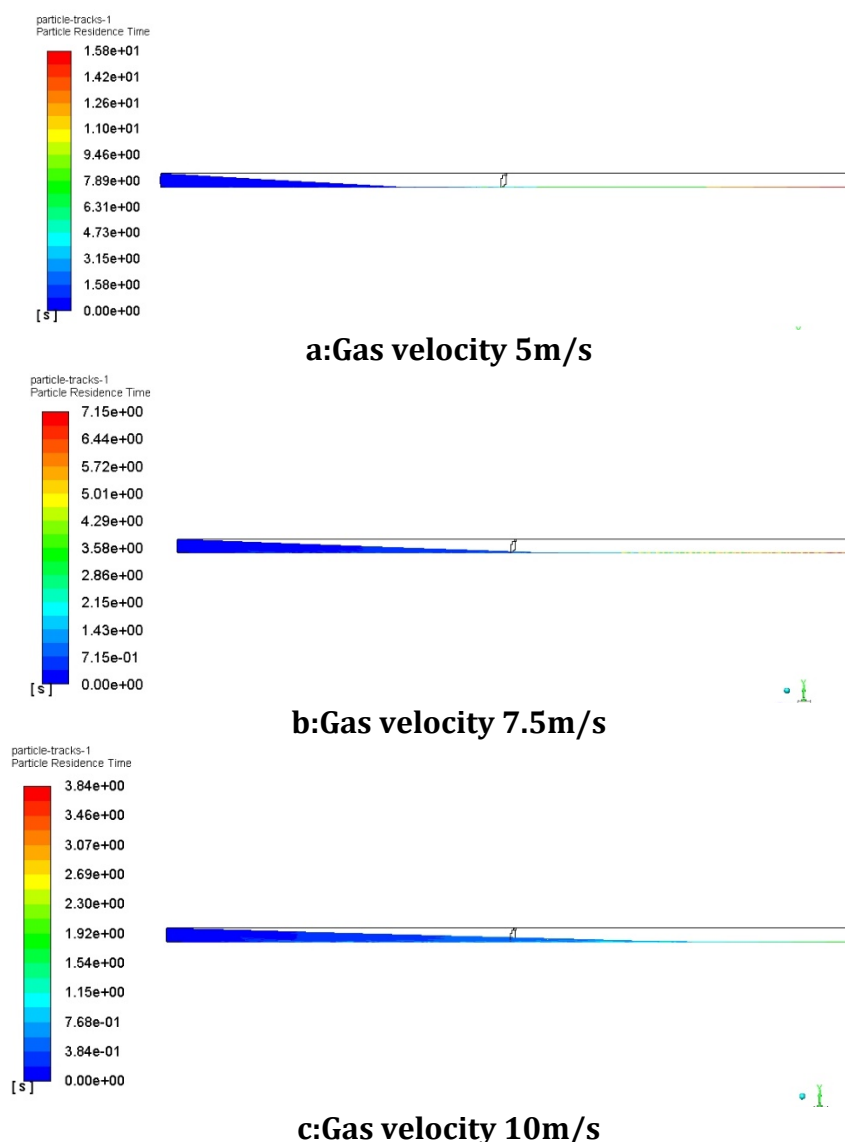


Fig 5. Relationship between Gas Velocity and Gas Phase Pressure Drop

Figures 4 and 5 illustrate the variation of horizontal pipe pressure at different gas velocities. It can be clearly seen from the diagram that the farther away from the outlet, the greater the gas pressure drop and the lower the gas pressure. In addition, with the increase of gas velocity, the pressure drop in the pipeline will also increase. According to Bernoulli's formula, the kinetic energy also increases.

The flow state of particles is one of the important characterization parameters. Figure 6 shows the residence time of particles in the pipe at different gas velocities. It can be seen in the figure that particles hardly stay at the entrance of the horizontal pipe. Then, due to the action of gravity, particles begin to deposit downwards and gradually converge at the bottom of the pipe. As particles accumulate, their residence time in the pipe becomes longer.

Firstly, we take the gas velocity of 5 m/s as an example. In the diagram, we can see that the velocity of particles at the inlet is 5 m/s. After entering the horizontal pipe, the velocity decreases rapidly. When the velocity reaches 1/3 of the horizontal pipe, it decreases to a lower speed. The result shows that the particle velocity is only 0.54 m/s at this time. At this point, the friction force on the particles is balanced with the force of the gas, and the particles keep moving at a constant speed. Because the particle size and mass flow rate are small, it will not cause serious accumulation, but we can see that the particle residence time is long, reaching 10s.



