Study on Flow Field Characteristics of Nozzle Water Jet in Hydraulic cutting

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Abstract: Based on the theory of hydrodynamics, a mathematical model of nozzle water jet flow field in hydraulic cutting is established. By numerical simulation, the effects of nozzle convergence angle, nozzle outlet diameter and cylindrical section length on water jet flow impact is obtained, and the influence of three factors on the nozzle water jet flow field is analyzed. The optimal nozzle parameters are obtained by simulation as follows: convergence angle is 13 °, cylindrical section length is 8 mm and nozzle outlet diameter is 2 mm. Under this optimal nozzle parameters, hydraulic cutting has the best comprehensive effect.

1. Introduction

In recent years, with the deepening of coal mining depth, in-situ stress increases, and original coal gas content increases, which increases the risk and gas outburst during coal mining [1]. At the same time, the permeability of most coal seams in China is poor, which makes it difficult to extract and utilize coal seam gas. The problems of low extraction volume and fast flow attenuation are more serious. The common gas extraction method is very difficult to solve the coal seam gas problem. Drainage gas is an important measure to control coal mining and gas outburst. Therefore, the permeability of coal enhancement technology can expand coal seam cracks by external force, improve coal seam permeability, and improve gas extraction effect of coal seam, so as to achieve the purpose of outburst prevention [2, 3]. For a poor permeability of coal, hydraulic cutting technology can improve coal and rock cracks, increasing permeability of coal [4-7].

Effect of hydraulic cutting is closely related to the parameters of water jet nozzle. Many scholars [8-11] have studied high-pressure water jet nozzles for different applications, but it is difficult to obtain water jet nozzles with universal adaptability. Therefore, according to an application of actual situation, select an appropriate nozzle to adapt.

2 Characteristics of water jet flow field in hydraulic cutting

2.1Mathematical model of water jet flow

Water is ejected by external force through the nozzle is a free jet. According to the basic equation of viscous motion, the water jet equation is deduced. Water is an incompressible fluid, continuity equation (1) and N-S (2) equation as follows:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \quad (1)$$

$$X - \frac{1}{\rho}\frac{\partial p}{\partial x} + \eta\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right) = \frac{dv_x}{dt}$$
$$Y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \eta\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right) = \frac{dv_y}{dt} \quad (2)$$
$$Z - \frac{1}{\rho}\frac{\partial p}{\partial z} + \eta\left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right) = \frac{dv_z}{dt}$$

The above two equations can be combined to obtain solutions of the flow field.
Turbulence kinetic energy k and turbulent dissipation rate ε can be obtained.

$$k = \frac{3}{2}\left(\bar{u}I\right)^2 \quad (3)$$

$$\varepsilon = \rho C_\mu \frac{k^2}{\mu}\left(\frac{\mu_t}{\mu}\right)^{-1} \quad (4)$$

2.2 Model setup

Taking into account hydraulic cutting process, the diameter of high-pressure water supply pipe is far greater than the diameter of nozzle. According to the theory of fluid mechanics, in order to reduce energy loss of high pressure water from potential energy to kinetic energy. Theoretically, the inner surface shape of nozzle should be as close as possible to streamline connection with nozzle inlet, but this nozzle production is difficult. So the current hydraulic cutting nozzle is cylindrical cone-shaped nozzle. Schematic picture of nozzle is shown in figure 1.

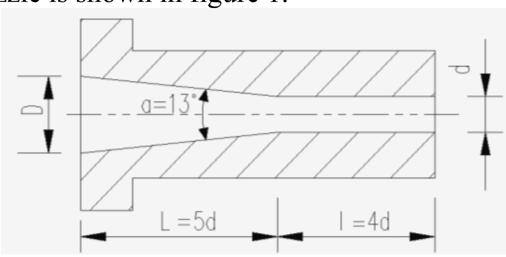

Figure 1 Schematic picture of nozzle

At the same time, water jet ejected from the nozzle will encounter an influence of the water reflected from coal wall, and this simulation uses the submerged water jet principle. According to previous studies, FLUENT numerical model parameters are selected as follows: convergence angle is 13 °, convergence segment length is 5mm, cylindrical section length is 12mm, and cylinder diameter is 3mm.

2.3 Numerical simulation results

Water jet enters the slot and contacts with surrounding water, at the boundary of contact, a discontinuity is formed, and then it continues to develop into a mixed layer. At a certain distance from nozzle location, the central part of the water jet is not affected by external water body in the drilling. It still maintaining a speed of the jet, this part is called the core area. The velocity of water jet is the largest at the axial position, and velocity of water jet in all positions follow a trend of first increasing and then decreasing. At the same time, velocity decays very quickly after water jet ejected from nozzle.

