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RESEARCH PAPER

Cuttings carrying characteristics of back-reaming pneumatic impactor exhaust during drilling operation

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Abstract: The flow fields of chip removal from the impactor's exhaust hole to its rear head were established to study the cuttings carrying characteristics of back-reaming pneumatic impactor exhaust by utilizing the computational fluid dynamics theory and simulation software Fluent. Based on the structure and working principle of the impactor, the gas solid two phase flow was simulated, and the gas phase characteristics of the flow field and the moving trajectory and concentration distribution of particles were obtained. The research shows that: once the exhaust enters the field its speed will slow down and the field pressure will gradually decrease from the entrance to the exit; cuttings particles will gather around the bottom and there is minor variation in their average concentration as they are distributed along a contrary direction against the entrance while the maximum concentration descends along the same direction and finally becomes stable. Moreover, the effect of drilling speed and exhaust mass flow of the impactor on the solid carrying characteristics was analyzed. The result demonstrates that: as the drilling speed increases, the carrying ability of exhaust decreases and when the rated operation pressure is 0.8 MPa, the drilling speed should be less than 12.6 m/h; as the mass flow rate of exhaust increases, the carrying ability increases as well, and the mass flow rate should be moderately increased under the condition of ensuring the working performance of the impactor.

Key words: gas drilling; back-reaming; pneumatic impactor; cuttings flow field model; cuttings carrying characteristics; gas-solid two-phase flow; numerical simulation

Introduction

Trenchless technology[1], a construction technology for paving and repairing underground pipeline by using drilling and tunneling equipment, can help achieve pipe lying with no earth surface avulsed and no damage to traffic, environment and buildings. In order to drill in complex strata like rock and pebble formations during trenchless construction, a new type of pneumatic impact equipment, back-reaming pneumatic impactor[2], is designed. This impactor relies on high pressure air offered by air compressor to realize drilling operation. When the air flows through the complex gas path structure in the equipment, the piston will be pushed to move periodically at high speed, thus impacting the drill of the impactor. Compared with traditional drilling equipment, the impactor can greatly improve the drilling efficiency in complex rock and pebble strata[3]. Cuttings carrying ability of the back-reaming pneumatic impactor's exhaust is not only related to whether the cuttings particle can be exhausted to the outside of the hole but also the whole performance of the impactor. This paper, by utilizing gas-solid two phase fluid mechanics, pneumatic conveying theory of solid particle materials and computational fluid dynamics (CFD) software FLUENT[4], has made a theoretical analysis of the flowing rules of the cuttings generated from the drill, in annular clearance between the impactor and the wall of rock hole, studies the gas flow rules in this gas circuit and the motion characteristics of cuttings, and analyzes the influence of drilling speed and the mass flow rate of exhaust upon the carrying ability. Essentially speaking, there are many similarities between the research questions in this paper and cuttings carrying of gas drilling in horizontal section, which thus can be taken as reference.

1. Cuttings flow field model of back-reaming pneumatic impactor

The back-reaming pneumatic impactor consists of bit, air intake lever, piston, piston valve and cylinder, and rear head (Fig. 1). The diameter of reaming hole is 190 mm, cylinder diameter is 160 mm, and the length of the impactor is 1 500 mm. In Fig. 1, the diameter of the three gas exhaust nozzles evenly distributed in the drill is 22 mm. High pressure gas from the air compressor is discharged from exhaust chamber through the exhaust nozzle to cuttings flow field of the

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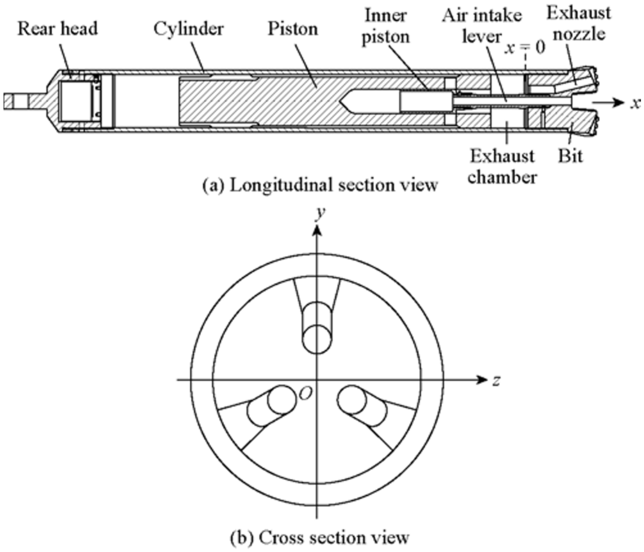

Fig. 1. Grid model of cuttings flow field of the back-reaming pneumatic impactor.

impactor after driving the impactor for a complete work cycle. Then airflow enters into the cavity formed by the bit surface and the rock wall through the nozzle, and flows reversely into the annular channel formed by the impactor cylinder and the hole wall as it is blocked by the rock wall. Finally, the cuttings are discharged outside the drill hole through the annular channel. The distance between the bit and rock wall surface is 10 mm (height of drill tooth), the inner diameter and the outer diameter of the flow field are 160 mm and 190 mm respectively. As the flow field of rock cuttings of the back-reaming pneumatic impactor is rather complex, a mixed grid is adopted. The annular channel formed by the impactor cylinder and the hole wall is divided by structured grid of hexahedron unit, which can improve the calculation accuracy and reduce computation cost; while the cavity formed by bit surface and the rock wall and gas exhaust nozzle with more complex shape is divided by unstructured grid of tetrahedron unit[5–6].

