Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2017, 4(7):160-168**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Optimum Design of Foam Dust nozzle in Fully- mechanized Face

Zhen Wei[1]*, Zhongliang Lu[1, 2], Hongli Wang[3], Dingling Zhang[4]

[1]School of Safety Science and Engineering, Henan Polytechnic University, Henan, Jiaozuo, China;
[2]Professor, The Collaborative Innovation Center of coal safety production of Henan Province, Henan, Jiaozuo, China;
[3]Associate Professor, School of Mathematics and Information Science, Henan Polytechnic University, Henan, Jiaozuo, China.
[4]Lecturer, School of Mathematics and Information Science, Henan Polytechnic University, Henan, Jiaozuo, China

Abstract When the foam dust removal process is applied in the fully mechanized coal mining face, most of the foam produced by the foaming equipment is submerged to cover the dusty working surface, which is used to suppress the outward diffusion of dust. However, the foam that couldn't cover the dust source will block the roadway, affecting the operator's sight, and have a serious impact on production safety. Based on the above-mentioned situation, we firstly analyzed the mechanism of foam dust removal, and then introduced the preparation process of foam. In order to achieve the full use of foam and improve the work environment to eliminate security risks, we designed a new kind of nozzle, combining with the annular arrangement. Finally, used FLUENT to compare the design export with the traditional round one by simulation to determine the best size.

Keywords Dust; Froth Dedusting; Nozzle Outlet; Jet; Numerical Simulation

Introduction

Nowadays, coal plays a leading part in Chinese total primary energy consumption and economy. China's coal production in 2014 was 3.87 billion tons, accounting for about 70% of its total primary energy consumption, which is predicted to still take up 50% in 2050 [1]. Dust as one of the five major disasters in coal mines [2], which badly threatens the production safety. Fully mechanized excavation face has always been the dust-producing area in coal mine. With the rapid improvement of mechanical automation, high dispersion dust has been dispersing in the tunnel, posing the threat to workers' lives and equipment. Therefore, it's being the key point of dust control.

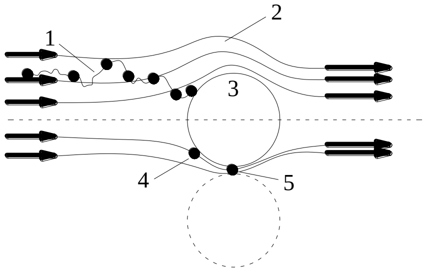
At present, the usual dust management measures adopted under coal mine are as follows: coal seam water infusion, spraying and dust settling, dust collector, ventilation and dust control [3-5], etc. Each measure possesses some dedusting effects, but still exists some shortcomings. Froth dedusting as a new application has the advantages of high dust extraction efficiency, low water consumption and high capturing efficiency on respirable dust. Yet problems still exist, such as lower froth utilization ratio and froth deposit that hinders drivers' sight. Based on the case above, one nozzle combined with cyclic arrangement will be devised to clarify workers' sight while ensuring dedusting efficiency, to improve foam utilization [6].

2. Froth dedusting

2.1. Mechanism of Froth dedusting

Froth dedusting means that by mixing water and foaming agent according to some proportion via specific device. The mixed liquid generates a large amount of high efficiency and expansion froth through froth producing equipment, then it will be sprayed out of nozzle to cover dust source. Foam group has large volume and surface area, causing dust to be quickly moistened and refrained to reach the effect of dust removing [7].

Fig. 1 shows that dust particle reaching foam surface usually experiences such processes as colliding, mulching and diffusing etc. After going through the processes above, dust finally reaches foam surface. As a result of adding the foaming agent, the surface tension of the foam is significantly decreased, while the wetting ability of the foam to the dust is remarkably improved. After the reactions, the suspended and dried dust is rapidly wetted and its weight changes. When the weight is greater than the buoyancy, the particles would settle and fall to the ground.



