Orthogonal Experiments on the Key Structural Parameters Optimization of Mine Dust Removal Foam Generator by FLUENT Numerical Simulation

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Abstract: As an important countermeasure of dust control in mine, the efficiency of foam generator is seriously affected by the key structural parameters itself, including the baffle inclination angle (θ), the disturbance flow distance (L) and the diffusion angle (α). To ascertain the relation of the three parameters, the axial cross section velocity field and gas phase distribution field in the foam generator were simulated by FLUNET software and mixture method, standard κ-ε turbulence model and SIMPLEC algorithm. At the same time, the orthogonal tests were conducted for reducing amount of calculation. The results show that when θ=30°, L=22mm, α=74°, the foam generator is on the optimal working condition. And the importance degree of the key structural parameters is successively θ, L and α. It can play a certain reference role in the actual design of the foam generator for the dust removal technology improvement of the foam generator.

1. Introduction
With the continuous improvement of the comprehensive mechanization under the mine in recent years, the dust concentration in the air at the underground working space is usually higher and higher. Dust is the most direct and serious cause of the pneumoconiosis. According to the statistics of the Ministry of Health in 2014, nearly 30,000 occupational diseases were reported nationwide and 26873 cases of occupational pneumoconiosis, which it increased 3721 cases compared with 2013, were accounted for 89.6% of the total number of cases reported in occupational diseases. In addition, it can also cause coal dust explosion accidents [1-2]. In order to prevent and control mine dust, conventional dust removal technology such as ventilation dust removal, spray dust removal and dust collector removal was widely used. The ventilation dust removal operation is simple and the cost is low, but the efficiency of dust removal is low, and it is easy to cause secondary pollution. The dust is mostly hydrophobic and the surface tension of water is large, which induce low efficiency of spray dust reduction. When the dust collector has complex structure and high noise, which is affected by unsafe factors in the well, the treatment air volume is limited [3]. Due to the limitations of the above dust removal methods, the results of dust removal are lower than that of the standard.

Foam dust removal is an emerging dust removal technology in the mine with low water consumption and high efficiency of dust removal. But it also has the defects of foaming agent development and poor foaming effect of foam generator [4]. As the key technology of foam system, the foam generator has an important influence on the dust removal efficiency of the whole foam dust removal system.
In this paper, the gas-liquid two-phase flow process in the foam generator was simulated by Fluent software. Orthogonal test was used to optimize the internal key structural parameters of the foam generator.

2. Modeling and setting of boundary conditions

2.1 Establishment of foam generator model

According to the actual liquid supply and flow rate of the foam generator at working face and the Bashenov’s test, the optimum diameter of the throat cavity is as follows: \( d_3 = d/3 \) (d is the diameter of the fluid inlet pipe. According to the actual working conditions, \( d = 30 \text{mm} \)) [5]. The maximum diameter of the foaming device is \( D_0 = 100 \text{mm} \). Others parameters are shown in Table 1.

| Design parameter | Size or quantity (mm) |
|------------------|-----------------------|
| Throat diameter   | 10                    |
| Throat long       | 20                    |
| Diameter of large end of taper pipe | 100              |
| Taper length      | 30                    |
| Diameter of disturbing vents | 4                  |
| Radius of curvature of inlet elbow | 25               |
| Inlet pipe diameter of spoiler | 10                |
| Pipe diameter of inlet port | 30                |
| Pipe diameter of foam generator outlet | 30             |
| Full length of foam generator | 330  |

The basic requirement of physical foaming in the equipment is to make gas-liquid two phases fully mix for uniform and stable foam liquid. By using the principle of jet flow and the characteristics of high speed and low pressure in Venturi Pipe, the air flow blends the foaming liquid for high speed and steady state in the throat. In the diffusion stage, a scrambler is set to disperse the liquid flow beam, which forms the turbulent eddy current on the sloping plane in the front of the foam generator and the spoiler, and the gas-liquid two phases is evenly mixed by increasing the contact surface. At the same time, there are a certain number of air holes in the main section of the scrambler, and high pressure gas jets from the holes in the spoiler, and the air flow impinges on the liquid to form a high speed and disorder gas-liquid two-phase mixed flow and some foams. And then under the impact of the foam mixing chamber baffle, the mixed flow was further fully mixed to produce more uniform foam group and finally the foam outlet flow out. In order to facilitate modeling and simulation, the model omits the peripheral and internal secondary components of the foam generator, and simplifies the two-dimensional structure diagram of the dust-removing foam generator. The two-dimensional and three-dimensional structure diagram is respectively shown in Fig. 1.

