Numerical Simulation of Cooling Effect of Different Spray Water Temperature on Coal Face based on CFD

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Abstract. In order to effectively restrain the adverse effects of high temperature environment on the working area of fully mechanized coal mining face, a mathematical model describing the interaction between droplets and air flow was established and the accuracy of the model was verified. Finally, under the same ventilation conditions, the temperature distribution of the nozzle under different temperatures was studied in detail. The results show that the temperature distribution in different areas along the roadway is basically the same when the spray scheme is applied at different temperatures, and all of them decrease first and then increase. In all spray schemes, the best cooling effect is achieved by using K2.0 nozzle and spray water temperature of 278k.

Keywords: Coal face; Numerical simulation; Ventilation and cooling; Spray; Numerical simulation.

1. Introduction

With the continuous increase of mining depth, the geological conditions worsen, the broken rock mass increases, the in-situ stress increases, the water inflow increases, and the ground temperature rises, which brings a series of problems, such as deep ground pressure, lifting capacity, deterioration of working environment, ventilation and cooling, and sharp increase of production cost, which inhibit the improvement of production capacity and the full recovery of mineral resources, among which the most prominent problem is the temperature increase.[1-7] The temperature of underground strata increases with the increase of depth. According to statistics, the rock temperature increases with a gradient of 3 °C / 100M below the normal temperature zone. In a deep well more than 1 km, the rock temperature will exceed the human body temperature. For example, in the western mine of South Africa, the rock temperature is as high as 80 °C at the depth of 3000 meters. A method of spray cooling is put forward to treat heat hazards in mines. Underground coal mining face, the airflow flows through the spray area and heat exchange. The water mist ejected from the nozzle is composed of water droplets with micron diameter. The heat transfer area of the air and water increases greatly, so as to accelerate the heat exchange efficiency of the droplet and the underground hot air. Because of the small size of fog particles, the heat exchange with air flow can be regarded as a transient heat and mass transfer process. In this process, the heat is transferred from the high temperature gas to the low temperature droplets,

**Note:** The rest of the text is not visible in the image provided.
and the water vapor formed by evaporation is released into the ambient gas in the form of convection and diffusion.

2. Numerical simulation
In this study, rhino 3D modeling software is used to build the physical model. The modeling accuracy of the software reaches the industrial standard. The physical model can be quickly established by using the built-in controls. The Fluent built-in solver is used to calculate the flow field and temperature field. At the same time, the post-processing software provided by ANSYS can comprehensively check the wind temperature, wind speed and other parameters in the space environment, and can evaluate the cooling effect. Therefore, the thermal environment of fully mechanized working face can be simulated by using these software.

2.1. Physical model
The size of the working face of this model is 150m × 4.2m × 4.3m, and the sizes of inlet and return air roadways are both 80m × 4.2m × 4.3m. The width of the hydraulic support is 1.5m, there are 95 hydraulic supports, and the first seven supports move forward by 0.8m; there is a double drum shearer at 18.5M from the coal mining face to the air intake roadway, the length of the shearer is 12 meters, the diameter of the drum is 1.6m, the mining height is 4.3m, and the cutting depth is 0.8m. In this study, a cone spray solid nozzle, which is commonly used in external spray system, is selected. It is a flaring nozzle with a X shaped guide core. The diameter of the nozzle is 2.0mm. The liquid flows at high speed under the water pressure of 2-8MPa, and a centrifugal vortex is formed in the guide vane. It can spray tiny particles of 50 to m diameter from the jet hole. The positive direction of X axis indicates the direction from the working face to the entrance of air inlet roadway, the positive direction of Y axis represents the direction from the air inlet side to the return air measurement in the working face, and the positive direction of Z axis represents the direction from the roadway floor to the roadway roof.

Fig. 1 geometric model

2.2. Grid generation and grid independence test
In the numerical simulation, the number of grids has an important impact on the simulation results, but if the number of grids is too large, the calculation amount of simulation is too large, which affects the
efficiency. Therefore, in order to ensure both the results and the computing speed, we test the grid independence. Three kinds of grids with different densities are generated, namely low, medium and high quality meshes. Three kinds of grids with different quality are shown in Fig. 2. Fluent software was used to simulate the distribution of wind speed and temperature in coal face under different grid quality. In the geometric model, five measuring points are set up: point a (x = 2.2, y = 10, z = 2.15), point B (x = 2.2, y = 30, z = 2.15), point C (x = 2.2, y = 50, z = 2.15), point d (x = 2.2, y = 70, z = 2.15), and point E (x = 2.2, y = 90, z = 2.15) are set. As shown in Figure 3, the wind speed data of these five measuring points are exported and analyzed. As shown in Fig. 4, it can be seen that when medium and high grid quality is used, it is highly consistent with the measured data. When the grid quality is low, there is a big deviation between the simulation results and the measured data, which means that the low-quality grid generation is unreasonable. Considering the influence of simulation efficiency and other factors, the geometric model is divided into medium quality meshes. There are 2540096 grids in the geometric model, which can be used for numerical simulation.

![Fig.2 three different quality finite element meshes](image)

![Fig. 3 location of measuring points](image)
Fig. 4 Simulation of different mass grids and actual measured wind speeds

2.3. CFD numerical simulation
In view of the three-dimensional stable flow field and temperature field in fully mechanized mining face, the mass conservation equation, momentum equation, energy conservation equation and turbulence model equation are solved by Fluent. Before the numerical simulation of fully mechanized working face, the wind speed and temperature calculated by several common turbulence models, such as zero equation model, standard \( k-\varepsilon \) model and RNG \( K-\varepsilon \) model, are compared and analyzed with the measured results by anemometer and thermometer. The results show that the RNG \( K-\varepsilon \) model is more reliable and accurate than the standard \( k-\varepsilon \) model in the motion of large streamline curvature, which can describe the effect of small-scale turbulence. Therefore, RNG \( K-\varepsilon \) model is selected in this study.

