International Journal of Advanced Engineering and Management Research
Vol. 2 Issue 4, 2017

www.ijaemr.com ISSN: 2456-3676

NUMERICAL SIMULATION ON HIGH-PRESSURE DENSE-PHASE PNEUMATIC CONVEYING OF PETROLEUM COKE PARTICLES IN VERTICAL PIPE

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ABSTRACT

The method of theoretical analysis and numerical simulation is used to study the velocity distribution and pressure drop of gas-solid two-phase flow in a vertical pipe. Based on the Euler model and the particle dynamics theory, a mathematical model suitable for the dense phase gas transportation process of petroleum coke was established. The model considers the collision and friction of petroleum coke particles, while also considering the friction between the particles and the tube wall, analysis of superficial gas velocity, particle diameter and the influence of petroleum coke particle mass flow rate in a horizontal pipe gas-solid two-phase velocity, concentration and distribution of pressure drop.

Key Words: Petroleum coke particles; Frictional stress; Apparent gas velocity; Pneumatic conveying; Pressure drop law

0. Introduction

High pressure dense phase pneumatic conveying is a kind of method to transport materials with low speed. Compared with dilute phase pneumatic conveying, it has the advantages of low energy consumption, large conveying capacity, low wear and so on. Therefore, it has been widely used in many fields such as chemical industry, energy, agriculture and so on. High pressure dense phase pneumatic conveying of petroleum coke is a key link in the technology which making hydrogen by gasifying petroleum coke particles[1-5].At present, due to the limitation of the experimental equipment and technical means, the flow parameters of gas-solid two-phase flow in the high pressure and super dense phase conveying pipeline can not be accurately measured[6-10].

In this paper, the volume concentration of petroleum coke particles is up to 30% in the high pressure dense phase pneumatic conveying pipeline. The collision between particles and particles, particles and pipelines are bound to be very frequent. In these collisions, the friction stress is produced, and the energy and momentum transfer and dissipation between particles are carried out by the friction stress. This makes the friction stress become an important part of the solid stress and wall shear stress. It must be fully considered. In the past, when the particle dynamics is used to solve the problem of vertical tube, the frictional stress in the particle between the wall is often ignored, which leads to large errors in the numerical simulation. In this paper, we consider the influence of the friction stress on the basis of the two-way coupling of gas and solid, and overcome the shortcomings of previous studies. On the vertical pipe petroleum coke high-pressure super dense phase pneumatic conveying process is simulated, and connecting with the experiment condition, the accuracy of the model was verified. At the same time, the pressure drop in vertical pipe is analyzed, and the influence of superficial gas velocity on the conveying characteristics is discussed.

1. Mathematical model

1.1 Governing equation

Continuity equation:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g v_g) = 0$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s v_s) = 0$$

Momentum equation:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g v_g) + \nabla \cdot (\alpha_g \rho_g v_g v_g) = -\alpha_g \nabla p_g + \nabla \cdot \tau_g - F_{sg} + \alpha_g \rho_g g$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla \cdot (\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla p_g + \nabla \cdot \tau_s - F_{sg} + \alpha_s \rho_s g$$

—volume fraction, —density, —velocity vector, —stress tensor, —gas pressure, —drag force, —Gravity acceleration, Subscript g—gas, Subscript s—solid particle.

Due to poor gas-solid two phase velocity and the drag force is the dominant force of interaction, so in this paper the model only considering pulling force.

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

—drag coefficient. It used the Huilin-Gidaspow model proposed by Professor LUN[10].

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

$$\psi = 0.5 + \frac{arctan\,[262.5(\alpha_s - 0.2)]}{\pi}$$

1.2 particle dynamics theory

Savage and other scholars believe that the stress between solid particles can be seen as the composition of dynamic stress and friction stress.

$$\tau_s = \tau_s^k + \tau_s^f$$

$$\tau_s^k = [-p_s^k + \alpha_s\lambda_s^k(\nabla\cdot v_s)]I + 2\alpha_s\mu_s^k S_s$$

$$S_s = \frac{1}{2}[\nabla v_s + (\nabla v_s)^T]I - \frac{1}{3}(\nabla\cdot v_s)I$$

—particle dynamic stress tensor, —frictional stress, —solid pressure, —solid viscosity coefficient, —solid volume viscosity coefficient, —solid phase velocity deformation rate tensor, —unit tensor.