![Fig. 1 Two-dimensional and three-dimensional structure of foam generator](image)

2.2 Mesh generation

Gambit 2.4.6 is used to mesh, and Tet/Hybrid unstructured mixed mesh in Gambit is used to divide the mesh. The flow inside the foam belongs to the finite space jet flow in irregular region. The mesh density has a certain influence on the simulation results [6]. The internal area of the scrambler is air, the Interval
Size of the grid is 0.2, the rest of the grid is the mixture area, and the Interval Size of the grid is 0.3. The mesh quality is better, the skew degree, aspect ratio and so on are in the reasonable range. Within the range, the total number of generated computational meshes is about 350000. In order to ensure the mesh quality and the accuracy of the calculation results, the spoiler hole and jet region are locally encrypted, and the smooth mesh processing is carried out to improve the simulation effect.

2.3 Boundary conditions and solution setup

The geometric model completed by Gambit2.4.6 was imported into FLUENT 15.0. The density of foaming agent solution at the inlet of foam was 1200 kg/m$^3$, and the viscosity was 0.02 Pa·s. The inlet boundary of gas phase and liquid phase was both set as velocity inlet, the velocity ratio of gas and liquid phase was 10, and the turbulence intensity was 5. The outlet boundary is set as the pressure outlet. Considering the pressure of the foam conveying system, the outlet pressure is set at 5 MPa, wall with no slip boundary condition. Using FLUENT 3D solver, the gravity direction is y-axis negative direction, the size is 9.8m/s$^2$. The muti-phase flow model uses Mixture model, setting water as the main phase and gas as the second phase. The unsteady mode is selected, and the SIMPLEC algorithm with velocity and pressure coupling is selected to solve the problem. At the same time, the turbulence model is chosen as the standard k-ε model. The pressure equation is set to a standard scheme, the volume fraction is set to QUICK difference scheme, momentum equation, turbulent kinetic energy and turbulent dissipation rate are set to the second order upwind scheme to iterate, the outlet flow rate and the foaming fluid flow rate are adopted. The relative deviation of intake flow rate is less than 0.1% determines the sign of convergence.

3. Orthogonal tests of foaming apparatus

3.1 Orthogonal experiment design

Orthogonal test design is a method to study multiple factor and multilevel optimal design by means of mathematical statistics and orthogonality. It selects representative parts from a large number of experiments according to orthogonality [9]. Therefore, the experimental scheme arranged by the orthogonal test method can reflect the influence of various factors and levels on the index more comprehensively. Based on the results of a large number of simulation tests before the laboratory, the diffusion angle of the main structural factors affecting the foaming effect is 74°, 90°, 106° respectively, and the disturbance distance of 14mm, 18mm, 22mm, baffle inclination angle is 30°, 45°, 60° respectively. The design of orthogonal test is shown in Table 2.

