Numerical Simulation of Gas Migration Rules and Comparison between U shape and U+L shape Ventilation System

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ABSTRACT

This paper offers an overview of numerical simulation with the aim of improving the knowledge and reference of coal mine gas distribution rule, and providing a case study of the optimization of ventilation system and environment protection. The numerical simulation experiments based on U shape ventilation system and U+L shape ventilation system are performed respectively. The results indicate that U+L shape ventilation system is more effective than its counterpart in terms of accelerating the gas flow, balancing the air pressure, and lowering the gas content of the upper corner. Besides, the field verification shows that the average gas content of tail airway, upper corner and air outlet have decreased from 1.86%, 0.79% and 0.58% (U shape ventilation system) to 1.68%, 0.75% and 0.55% (U+L shape ventilation system) respectively, and the average gas drainage rate of special drilling tunnel has increased from 43.4 $m^3 \cdot min^{-1}$ (U shape ventilation system) to approximately 51.8 $m^3 \cdot min^{-1}$ (U+L shape ventilation system).

KEY WORDS: coal mine; gas disaster; U+L shape ventilation; numerical simulation

1.- INTRODUCTION

Coal mine gas issues have created severe difficulties in the mining industry and environment protection around the world, and led to high expenditures, intense research efforts and determined attempts to enhance the various ventilation and gas drainage techniques [1]. The release of a large number of harmful gases by mine working face and goaf, the worst-hit area of mine strata problems, is the cause of mine safety problems, serious accidents, many casualties and greenhouse effect [2]. As a result, safety mining technologies including field investigation, numerical simulation and laboratory test have been improved over the past decades as experts around the world are paying more attention to the rules of gas emission and outburst in mine working faces and goafs [3]. However, it is still extremely difficult to precisely observe gas movement in ventilation system, upper corner, working face and goaf, and effectively predict process behavior under different situations and constraints in fieldwork [4]. In order to refine the knowledge and reference of coal mine gas distribution rule, ensure the safety production, and create a chance of high production, a numerical model with a CFD code has been established in the simulation laboratory.

2.- CFD NUMERICAL SIMULATION

CFD modelling has been used in the mining and energy environment since the 1990s, including methane and spontaneous heating control, mine fires and explosions, methane control, ventilation velocity in tunnel fires, methane emissions and goaf gas, controlling longwall goaf heating, and gas behaviors in auxiliary ventilation of mining headings [5]. Gas flow rule in coal mine is a complicated process due to numerous factors are involved, including ventilation system layout, gas content, emission rate and compositions, working face orientation and dip, gas buoyancy and goaf permeability [6]. Lately, a large number of CFD models have been established to achieve further understanding of gas flow mechanics, characteristic and distribution rules in mine working face and goaf.

2.1.- Theoretical basis of numerical simulation

FLUENT is a finite volume computational fluid dynamics code that solves the Navier-Stokes equations for both compressible and incompressible flows. An elementary calculation of transfers to and from the neighbouring volumes is performed for each surface of the mesh. These exchanges depend on the incoming and outgoing flows and the intrinsic characteristics of the flow regions. A key feature of this code is its user-defined function capability, or UDF, which allows the user to develop stand-alone C programs that can be dynamically linked with the FLUENT solver to enhance the standard features of the code. Applying the fundamental laws of mechanics to a fluid gives the governing equations for a fluid. The conservation of mass equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = S_m \tag{1}$$

Where: ρ is density, t is time, v is speed, Sm is the continuous phase mass including dispersive second constituent and user-defined source. Equation (1) is the general form of mass conservation equation for both compressible and incompressible flows and the conservation of momentum equation in an inertial reference system (without acceleration) is:

$$\frac{\partial}{\partial t}(\rho v) + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot (\tau) + \rho g + F, \tag{2}$$

Where: p is static pressure, τ is tensor of stress, ρg and F are the gravitational energy and the external energy. F also includes the source of satellite model, such as multiphase medium and user-defined source.