The continuity equation of gas can be written as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho v_i) = 0
\]

According to the law of conservation of mass, the following expression can be obtained:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

The momentum equation can be written as:

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
\]

The energy equation can be written as follows:
The governing equations are as follows:

\[ \frac{\partial}{\partial t} (\rho v_i T) = - \frac{\partial}{\partial x_i} \left( \frac{\mu}{\rho} \frac{\partial T}{\partial x_i} \right) + \frac{q}{c_p} \quad i = 1/2/3 \]

In the simulation software, \( \alpha \) = \( \alpha \varepsilon \approx 1.393 \), \( \mu_{\text{eff}} \) is the effective viscosity coefficient (PA · s), \( C_1 \varepsilon \) and \( C_2 \varepsilon \) are model constants, \( G_k \) is the generation term of turbulent energy \( k \) caused by average velocity gradient (PA / s), and \( R \varepsilon \) is an additional term.

2.4. Boundary conditions

The working environment of the fully mechanized mining face is relatively complex, so we should simplify the building model on the basis of not affecting the regularity of physical phenomena and simulation results when we conduct numerical simulation. According to the known main factors affecting the problem and the principle of simplifying the simulation process, the following assumptions are made:

(1) In this case, the change of air density can be ignored. The ventilation airflow in the fully mechanized working face is regarded as an incompressible fluid. The heat on the surrounding rock surface is evenly distributed, and the thermal physical parameters are constant, and the wall roughness is uniform;

(2) Entrance and exit boundary: it is considered that the inlet air velocity of the fully mechanized mining face model is uniform, the air temperature at the entrance boundary is set as the same as the actual situation, the initial velocity of air flow is \( v = 2 \text{ m/s} \), the temperature of air supply is \( t = 300 \text{K} \), the influence of Goaf Air Leakage and roadway wall roughness on flow field can be ignored, and the outlet boundary is set as free reflux;

(3) When the shearer is not working, the heat dissipation of surrounding rock can be calculated as \( 170 \text{W/m}^2 \) by measuring the change of airflow temperature and the area of working face when the shearer is not working;

(4) Heat source conditions: the installed power of the shearer is \( 319 \text{kw} \), the average heat dissipation power is 30% of the installed power, i.e. \( 95.7 \text{kw} \). The model area of the shearer is \( 35 \text{m}^2 \). Assuming that the heat dissipation of the shearer is evenly distributed, the heat dissipation capacity of the shearer is \( 2734 \text{w/m}^2 \).

3. Simulation results

The immutable and frozen water spray system is not invariable in the actual application of the underground cooling system. Instead, it is controlled by the refrigeration equipment. The water temperature of the low-temperature spray is generally within \( 283 \text{K} \), and the lowest water temperature can be as low as \( 276 \text{K} \). When the spray is in the heat transfer with the air, when the spray reaches the same temperature as the air, the lower the temperature is, the more heat the spray will absorb. But lowering the water temperature will also cost more to cool the system. In order to ensure the cooling effect and save costs as far as possible, the effects of spray water temperature on \( 276 \text{K}, 278 \text{K}, 280 \text{K} \) and \( 282 \text{K} \) on the cooling effect are simulated, as shown in Fig. four 5. Record the temperature at the...
center of section b1-b6 under each water temperature, and make a broken line chart in Figure 6 for comparative analysis.

![Temperature distribution on Section B at different water temperatures](image)

**Fig. 5** Temperature distribution on Section B at different water temperatures

![Temperature at different temperatures of spray sections at different temperatures](image)

**Fig. 6** Temperature at different temperatures of spray sections at different temperatures

According to Fig. 5, it can be seen that there is a significant temperature drop between the section B1 and the section B2. This is because the low-temperature spray comes out of the nozzle and heat exchanges with the hot air, and the temperature decreases rapidly. The temperature drop in this area is mainly affected by spray. There is a marked increase in temperature in the B4 interval between B2 to
section, which is mainly due to the two aspects of temperature change in this area, which are affected by low temperature spray and heat production of shearsers. Shearer work produces a lot of heat. The temperature increase in this area is mainly affected by the working heat of the shearer. Secondly, the low-temperature spray continues to heat exchange in the air, the temperature gradually increases, and the cooling effect gradually decreases. By comparing the slope of the two heating curves between the section B2 and the section B4, it can be found that the temperature change in this area is more and more influenced by the shearer, and the cooling efficiency decreases with the increase of distance. The cooling between the section B4 and the section B6 is mainly due to the fact that with the distance from the shearer, the temperature is less and less affected by the heat production of the shearer, and the temperature change in this area is affected by spray cooling and rock wall heat production.

By calculating the average temperature of the middle point of each section of water spray at different temperatures, it can be concluded that the average temperature of the middle point of each section decreases by 0.55K and 0.35K at the same temperature between 282K, 280K and 278K. However, as the spray water temperature continues to decrease from 278K to 276K, the average temperature of the mid point of each section decreases by only 0.1K. It can be thought that when the water temperature drops to 278K, lowering the water temperature will not play a significant role in the cooling effect of the spray cooling system, but will increase the cost of the cooling system. It is not difficult to see that the water temperature of the nozzle determines the effect and cost of the spray cooling system, so the study of the water temperature in the spray system is also essential.

4. Conclusion

To sum up, through the calculation and analysis of the temperature field distribution of a nozzle in the working state of different water temperatures, it can be concluded that: for the selected coal mining face, the selection of water temperature 278k is the most economical scheme to ensure high cooling effect. Therefore, it can provide guidance for mine cooling.

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