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DETERMINATION OF SPONTANEOUS COMBUSTION “THREE ZONES” IN GOAF OF NO.713 FULLY MECHANIZED LONGWALL OF QINAN COAL MINE**

1. Introduction

Mine fire is one of the major disasters in coal mine. In our country 56% coal mine exists spontaneous combustion problem, among them, the goaf spontaneous combustion take up subject status. The research of spontaneous combustion in the goaf is mainly about heat dissipation zone, oxidation zone and suffocation zone. The distribution condition and the range of the “three zones” spontaneous combustion in goaf is one of important basis of the parameters which are the prevention and control of the spontaneous combustion. For these hold the balance to nitrogen injection of mined-out area, grouting, face mining sequence and mining strength and so on, the scope of the working face spontaneous combustion “three zones” directly decides the position of nitrogen injection, nitrogen injection quantity, nitrogen injection intensity and other technological parameter, and decided the grouting time, grouting quantity, drawing speed of working face and so forth. So, experts and scholars throughout home and overseas have made a lot of research and have acquired some achievements. And the division of coal goaf spontaneous combustion “three zones” is mainly based on the change of oxygen concentration, change of temperature and air leakage speed, etc. How to obtain these parameters? By coal bed itself conditions which include geological conditions, mining technology and ventilation mode is different, and the research approach we adopt is different, the results are quite different. This paper is based on the essence of “three zones”, the factors are comprehensive considered which consist of air leakage speeds, oxygen

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concentration and temperature to study the coal goaf spontaneous combustion “three zones” distribution laws.

2. Outline of the studied working face

Research object of this article is No. 713 working face of the second district sublevel on the left of 81 mining area of Qinan Coal Mine in Anhui province China, the upside for No. 711 working face of mined area, the No. 715 face entity coal seam at bottom, the right bounded by main roadway protection pillar, and the left bounded by F3 fault protection pillar. Tunneling of the two layers of coal is coal 71 and coal 72, of which coal 71 thick 0.7–1.9 m, an average of 1.6 m, coal 72 and coal 71 spacing 0.8–1.8m, an average of 1.2 m, lithology for mudstone, and the coal 72 thick 1.7–3.2m, an average of 2.7 m. The two coal seam without dirt band belong to more stable simple structural coal seam. The elevation of the mining face is between – 501.6 m and 533.3 m, the long of the face is 788 m and the tilt long is 144 m.

The mining method of No. 713 coalface adopts fully mechanized, roof control with caving method, “a source a collect” U ventilation mode and air quantity $Q = 1000 \text{ m}^3/\text{s}$, as shown in Figure 1. The top and floor rock nature of coal seam as is shown in Table 1.

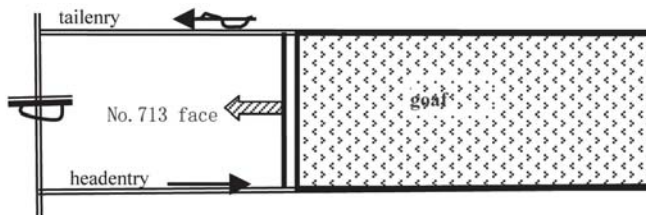


Fig. 1. Layout of No. 713 working face

3. Spontaneous combustion parameters testing method in goaf of fully mechanized working face

Spot determination method adopt direct test method which it used to test some parameters of goaf spontaneous combustion. The test system should consider reliability, conveniences and economy, so, the observation system of mined-out area “three zones” install four points respectively in the up and down airway of No. 713 working face, meanwhile, install tube to collect gas and install thermocouple which are produced by Special Type High Temperature Cable Of Shang Hai Ming Yang De Limited Company to test temperature of residual coal. Finally, tube and thermocouple should be tied together and be to protect them by using of steel pipe and improve the system reliability.

