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# Study on Abrasive Mixing Chamber of Pre-Mixed Water Jet

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**ABSTRACT**

In order to reveal the flow law of isothermal, incompressible, steady, liquid-solid turbulent flow in mixing chamber of premixed abrasive water jet, the FLUENT software is used. The flow law of liquid-solid two phase flow is obtained. Abrasive mixing chamber models with four different sizes are used in this simulation, key design parameters of mine abrasive mixing chamber are determined. The flow laws of liquid-solid two phase flow in abrasive mixing chamber model with 7 different abrasive volume fraction are simulated, the results indicate that, the system have better cutting effect when abrasive volume fraction between 6%-10%. The results have important theoretical basis on optimum performances, material and parameters of mining abrasive mixing chamber. According to the numerical simulation and the theoretical analysis mining abrasive mixing chamber is developed, and the laboratory cutting experiments is investigated, the needed mining abrasive mixing chamber is gotten. This research has great significance on coal mine gas disaster prediction, gas drainage and safety production.

**Key words**: pre-mix; water jet; abrasive mixing chamber; numerical simulation; safety cutting

## 1. INTRODUCTION

A kind of cold cutting technology of abrasive water jet cutting without sparks at work can be used in flammable, explosive, high temperature and other dangerous environment. It is more suitable for the field of coal. Important contributions to the development and application of water jet technology have been made by many scholars[1-3]. The pressure required of the pre-mixed abrasive water jet system is only 1/7-1/10 of the later mixed system under the same conditions through the experiment by Zhang[4].The wear mechanism and structure optimization of pre-mixed abrasive nozzle was studied by many scholars, and the transverse movement force of the abrasive particles is the main cause of nozzle wear[5]. Cutting nozzle efficiency is the highest, the largest nozzle wear through the experiment by Cui[6]. The new nozzle structure were designed by Ding and You[7]. In recent years, research and applications of pre-mixed abrasive water jet cutting technology are more wide-ranging. The pre-mixed abrasive water jet helping drilling and coal slotted relief adopted in the field of coal are efficient technical methods for improving the pre-pumping effect of low permeability coal seam gas. The water jet cutting technology was applied into outburst prevention design by Tang. The method of abrasive water jet breaking coal and rock was studied by Li[8]. The technology used in the field of coal was proved safe

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through the study of acceleration mechanism of pre-mixed abrasive jet used in cutting safely by Li and Guo[9]. In recent years, the technology and equipment of high-pressure abrasive jet cutting, drilling and penetration enhancing were studied and applied in Ping Ding Shan Coal Group by Lin[10]. Many researches were done in the aspects of abrasive water jet cutting and drilling to prevent coal and gas outburst. The technology of high-pressure abrasive water jet cutting was developed and applied into the seam roadway heading face for application testing by Li[11].

A key part of the pre-mixed abrasive water jet technology is that abrasive should be mixed evenly in the abrasive mixing chamber and fluidized and the abrasive should flow into high-pressure pipeline with its maximum speed, the supply of abrasive is crucial, especially, the amount of abrasive jet cutting and stability, uniformity of supplying abrasive have a direct influence on performance and quality of cutting. Therefore, the performance, materials and the processes of the abrasive mixing chamber must be paid attention to studying. The improvement of the abrasive mixing chamber is an important sign of equipment technical level improving. How to improve the abrasive mixing effect, it has an important theoretical and practical value for improving the effectiveness and efficiency of cutting for that high efficiency abrasive mixing chambers designed. Because the production of abrasive cavity opening is cumbersome, this paper used numerical simulation to simulate liquid-solid two-phase flow in the abrasive mixing chamber, it is helpful to develop the internal structure of the abrasive chamber well. It can also make the production process simple and reduce costs and improve efficiency, at the same time, it can provide a theoretical basis for the design of abrasive water jet mixing chamber.