Solid state pressure using the theoretical model proposed by Professor LUNin 1984.

$$p_s^k = \alpha_s\rho_s\Theta_s + 2\rho_s(1+e_{ss})\alpha_s^2 g_{0,ss}\Theta_s$$

—particle pseudo temperature parameter, —particle radial distribution function.

$$g_{0,ss} = [1 - ({}^{\alpha_s}/_{\alpha_{s,max}})^{1/3}]^{-1}$$

The viscosity coefficient of solid phase includes the collision viscosity and dynamic viscosity.

$$\mu_s^k = \mu_{s,col} + \mu_{s,kin}$$

$$\mu_{s,col} = \frac{4}{5}\alpha_s\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{1/2}$$

$$\mu_{s,kin} = \frac{10\rho_s d_s\sqrt{\Theta_s\pi}}{96(1+e_{ss})g_{0,ss}}\left[1 + \frac{4}{5}(1+e_{ss})\alpha_s g_{0,ss}\right]^2$$

—particle collision viscosity, ⊢—particle dynamic viscosity, —particle diameter, —interparticle collision recovery coefficient.

$$\lambda_s^k = \frac{4}{3}\alpha_s\rho_s d_s g_{0,ss}(1+e_{ss})(\frac{\Theta_s}{\pi})^{1/2}$$

Solid phase temperature equation:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s\Theta_s) + \nabla\cdot(\alpha_s\rho_s v_s\Theta_s)\right] = \nabla\cdot q_s + \tau_s:\nabla v_s - \gamma_{\Theta_s} + \phi_{gs}$$

—density of heat flow rat, τ_s—particle pulsation produced by shear stress in solid phase, —pseudo temperature particle collision dissipation term, —the exchange fluctuation between gas phase and solid phase.

$$q_s = k_{\Theta_s}\nabla\Theta_s$$

—pseudo heat flux.

For the friction stress, Johnson et al think that only when the volume fraction of solid phase reaches 50%, the influence of the friction stress should be considered. But Xiong Yuanquan[11]believes that, in high pressure dense phase pneumatic conveying, the role of friction stress should be considered when the volume fraction of solid phase is higher than 10%.

$$\tau_s^f = -\mathrm{p_f}\cdot\mathrm{I} + 2\alpha_s\mu_{s,\mathrm{f}}S_s$$

$$\mu_{s,\mathrm{f}} = \frac{\mathrm{p_f}\sin\phi}{2\sqrt{I_{2D}}}$$

$$\mathrm{p_f} = \begin{cases} \mathrm{A}\dfrac{(\alpha_s-\alpha_{s,min})^{\mathrm{r}}}{(\alpha_{s,max}-\alpha_s)^{s}}, & \alpha_{s,min} < \alpha_s < \alpha_{s,max} \\ 0, & \alpha_s \le \alpha_{s,min} \end{cases}$$

—frictional pressure, —friction angle between particles, A=0.1, r=2, s=5, α=0.1, α=0.55.

Turbulent transport equation:

$$\nabla(\alpha_i\rho_i U_i\varepsilon_i) = \nabla\cdot\left(\alpha_i\frac{\mu_{t,i}}{\sigma_\varepsilon}\nabla\varepsilon_i\right) + \frac{\varepsilon_i}{k_i}\left(C_{1\varepsilon}\alpha_i G_{k,i} - C_{2\varepsilon}\alpha_i\rho_i\varepsilon_i\right)$$

$$+C_{3\varepsilon}\frac{\varepsilon_i}{k_i}[\beta(C_{li}k_l - C_{il}k_i) - \beta(U_l - U_i)\cdot\frac{\mu_{t,l}}{\alpha_l\sigma_l}\nabla\alpha_l + +\beta(U_l - U_i)\cdot\frac{\mu_{t,i}}{\alpha_i\sigma_i}\nabla\alpha_i]$$

In the equation, the subscript *l* represents the solid phase when the current standard *i* represents the gas phase, and the subscript *l* represents the gas phase when the standard *i* represents the solid phase.

—turbulent kinetic energy of i phase, —average velocity, —the turbulent kinetic energy produced by the mean velocity gradient of I phase, =1.42, =1.92, =1.3, =1, =1.3.

2.Simulation condition

The vertical pipe diameter is 100mm and length is 4m. Grid is a hexahedral mesh. As shown in Figure 1, the O mesh is used in the meshing of the end surface. It has a total of 574 thousand grids.