TABLE 1

The top and floor rock natures of the coal seam

Category	Name	Thickness, m	Nature
Main roof	mudstone	$\frac{2.7\sim 3.0}{2.8}$	dark gray, bulk, densification, many fossil plant fragments
	coal 63	$\frac{0\sim 1.1}{0.5}$	blackness, powder and pieces shape, semi-bright coal, weak bitumen luster pitch glance
	mudstone	$\frac{3.6\sim 3.7}{3.6}$	gray, bulk, few powder sandy, many fossil plant fragments
	fine sandstone	$\frac{5.0\sim 5.9}{5.4}$	light gray, thickness seam, tilt flat bedding, crack growth, rich fossil plant fragments
	fine siltstone	$\frac{7.3\sim 8.0}{7.6}$	gray, bulk, densification, fine powder sandy structure, separation flareout, rich fossil plant fragments
	mudstone	$\frac{2.7\sim 6.6}{4.6}$	gray with purple spot, massive density, rich fossil plant fragments
	siltstone	$\frac{1.7\sim 4.1}{2.9}$	gray, bulk, some area with fine sandstone, a few fossil plant fragments
	medium sandstone	$\frac{4.0\sim 12.8}{8.4}$	off-white, medium grain bulk, mainly composed of quartz and feldspar, cracks with set of calcite
Immediate roof	mudstone	$\frac{0.8\sim 2.0}{1.4}$	gray, dark gray, bulk, vertical crack growth, horizontal bedding, fossil plant fragments
False roof	none		
Immediate floor	mudstone	$\frac{0.8\sim 3.8}{2.3}$	gray, black and gray, massive mudstone, vertical crack growth, easy to slime, Sandy composition, fossil plant fragments
Main floor	siltstone	$\frac{2.5\sim 13.7}{8.0}$	off-white, dark gray siltstone, block structure, horizontal bedding, thin layer mudstone, vertical crack growth, fossil plant fragments

To investigate the coal goaf spontaneous combustion parameters change with advance of the face, the observation station are installed respectively 148 m from No. 1 point and No. 8 point as shown in the Figure 2. The protection equipment of every temperature probe and tube probe is shown as Figure 3. Gas collection pump and temperature collector are installed in observation station. When face forward, the acquisition probe gradually enter the goaf, then the gas which is collected by gas collection pump in observation station is sent to ground to analyze with SP-3430 gas chromatograph, and we can get the change rule

of all kinds of gas concentration at end. The temperature collector DY-3103 that is four and a half digital meter measure the thermocouple electric potential and get all the probe's temperature.