In the pre-mixed abrasive water jet device system, a part of the high-pressure water from high-pressure pump flows to the top of the abrasive mixing chamber; a part of the high-pressure water flows to the bottom of the abrasive mixing chamber through the throttle valve, which make abrasive fluidized, so that the water could be injected into the high-pressure pipeline. The other part of the high-pressure water flows to the mixing chamber. The abrasive gets into the mixing chamber under combined action of pressure and its own weight, but the abrasive material in the abrasive mixing chamber mixes homogeneously in water because its local pressure drop and local vortices when the high-pressure water passes the throttle bore, then the abrasive material mixes sufficiently with high-pressure water in the high pressure water pipe, which flows into the nozzle bore through high-pressure pipeline and injection from the nozzle device finally. The pre-mixed abrasive water jet system is formed through accelerating by nozzle to make abrasive and water mixed quickly.

## 2. MATHEMATICAL MODEL

The main feature of the pre-mixed abrasive water jet is abrasive has been mixed before accelerated fluid through nozzle. The volume fraction of the abrasive particles is generally small. Therefore, the fluid can be regarded as continuous phase according to the lagrangian discrete phase model. The flow field can be gotten through solving directly N-S Equation when fluid was described in Euler coordinates. The abrasive particles can be regarded as a discrete phase. The trajectory of particle can be gotten through calculating the movement of particles in the flow field when abrasive particles were described in Euler coordinates.

**(1) Control Equation of Continuity**

Flow field of chamber of pre-mixed AWJ is isothermal, incompressible, steady, and solid-liquid mixed field. Continuous phase control equation is described by Reynolds time averaged N-S equation. As quadratic term has an additional Renault stress after time averaged treatment, it need to add suitable turbulence model to solve the closed issue of the equation and the standard k-ε equation turbulence model under high-Reynolds is adopted.

Equations are as follows:

Continuity equation is

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \tag{1}$$

X-axis momentum equation is

$$\begin{aligned}\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}&=\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial u}{\partial y}\right)\\&-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial x}\right)\end{aligned} \tag{2}$$

Y-axis momentum equation is

$$\begin{aligned}\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}&=\frac{\partial}{\partial x}\left(\mu_e\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial y}\right)\\&-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial y}\right)\end{aligned} \tag{3}$$

Equation of turbulent kinetic energy $k$ is

$$\begin{aligned}\frac{\partial(\rho uk)}{\partial x}+\frac{\partial(\rho vk)}{\partial y}&=\frac{\partial}{\partial x}\left((\mu+\frac{\mu_t}{\delta_k})\frac{\partial k}{\partial x}\right)\\&+\frac{\partial}{\partial y}\left((\mu+\frac{\mu_t}{\delta_k})\frac{\partial k}{\partial y}\right)+P_V-\rho\varepsilon\end{aligned} \tag{4}$$

Equation of dissipation rate $\varepsilon$ of turbulent kinetic energy is

$$\begin{aligned}\frac{\partial(\rho u\varepsilon)}{\partial x}+\frac{\partial(\rho v\varepsilon)}{\partial y}&=\frac{\partial}{\partial x}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial k}{\partial x}\right]\\&+\frac{\partial}{\partial y}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial k}{\partial x}\right]+\left(c_1P_p-c_2\rho\varepsilon\right)\frac{\varepsilon}{k}\end{aligned} \tag{5}$$

Where, $u, v$ is average velocity of water at X-axis and Y-axis respectively, $\rho$ is the density of water, $\mu$ is the dynamic viscosity coefficient; $\mu_e$ is the effective viscosity coefficient, $\mu_e = \mu + \mu_t$ ; $\mu_t$ is the vortex viscosity coefficient, $\mu_t = c_\mu \rho k^2 / \varepsilon$ . $c_\mu, c_1, c_2, \sigma_k, \sigma_\varepsilon$ are empirical values. They can be obtained through experiments, their values are $c_\mu = 0.09, c_1 = 1.44, c_2 = 1.92, \sigma_k = 1.0, \sigma_\varepsilon = 1.3$ . $P_p$ is the change rate of turbulence energy due to the change of stress, it can be obtained from follow equation

$$P_p = \mu_t \left\{ 2\left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right\}$$

**(2) Control Equation of Solid Abrasive Particles**

The stress of particles in chamber of pre-mixed AWJ is very complicated and particles are not only impacted by drag of the high-speed water, but also by gravity, pressure force, Basset force, Magnu, lift, Saffman lift. Also these forces bring great difficulties to solve the equations. According to theory of two-phase flow [12], there are generally the following models for studying particle movement: dynamics model of a single particle, particles simulating fluid model (or more fluid model) and the particles orbital model (or Eulerian-Lagrangian mixed model). At present, the particles orbital model is used widely for simulating the turbulent flow, because it can save storage and time of computing, simulate easily the complex experience of the particles and avoid pseudo-proliferation[15,16]. The general mesh size of the abrasive used by pre-mixed AWJ cutting system is from 80 to 40. According to theory of the liquid-solid two-phase flow, abrasive will be as a discrete phase with ignoring the forces between particles and the impact of particles on the water.

