HONGQING ZHU
WENTAO LIAO
KAI SHENG
and
BEI-FANG GU

Study on optimization of hydraulic cutting nozzle and application

Based on the theory of hydrodynamics, a mathematical model of nozzle water jet flow field in hydraulic cutting is established. By numerical simulation for FLUENT software, the effects of nozzle convergence angle, nozzle outlet diameter and cylindrical section length on water jet flow impact is obtained and analyzed. At the same time, a mathematical model of the nozzle outlet velocity is deduced by the simulation results. Furthermore choose optimization of nozzle parameters in the field test, which its convergence angle is 13°, convergence segment length is 10 mm, cylindrical section length is 8 mm and nozzle outlet diameter is 2 mm. Application and testing in coal mine show that this nozzle has the best comprehensive effect in hydraulic cutting field test and improve gas extraction efficiency .

Keywords: *Hydraulic cutting; water jet flow field; optimization of nozzle parameters; mathematical model; gas extraction.*

1. Introduction

In recent years, with the deepening of coal mining depth, in-situ stress increases, and original coal gas content increases, which again increases the risk and gas outburst during coal mining, and [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 [4-10].

Messrs. Hongqing Zhu, Wentao Liao and Kai Sheng, College of Resource and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100 083 and Bei-fang Gu, North China University of Water Resources and Electric Power, Zhengzhou 450 046, China. Corresponding author: wentaolion618@qq.com

Hydraulic cutting measures through the high-pressure water pump to produce high-pressure water, through the water pipeline, sealing drill pipe and drill through the hole in the nozzle of the jet, forming a high-pressure water jet, and impact of coal in the formation of cutting. So that the formation of pressure relief around coal, to play the role of coal seam permeability, thereby enhancing the gas extraction efficiency [11]. And the stress can make coal rock elastic deformation, when impact force is small, the elastic deformation of coal rock will be quickly restored and a tensile stress will be produced. At the same time, shear stress and tensile stress will be generated in the impact area. Under the combined action of three stresses, a large number of fractures are produced in the coal rock [12].

Effect of hydraulic cutting is closely related to the parameters of water jet nozzle. Many scholars [13-22] have studied high-pressure water jet nozzles for different applications, but it is difficult to obtain water jet nozzles with universal adaptability. Therefore, based on an application of actual situation, an appropriate nozzle should be selected.

2. Characteristics of water jet flow field in hydraulic cutting

2.1 Mathematical 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:

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

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

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

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

The above two equations can be combined to obtain solutions of the flow field. Flow viscosity μ_t is:

$$\mu_t = \rho \cdot C_\mu \frac{k^2}{\varepsilon} \quad \dots \quad (3)$$

where C_μ is an empirical constant.

Equation (3) contains turbulent kinetic energy k and turbulent kinetic energy dissipation rate ε.

The turbulence intensity I is:

$$I = u'/\overline{u} = 0.16\left(Re_{D_H}\right)^{-1/8} \quad \dots \quad (4)$$

where u' and $\overline{u}$ are turbulence pulsation velocity and turbulent average velocity, respectively, and Re_{D_H} is the Reynolds number when hydraulic diameter is taken as D_H. Considering the length of turbulent flow l is known, turbulence kinetic energy k and turbulent dissipation rate can be obtained.

$$k = \frac{3}{2}\left(\overline{u} l\right)^2 \quad \dots \quad (5)$$

$$\varepsilon = \rho C_\mu \frac{k^2}{\mu}\left(\frac{\mu_t}{\mu}\right)^{-1} \quad \dots \quad (6)$$

2.2 Model set up

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, energy loss of high pressure water from potential energy to kinetic energy is reduced. 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 Fig.1.

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.