| Testing number | Angle of flare(A) /° | Scrambling distance(B) /mm | Baffle angle (C) /° | Error sequence | Testing program |
|----------------|----------------------|----------------------------|--------------------|---------------|----------------|
| 1              | A$_1$(74)            | B$_1$(14)                  | C$_1$(45)          | D$_1$         | A$_1$B$_1$C$_1$D$_1$ |
| 2              | A$_1$(74)            | B$_2$(18)                  | C$_2$(60)          | D$_2$         | A$_1$B$_2$C$_2$D$_2$ |
| 3              | A$_1$(74)            | B$_3$(22)                  | C$_3$(30)          | D$_3$         | A$_1$B$_3$C$_3$D$_3$ |
| 4              | A$_2$(90)            | B$_1$(14)                  | C$_2$(60)          | D$_3$         | A$_2$B$_1$C$_2$D$_3$ |
| 5              | A$_2$(90)            | B$_2$(18)                  | C$_3$(30)          | D$_1$         | A$_2$B$_2$C$_3$D$_1$ |
| 6              | A$_2$(90)            | B$_3$(22)                  | C$_1$(45)          | D$_2$         | A$_2$B$_3$C$_1$D$_2$ |
| 7              | A$_3$(106)           | B$_1$(14)                  | C$_3$(30)          | D$_2$         | A$_3$B$_1$C$_3$D$_2$ |
| 8              | A$_3$(106)           | B$_2$(18)                  | C$_1$(45)          | D$_3$         | A$_3$B$_2$C$_1$D$_3$ |
| 9              | A$_3$(106)           | B$_3$(22)                  | C$_2$(60)          | D$_1$         | A$_3$B$_3$C$_2$D$_1$ |

In this paper, the orthogonal test L9 (3$^4$) scheme with 3 factors and 3 levels is selected, and nine groups of design schemes are selected. The average value of the three results of the exit section is obtained from each group of numerical models. A series of errors is added to reflect the error caused by
repeated tests, and it is convenient for subsequent analysis and calculation. In addition, the other boundary conditions are in complete agreement with the initial conditions set in nine groups.

3.2 Simulation results analysis

After each condition is set up, iterative calculation is carried out. After convergence, the result calculated by Fluent 15.0 is represented by self-processing Plot/Display image, and the flow field is visualized by importing the post-processing software tecplot 360. The gas-liquid development and the uniform distribution of foam in the mixing chamber can be seen directly and clearly.

All three factors have great influence on the gas-liquid distribution in the mixing chamber, which indicates that the diffusion-angle spoiler angle is the key structural parameter of the foaming device. The effect of gas and foaming fluid on gas-liquid mass transfer in the improved foaming apparatus is better.

Fig. 2 Cloud image of axial velocity field

Fig. 3 Cloud diagram of axial gas distribution field

Fig. 2 shows 9 groups of axial velocity cloud images of the foaming apparatus under different working conditions. As shown in figure 5, when the diffusion angle is 74°, 90°, 106° the flow characteristics are basically the same under different structural parameters, and the average velocity in the foam mixing cavity is about 4m/s. It can be seen that the variation of the scrambling distance affects the jet diversion. The larger the disturbance distance is, the larger the jet energy loss is, and the smaller the separation effect is, the less the flow separation effect is. The fluid concentration in the main section of the scrambler increases the local velocity to about 7 ~ 8 m/s. This is due to the spoiler owner. A
steady swirl is formed around the body segment, and the larger the baffle angle is, the larger the eddy current is. Although it can mix gas and liquid to a certain extent, it is not conducive to the full forward development of turbulence. When the disturbance distance is fixed, the change of diffusion angle has direct influence on the trend of jet development, and the change of obliquity of baffle also has the effect of blocking disturbance to different extent on the turbulent development of beam splitting, which makes the foaming liquid produce more fine foam. It will also have an effect on the development of turbulence. When the obliquity of the baffle is fixed, the variation of the spoiler distance and the diffusion angle can directly affect the development trend and mixing effect of the foam liquid jet. On the whole, L=22mm, α=74°, θ=30°, the velocity distribution of internal velocity field is more uniform, and the effect of gas-liquid mixing development is more idea.