Discrete mathematics equation is established using Euler-Lagrange model:

$$\frac{dU_{Pt}}{dt} = \frac{3\mu C_D \operatorname{Re}_P}{4\rho_\rho d_\rho^2}(U_{ci} - U_{pi}) \qquad (6)$$

Where, $U_{ci}, U_{pi}$ denote velocity component of water and particle respectively, $d_p$ denotes the diameter of abrasive particles, $\rho_p$ denotes the density of abrasive particles, $C_d$ denotes drag coefficient, $C_d$ =0.44.

## 3. NUMERICAL SIMULATION

### 3.1 Dimensional model

The purpose of simulating the flow field in abrasive mixing chamber is studying the movement rules of liquid-solid two phase and optimizing the design in order to achieve the purpose of making abrasive particles mixed fully with high-pressure water. The movement rules of the flow field can be simulated by FLUENT software.

The lower part of the abrasive chamber is chosen during this simulation in order to obtain the well abrasive mixing effect. The bypass water pipeline of abrasive chamber is only considered. The abrasive is mixed with injected high-pressure water in the abrasive chamber. The mixed water and abrasive discharge from the lower outlet. Then the high speed water carries discharged mixed flow from the lower outlet injected into the nozzle.

It can meet most needs of cutting when the volume of abrasive mixing chamber is 8L according to the condition of the mine and previous research results[17-19], this chamber with 8L that suits with underground working condition. The abrasive mixing chamber itself is a high pressure vessel with the same pressure of system. When the pressure is constant, the wall thickness is proportional to the diameter of the abrasive mixing chamber according to the wall thickness calculation expressions of the pressure vessel. Therefore, the size of the volume depends on its height not diameter for manufacturing conveniently. Four models with different sizes of mixing chambers were designed and selected under the condition that the volume of the mixing chamber is 8L. The ratio of height to diameter of four models marked A, B, C and D is shown in Tab.1.

The mixing chamber is simplified a two-dimensional model and the lower part of chamber is flat ellipsoid. It is simplified a problem of mansard plane to deal. Then, it should be adopted the same inlet angle and diameter for four different mixing chambers. The inlet diameter, exit diameter and vertical length of the abrasive chamber are 10mm, 18mm and 10mm. The mesh should be adopted triangular structured grid according to geometric features of the abrasive chamber.

Tab.1 Different sizes of abrasive mixing chamber

| Number | Height | Inner diameter |
|---|---|---|
| A | 400 mm | 160 mm |
| B | 500 mm | 140 mm |
| C | 700 mm | 120 mm |
| D | 270 mm | 200 mm |

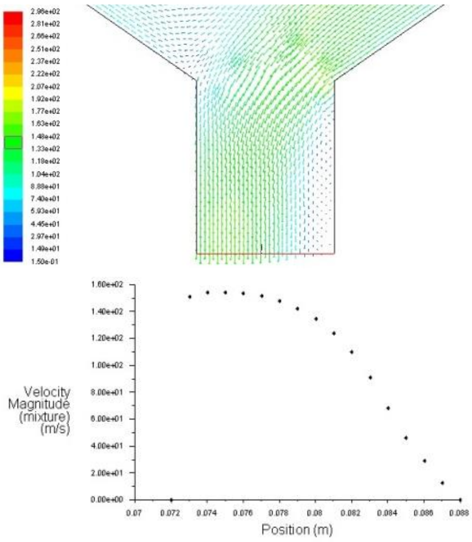
Tab.2 Material parameters

| Flow | Density（kg/m$^3$） | Viscosity(kg/(m·s)) |
|---|---|---|
| Water | 1e3 | 1e-3 |
| Abrasive | 4e3 | 1.7894e-5 |