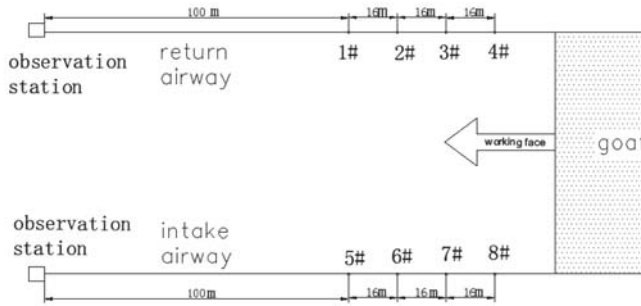


Fig. 2. Observation points arrangement in No. 713 working face

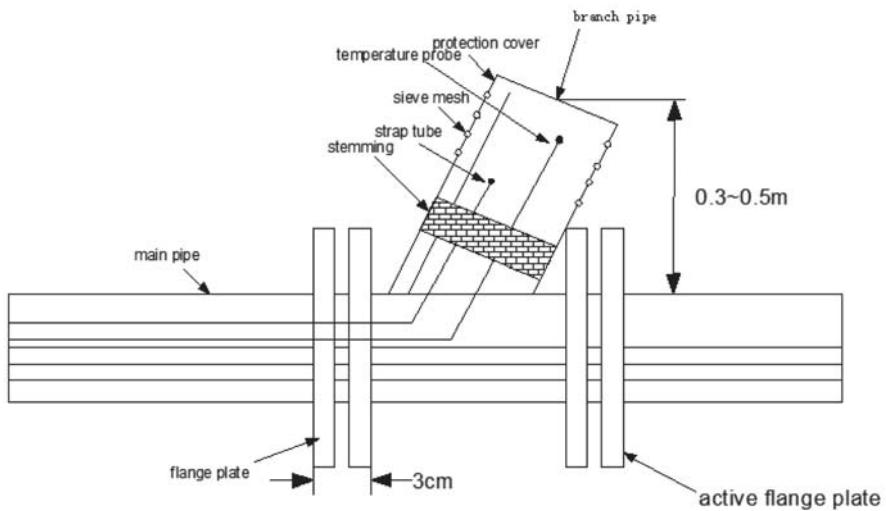


Fig. 3. Probe location and protection structure

4. Results and analysis of spontaneous combustion parameters tested in goaf

4.1. Oxygen concentration changes in goaf

According to oxygen concentration measurement results, draw the figure of the oxygen concentration of the intake airway and return airway with the variation of distance as shown in Figure 4 and 5.

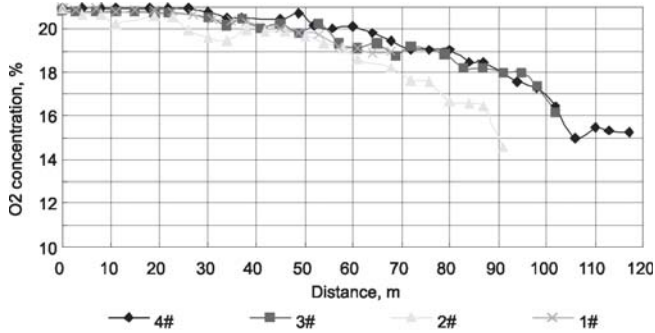


Fig. 4. Oxygen concentration changes in goaf along return air side

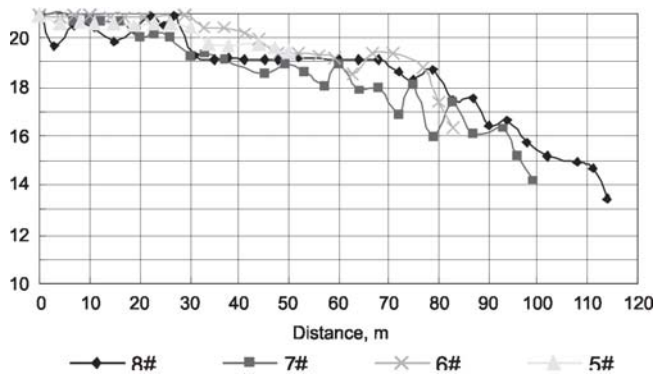


Fig. 5. Oxygen concentration changes in goaf along intake air side

According to the oxygen concentration measured results show that when the point gradually enters the mined-out area, the oxygen concentration of the point changes gradually. The point in return air side 25 m from the face, oxygen concentration changes a little; in the range of 25 to 80 m from the face, oxygen concentration drops gradually; the oxygen concentration drops quickly in the face of more than 80 m distance. The point in intake air side 30 m from the face, oxygen concentration changes a little; in the range of 30 to 90 m from the face, oxygen concentration drops gradually; the oxygen concentration falls rapidly in the face of more than 90 m distance.

4.2. Methane concentration changes in goaf

In the goaf, according to methane (CH_4) concentration measurement results, draw the figure of the methane (CH_4) concentration of the intake airway and return airway with the variation of distance as shown in Figure 6 and 7 (black boldline for the point averages).