2. Mathematical models

In the complex layers with hard rock and gravel-cobble, the drilling speed of the impactor is relatively slow. When the bit diameter is 190 mm, drilling speed of the impactor is 4.2 m/h and the rock density is 2 400 kg/m^3, the mass flow rate of rock cuttings and exhaust gas would be 0.08 kg/s and 0.02 kg/s respectively. Therefore the volume ratio of solid phase to air phase in the field is much less than 10%. Since interaction between solid particles is slight, and can be ignored[7], Eulerian-Lagrangian method[8] was adopted in the simulation in which cuttings particles were taken as discrete phase, and the equation was solved in Lagrange coordinate system.

Cutting particles are affected by a number of forces in the flow field, including pressure drag, frictional drag, basset force (an unsteady aerodynamic force generated by the relative acceleration between particle and fluid in two phase flow), pressure gradient force, velocity gradient, inertial force and gravity. Among them, pressure drag has the largest impact. When the particle is large in diameter, the influence of the gravity would be substantial, while the influence of other forces is very small, and negligible.

Based on the gas-solid two-phase flow in the cutting flow field, a mathematical model has been established and the governing equations of this model include continuity equation, momentum conservation equation, and energy conservation equation[9].

Continuity equation:

$$\frac{\partial \rho_{\mathrm{m}}}{\partial t}+\nabla\cdot\left(\rho_{\mathrm{m}}\boldsymbol{v}_{\mathrm{m}}\right)=0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{m}}\boldsymbol{v}_{\mathrm{m}}\right)+\nabla\cdot\left(\rho_{\mathrm{m}}\boldsymbol{v}_{\mathrm{m}}\cdot\boldsymbol{v}_{\mathrm{m}}\right)=-\nabla p+\rho_{\mathrm{m}}\boldsymbol{g}+\boldsymbol{F}+\nabla\left[\mu_{\mathrm{m}}\left(\nabla\boldsymbol{v}_{\mathrm{m}}+\nabla\boldsymbol{v}_{\mathrm{m}}^{\mathrm{T}}\right)\right] \tag{2}$$

Energy conservation equation:

$$\frac{\partial}{\partial t}\sum_{i=1}^{2}\alpha_i\rho_i E_i+\nabla\cdot\sum_{i=1}^{2}\alpha_i\boldsymbol{v}_i\left(\rho_i E_i+p_i\right)=\nabla\cdot\left(k_{\mathrm{e}}\nabla T\right) \quad (i=1,2) \tag{3}$$

where $E_i=\frac{1}{2}v_i^2$

The cutting flow field of the impactor is gas-solid two-phase turbulent flow[10]. To solve the numerical calculation of complex three-dimensional turbulent flow, direct solution would require high performance of the computer, thus approximation and simplification are usually used in practical engineering application to reduce the simulation difficulty. RNG k-ε model was adopted in this paper to solve the flow field[11]:

$$\begin{cases}\dfrac{\partial}{\partial t}(\rho k)+\dfrac{\partial}{\partial d_j}\left(\rho k u_j\right)=\dfrac{\partial}{\partial d_j}\left(\alpha_k\mu_{\mathrm{e}}\dfrac{\partial k}{\partial d_j}\right)+G_k+G_{\mathrm{b}}-\rho\varepsilon\\[2ex]\dfrac{\partial}{\partial t}(\rho\varepsilon)+\dfrac{\partial}{\partial d_j}\left(\rho\varepsilon u_j\right)=\dfrac{\partial}{\partial d_j}\left(\alpha_\varepsilon\mu_{\mathrm{e}}\dfrac{\partial\varepsilon}{\partial d_j}\right)+C_1\dfrac{\varepsilon}{k}G_k-C_2\rho\dfrac{\varepsilon^2}{k}\end{cases} \tag{4}$$

where $\mu_{\mathrm{e}}=\mu+\mu_{\mathrm{t}}$

Air was choosen as the gas phase in the simulation with a density of 1.225 kg/m^3 and kinematic viscosity of 1.78×10^{-5} Pa·s. The gas discharged from the exhaust nozzle into the flow field took the mass flow inlet at a mass flow rate of 0.02 kg/s and initial gauge pressure of 0.22 MPa, and pressure outlet with a pressure of 0.10 MPa. The cuttings particles were discharged from the rock wall at the bottom of the hole at a mass flow rate of 0.08 kg/s. These particles were assumed to be 5 mm in diameter and 0 m/s in initial velocity.

3. Results of mathematical simulation and discussion

3.1. Characteristics of gas phase

Fig. 2 shows the gas phase characteristics of cuttings flow field at the bottom of the back-reaming pneumatic impactor. It can be seen that when the gas flow is in the exhaust nozzle, the velocity gradually increases while gaseous pressure