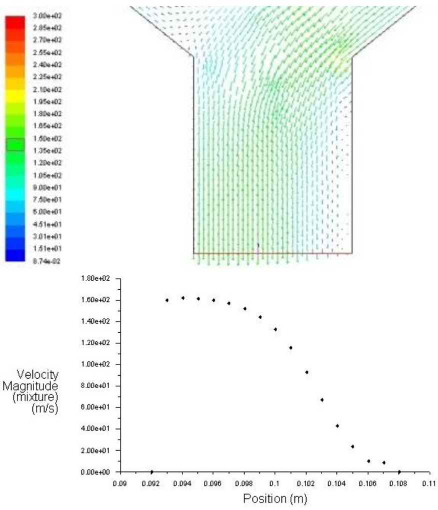
The boundary condition of pressure inlet is 30MPa. The initial inlet velocity of two-phase flow is 0. The volume fraction of the abrasive is 6%. The initial boundary condition of outlet is standard atmospheric pressure. The parameters of two phase material used in this simulation is shown in Tab.2.

**3.2. Results and discussion**

The velocity of mixed phase on the outlet section of four different abrasive mixing chambers is shown in Fig.1.




(A)

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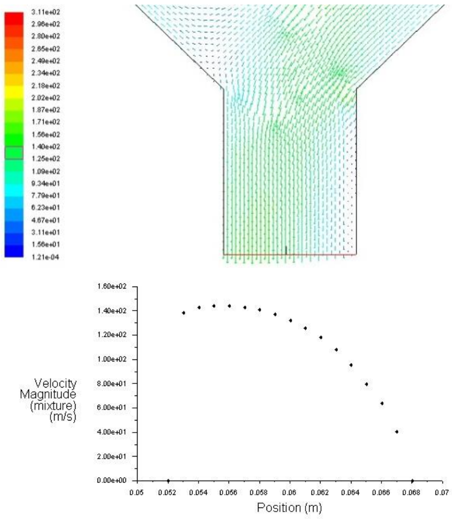


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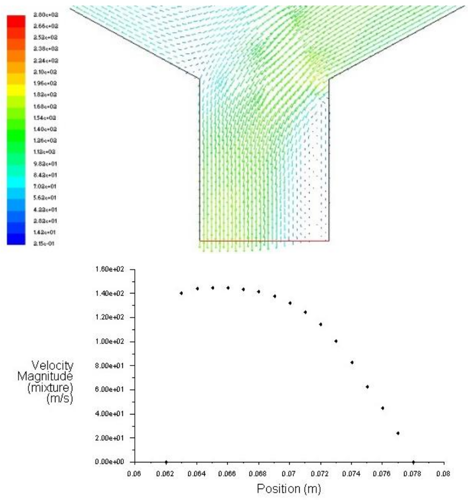



(D)

Fig.1 Outlet velocity of different abrasive mixing chamber models

The velocity of mixed phase on the outlet section of four different abrasive mixing chambers exhibited obvious differences because of different shapes. The maximum velocity of mixed phase from each cross-section is shown in Fig.2.

The velocity of abrasive is one of the main factors affecting abrasive water jet cutting effect. The larger velocity is, the greater kinetic energy of the abrasive has, and the stronger cutting capability can be gotten. The mixed phase of abrasive mixing chamber numbered B outlet have the maximum velocity under the same condition of inlet shown in Fig.2, so the model with number B is the optimum abrasive mixing chamber.

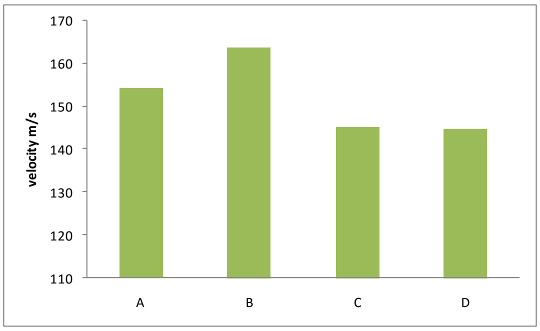
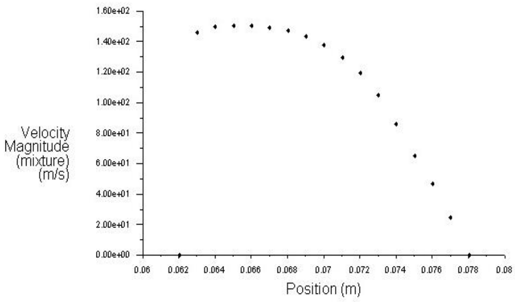



Fig.2 The max velocity of four abrasive mixing chambers

### 3.3. Simulation of abrasive concentration

Concentration of abrasive has an important influence on the cutting capability of abrasive water jet. So it is important to find the adapted concentration from technical, economic, security and other aspects.