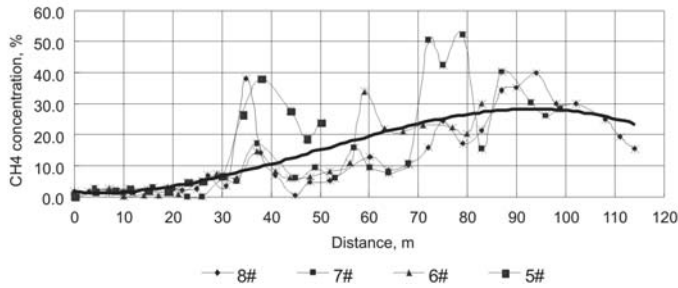


Fig. 6. Methane concentration changes goaf along return air side

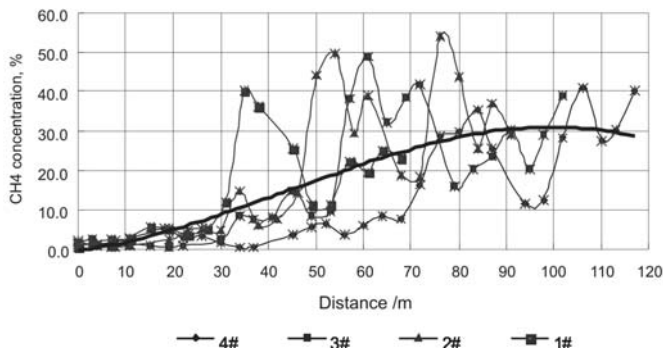


Fig. 7. Methane concentration changes in goaf along intake air side

From methane (CH_4) concentration distribution of Figure 6 and Figure 7, we can lead to the conclusion that in return air side 25 m from the face, methane (CH_4) concentration is lower; in the range of 25 to 80 m from the face, gas concentration increase gradually along with working face being advanced; the methane (CH_4) concentration is basic unchanged in the face of more than 80 m distance, this illustrate that mined-out area gradually enter into the compacted zone. In intake air side, 30 m from the face, methane (CH_4) concentration is lower; in the range of 30 to 90 m from the face, gas concentration increase gradually along with working face being advanced; the methane (CH_4) concentration is basic unchanged in the face of more than 90 m distance, this illustrate that mined-out area gradually enter into the compacted zone. These are contrary to the rule of the oxygen concentration of the point in return air side and in intake air side, but the scope of the concentration change are consistent.

4.3. Carbon dioxide concentration changes in goaf

In the goaf, according to dioxide (CO_2) concentration measurement results, draw the figure of the dioxide (CO_2) concentration of the intake airway and return airway with the variation of distance as shown in Figure 8 and 9 (black boldline for the point averages).