1-Brownian Movement of dust 2-gas flow line
3-foam 4-collision 5-coverage

Figure 1: The interaction between dust and foam

Compared with other dust removing measures, froth dedusting has the following features: ① Foam sprayed on the dust source can constitute on the dust source with no gap coverage, preventing dust diffusion [8]. ② Foam covered on dust source has larger volume and surface area, enabling the contacting percentage between dust and foam to increase. ③ Foam liquid with surfactant [9-11] increases the ability of dust absorbing and prolongs the time of foam drainage, blowhole diffusion and half-life period, its stability increases [12]. Meanwhile, the surface tension of foam declines to a large degree, enabling dust moistened after being rapidly contacted with foam, improving dust removing efficiency comprehensively.

2.2 Technological Process of Dedusting

As shown in Fig. 2, the main equipment includes: water-storage tank, pump, proportioner, medicament adding pump, foaming device, air compressor, nozzle device. The key steps during the technological process include: ① Add the clean water into the foaming agent pipeline according to the proportion to the mixer by using medicament adding pump, which is used to make them fully blended. ② Draw the compressed air produced from air compressor into froth producing equipment, foaming agent mixed liquor and the compressed air in the froth producing equipment will form into high-property froth by means of jetting, entraining, disorder and so on. ③ The mixture will reach nozzle equipment via pipeline, spraying to dust source to make no gap coverage.

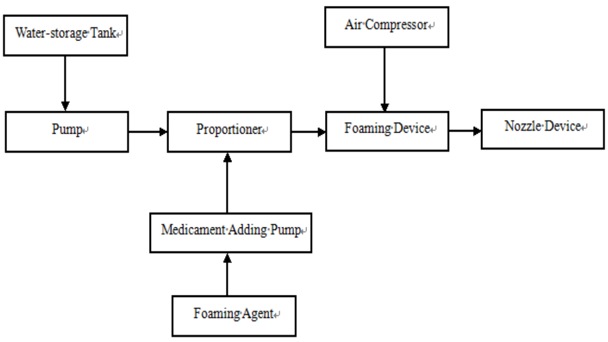


Figure 2 The Schematic of the Process of Froth Dedusting

2.3. Optimization Design of Nozzle Outlet

Without regard of air current influence on dust diffusion, it can be seen by combining the working mode of vertical shaft-type tunneling machine, the dust mainly flies off along the tangential of rotation of cutting head when cutting head crushes coal-rock mass. To prevent the dust from diffusing, and also combining with the dust flying feature, the annular arrangement will be adopted to make the froth into annular seamless wrapping on the contacting point of cutting head and coal-rock mass.

Sprinklers are widely used in garden afforests, agricultural production, spray dust removal, etc. The purpose of these nozzles is atomizing the liquid, only for single-phase fluids, and not appropriate for bubble-like two-phase or multiphase fluids [10-12]. However, the theoretical system for foam fluid dispersion is not yet very mature, there are many factors that affect the effect of foam nozzle spray. This paper aims to optimize the design of the foam nozzle and determine the optimal size, improving the foam utilization.

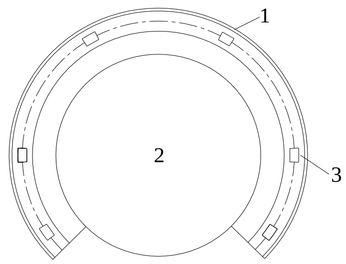
The circular outlets of nozzles are mostly used in coal mine, which has a large amount of flowing, low pressing gradient and the froth will not crack with rapid pressure change. When such kind of jetting flows into working face while the jetting cross section of circular outlet is round, quite a number of froth will fail to cover effectively on cutting head, causing the froth utilization ratio to decrease. Therefore, devising the nozzle outlet into plane sector outlet in view of the characteristics of plane jet, making the constraint on the jetted froth, which is adding diffusion effects of long axis, constraining the diffusion effects of short axis, creating larger covering with the outside of cutting head, making more froth close to the vertical orientation of cutting head.

Combined with literature [13-14], the devised nozzle is shown in Fig. 3, the short axis width is about 8mm, the long axis width of 20mm, the sector central angle of 120°, using the streamlined design.