The model of abrasive mixing chamber numbered B with different concentrations like 3%, 6%, 9%, 15%, 20%, 25%, 30% were simulated. The mixed phase outlet velocity of abrasive mixing chamber is regarded as the evaluation value, the outlet velocity of abrasive with different volume fraction are shown in Fig.3.

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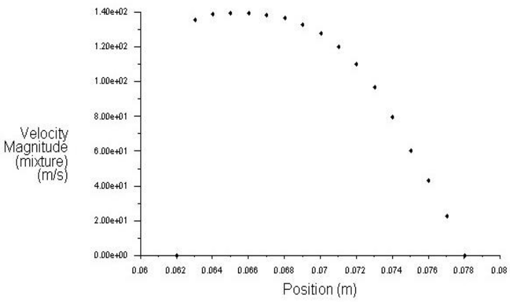


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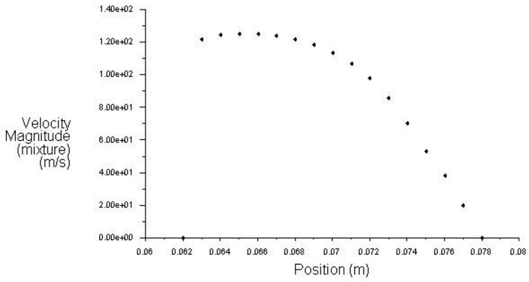


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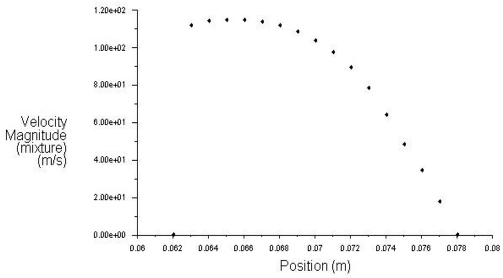


30%

Fig.3 Outlet velocity of abrasive with different volume fraction

The maximum outlet velocity of abrasive mixing chambers under 7 kinds of different volume fraction is shown in Fig.4.

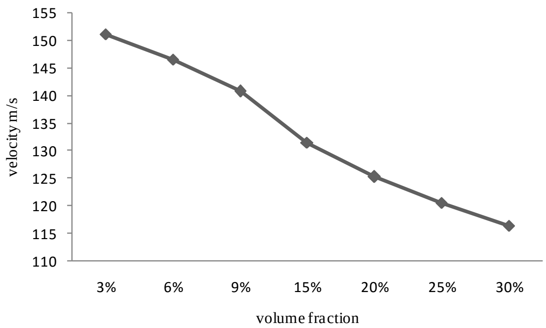


Fig.4 Outlet velocity of abrasive with different volume fraction

It can be seen that the mixed phase velocity of abrasive mixing chamber outlet reduces drastically along with the addition of volume fraction of abrasive from Fig.4. The reason is that the kinetic energy loss due to the collision between the abrasive particles and high-pressure water. The loss would increase along with the increase of the volume fraction of the abrasive. Therefore the outlet velocity of abrasive mixing chamber would reduce.

Fig.4 shows the mixed phase of abrasive water jet has a larger velocity when the volume fraction of abrasive under 10%. The velocity of mixed phase reduces significantly with the increase of volume fraction of abrasive. But the cutting capability can't be meet if the volume fraction of abrasive is too low and the effects of erosion and release would be weakened. Therefore, the volume fraction of abrasive should be controlled between 6%-10%.