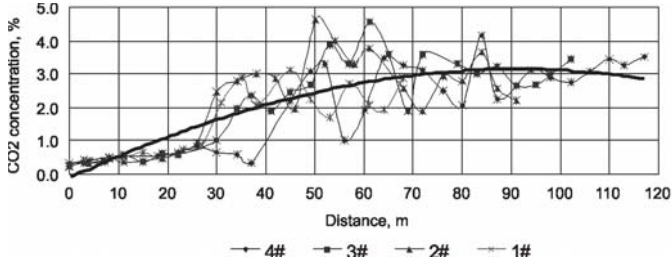


Fig. 8. Dioxide concentration changes in goaf along return air side

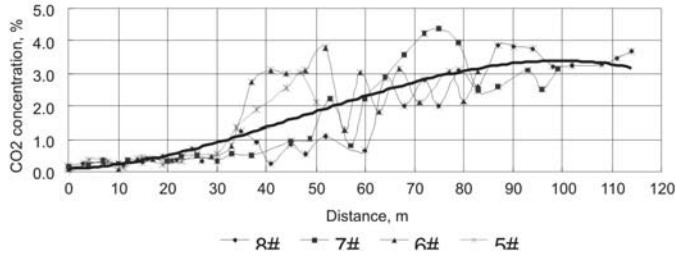


Fig. 9. Dioxide concentration changes in goaf along intake air side

From dioxide (CO_2) concentration distribution of Figure 8 and 9, we can lead to the conclusion that in return air side, 25 m from the face, dioxide (CO_2) concentration is lower and change slowly; in the range of 25 to 80 m from the face, dioxide (CO_2) concentration increase gradually and growth rate is accelerated along with working face being advanced, this show that in the mined-out area, the coal is oxidated step by step and it go into the spontaneous combustion zone; the dioxide (CO_2) concentration is changed slowly in the face of more than 80 m distance, this illustrate that mined-out area entere into the suffocation zone. In intake air side, 30 m from the face, dioxide (CO_2) concentration is lower and change slowly; in the range of 30 to 90 m from the face, dioxide (CO_2) concentration increase gradually and growth rate is accelerated along with working face being advanced, this show that in the mined-out area, the coal is oxidated step by step and it go into the spontaneous combustion zone; the dioxide (CO_2) concentration is changed slowly in the face of more than 90 m distance, this illustrate that mined-out area entere into the suffocation zone. These are contrary to the rule of the oxygen concentration of the point in return air side and in intake air side, but the scope of the concentration change are consistent.

4.4. Temperature changes in goaf

There have six temperature probe in the goaf No. 713 working face, they are No. 3, No. 2, No. 1, No. 7, No. 6, No. 5 in return air side and intake air side. Every point temperature change is shown in Figure 8 and 9 (black boldline for the point averages).

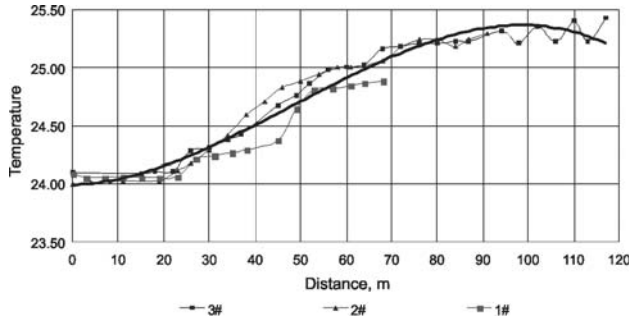


Fig. 10. Temperature changes in goaf along return air side

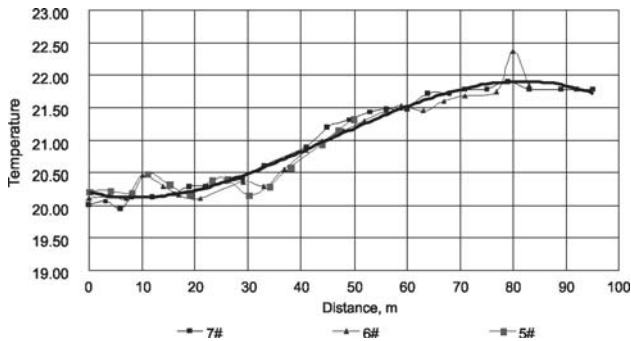


Fig. 11. Temperature changes in goaf along intake air side

According to the temperature measured data, we can know that top temperature is 25.3°C and the average is 24.7°C in return air side and top temperature is 22.4°C and the average is 20.9°C in intake air side. The temperature in return air side overtop it in intake air side, this evidence that return air side is air leakage collect.

From temperature distribution of Figure 10 and 11, we can lead to the conclusion that in return air side, 25 m from the face, average temperature is lower and change slowly; in the range of 25 to 80 m from the face, average temperature increase gradually along with working face being advanced and residual coal is in a position of self-heating stage; the temperature is changed slowly and have the trend to decline in the face of more than 80 m distance, this illustrate that mined-out area gradually entered into the compacted zone. In intake air side, 30 m from the face, the temperature is lower; the temperature is higher in the range of 30 to 90 m from the face, this illustrate that residual coal is oxidated; the temperature is declined obviously in the face of more than 90 m distance, this illustrate that mined-out area entered into the suffocation zone. The change of temperature in return air side and in intake air side is consistent with the change of oxygen concentration of the point which judges “three zones” in the mined-out area.

5. Numerical simulation of airflow field in goaf

5.1. Basic assumption

- 1) Incompressible stope fluid;
- 2) Upward and downward entries in same horizontal level and regardless of the effect of potential energy;
- 3) Gob flow-field regard as isotropic porous media;
- 4) Gob air leakage drag coefficient remain unchanged in vertical Z direction.