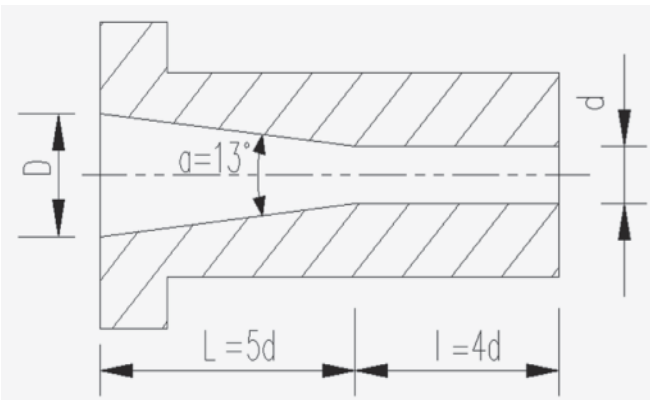

Fig.1 Schematic picture of nozzle

According to previous studies, FLUENT numerical model parameters are selected as follows: convergence angle is 13°, convergence segment length is 5 mm, cylindrical section length is 12 mm, and cylinder diameter is 3 mm.

2.3 Numerical simulation results

From Fig.2, we can see the state of flow field after water jet ejected from the nozzle. 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 maintains 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. While velocity decays very quickly after water jet ejected from nozzle.

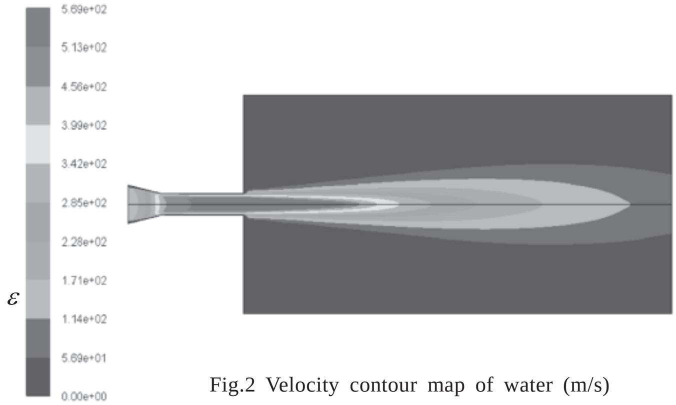

Fig.2 Velocity contour map of water (m/s)

It can be seen from Fig.3 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. For jet outside the nozzle, the region with larger turbulence kinetic energy is located on both sides of core region, and the region with smaller turbulence kinetic energy is located in core region, which is quite consistent with a turbulence situation in reality.

It can be seen from Fig.4 that the region with large

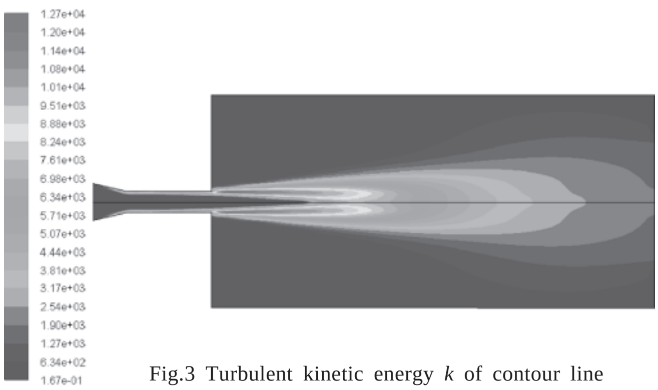

Fig.3 Turbulent kinetic energy k of contour line

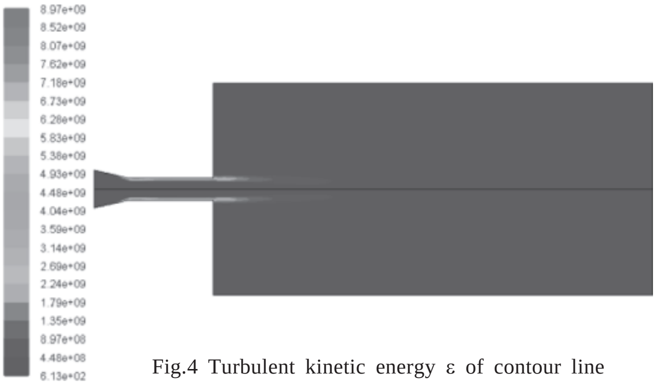

Fig.4 Turbulent kinetic energy ε of contour line

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 accelerating. 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.