Fig. 3 is a cloud diagram of nine groups of axial gas distribution. It can be seen that the distribution range of volume fraction of the whole gas phase in the mixing cavity is basically from 40 to 70, and the mixing effect accords with the characteristics of gas-liquid two-phase flow. When the diffusion angle is the same, the disturbance distance changes in a certain range, which affects the effect of jet diversion, and the distribution of disturbance distance tends to gravity direction over the atmospheric phase distribution, which is caused by the energy loss behind the throat jet. The obliquity angle of baffle has obvious influence on the gas phase volume distribution of the mixing chamber. The bigger the baffle angle is, the more it is concentrated locally in the main area of the spoiler, and the volume fraction of the gas phase is more than 70%, which is not conducive to the mass transfer between foaming fluid and air and the development of turbulence. The larger the diffusion angle is, the more the jet distributes and causes the adherent flow. Therefore, the proper combination of three key structural parameters can play the role of shunt and facilitate the subsequent full mixing. It can be seen that the volume distribution of the third group exit gas phase is relatively uniform and the mixing effect between the foaming chamber and the gas liquid is better.

4. Effect of key internal structure parameters on foaming Sensitivity analysis

4.1 Multi-objective Matrix Optimization Analysis method

| test number | angle of flare α | Scrambling distance L | Baffle inclination angle θ | Error sequence | Evaluating indicator | ① | ② |
|-------------|-----------------|----------------------|---------------------------|----------------|----------------------|----|----|
| 1           | A₁(74)          | B₁(14)               | C₁(45)                    | D₁             | 17.23                | 0.3700 |
| 2           | A₁(74)          | B₂(18)               | C₂(60)                    | D₂             | 27.51                | 0.3284 |
| 3           | A₁(74)          | B₃(22)               | C₃(30)                    | D₃             | 3.27                 | 0.6584 |
| 4           | A₂(90)          | B₁(14)               | C₂(60)                    | D₃             | 18.47                | 0.2874 |
| 5           | A₂(90)          | B₂(18)               | C₃(30)                    | D₃             | 17.53                | 0.5136 |
| 6           | A₂(90)          | B₃(22)               | C₁(45)                    | D₂             | 19.80                | 0.3682 |
| 7           | A₃(106)         | B₁(14)               | C₂(60)                    | D₃             | 12.44                | 0.4118 |
| 8           | A₃(106)         | B₂(18)               | C₁(45)                    | D₃             | 26.51                | 0.3534 |
| 9           | A₃(106)         | B₃(22)               | C₂(60)                    | D₁             | 20.02                | 0.3086 |

| Factors ① |  |  |  |  |
|------------|  |  |  |  |
| k₁         | 16.003         | 16.047         | 21.180         | 18.260         |
| k₂         | 18.600         | 23.850         | 22.000         | 19.917         |
| k₃         | 19.657         | 14.363         | 11.080         | 16.083         |

| Factors ② |  |  |  |  |
|------------|  |  |  |  |
| k₁         | 0.452          | 0.356          | 0.364          | 0.397          |
| k₂         | 0.390          | 0.398          | 0.308          | 0.369          |
| k₃         | 0.358          | 0.445          | 0.528          | 0.433          |
A visual analysis of the sensitivity of each factor to the foaming effect is made by using range analysis, which is shown in Table 3. From the direct analysis of the test results, it can be seen that the optimal scheme is $A_1B_3C_3$ for the gas phase inhomogeneity of the index, and the influence factors are obliquity angle of baffle, disturbance distance and diffusion angle, and for the two-average turbulent kinetic energy of the index, the optimal scheme is $A_1B_3C_3$. The optimal scheme is $A_1B_3C_3$, and the influence factors are obliquity of baffle, diffusion angle and scrambling distance. If there are different schemes, we usually need to use comprehensive balance method and comprehensive scoring method to solve the problem. By using matrix analysis method, we can calculate the weight matrices of the three inspection indexes that affect the test results. In order to get the best scheme quickly.

From the calculation, it can be concluded that the primary and secondary order of the influence of each factor on the index value of orthogonal test is CBA, that is, the obliquity of baffle is the most obvious, and the disturbance distance and diffusion angle are the second. The weight of factor $A_1B_3C_3$ is the largest, so the optimum combination scheme of orthogonal test is $A_1B_3C_3$, $\theta = 30^\circ$, $\alpha = 74^\circ$, $L = 22\text{mm}$.