## 4. ABRASIVE MIXING CHAMBER DESIGNING

According to the results of numerical simulation， a method of local slurry was used to develop the abrasive mixing chamber. A tee was increased on one side of the inlet pipe of the abrasive mixing chamber, it can shunt the flow to make high-pressure water flow into abrasive mixing chamber, and form abrasive slurry, the high-pressure water on the other side directly through the valve's straight pipes, high-pressure water is mixed with an abrasive slurry and formed an abrasive water jet then exported to nozzle. The abrasive slurry is controlled by lower valve body of the abrasive mixing chamber. When the lower valve body is closed, the abrasive slurry can't confluence with water piping and then the system forms water jet, as shown in Fig.5. The regulation of the abrasive concentration is achieved by using an adjustable throttle valve adjusting the flow ratio of the main and diversion circuit, the size of the abrasive concentration is determined by the amount of water in the shunt conduits. In order to prevent water or abrasive in the abrasive mixing chamber from refluxing through the shunt conduit when it doesn't work, a one-way valve was set up in bypass pipeline ,and a one-way diversion waterways were formed, Thus the diversion water can be stopped automatically after stopping pump.

Abrasive mixing chamber belongs to the inner high-pressure vessel. According to the general procedure of designing pressure vessel, the type of pressure vessel should be determined firstly, according to Safety Technology Supervision of Pressure Vessel, the abrasive mixing chamber belongs to the third category pressure vessel. The system working pressure is 30Mpa, in order to prevent overpressure, the pressure of abrasive mixing chamber is designed 40Mpa,and the thickness can be obtained by the equation. The aspect ratio of designing pressure-volume is generally 2-5. The designing inner diameter is 140mm, height is 500mm and the aspect ratio of abrasive mixing chamber is 3.6, which meets the design requirements.

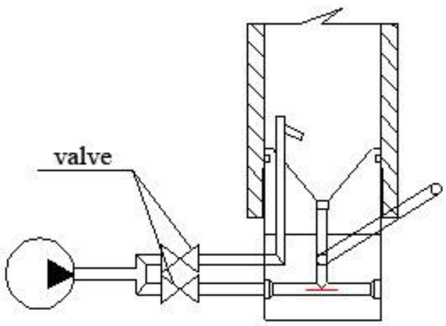


Fig.5 Assembly drawing of abrasive mixing chamber

The laboratory cutting experiments were tested in China University of Mining and Technology (Beijing) abrasive water jet cutting platform, as it is shown in Fig.6, the cutting pictures were taken by high-speed photography, the pressure of water was 35MPa, and the diameter of nozzle exit was 0.8mm, the target distance was 10mm, and the velocity of cutting was 50mm/min, and the concentration of abrasive was controlled between 6%-10%.When the 45# steel specimen was cut by using this abrasive mixing chamber, the cutting depth can up to 30mm, which could achieve the desired requirements.

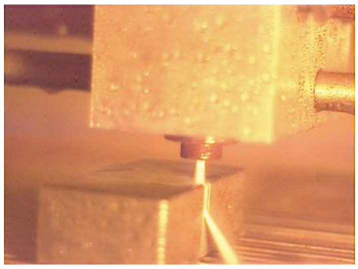

Fig.6 45 # steel cutting

## 5. CONCLUSIONS

(1)The mathematical and dimensional model of two-phase flow in pre-mixed abrasive water jet mixing chamber have been established and its boundary condition has been determined. The isothermal, incompressible, steady-state liquid-solid turbulence in abrasive mixing chamber was simulated using FLUENT software. The law of velocity in the flow field was analyzed. The numerical simulation results formed the foundation of optimizing the performance, materials and technology of abrasive mixing chamber.

(2)Four different structural dimensions of abrasive mixing chamber model were simulated and the ratio of height to diameter of four abrasive mixing chamber models was determined. The height and diameter of optimal structure size are 500mm and 140mm.

(3)The outlet velocity of abrasive mixing chambers with different volume fraction has been gotten through simulation. The volume fraction of abrasive should be controlled between 6%-10% based on the technical, economic, security and other factors.

(4) The abrasive mixing chamber used in the mine field had been developed according to numerical simulation and theoretical analysis. The abrasive mixing chamber can modulate abrasive slurry that has appropriate concentration, and laboratory cutting experiments were tested. The abrasive slurry can be sent to nozzle through high-pressure pipeline. Then it could form abrasive water jet after accelerating by nozzle to meet the needs of safety cutting in the field of mine, which could achieve the desired requirements.

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**CONFLICT OF INTEREST**

No conflict of interest was declared by the authors.

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