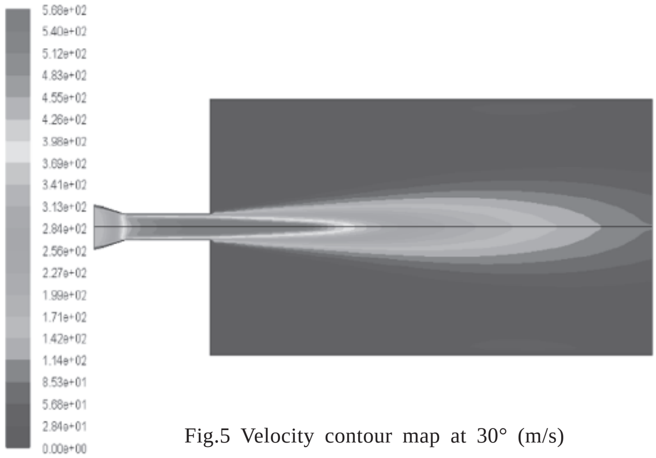

Fig.5 Velocity contour map at 30° (m/s)

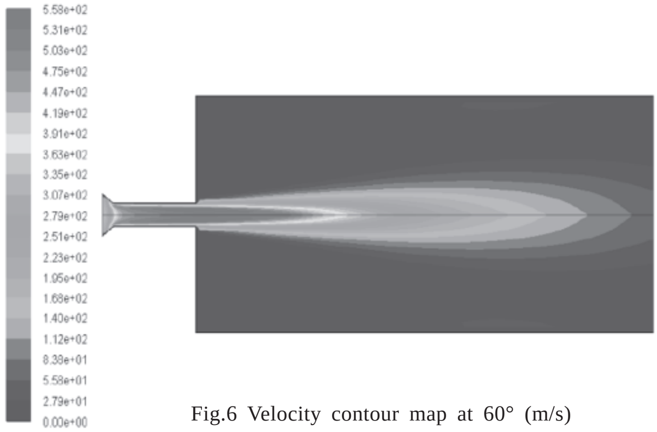

Fig.6 Velocity contour map at 60° (m/s)

3. Influence of nozzle parameters in hydraulic cutting and experimental study

3.1 Convergence angles on jet flow field

The simulation results in Fig.1, Fig.5 and Fig.6 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.

Table 1: Water velocity of different water pressure

Pressure	0	13	20	30	50	60	90	120	180
Velocity	201	187	182	180	174	170	161	153	140

3.2 Nozzle outlet diameters on flow field

When the nozzle outlet diameter is 1.4, 1.6, 1.8, 2 mm and other parameters unchanged. Nozzle has the largest axial velocity whose 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 hence 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 and has larger energy. Therefore, nozzle outlet diameter affects the law of water jet velocity and larger the outlet diameter is, the better is the water jet impacting the coal body. In a same position away from the axial position, the larger the nozzle outlet diameter, the greater is the axial pressure.

3.3 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), and d is the nozzle outlet diameter (Fig.1). The other parameters convergence angle is 13°, convergence segment length is 5 mm, and the nozzle outlet diameter(d) is 2 mm.

Through numerical simulation, velocity and dynamic pressure of water jets on the axis are similar to different cylindrical section length, increases with the increasing of cylindrical section length. 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. But velocity and dynamic pressure of jet are lower than other cylindrical section. 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.

3.4 Mathematical model of water velocity

Through the FLUENT numerical simulation above, the influences of nozzle parameters in flow field is studied, and the optimum nozzle parameters are selected. This section takes into account poor timeliness of the numerical simulations. Therefore, a mathematical method is adopted to establish the mathematical model, and the water effluent velocity as the independent variables.