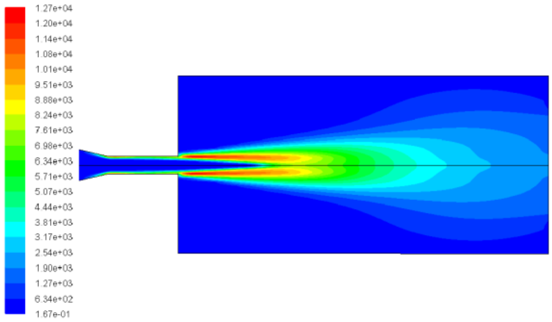

Figure 2 Turbulent kinetic energy k of contour line

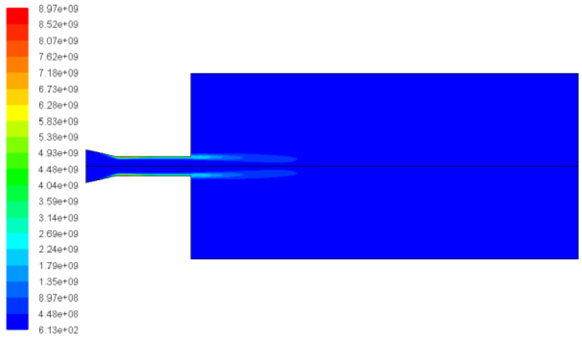

Figure 3 The dissipation rate of turbulent kinetic energy ε of contour line

It can be seen from figure 2 that the region with large turbulence kinetic energy in nozzle is located in the vicinity of boundary between convergence segment and cylindrical section and the inner wall of cylinder. And figure 3 shows that the region with large dissipation rate of turbulent kinetic energy distributes in the following locations: convergence angle, inner wall of the cylinder and nozzle outlet.

After water jet ejected from nozzle, the jet velocity first increases, and then gradually decreases. Velocity of water jets in convergence segment is increasing and the rate of increase is increasing. When jet is close to nozzle outlet, the velocity increases most. After leaving the nozzle of jet, there will be a constant velocity region. This constant velocity region within jet is a maximum speed and equal. This constant velocity of jet outside core region is gradually reduced until the velocity is zero.

3 Influence of nozzle parameters in hydraulic cutting and experimental study

3.1 Influence of different convergence angle on jet flow field

The simulation results in figure 1, figure 4 and figure 5 show that water jets have the longest sustained acceleration time in convergence segment when convergence angle is 13 °. As convergence angle continues to increase to 30 ° and 60 °, the length of acceleration section is gradually reduced. The nozzle with convergence angle of 60 ° has a large velocity loss at the taper angle, and velocity of water jet in cylindrical section is unbalanced, which affects water jet velocity. Therefore, its maximum velocity is lower than the convergence angle of nozzle is 13 ° and 30 °. The nozzle with a convergence angle of 60 ° has a velocity in the cylindrical section and in the core region which is less than 13 ° and 30 °. The dynamic pressure at convergence angle of 13 ° in the core zone is slightly higher than that at 30 °, which is much larger than the dynamic pressure at 60 °. One of the most important parameters of a water jet nozzle is the length of the water jet core area. When α = 13°, the core area of water jet is the longest, water jet velocity is the maximum and jet bundle is the best ,so water jet impact force is the biggest. Considering effect of convergence angle on water jet velocity and dynamic pressure, the nozzle with 13 ° is more advantageous to maintain faster water jet velocity and larger dynamic pressure. Therefore, nozzle convergence angle is 13 °, the effect of cutting coal is better.

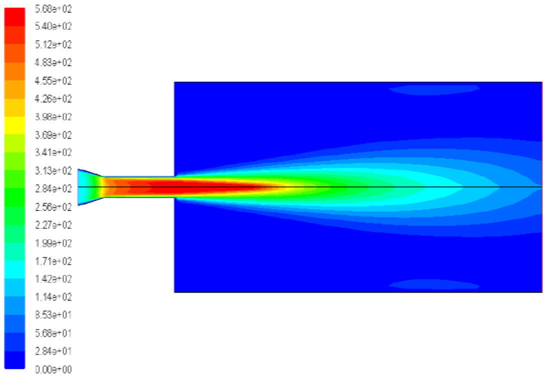

Figure 4 Contoured velocity of water at 30° inner cone distance (m/s)