Figure 3: Schematic of the Devised Nozzle

The foam mixture is ejected from the orifice, slit or nozzle, and the diffusion movement in the gas after escaping the solid boundary is defined as the bubble jet. Foam jet is a multiphase flow problem, since the size of a single bubble is much smaller than the geometric size of the jet, it can be approximated as a homogeneous flow. The boundary layer of the foam mixture and the outside air has a large velocity gradient that is not continuous, and the mixed liquid jet will fluctuate during the course of the movement. Then it will form a vortex and cause the bubble turbulence, foam mixture and air in the boundary layer blending would blend under the action of turbulence. During the blending process, it gradually performs from the boundary layer toward the central area of the bubble jet. After a certain time, the blending process occurs at the central area so that the jet is turbulence cross the entire section. Besides, the devised outlet adopts streamlined design, mainly in order to increase the fluid diffusion effect along the export of long axis direction, and constrain the proliferation of the bubble flow along the short axis, then get a larger coverage in the parallel direction with the cutting head, making more bubbles move closer to the cutting head in the vertical direction.

As the installation position of the nozzle is mostly located in the no-support area, where coal-rock mass often drops. In order to prevent the nozzle from being smashed to lose efficacy, the upper nozzle will be supported with circular steel plate while being given circular arrangement, with the steel thickness of 7~10mm. Fig. 4 shows the annular arrangement and protection way of the nozzle.



1−baffle 2−cutting head
3−the devised nozzle

Figure 4: The Nozzle Arrangement

The annular arrangement is adopted on the nozzle, which enables some emitted froth to form the complete coverage on the cutting head. When the cutting head breaks the coal-rock mass, the froth can deeply penetrate into the coal and rock body, restraining the dust diffusion from the source. Another part of froth is absorbed around the cutting head, the froth captures the escaped dust while moisturizing the cutting head around. The annular arrangement also enables the froth to reach the bottom of the cutting head so that the bulk of coal-rock is still wrapped after being separated from the wall surface, avoiding the occurrence of the fugitive dust and clarifying the sight of driver to ensure production security.

3. Numerical Simulation

In order to verify the diffusion effect of the design export, the circular export is used as the reference object. Meanwhile, the flow of the two kinds of outlets is simulated by using the FLUENT module in ANSYS Workbench.

3.1. Establishment of Mathematical Model

The model $k-\varepsilon$ chosen in this paper [15-17] is based on the equation for turbulent kinetic energy, and then introduces a commonly used turbulence model for turbulent kinetic energy dissipation rating (ε), which is defined as:

$$\varepsilon = \frac{\mu}{\rho}\overline{\left(\frac{\partial u_i'}{\partial x_k}\right)\left(\frac{\partial u_i'}{\partial x_k}\right)} \tag{1}$$

Turbulent viscosity can be defined as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{2}$$

where C_μ is an empirical constant.

According to the equations of N-S and $k-\varepsilon$, continuity equation can be defined as:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{3}$$

$$\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=S \tag{4}$$

$$E=\begin{bmatrix}\rho uu-\mu_{eff}\dfrac{\partial u}{\partial x}\\ \rho uv-\mu_{eff}\dfrac{\partial v}{\partial x}\\ \rho uw-\mu_{eff}\dfrac{\partial w}{\partial x}\end{bmatrix}, \quad F=\begin{bmatrix}\rho uu-\mu_{eff}\dfrac{\partial u}{\partial y}\\ \rho uv-\mu_{eff}\dfrac{\partial v}{\partial y}\\ \rho uw-\mu_{eff}\dfrac{\partial w}{\partial y}\end{bmatrix}, \quad G=\begin{bmatrix}\rho uu-\mu_{eff}\dfrac{\partial u}{\partial z}\\ \rho uv-\mu_{eff}\dfrac{\partial v}{\partial z}\\ \rho uw-\mu_{eff}\dfrac{\partial w}{\partial z}\end{bmatrix},$$

$$S=\begin{bmatrix} \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(u_{eff}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial x}\right)-\frac{\partial p}{\partial x} \\ \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(u_{eff}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial y}\right)-\frac{\partial p}{\partial y} \\ \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(u_{eff}\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial z}\right)-\frac{\partial p}{\partial z} \end{bmatrix}$$

where $\mu_{eff}=\mu+\mu_t$, the sum of molecular viscosity and turbulent viscosity means the effective viscosity coefficient.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

$$G_k=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{7}$$

Equation (7) means the generation of the turbulent kinetic energy (k) caused by the average velocity gradient. In the above equations, the empirical constants C_μ、 $G_{1\varepsilon}$、 $G_{2\varepsilon}$、 σ_k、 σ_ε [17] are shown as follows:

Table 1: Constants that describe the standard $k-\varepsilon$ model

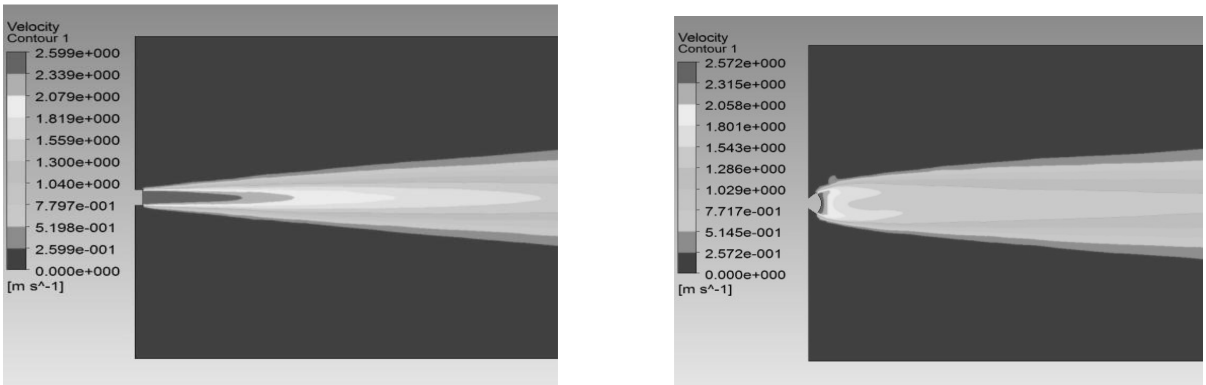
C_μ	$G_{1\varepsilon}$	$G_{2\varepsilon}$	σ_k	σ_ε
0.09	1.44	1.92	1.0	1.3

3.2 Setting of Simulation Parameter

For the simulation, the circular outlet diameter is defined as 15mm, the long axis width of the devised nozzle is 20mm, the short axis width of the devised nozzle is 8mm, the sector central angle of devised nozzle is 120°, the boundaries area is devised as 300 mm ×500 mm. The gridding division will be made by using quadrilateral elements, the element size set as 2 mm and the divided areas of Orthogonal Quality as 0.99 and 0.76 respectively, which will better reflect the real state of jet. The inlet and outlet are respectively selected as the pressure-inlet and pressure-outlet. The Gauge Total Pressure is set as 152248 Pa, adopting the standard $k-\varepsilon$ turbulence model. The solution will be made by using SIMPLE algorithm.

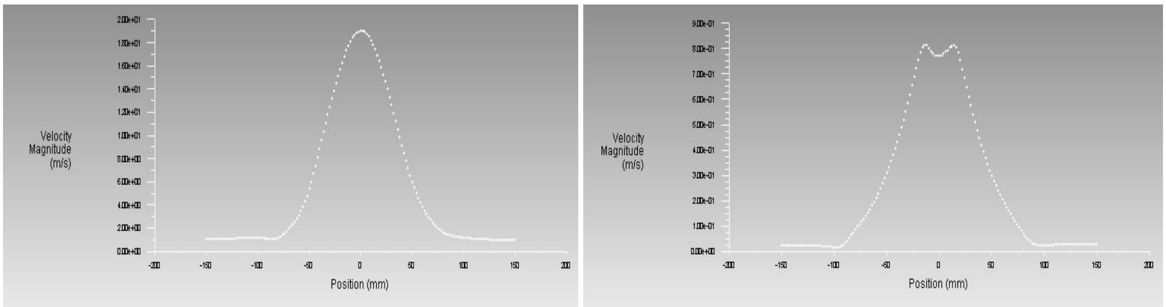
4. Results and Discussion

The simulation results are shown as follows:



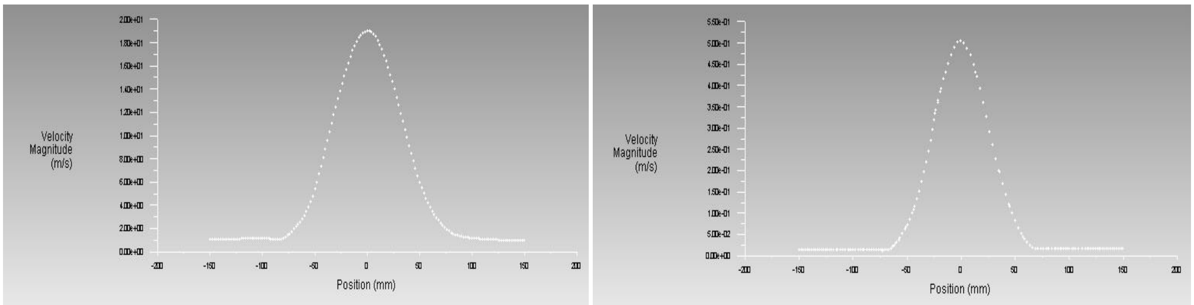
a) The Diffusing Effect of Circular Outlet Jetting *b) The Diffusing Effect of Devised Outlet Jetting*

Figure 5: Schematic of the Diffusing Effects of Different Outlets Jetting



a) Velocity Distribution at 400mm from the Circular Outlet b) Velocity Distribution at 400mm from the Devised Outlet

Figure 6: Jet Velocity Distribution of the Long Axis at 400mm from the Nozzle Outlet



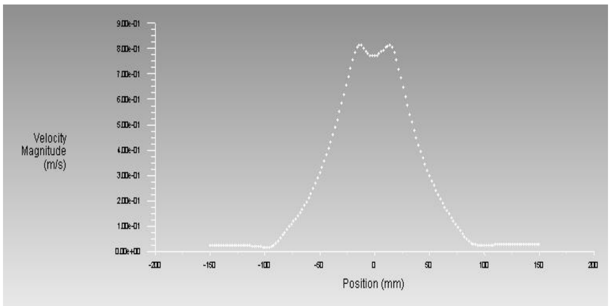
a) Velocity Distribution at 400mm from the Circular Outlet b) Velocity Distribution at 400mm from the Devised Outlet

Figure 7: Jet Velocity Distribution of the Short Axis at 400 mm from the Nozzle Outlet

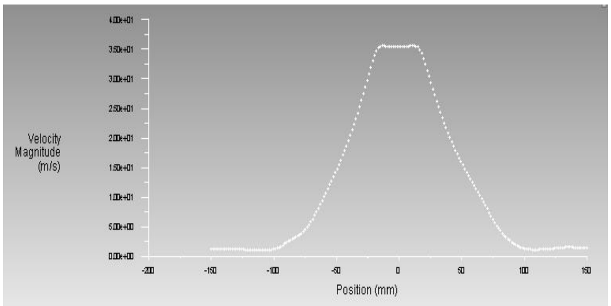
It can be seen from fig. 5 that the devised nozzle outlet has a better effect on jet diffusion than circular outlet. Fig. 6 shows the maximum width of the jet velocity distribution of the long axis at 400 mm from the circular outlet is about 150 mm, while the maximum width of devised outlet is about 200 mm. Fig. 7 shows the maximum width of the jet velocity distribution along the short axis of circular outlet at 400 mm is about 150 mm, while the one along short axis of circular outlet at 400 mm is about 120 mm.

According to fig. 5~7, the froth sprayed from the devised nozzle outlet in the paralleled direction with the cutting head has bigger covering range than the circular outlet, while the diffusion in the short axis being constrained, more froth is gathered to the cutting head. Suppose that there exists one maximum circular covering, in which the froth all can cover the cutting head, while the froth beyond the scope cannot do. When the two kinds of nozzle produced the froth with the same volume, combined with the above simulation analysis, assuming that the devised nozzle enables the froth to be in larger proportion within the scope. For the round outlet, the long axis is shorter and the short axis is longer, which causes a considerable part of the foam cannot reach the cutting head and the utilization rate is low. If the two kinds of outlets are required to achieve the same amount of coverage on the cutting head, the devised nozzle will be better than the circular one to fulfill the coverage on the cutting head in less time.