Three convergence angles of 13°, 30°, and 60° were selected for simulation. In order to make the fitting result more accurate, an additional six contraction angles were simulated. According to the simulation results, the relationship between the velocity of nozzle and the convergence angles is shown in Table 1. In this table, the pressure unit is Mpa, and the velocity unit is m/s.

According to the relationship between nozzle water velocity and convergence angle, it can be obtained by fitting

$$v = me^{-0.0019\alpha} \quad \dots \quad (7)$$

In this formula: v - nozzle water velocity, m/s; m - fitting parameter; α - nozzle convergence angle, °.

Similarly, in order to study the relationship between nozzle inlet water pressure and outlet water velocity when convergence angle is 0°. And an additional 7 inlet water pressures were simulated. And according to the simulation results were fitted

$$v_0 = 44.159 p^{0.5} \quad \dots \quad (8)$$

By the formula (9) available, when the convergence angle is 0, equal to the nozzle water speed, namely:

$$m = 44.159 p^{0.5} \quad \dots \quad (9)$$

Taking into account the geometrical features of the nozzle, the expression of nozzle outlet velocity can be deduced:

$$v = 44.159 p^{0.5} e^{-0.0038 arctan \frac{D-d}{2L}} \quad \dots \quad (10)$$

At the same time, taking into account hydraulic cutting seam has a faster water jet velocity, pressure loss along the pipeline pressure loss and local pressure loss cannot be ignored. Based on this, a mathematical model of the nozzle outlet velocity is established, which contains the pipeline pressure loss.

The total pressure loss of the pipeline is equal to the sum of the pressure loss along the path and the local pressure loss.

$$\nabla p = \nabla p_\lambda + \nabla p_\varsigma \quad \dots \quad (11)$$

$$p = p_0 - \lambda \frac{l_0 \rho v_0^2}{2d_0} - \varsigma \frac{l_0 \rho v_0^2}{2} \quad \dots \quad (12)$$

So, substituting equation (13) into equation (8) can be deduced water effluent velocity v.

$$v = \frac{p_0^{0.5}}{\left[l_0 \rho \left(\frac{\lambda - \varsigma d_0}{2d_0} \right) + 1 \right]^{0.5}} e^{-0.0038 arctan \frac{D-d}{2L}} \quad \dots \quad (13)$$

where p_0 is high-pressure pump working pressure, MPa; ς is local resistance coefficient; λ is resistance coefficient in pipe; d is nozzle outlet diameter, mm; D is nozzle inlet diameter, mm; L is nozzle cylindrical section length, mm; l_0 is the length of pipe, m; v_0 is water velocity in pipe, m / s; d_0 is the pipe diameter, m.

4. Nozzle parameters optimization and test

4.1 Nozzle processing and testing

This test mine has a flat coal wall and a suitable floor space. Test pump pressure is uniformly fixed at 30 Mpa, distance between the fixed nozzle and coal wall is 50 mm. Nozzle is used to impact the coal wall for 1min with three kinds of nozzles respectively. Hydraulic cutting depths and hydraulic cutting heights are measured. The results are shown in Table 2. In this table, the unit of nozzle diameter, cutting depth and cutting width are in mm.

It can be seen from Table 3, when nozzle diameter increase from 1mm to 2mm, cutting depth increase nearly double, and cutting width is also significantly improved. When nozzle diameter increases from 2 mm to 3 mm, cutting depth appears

Table 2: Test result

Nozzle diameter	Cutting depth	Cutting width
1	425	16
2	805	25
3	535	35

to reduce, cutting width increases by 10 mm. Considering actual production conditions and the field test results, the optimal nozzle parameters in hydraulic cutting are selected. The nozzle outlet diameter is 2 mm, the convergence segment length is 10 mm, the cylindrical section length is 8 mm, and the convergence angle is 13°.