2.2.- Calculation method and stage

The establishment of numerical model consists of several basic steps. The first step is to go to working field to collect the basic information, such as geometries, relevant parameters, rate of gas flow, goaf dropping characteristic etc. The second is to establish the 3D finite element model of the mine face, goaf, and tunnel and drainage borehole. The third is to set up gas flow models and boundary conditions through User-Defined Functions. The fourth is to simulate the condition of working face and goaf. The fifth is to calibrate and validate the simulation model by using working field measured data. The last step is to conduct extensive parametric researches and technique evolution by optimizing the numerical model.

3.- ESTABLISHMENT OF SIMULATION MODEL

3.1.- General Situation of the Mine

Fujiayan coal mine, which is located in Shanxi province, China, contains 7 coal seams with an average thickness of 5.74m. Coal seam #10, with a high gas content (approximately up to

56.43m^3/t), has created severe difficulties in work safety and environment protection. Working face's length and strike length of coal seam #10 are 150m and 1500m. The U shape ventilation system is adopted and longwall retreating extraction is used as the extracting method. Several gas drainage methods have been performed by Fujiayan coalmine in order to improve mine safety and develop production. However, the results of goaf gas drainage are far from satisfactory, and it can be seen in Table 1.

Table 1. Measured results of gas content in coal seam 10#

Sampling places	**Depth (m)**	**Gas composition (%)**				**Content of gas (m^3/t)**
		CH_4	CO_2	N_2	C_2-C_8	
Air outlet tunneling point (10m)	400	90.30	1.59	7.96	0.15	10.08
Between Air outlet air connection tunnel (60m)	450	93.02	3.34	3.43	0.21	11.50
Shaft station 2 and intersection east (18m)	515	96.66	0.87	2.40	0.07	12.20

3.2.- Introduction of U+L shape ventilation network

U+L shape ventilation system consists of track roadway (air inlet), working face, beltway (air inlet), and air return roadway (Figure 1). The inlet airway, directly opposite to upper corner, balances the pressure of the upper corner, restrains the gas discharge of the upper corner, and compels the high concentrated gas to flow over into outlet airway. The U shape ventilation system is adopted and longwall retreating extraction is used as the extracting method. Based on the gas control theory, U+L shape ventilation system is able to accelerate the gas emission, diffusion and flow, and reduce the gas concentration in the local area, and thus effectively solve the problem of the over-limit of gas concentration in the working face.

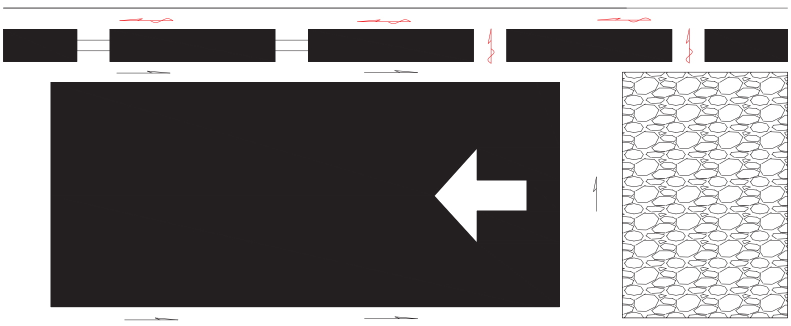

Figure 1. U+L shape ventilation system including two air inlets and one outlet

3.3.- Establishment of numerical simulation model

In this CFD simulation experiment, gas movement inside coal body, diffusive motion inside pore and gas adsorption process follow Darcy's and Hooke's law as well as the Langmuir's equation, while gas desorption process inside coal body is ignored. Mine working face and goaf are regarded as porous medium, gas is regarded as an ideal gas, and porous flow process is regarded as an isothermal process. Therefore, the standard equation of fluid flow combines with momentum source in order to perform the numerical simulation. In laminar flow of porous medium, the pressure is directly proportional to the speed, and the convection acceleration and diffusion are ignored. Numerical simulation based on the fundamental equation of gas flow of mine working face and goaf establishes the numerical model by determining the boundary conditions. Thus, gas flow and distribution rules are obtained. In this research, a standard k-e equation (k is Turbulent Energy and e is dissipation rating) is used to calculate the turbulent transport through the flow region since it can be used to simulate a large-scale turbulent flow.