5.2. Physical model of goaf

According to the reality of the 713 full mechanized mining face, the condition is that sectional area of face, intake airway and return airway is actual measurement-oriented and gob height is consistent with face height, and then we get the 3D stope mining face physical model diagram as shown in Figure 12.

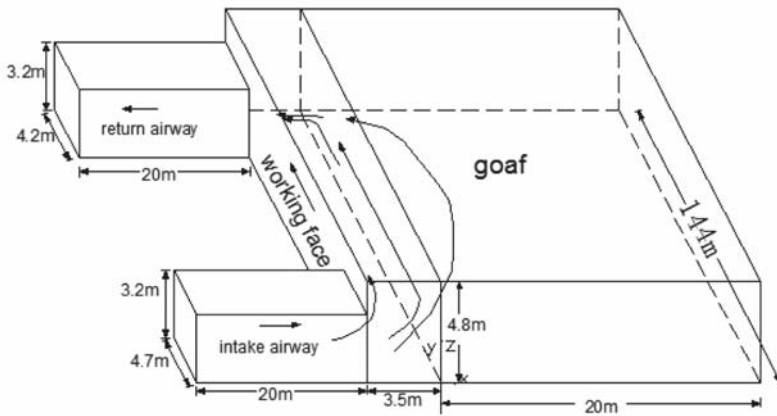


Fig. 12. Physical model of goaf:

X — goaf strike; Y — goaf dip; Z — goaf vertical direction

5.3. Mathematical model of goaf

Consideration about incompressibility of air flow in working face, we can obtain simplified steady quality and momentum conservation equation of i direction in gob [9].

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (1)$$

$$-\frac{\partial p}{\partial x_i} = \frac{\mu}{\alpha} v_i + C_2 \frac{1}{2} \rho |v_i| v_i \quad (2)$$

Where:

- p — is static pressure, Pa,
- v_i — is unit average flow velocity i direction, m/s,
- α — is porous media permeability, m^2 ,
- C_2 — is inertia factor, 1/m,
- ρ — is fluid density, kg/m^3 ,
- μ — is fluid dynamic viscosity, Pa·s.

Due to the spontaneous combustion zone in the mined-out area be exposed to transition flow regime, apply ventilation network simulate the filter flow field in the mined-out area, which adopt aerodynamic resistance characteristic equation in gob as follow.

$$h = R_1 Q + R_2 Q^2 \quad (1)$$

Where:

- h — is air leakage resistance, Pa,
- R_1 — is laminar air resistance, $Pa \cdot s/m^3$,
- R_2 — is turbulent air resistance, $Pa \cdot s^2/m^6$,
- Q — is air-leakage rate, m^3/s .

Consideration about the air resistance change of mined-out area tendency, the calculation formula for air leakage of the air resistance is [10, 11]:

$$R_1 = ax^c \frac{l}{s \cdot k(y)} \quad (2)$$

$$R_2 = bx^{0.5c} \frac{l}{s^2 \cdot k(y)} \quad (3)$$

empirical coefficient

where:

- a, b — are empirical coefficient, which depend on roof and rock properties as shown table 2,
- y — is gob dip separation, m,
- x — is the distance in the mined-out area from working face, m,
- l — is the length of the filter flow branch in mined-out area, m,
- s — is sectional area of the filter flow branch in mined-out area, m^2 ,

- $k(y)$ — is the air drag coefficient in the mined-out area tendency,
 c — is compaction coefficient of fallen rock, which is concerned with drawing speed V_f (m/d).

According to the type (4) calculation.

$$c = 1.0e^{0.1(5.0-V_f)} \quad (4)$$

where V_f is drawing speed, m/d.