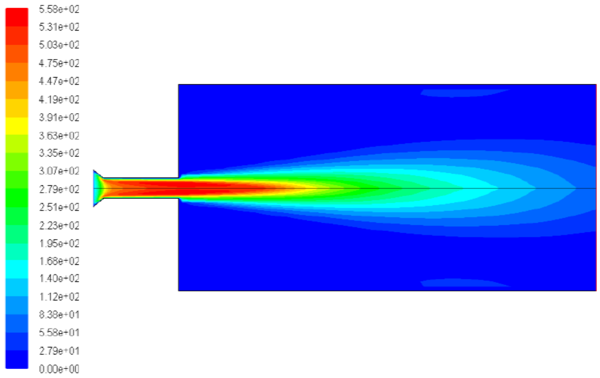

Figure 5 Contoured velocity of water at 60° inner cone distance (m/s)

3.2 Influence of different nozzle outlet diameters on flow field

When the nozzle outlet diameter is 1.4, 1.6, 1.8, 2 mm and other parameters unchanged. The nozzle has the largest axial velocity which nozzle outlet diameter is 2 mm. Because water jet through the nozzle to accelerate after convergence segment, nozzle outlet diameter is larger, outlet water jet diameter is larger. As a result, the axial velocity of nozzle decreases slowly, while nozzle with a small outlet diameter has a faster axial velocity reduction and a larger energy loss. With an increase of nozzle outlet diameter, radial water jet velocity also increases, and the larger outlet velocity also makes larger diameter of water jet has larger energy. Therefore, nozzle outlet diameter affects the law of water jet velocity is that the larger the outlet diameter is, the better the water jet impacting the coal body. In a same position away from the axial position, the larger the nozzle outlet diameter, the greater the axial pressure.

3. 3 Influence of different cylindrical section length on flow field

Cylindrical section length also has a great influence on the water jet flow field. Therefore, four models for numerical simulation are established , the variables for the cylindrical section length, respectively 4mm (2d), 8mm (4d), 12mm (6d), 24mm (12d).The other parameters are convergence angle is 13 ° , convergence section is 5 mm, and the nozzle outlet diameter(d) is 2 mm.

It can be seen from figure 6 and 7 that, comparing the two curves, velocity and dynamic pressure of water jets on the axis are similar with different cylindrical section length, increases with increasing of cylindrical section length. When cylindrical section length reaches 24mm, the maximum is reached. For water jets located in core region, the length of core region is inversely related to cylindrical section length, so nozzle with a cylindrical section of 4 mm length has the largest core region. Water jet velocity and water jet flow pressure on the axis are the maximum when cylindrical section is 24 mm, but dynamic pressure showed a rapid decline trend. When cylindrical section is 4 mm, core area is the largest at this time, but velocity and dynamic pressure of jet are lower than other cylindrical section. Based on the above analysis, considering the change of water jet velocity and dynamic pressure, it is reasonable to select the length of 4d or 6d as a cylinder section.

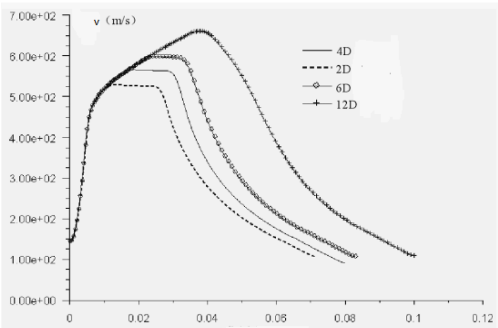

Figure 6 Comparison of water velocity on different cylindrical section

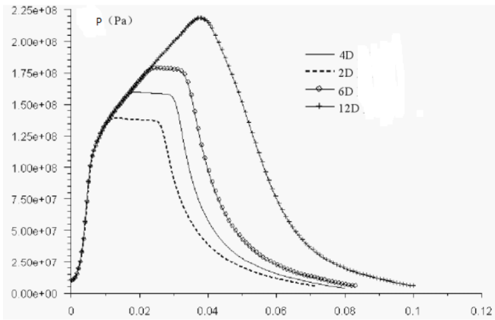

Figure 7 Comparison of water dynamic pressure on different cylindrical section

4 Conclusion

（1）Based on the theory of hydrodynamics and by FLUENT numerical simulation, water jet velocity is the highest at the axial position, and a trend of velocity in all positions follow that first increase, and then decrease. When $\alpha = 13°$, water jet velocity reaches the maximum value and jet bundle is the best, so water jet impingement force is the biggest. And the larger the nozzle outlet diameter is, the more favorable the water jet impacting the coal body.

（2）Taking into account jet velocity and dynamic pressure change, it is reasonable to choose 4 or 6 times nozzle outlet diameter as the length of cylinder section.

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