4.- SIMULATION RESULTS

4.1.- Simulation results of U shape ventilation system

Air inlet boundary setting: VELOCITY-INLET; Air outlet boundary setting: OUTFLOW; boundary conditions obtained from field. The air velocity of inlet is 1.5 m/s, and the pressure of outlet is 90kPa. The simulation experiment based on U shape ventilation system is performed. To facilitate the research, figures of different cross-sections of goaf gas concentration distribution are selected with Z=0m (Working face floor), Z=7m (Working face roof), Z=15m (Caving zone), Z=30m (Fracture zone) and Z=50m (Bending Subsidence zone), and it can be seen in Figure 2

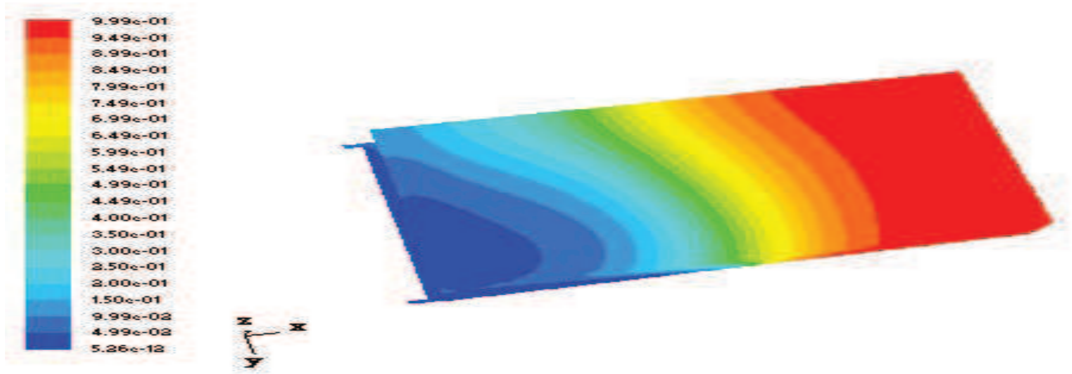

Figure 2. goaf gas concentration distribution in three-dimensional (U shape ventilation system)

It can be seen from Figure 2 that the gas is mainly gathered in the upper corner of the working face. Firstly, along the mining direction of the working face, gas concentration gradually increases from the working face to the deeper goaf and then it tends to be steady after a certain distance. Secondly, along the vertical direction of the working face, gas content gradually increases from the floor to the roof and fracture zones as the air volume gradually decreases from the top to the bottom. Lastly, along the width direction of the working face, gas content gradually increases from the air inlet side to the outlet. The air leakages of the goaf and different pressures between air inlet and outlet result in the overflow of plenty of gas concentrated in the upper corner.

4.2.- Simulation results of U+L shape ventilation system

The parameters and boundary conditions of the simulation experiment based on U+L shape ventilation system are the same as those of U shape ventilation system. The air velocity of inlet is 1.5 m/s, and the pressure at the outlet is 90kPa. Besides, figures of different cross-sections of the goaf gas content distribution are selected from the simulation experiments with Z=0m (Working face floor), Z=7m (Working face roof), Z=15m (Caving zone), Z=30m (Fracture zone) and Z=50m (Bending Subsidence zone), and it can be seen in Figure 3.