TABLE 2
 a and b values of fallen rocks of different lithology

Category	a	B
Soft clay rock, shale	0.6~1.0	101
Medium hard clay shale	0.2~0.5	71~100
Hard clay shale, sandstone	0.06~0.1	51~70
Sandstone, limestone	0.03~0.05	35~50

In the sloping direction, because the roof near upper and down airway is supported by solid coal in the mined-out area, the overlaying strata without support in the middle of mined-out area, and the roof fallen rock deflection is also different. The pore rate of center part is smaller than one near upper and down airway in goaf, and air resistance is larger. If make $k(y)$ for the wind drag change coefficient, we can get follow calculation formula.

$$k(y) = \frac{H_1}{H_2} + \left(1 - \frac{H_1}{H_2}\right) \sin\left(\frac{\pi}{l_y} y\right) \quad (5)$$

where:

- H_1 — is overlaying strata deflection of center part in mined-out area,m,
 H_2 — is upper and down boundary strata deflection,m,
 l_y — is tendency long of mined-out area, m.

According to the actual mine conditions and related material [10], H_1/H_2 take 1.30. Combined with the actual roof lithology of the face, lithology factor takes $a = 0.05$, $b = 50$. We can obtain viscous resistance and inertia resistance coefficient respectively.

$$\frac{1}{\alpha} = \frac{R_1 s}{\mu l} = \frac{0.08x^{1.13}}{\mu \left[1.3 - 0.3 \sin \left(\frac{y}{144} \cdot \pi \right) \right]} \quad (6)$$

$$C_2 = \frac{2R_2 s^2}{\rho l} = \frac{120x^{0.56}}{\rho \left[1.3 - 0.3 \sin \left(\frac{y}{144} \cdot \pi \right) \right]} \quad (7)$$

5.4. Simulation Results and Their Analysis

FLUENT, one calculation software of professional Fluid Dynamics, is used to simulate and some results are got.

The distribution of air leakage from working face of different distance in the direction of dip to goaf is shown in Figure 13. (The amount of air leakage, which is positive, means leaking in, and negative leaking out). Two other contour maps of face are also got of three-dimensional flow field at the tangent plane of $z = 1.5$ m and $z = 3.0$ m and two-dimensional flow field at the tangent plane of $z = 1.5$ m, which are shown in Figure 14 and 15.

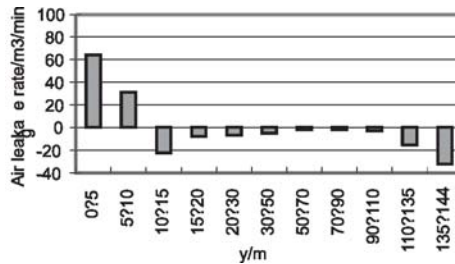


Fig. 13. Histogram of air leakage along the dip of working face

It is shown in Figure 13 that the main region of air leakage from face to goaf is the inlet side 0–30 m (the total amount of air leakage is $1.58 \text{ m}^3/\text{s}$), which brings sufficient oxygen here. And it is consistent with the slower decrease of the density of oxygen of the inlet roadway compared with the middle of the face and the outlet roadway according to measuring. In the middle of the face, the amount of air leakage is relatively little and the amount of wind changes little. Finally, the air leaking in goaf flows to outlet road from the outlet side of the face. The distribution of amount of air leakage of this face is basically consistent with the distribution of amount of air leakage of blasting mining face in journal of 12, and so the result of simulation is rational.

In Figure 14, it show the distributions of the flow field contour of the two tangent plane are basically consistent and it is mainly because the change of air leakage resistance

coefficient of the goaf in the direction of z is not considered . It can be got from Figure15 that the flow rate of air of leakage of the goaf larger around the lower corner of the face, which mainly results from effect of inertia of the kinetic energy of the air flow and causes the most of the leaking air of goaf flows from the lower corner of the face , consistent with the amount of air leakage of goaf being the most in the direction of y , $0\div 30$ m, of the face in Figure 2. Along the strike of the goaf, the flow rate decreases rapidly and it is mainly because the resistance coefficient is getting bigger gradually as the goaf is being squeezed. Although the distribution of the resistance coefficient in the direction of y is symmetrical, obeying the sine function, the distribution of the flow field contour of the goaf is incompletely symmetrical.

