COMSOL-based study on flow field characteristics and gas concentration distribution laws on the coal face under Y-Shape ventilation conditions

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Abstract. Under the condition of Y-Shape ventilation, it can solve the problem that the gas concentration in the upper corner and the return laneway is beyond the limit of the traditional U-Shape ventilation. The physical model of gas flow in the working face and the mined-out area is established by using the COMSOL Multiphysics. In addition, the distribution of flow field and gas concentration distribution in the working face and mined-out area under the condition of Y-Shape ventilation are studied in accordance with the data obtained from the field; The flow of wind in the mined-out area shows an anti-"L." type distribution, and the concentration of gas in the mined-out area decreases rapidly.

1. Introduction
Gas is an important factor jeopardizing mine safety and efficient production. The gas disaster is one of the most serious disasters for coal mines [1]. Gas will pose three major types of threats to mine safety: explosions, outbursts, and suffocation. Particularly, gas explosions and coal-gas outbursts will inflict significant harm on coal enterprises and pose serious threats to the lives of underground workers and the safety of mine facilities [2]. Under the conditions of a traditional U-shaped ventilation system, it is impossible to do well with gas exceeding the limit in tunnels. Especially the upper corner on the coal face, which is most vulnerable to gas accumulation, often sees gas concentration exceed the limits. The most fundamental reason is that the convergence of goaf air leakage flow fields at the upper corner is prone to gas build-up. One of the most effective ways to resolve gas concentration overrun at the upper corner is to change the flow direction of the air leakage in the goaf so as to increase convergence points of air leakage and reduce the amount of the gas flowing from the goaf to the upper corner[3-5].

There are many studies on the laws of gas emission on the coal face at home and abroad, and most of them were carried out in combination with specific mines. There have no precise laws yet on the gas distribution over the coal face and goaf, especially on the detailed gas concentration distribution and flow field distribution over the coal face and goaf. Therefore, this paper is to give a numerical analysis of J-Shape ventilation for flow field characteristics and gas concentration distribution laws of coal face and goaf. The findings can serve as theoretical base for prediction of gas distribution over the
coal face and goaf of a mine.

2. Gas Flow Model of Coal Face and Goaf

2.1 Gas Flow Equations of Coal Face

For gas flow laws in pipes, Navier-Stokes equations work best, which can be resorted for a solution to both breeze and turbulence [6-8]. As a coal face can be approximately seen as a pipe flow, this paper employs Navier-Stokes equations as the fluid flow equations for a coal face:

\[ -\nabla \cdot \eta (\nabla u_{ns} + (\nabla u_{ns})^T) + \rho u_{ns} \cdot \nabla u_{ns} + \nabla p_{ns} = 0 \]  

(1)

\[ \nabla \cdot u_{ns} = 0 \]  

(2)

Where:
\[ \eta = \text{viscosity coefficient, kg/ (m*s)}; \]
\[ u = \text{velocity vector, m/s}; \]
\[ \rho = \text{liquid density, kg/m}^3; \]
\[ p = \text{pressure}; \]

The dependent variables of Navier-Stokes equations are velocity (u) and pressure (p), respectively, with the suffixes expressed by “ns”.

2.2 Gas Flow Equations of Goaf

The goaf teems with falling gangue, which is abundant in pores and fractures in it. In the meantime, the falling gangue is the frame to form pores and fractures. Together the pores and fractures, its gaps and cracks, the gangue can be regarded as a porous medium. As the falling gangue heaps up randomly, the goaf can be considered an isotropic inhomogeneous medium field. Mixed gas flowing in a goaf is non-linear filtration and mass transfer of diffusion in a porous medium. Based on the characteristics of gas flowing in a goaf and the theories of poromechanics, a goaf can be considered as a continuous filtration space, so that the law of conservation of mass and non-linear filtration equations can be directly used for porous media.

\[ -\nabla \cdot \left( \varepsilon \frac{\eta}{\varepsilon} (\nabla u_{br} + (\nabla u_{br})^T) - \left( \frac{\eta}{\varepsilon} u_{br} + \nabla p_{br} \right) \right) = 0 \]  

(3)

Where:
\[ \varepsilon = \text{porosity}; \]
\[ k = \text{permeability}. \]

In carrying out simulation with COMSOL software, the selection of the goof permeability size has an important impact on the air flow field and gas distribution in the coal face and goaf. In practical production, as the coal face advances, the gangue in the goaf is continuously compacted, the permeability and gangue size reducing constantly in the opposite direction of the advance of the coal face. It can be assumed that the changes of the goaf porosity (n) and the gangue size (Dp) over distance comply with the parabola law when less than 100m distant from the coal face and no changes will take place when more than 100m distant.