### 4.2. Variance analysis of multi-index orthogonal test

Based on the theory of orthogonal test, the value of the inspection index obtained from the simulation test is analyzed and processed. The variance analysis of the orthogonal test results is carried out by using the data statistics and analysis software SPSS. The significance test is shown in the Table 4.

| Factors          | Quadratic sum | Degrees of freedom | Mean square | F          | Significant level | Contribution rate |
|------------------|---------------|--------------------|-------------|------------|-------------------|-------------------|
| Angle of flare   | 21.206        | 2                  | 10.603      | 0.956      | 0.511             | 0.05              |
| Scrambling distance | 153.722     | 2                  | 76.861      | 6.932      | 0.126             | 0.37              |
| Baffle obliquity | 221.929       | 2                  | 110.964     | 10.007     | 0.091             | 0.53              |
| Error sum        | 22.177        | 2                  | 11.088      |            |                   | 0.05              |
| Total sum        | 419.034       |                    |             |            |                   | 1                 |

Based on the analysis of variance, the contribution rate of each factor to the variation of the test index (the ratio of the sum of factor square to the sum of total square) is calculated. The magnitude of the contribution rate can quantify the importance of the factor. The greater the contribution rate of the square
sum of a certain factor to the total sum of squares, the stronger the influence of the factor on the evaluation index [11]. For general engineering problems, the significant level of a certain factor $\alpha \leq 0.1$ can be regarded as a significant factor, that is, an important influence factor [12].

The comprehensive analysis of variance analysis shows that the factors salience can be seen that the factors affect the primary and secondary order C-B-A, that is, the primary and secondary sensitivity order is the most obvious influence of the baffle inclination on the foaming effect, while the disturbance flow distance and diffusion angle second. This is consistent with the results obtained from the previous matrix analysis.

4.3 Comparison of optimal conditions
Comparing the best working conditions obtained by the orthogonal test with the original working conditions, since the optimal combination of orthogonal design tests is just in the orthogonal table, there is no need to re-model, in initial conditions and boundary conditions, and other settings. The recalculation was carried out under the same conditions. The obtained method showed that the gas phase unevenness of the outlet section was 4.12, and the average turbulent kinetic energy was $0.6732 \text{m}^2/\text{s}^2$, which was basically consistent with the previous experimental analysis results, so the optimal working condition was verified.

5. Conclusion
1) The orthogonal experimental design is applied to the structural optimization of the foam generator for the first time. Through the combination of data results and images, the effect of the diffusion angle $\alpha$, the spoiler distance $L$ and the baffle inclination angle $\theta$ on the foaming of the foam generator is more fully grasped. The results of data analysis are reflected in the image.

2) The matrix analysis method and the variance analysis method were used to study and analyze the sensitivity of the key structural factors inside the foaming effect of the mine dusting foam generator. The results obtained by the sensitivity analysis of the two methods are consistent, that is the primary and secondary sensitivity order is the most obvious influence of the baffle inclination on the foaming effect, and the disturbance flow distance and the diffusion angle are respectively the second.

3) The optimal parameter combination scheme of the optimization model is that the diffusion angle $\alpha=74^\circ$, the spoiler distance $L=22$ mm and the baffle inclination angle $\theta=30^\circ$, and the re-verification of the optimal parameter combination scheme is carried out, and the supplementary numerical calculation is verified. This shows that the orthogonal design test analysis method using numerical simulation is reasonable and feasible, and provides design parameters for the application of foam dust removal technology, which has engineering reference value.

4) From the analysis of the process and results: it can be seen that in the structural design of such a foam generator, the baffle inclination and the spoiler distance are more significant factors that require detailed and prudent design to improve the actual dust removal efficiency of the mine foam generator.

Acknowledgments
The work was financially supported by Key Projects for Outstanding Youth Talent Support Program in Universities of Anhui Province (gxyqZD2016154), Key Technology R&D Program of Anhui Province (1804a0802208) and Key Science and Technology Program of Anhui Province (1301042104).

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