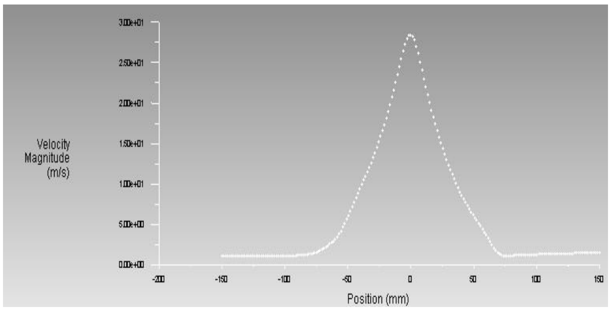
To figure out the optimum size of devised nozzle outlet, the simulated comparison of different sizes of outlets was made by using FLUENT software under the same conditions. The outlet with the long axis width of 20 mm, short axis width of 8 mm, and the sector central angle of 120 °, which is defined as outlet 1. The other two outlets are defined in table 2. The velocity distributions of foam emitted from 3 kinds of outlets at 400 mm distance are respectively shown in fig. 8 ~ 9 and table 2.



(a) Velocity Distribution along the Long Axis of Outlet 1

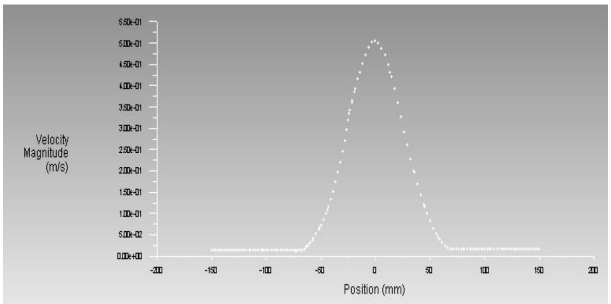


(b) Velocity Distribution along the Long Axis of Outlet 2

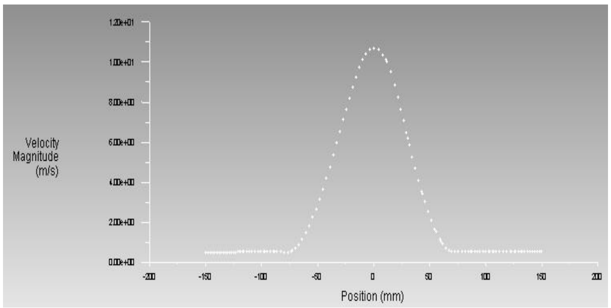


(c) Velocity Distribution along the Long Axis of Outlet 3

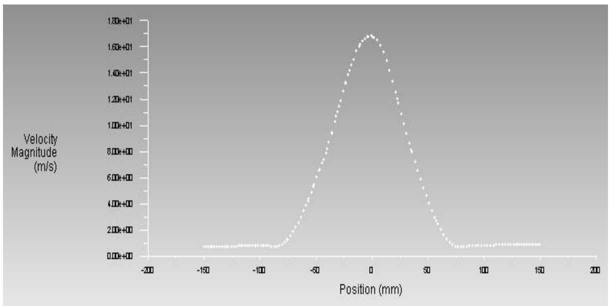
Figure 8: The Jet Velocity Distribution along the Long Axis at 400mm from Different Nozzle Outlet



(a) Velocity Distribution along the Short Axis of Outlet 1



(b) Velocity Distribution along the Short Axis of Outlet 2



(c) Velocity Distribution along the Short Axis of Outlet 3

Figure 9: The Jet Velocity Distribution along the Short Axis at 400mm from Different Nozzle Outlet

Table 2: Diameters of the jet for long and short axis from different outlets

Outlet	Long Axis width /mm	Short Axis width /mm	Central Angle / °	The jet width of long axis /mm	The jet width of short axis /mm
1	20	8	120	200	120
2	25	5	140	200	150
3	30	10	100	150	160

As can be seen from the simulated results above, though the long axis of outlet 2 increases in width, long axis width of jetting is similar to outlet 1, short axis of jetting increases in width significantly. Compared with outlet 1, long axis width of jetting for outlet 3 significantly decreases, short axis width of jetting remarkably increases. The jetting constraint effects of both outlet 2 and outlet 3 are not as good as outlet 1. Therefore, the dimension of outlet 1 is finally determined as the optimum one.