4.2 Optimization of nozzle parameters

The nozzle is optimized through the previous study, and the nozzle profile after optimization is shown in Fig 7. The three nozzles are each 120° and are perpendicular to the same plane of the drill pipe. The drill bit is identical to the numerical simulation and experimental study, as shown in Fig 8. The drill bit is driven by drill pipe, and three nozzles are evenly drained when the cutting is done. The cutting effect is good, which avoids the uneven distribution of nozzles in the hydraulic cutting bit.

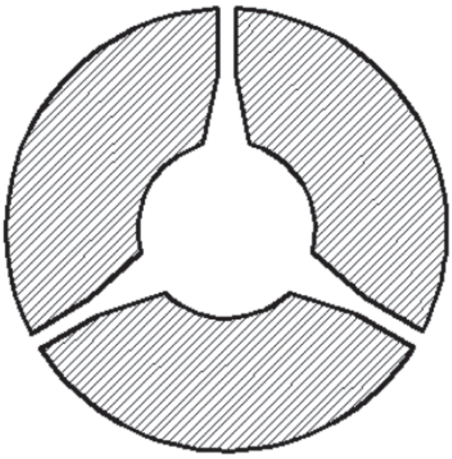

Fig.7 Profile of drill pipe

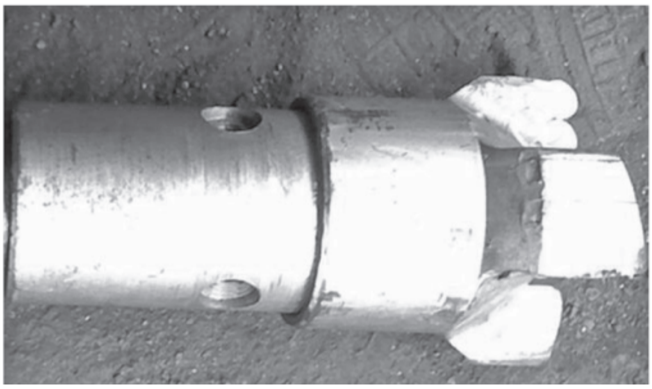

Fig.8 Entity of drill pipe

5. Application

5.1 Effect of gas extraction in coal mine

The test mine belongs to coal and gas outburst mine. At present this mine is mining the No. 6 coal seam with gas outburst risk. The gas extraction index of the test mine change before and after hydraulic cutting is as follows. Before the implementation of hydraulic cutting drilling, the average gas density is 15%. After hydraulic cut, the gas density increased to 20%. Gas pumping per minute pure flow from its original 0.20 to 0.28 cubic meters to 0.31 to 0.36 cubic meters, while the extraction volume increased by about 2 times. Therefore, the implementation of hydraulic cutting measures on the mine drilling gas extraction has been greatly improved.

5.2 Influence of general gas extraction drilling

In the hydraulic cutting seam within the scope of the general gas extraction drilling, gas extraction effect will have varying degrees of change. In order to study the impact of this situation, gas extraction parameters of drilling changes are collected and recorded by common drilling located around the hydraulic cutting drilling. Different distance from the hydraulic cutting drilling, the affected extent of ordinary pumping drilling by hydraulic cutting measures is different. The gas flow and gas density in most of the gas extraction drilling within the influence range of hydraulic cutting measures are increased. The distance closer to hydraulic cutting drilling, gas flow and gas density are increasing significantly. Farther away from the hydraulic cutting drilling, the increase is smaller. Overall, the drilling gas flow increased significantly.

6. Conclusions

(1) Based on the theory of hydrodynamics, the k-ε model mathematical expression of water jet flow field of hydraulic cutting nozzle is obtained.

(2) 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. Simultaneously, based on the simulation of nozzle flow velocity at different inlet pressures and convergence angle equal to zero, a mathematical model of nozzle outlet water velocity is deduced.

(3) The cutting depth and width of three kinds of nozzles were obtained by a field test. After comparative analysis, it is considered that the optimal nozzle with diameter is 2 mm, convergence segment length is 10 mm, cylindrical section length is 8 mm, and convergence angle is 13°.

(4) Using this optimal nozzle in hydraulic cutting to coal mine, gas extraction index has been greatly improved.

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