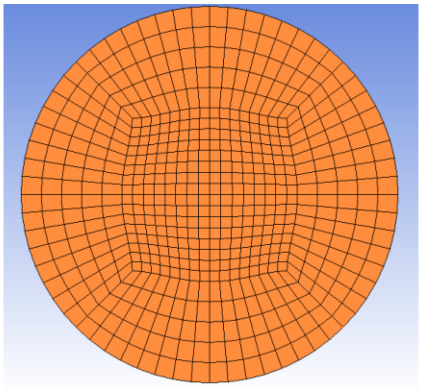


Fig1 Themesh of end surface

2.1 Inlet and outlet conditions

For the gas, the inlet is set to the velocity inlet. Outlet is set to outflow.

$$v_{g,in}(r) = \frac{60}{49} \times \frac{U_g}{1-\alpha_{s,in}}(1-\frac{2r}{D})^{1/7}$$

—superficial gas velocity, —solid volume fraction at the entrance, —distance from the center of the pipe at any point of the inlet section, D—pipe diameter.

For the solid phase, the axial velocity at the entrance is evenly distributed. Outlet is set to outflow.

$$v_{s,in} = \frac{M_s}{\alpha_{s,in}\rho_s A}$$

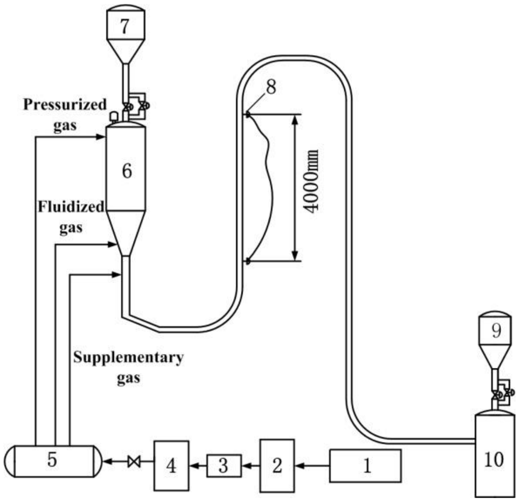
—Solid mass flow, —pipe area.

2.2 Wall Conditions

For the gas phase, no slip boundary condition is adopted. Wall condition of solid phase useslip boundary conditions of solid phase proposed by Johnson and Jackson. The specular reflection factor is 0.05, and the coefficient of collision between particles and wall is 0.5. The elastic recovery coefficient is about 0.95. The friction angle between the particle and the particle, both the friction angle between the particle and the wall are set to 30 degrees.

3.Test Equipment

High pressure dense phase petroleum coke pneumatic conveying test device as shown in Figure 2. It is mainly composed of a material tank, material receiving tank and pipings which connect the two.The petroleum coke particles inside the material tank by the flow of air pressure and wind driven into the pipeline. In tank outlet introduction of complementary wind adjust feeding pipe fixed in the process of gas ratio.Pressurized air is to keep hair material tank pressure. The pressure in the receiving tank is regulated by the pressure regulating valve. The object of this study is the 4000mm vertical upward pipeline.Differential pressure transmitter is arranged on both sides of the pipeline to measure the pressure difference.The inner diameter of pipeline is 100mm.The average particle size of the experimental petroleum cokeis 137 .Its density is 1350kg/m^3. The test of the transmission medium is nitrogen.



1- Air Compressor; 2、4 -Buffer Tank, 3- Dryer; 5-Gas Distributor;

6- Distribution Tank;7, 9- Dust Collector; 8- Differential Pressure Transmitter; 10- Receiving Tank

Fig2 Experimental device diagram

4. Results and Discussion

4.1 Considering the effect of friction stress on the simulation results

The pressure drop obtained by numerical simulation is compared with the pressure dropmeasured in experiment when the conveying pressure is 3.3Mpa and the mass flow rate of petroleum coke particles is 433.5kg/(m^2·s). The results are shown in table 1.

Table 1 Effect of friction stress on pressure drop of pipeline

superficial gas velocity (m/s)	Experimental pressure drop gradient (kpa/m)	Pressure drop gradient without considering friction	error (%)	Pressure drop gradient considering frictional stress	error (%)
4.31	**7.21**	**5.47**	**24.13%**	**6.14**	**14.84%**
5.88	**5.32**	**3.86**	**27.44%**	**4.42**	**16.92%**
6.21	**4.83**	**3.53**	**26.92%**	**4.16**	**13.87%**
6.68	**4.56**	**3.37**	**26.10%**	**3.82**	**16.23%**
7.81	**4.37**	**3.28**	**24.94%**	**3.72**	**14.87%**

It can be seen from table 1 that there is a large error between the pressure gradient values obtained from the simulation and the experimental results under the condition of the five groups. When considering the friction stress between the particles, and betweenthe particlesand the pipeline in the process, pressure drop error obtained by simulation is obviously reduced.And it is close to the experimental results.The calculation accuracy has been greatly improved. The results show that the influence of the friction stress on the high pressure dense phase pneumatic conveying process can not be ignored.