The relations of the gob porosity (n) and the gangue size (Dp) with the distance from the coal face are as follows:

\[ n = \begin{cases} 0.000019x^2 - 0.0038x + 0.25 & x \leq 100 \\ 0.06 & x > 100 \end{cases} \]  

(4)

\[ D_p = \begin{cases} 0.000005x^2 - 0.001x + 0.1 & x \leq 100 \\ 0.05 & x > 100 \end{cases} \]  

(5)

According to the Carman formula,

\[ \alpha = \frac{D_p^2}{150 (1-n)^2} \]  

(6)

Where:
\[ \alpha = \text{permeability, m}^2 \]
\[ D_p = \text{average size, m}; \]
\[ n = \text{porosity of porous media}. \]
3. Simulation Results and Analysis

3.1 Gas Analysis under Y-Shape Ventilation Conditions

Dynamic analysis is employed for the distribution laws of gas concentration in the coal face and goaf under Y-Shape ventilation conditions. This method selects the gas concentration distribution at six different points of time for analysis, shown as Fig. 1.

![Gas Distribution under Y-Shape Ventilation Conditions](image)

Figure 1. Gas Distribution under Y-Shape Ventilation Conditions

From Fig. 1, as for the gas concentration and flow direction in the goaf, the gas close to the coal face moves, with the effect of the air flow leaking into the goaf, to the depth of the goaf over time. As the air flow in the coal face mainly comes from the main intake airway of the coal face and the leaked air also infiltrate into from the main intake airway side, the air flow pressure in the goaf declines gradually from the main intake airway side to the return airway side. As a result, the gas in the goaf eventually moves towards the return airway. As time goes by, in the goaf, a lower gas concentration zone comes into being near the main intake airway. In this zone, the gas concentration reduces fast and the residual gas is less, but the area is small. This may be that the air flow close to the main intake airway, which gets speedy and intensive because the air leakage into the goaf mainly occurs near the main intake airway side, can rapidly reduce the gas content in the zone. On the other hand, however, due to the air flow’s moving from this zone into the goaf and then into its depth, the longer migration paths of the air flow and gas make the zone a small area. The intensive air flow in the zone is also another major cause for such phenomenon. The other zone (close the secondary return airway) shows characteristics different from the first one, representing a large area but a small gas reduction and higher gas residue. Contrary to the former, the cause for this phenomenon is that the gas migration path in this zone is shorter and the air leakage into the zone is divergent.

Under Y-Shape ventilation conditions, there will basically occur no gas accumulation at the upper corner of the goaf, because the separate source control and that reduces to a great extent the sources of the gas at the upper corner, the gas in the goaf not coming from near the upper corner into the coal face, but directly flowing into the return airway. As the air flow in the return airway is a mix of the air flows of two intake airways, the flow rate in the return airway will be higher, directly taking away the combined air flow coming out from the return airway and lessening the possibility of gas accumulation in the return airway.

From the Fig. 1, at the earlier stage of ventilation (0h-2d), the gas concentration in the goaf declines rapidly, and the area of the concentration reduction zone increases rapidly, too. At the later state (2d-5d), however, the speeds of the reduction in gas concentration and of the increase in the area of the concentration reduction zone slow down. This may be because that, on the one hand, in the goaf, with the increasing distance from the coal face, the air pressure gap decreases, the air flow rate reduces, and
the amount of the gas taken away along with the air flow falls accordingly, and on the other, in the depth of the goaf, the porosity and permeability further go down.