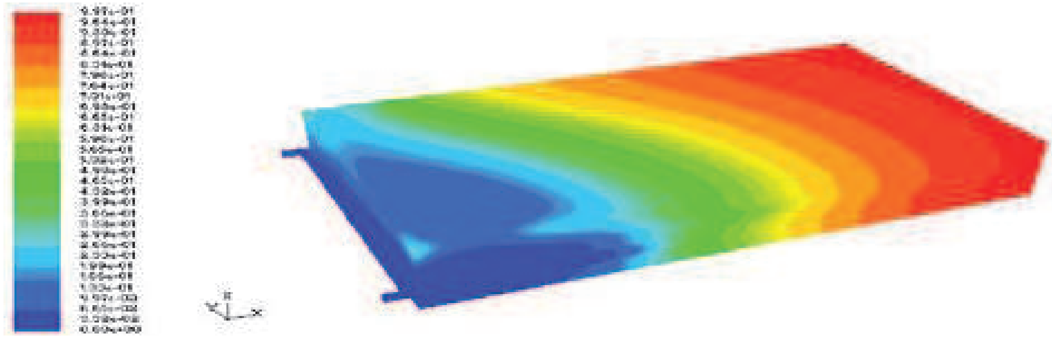

Figure 3. goaf gas concentration distribution in three-dimensional (U+L shape ventilation system)

It can be seen from Figure 3 that the high concentrated gas moderately moves to the deeper goaf from the upper corner. Along the mining direction, gas content gradually increases from the working face to the deeper goaf, and then tends to be steady after a certain distance. Specifically, the goaf gas content in the range between 0m and 45m basically remains unchanged (lower than 6%) because of the air leakage effect and different pressure between the air inlet and outlet. As is shown in Figure 4, the goaf gas content dramatically rises from 45m and reaches the peak to approximately 92% at 245m.

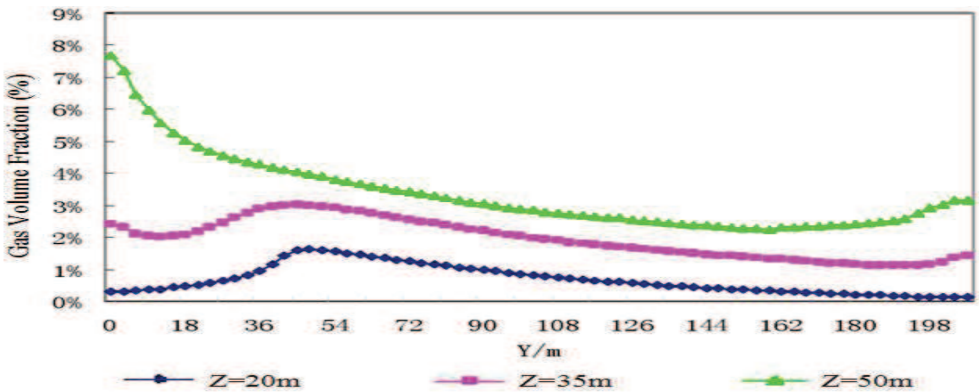

Figure 4. Goaf gas concentration distribution (from outlet to inlet side), Z=20m, 35m, and 50m

The simulation result shows that the gas content gradually increases from the floor to the caving and fracture zones. It is because the air volume and velocity gradually decreases from the top to the bottom, thus the gas accumulates in the upper goaf. Specifically, goaf gas content within the vertical range of 18m remains at a lower level while it rapidly increases in caving and fracture zone (from 18m to 35m). Particularly, the gas concentration tends to be stable and peaks at the second fracture zone (36m). The gas content gradually increases from the air inlet side to the outlet side, following the direction inlet-outlet and along all the width. Particularly, it peaks at 42m from the outlet side rather than the upper corner.

4.3.- Results comparison between U shape and U+L shape ventilation systems

In the case of the U shape ventilation system, a large amount of high concentrated gas constantly flows into the upper corner due to the air leakage of goaf, different pressures between the air inlet and outlet. By contrast, U+L shape ventilation system is made up of two air inlets and one outlet, which accelerates the gas emission, diffusion and flow, balances the air pressure of the upper corner, restrains the gas discharge of the upper corner, and compels the high concentrated gas to flow into the air outlet. Therefore, the gas content in local area is diluted and lowered. The over-limit of gas content in the working face is effectively resolved by changing the ventilation system from U shape to U+L shape.