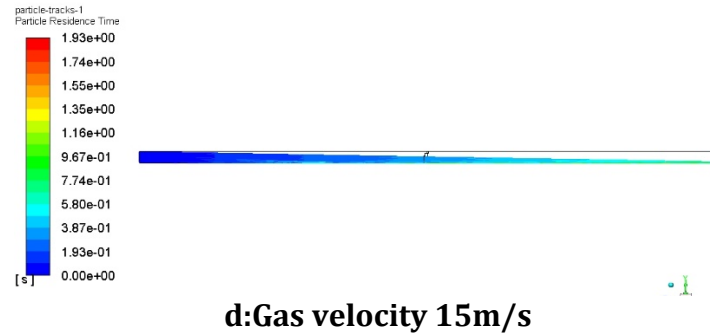
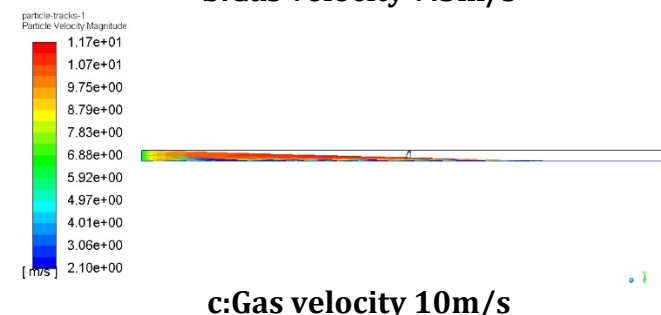
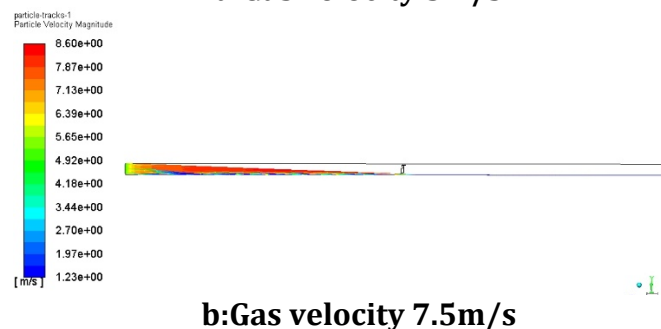
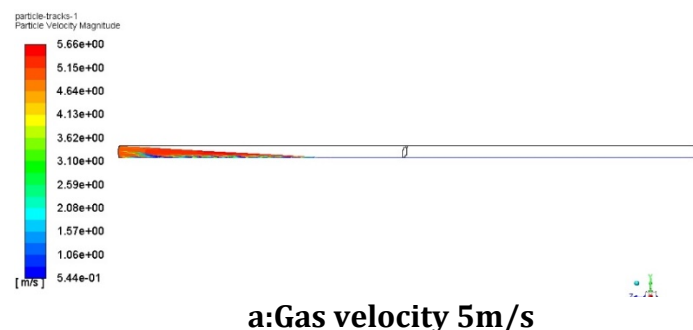


Fig 6. Particle residence time at different gas velocities

Based on the above analysis, the oil well cement particles have caused initial accumulation under the above conditions. Change the conveying conditions and compare with the above results. Set inlet gas speed to 7.5 m/s, 10 m/s and 15 m/s respectively. The pressure and velocity changes in the pipeline are basically the same as above. The analysis is no longer carried out here, mainly on the flow state of particles.

Figure 6 shows the residence time of particles at gas velocities of 5 m/s, 7.5 m/s, 10 m/s and 15 m/s respectively. By comparison, it can be seen that the longer the gas velocity is, the smaller the particle presence time will be. The greater the gas velocity, the smaller the decrease in the presence time. The maximum existing time of particles is 15.8 s, 7.2 s, 3.8 s and 1.9 s at gas velocity of 5 m/s, 7.5 m/s, 10 m/s and 15 m/s, respectively.

Figure 7 shows the particle velocities at 5 m/s, 7.5 m/s, 10 m/s and 15 m/s, respectively. In the graph we can see that the particle stabilization velocities are 0.54 m/s, 1.23 m/s, 2.1 m/s and 4.9 m/s, respectively.



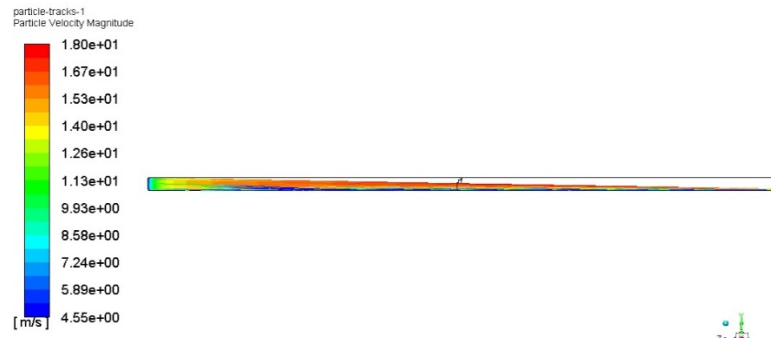


Fig 7. Particle velocities at different gas velocities

4. Summary

Through the analysis of particle existence time and particle movement speed, it can be seen that increasing gas velocity can significantly improve the flow performance of particles, improve the speed of particles when flowing stably, reduce the time of particles existing in the pipeline and reduce the probability of pipeline blockage.

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