As time goes on, the air flow can eventually reduce the gas concentration in the goaf to a very small range. As show in 5d of Fig. 1, the gas concentration of the whole goaf is very low, and the zone having gas accumulation is very small. In practical production, however, the coal face will be in a dynamic balanced process, not a static state. As the coal face advances, the goaf will also move forwards. In this case, the gas in the goaf is continuously being supplemented, so that the air flow infiltrated into the goaf cannot take away all the gas in the goaf. Therefore, in practical production the gas distribution in the goaf will be shown as 1d, 2d in Fig. 1.

As for the gas distribution over the coal face, the gas concentration near the coal walls will be higher than that far away from them due to significant emission in these places by coal uncovering. Besides, a small gas accumulation zone will appear along the coal walls close to the intake airway. Similar to the flow field analysis above, the reason for such phenomenon is that the changes in the air flow at the corner cause the air velocity in these places to slow down, and there will be gas emission near the coal walls. As for the gas distribution in the return airway, because the air flows infiltrated into the goaf converge, the gas the air flows bring from the goaf does so, too. As a result, the gas concentration near the goaf is higher than that far away from it.

4. Field Measured Data
Based on the measure data of a coal mine, an on-site measurement analysis is given to the gas concentration and distribution in the mining space and goaf with fully-mechanized top coal caving to learn about their gas concentration distribution.

![Figure 2. 4D Image of Gas Distribution and Air Flow Fields in Return Airway and Coal Face](image)

From the Fig. 2 (a) above, gas accumulation occurs in the distance where the return air is near the coal face. The gas concentration is high in the upper part of the airway and low in the lower part. The reason is that there exist wind field vortexes at the junction of the secondary intake airway and the coal face, where the air velocity is low. At a certain distance from the coal face, the concentration of the gas close to the goaf side in the return airway is higher due to the convergence of gob gas. The gas concentration in both the upper and the lower parts of the airway tends to be consistent. Further away from the coal face, the gas in the return airway tends to be consistent in concentration and shows no accumulation, because of, on the one part, the decreasing deformation of the airway section, and on the part, the air velocity increases resulting from air flow convergence.

As Fig. 2(a) shows, the gas concentration and distribution laws in the stope are evident: the gas concentration is low at the side close to the goaf and high in the upper space close to the ceiling. The gas in the stope mainly comes from falling coal, coal walls, etc. The gas flows in the wind direction, therefore, the gas concentration is markedly higher than that in the starting section near the main intake airway due to the accumulation close to the return airway. The gas distribution laws of the stope need to be analyzed based on the air flow field distribution over the stope. The latter is the major
factor influencing gas flow and is inextricably linked with the gas distribution laws.

Fig. 3 shows that the gas concentration in the main and secondary intake airways are lower and gas accumulation occurs in the places close to the coal face because of vortexes induced by flow field changes. In the main intake airways, gas concentration is partially higher, because artificial broadening of airways for erecting advance support and facilitating feeding afterwards results in falling coal and gas effusion. In addition, the gas concentration in the main intake airway where a crusher stands is higher, which is also caused by gas effusion at falling coal breaking. On the whole, Y-Shape ventilation systems can ensure air input and can meet the gas requirements for safe production as well.

5. Conclusions

(1) The numerical simulations and field measured results tell that under the Y-Shape ventilation conditions, all the infiltrated air flows in the goaf converge into the return airway, instead of into the upper corner. Therefore, the potential gas concentration overrun due to gas effusion on the upper corner under conventional U-Shape ventilation conditions is eliminated.

(2) Under the Y-Shape ventilation conditions, the great mass of air leakage of the goaf occurs in the places of the coal face close to the main return airway, and the leaked air is intensive, the leaked air flow will take on a reversed “L” shape in the goaf. As the coal face moves from bottom to top, air leakage becomes less and less, and the air leakage is divergent.

(3) Influenced by the air flows infiltrated into the goaf, the goaf gas close to the coal face begins moving into the depth of the goaf and the return airway over time. However, because of air leakage, they will show two states. Therefore, there will form two zones in the goaf.

(4) As production goes on, coal uncovering will continue in the coal face. Therefore, gas concentration will be larger at the side close to coal walls and smaller at the side away from coal walls. Besides, gas concentration will gradually rise over the increasing distance from the coal face. In the return airway, due to the inrush of air flows leaked from the goaf, the gas concentration is higher at the side close to the gob and lower at the side away from the gob.

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