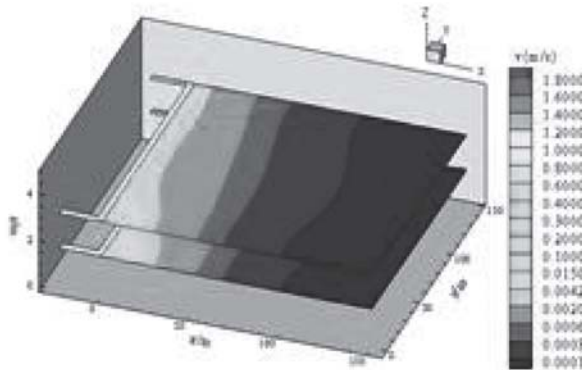


Fig. 14. Three-dimensional contour map of the flow field at the tangent planes of $z = 1.5$ m and $z = 3.0$ m

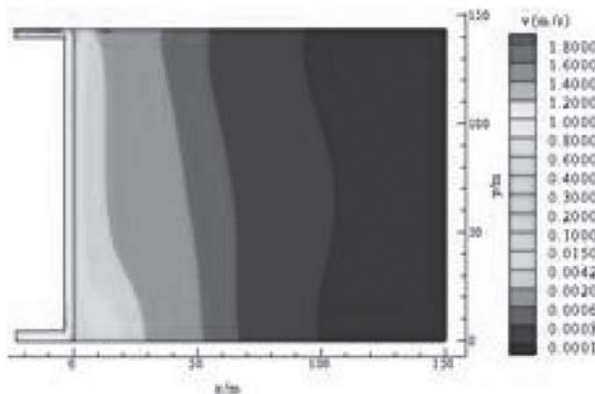


Fig. 15. Two-dimensional contour map at $z = 1.5$ m

6. Distribution of spontaneous combustion “three zones” in goaf

According to No. 713 face measured data of oxygen concentration, methane (CH₄) concentration, dioxide (CO₂) concentration and temperature of each measuring points change with the distance from the face in goaf in Section 3 of this article and the results of flow field numerical simulation in Section 4, we can draw the scope of coal working face gob spontaneous combustion “three zones” as shown in Figure 16.

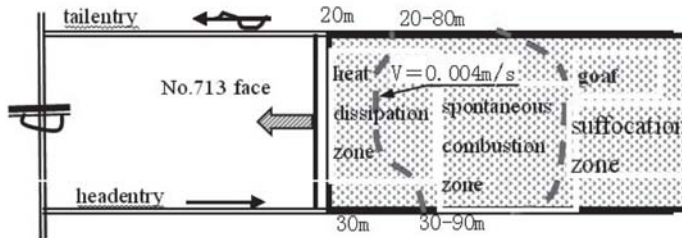


Fig. 16. The distribution of spontaneous combustion “three zones” in goaf

7. Conclusions

- 1) Testing system of spontaneous combustion parameters of coal in goaf was established, probe protection method was proposed, which provide a basic reference to spontaneous combustion parameters test in goaf of the similar working face.
- 2) Coal spontaneous combustion parameters tested in the goaf proved that the established mathematical model of the goaf is feasible, which provides a theoretical basis for numerical simulation of spontaneous combustion “three zones” in goaf of the similar working face.
- 3) Based on numerical simulation and analysis of gas concentration and temperature changes in goaf, the heat dissipation zone width in the goaf is 0–30 m from the working face, oxidation zone width is 30–90 m , suffocation zone width is 80–90 m from the working face.
- 4) According to numerical simulation of airflow field in goaf, the location of mayor air leakage into goaf is from 0 to 30 m, from working face. In the middle part of working face air leakage into goaf is little. Air leaked into the goaf flows to return airway.

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