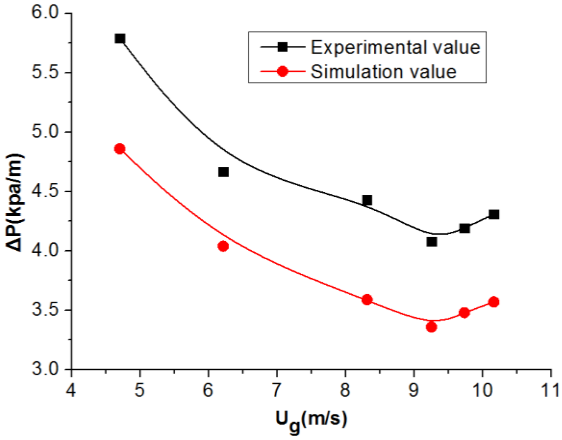


Fig3 the variation curves of pressure drop gradient with superficial gas velocity

Figure 3 shows the variation curves of pressure drop gradient with superficial gas velocity when the mass flow rate is 315.3kg/(m^2· s) andthe conveying pressure is 2.6Mpa. From the figure we can see, with the increase of superficial gas velocity, pressure drop gradient decreased gradually.And when the superficial gas velocity increases to a certain value, the pressure drop gradient reaches the minimum value.Then with the increase of superficial gas velocity, pressure drop gradient increased gradually. The superficial gas velocity corresponding to the minimum value of the pressure drop gradient is the optimal gas velocity. In a vertical tube, with the increase of superficial gas velocity, in order to maintain pulverized coal mass flow unchanged, it is necessary to reduce the volume fraction of petroleum coke.Which leads to solid phase particles falling pressure drop caused by gravity. Due to the friction, when the superficial gas velocity increases, The pressure loss caused by friction is bound to increase. Therefore, when the superficial gas velocity increases, the pressure drop gradient shows a first decrease and then increase. As can be seen from Figure 3, the simulation results are consistent with the experimental results. The error is about 15%. The results show that the friction stress in the dense phase pneumatic conveying can not be ignored again.

4.2The influence of superficial gas velocity on the flow characteristics

Figure 5 shows the numerical simulation of the effect of superficial gas velocity on the concentration distribution of petroleum coke when the mass flow rate is 315.3kg/(m^2·s) and conveying pressure is 3.3Mpa. The results show that the particle concentration decreases with the increase of superficial gas velocity. With the increase of the gas velocity, the drag force of the gas on the particles will increase and the particle velocity will increase. In order to maintain a certain mass flow rate of petroleum coke, the concentration of petroleum coke must be reduced. From the chart we can see that along the radius direction of the particle concentration distribution is not uniform. Maximum particle concentration appeared at r/R=0.7-0.8. It can be seen at the same time, the particle concentration near the wall is relatively low.

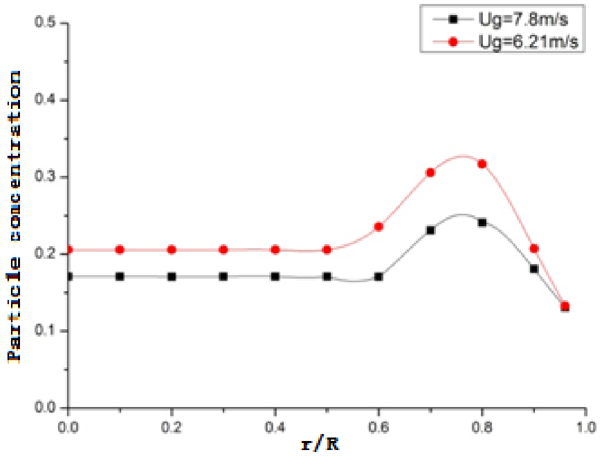


Fig4 Effect of superficial gas velocity on particle concentration

5. Conclusion

According to the characteristics of petroleum coke particles of high pressure dense phase pneumatic conveying in the process of high concentration, the paper built a mathematical model which considering the friction stress between the particles and the pipe. The comparison of simulation results and simulation results verified applicability of mathematical models. The results obtained by this model are more reliable than those obtained without considering the friction stress. At the same time, it is found that the pressure loss in the vertical tube decreases first and then increaseWith the increase of superficial gas velocity. In addition, it was found that the particle concentration decreased with the increase of superficial gas velocity.

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