Specifically, the gas content of the upper corner decrease from 9% to around 3%. It can be concluded that the most effective gas extraction spot constantly varies with the area where mining activities are performed. It is mainly located in the area of 45m-245m from the working face, 18m-35m from the floor, and approximately 42m from the side of air outlet.

5.- THE FIELD VERIFICATION OF SIMULATION RESULTS

5.1.- The layout and arrangement of gas drilling borehole

Based on the in situ measures and numerical simulated results of the coal seam #10, the layout of its drilling tunnels (Φ=94mm) is shown in Figure 5. To be specific, a tail tunnel (horizontally 15m from the mining seam) is excavated, and 6 gas drainage boreholes are drilled; three of them are evenly situated 20m from the floor, and 40m from the side of return airway. Another three boreholes in the distressed zone are collected, and vertically located in the zone of 30m from the floor, horizontally in the same level with 45m between each other.

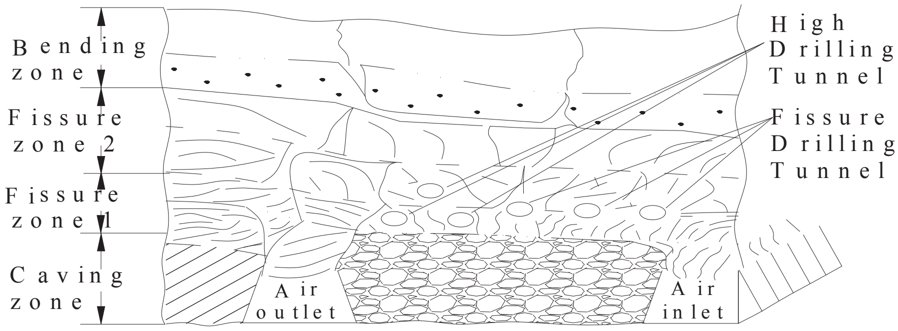

Figure 5. Section of the gas drainage boreholes layout and arrangement

5.2.- Results of gas content and drainage rate

5.2.1.- U shape ventilation drainage rate

It can be obviously seen from Figure 6 that the average gas content of tail airway, the upper corner and the return airway are 1.86%, 0.79% and 0.58% respectively in the U shape ventilation system of Fujiayan's coal mine.

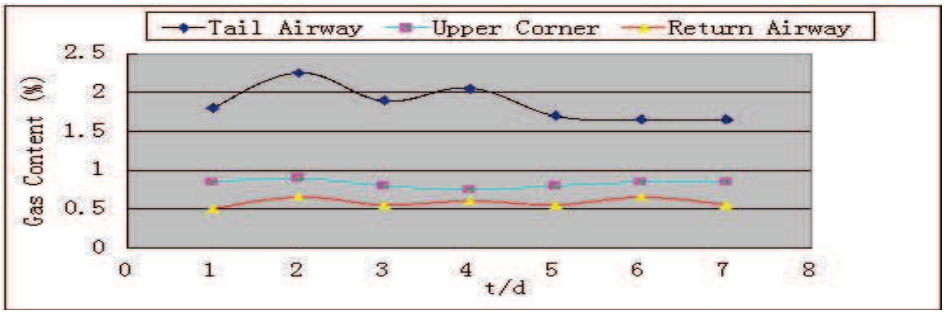

Figure 6. Measured result of gas content in different tunnels in U shape ventilation system

As is shown in Table 2, the average gas content of the upper corner is around 0.79% and the average gas drainage rate of high drainage tunnels is around 43.4 $m^3 \cdot min^{-1}$ in the U shape ventilation system of Fujiayan's coal mine.