5. Conclusion

- The outlet with the long axis width of 20 mm, short axis width of 8 mm, and the sector central angle of 120 ° is defined as the optimum devised one. Compared with the circular outlet, the devised nozzle will finish the coverage of the cutting head in shorter time for using the same amount of froth.
- The high-expansion froth that the nozzle produces in the arrangement of cutting rocker arm will form the circular drown on the dust from the working face, making the splashed dust captured by the produced froth simultaneously, thus improving the dust extraction efficiency.
- If firstly spray water before starting the froth dedusting to moisturize the dust, the influence of raised dust from the wind on the dust concentration will be decreased, further improving the dedusting effects.
- Through the FLUENT software to simulate the jet velocity distribution of different exports along the long and short axis, you can visually determine the nozzle jet effect, which can replace the experimental method. Besides, it greatly shortens the test cycle, reduces research funds and provides a new approach for the optimization design of the foam dust nozzle.

Acknowledgments

This study was supported by National Natural Science Funded Project of China (No. 51174109). We also thank reviewers for their valuable suggestions to improve this article.

References

[1]. Bo-quan Lin, Jian-hua Chang, Cheng Zhai. (2006) Analysis on coal mine safety situation in China and its countermeasures. *China Safety Science Journal*, 16(5):42-46.

[2]. Yan-qiang Li, Yue-ping Qin, Xiao-bin Yang, Liang Tian. (2011) New progress on coal mine dust in recent ten years. *Procedia Engineering*, vol 26:738-743.

[3]. Guo-shu Zhang. (2011) *Ventilation and Safety*. China University of Mining Press, 2nd Ed., 305-312.

[4]. Hua-wei Li. (2005) Comprehensive control of respirable dust in coal mines. *China Safety Science Journal*, 15(7):67-69.

[5]. He-tang Wang, De-ming Wang, Wan-xing Ren, etc. (2009) Research status and development trend for foam dust control technique in underground coal mines. *Metal Mine*, (12):131- 134.
[6]. Yi-kun Zhang. (2012) Study on dust control technology with foam in fully mechanized workface of Huoerxinhe coal mine. *China Safety Science Journal*, 22(02):151-156.
[7]. Long-zhe Jin, Jin-ping Li, Yu-fu Sun. (2010) *Coal Mine Dust Control Technology*. Science Press, 1st Ed., 236-240.
[8]. Xin-xiao Lu, De-ming Wang, He-tang Wang, etc. (2011) Experimental research on dedusting foam in underground coal mines. *Safety in Coal Mines*, 42(06):1-3.
[9]. Wan-xing Ren, De-ming Wang, Bin-wei Wu, etc. (2009) Dust control technology with mine foam. *Coal Science and Technology*, 37(11):30-32,36.
[10]. Wan-xing Ren. (2009) Research on the theory and technology for dust control by foam in underground coal Mines. Xuzhou: China University of Mining.
[11]. Peng-fei Zhao, Zhong-an Jiang, Zeng-lin Zhen, Xiao-feng Han. (2006) Foam dust remove technology and application in roadway heading face. *Coal Science and Technology*, 34 (12):38-41.
[12]. Jing Zhou, Yong-sheng Tan. (1999) Study on stable foam fluid. *Drilling & Production Technology*, 22 (6):75-78,81.
[13]. Xiao-dong Zhang, Zhi-guo Dong, Peng-fei Hao, etc. (2008) Design of flat fan nozzles and its experimental study. *Machine Design and Research*, 24(1): 89-92.
[14]. Hong-qi Li, Hong-bo Liu. (2008) The application of the FLUENT software in the process of designing flat fan nozzles. *Development & Innovation of Machinery & Electrical Products*, 21(5): 106-107,128.
[15]. Bao-yi Liu. (2014) Research on dedusting foaming agent orthogonal and corresponding experiment in fully mechanized excavation face. Jiaozuo: Henan Polytechnic University.
[16]. Zhu-lin Yuan, etc. (2013) *Gas solid two phase flow and numerical simulation.* Southeast University Press, 1st Ed., 58-60.
[17]. Zhao-shun Zhang, Gui-xiang Cui, Chun-xiao Xu. (2005) *Theory and modeling of turbulence.* Tsinghua University Press, 1st Ed., 209 -215.