Table 2. Data of gas content in the coal seam #10 of the U shape ventilation system

Observation	Gas content of the	Range of gas	Gas drainage content of

date	upper corner (%)	drainage content	the high drilling ($m^3 \cdot min^{-1}$)
27-08-2012	0.72	43-44	43.2
14-09-2012	0.84	44-45	44.3
20-10-2012	0.81	42-43	42.9
11-01-2013	0.77	44-45	44.1
12-02-2013	0.78	42-44	43.3
15-03-2013	0.82	41-44	42.6

5.2.2.- U+L shape ventilation drainage rate

It can be clearly seen from Figure 7 that the average gas content of the tail airway, upper corner and return airway decrease to 1.68%, 0.75% and 0.55% respectively in U+L shape ventilation system of Fujiayan's coal mine. This demonstrates that more gas flows into special gas drainage tunnels and as a consequence the gas content of upper corner in the working field moderately decreases from a hazardous situation.

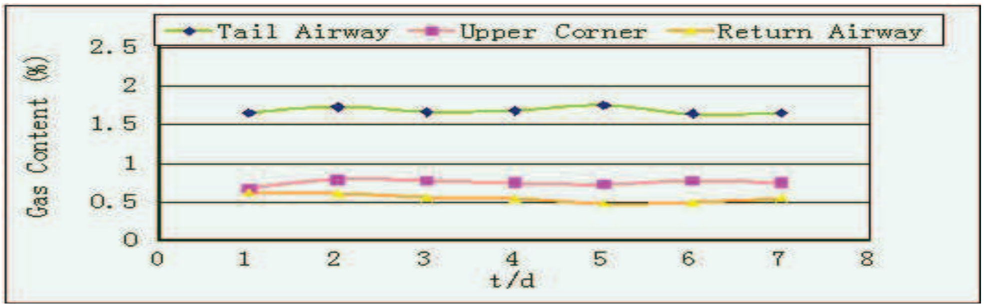

Figure 7. Measured results of gas content in different gas drainage borehole

Table 3 shows the average gas content of the upper corner decreases to 0.75% while the average gas drainage rate of high drilling tunnel increases to approximately 51.8 $m^3 \cdot min^{-1}$ in U+L shape ventilation system of Fujiayan coal mine.

Table 3. Data of gas content in coal seam #10 of U+L shape ventilation system

Observation date	Gas content of the upper corner (%)	Range of gas drainage content	Gas drainage content of the high drilling ($m^3 \cdot min^{-1}$)
28-07-2013	0.68	58-89	55.2
15-08-2013	0.79	55-84	51.3
21-09-2013	0.78	59-86	50.1
12-02-2014	0.75	56-81	50.5
11-03-2014	0.73	60-82	52.1
16-04-2014	0.78	65-87	51.4

6.- Conclusions

Some conclusion can be made from this study. Firstly, the simulation results of the U shape ventilation system indicate that the gas content of the upper corner can be effectively decreased by reasonably increasing the air volume in a certain extent. However, the gas over-limit problem in the working face and goaf cannot be completely resolved by unlimitedly increasing the air volume. The comparison results demonstrate that the high concentrated gas moderately moves to the deeper goaf from the upper corner by changing the ventilation network from U shape to U+L shape. Therefore, ventilation system with two air inlets and one air outlet could be an effective method to overcome the problem of the gas concentration in the working face and goaf. Secondly, the simulation results of the U+L shape ventilation system reveal the most effective gas extraction spot constantly varies with the area where mining activities are performed. It is mainly located in the area of 45m-245m from the working face (coal and rock separation area), 18m-35m (distressed and fracture zone), and 42m from the side of air outlet. Thirdly, the field verification shows that the average gas content of the tail airway, upper corner and air outlet decrease from 1.86%, 0.79% and 0.58% (U shape ventilation system) to 1.68%, 0.75% and 0.55% (U+L shape ventilation system) respectively. Besides, the average gas drainage rate of high drilling tunnel has increased from around 43.4 $m^3 \cdot min^{-1}$ (U shape ventilation system) to approximately 51.8 $m^3 \cdot min^{-1}$ (U+L shape ventilation system).

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