Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2013, 5(9):248-255

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Thermal dynamic system of the outcrop coal fire under the control of multi-ventilation power factors and its application

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ABSTRACT

The objective of this paper is to obtain the developing tendency of outcrop coal fire under the multi-ventilation powers and fire pressure, so as to provide technical support for the governance of the fire area and ensuring mine work safety. The structural characteristic of the thermal dynamic system of outcrop coal fire under the control of multi-ventilation power factors have been analyzed and the practical application has been carried out. The thermal dynamic system of the outcrop coal fire under the control of multi-ventilation power factors include five sub-systems, namely combustion, heat dissipation of coal and rock, gas seepage and oxygen supply, gas discharge, and goaf leakage. Then, the mathematical model of the thermal dynamic system is set up and is applied in the old Shaft II fire area of Didao coalmine. At last, the changes of combustion product concentration, pressure and seepage velocity in the outcrop, which is under the condition of the even air pressure fan of the old Shaft II is done or stop, are acquired. As the even air pressure fan of the old Shaft II stops working, the seepage range in the fire area will reduce, and then, the growth speed in the fire area will reduce to some extent. However, because the pumping action of the even air pressure fan disappears, part of the combustion product will flow into working area of the coalmine. Thus, it is recommended to add automatic air door and CO sensor between the old shaft II and shaft XI in -480m main haulageway, so as to monitor the impact of fire area on work safety, and gradually close the fire area.

Keywords: multi-ventilation power, outcrop, coal fire, thermal dynamic systems, numerical simulation

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INTRODUCTION

The thermal dynamic system of the outcrop coal fire refers to the dynamic organic integrity of the inter-conversion of the matter and energy, etc., which are produced by the flammable substance (coal) under the impact of the external environment. After appearance of the outcrop coal fire, under the impact of internal and external factors, the thermal dynamic system established in the combustion process has general characteristics of "system" in normal meaning. In order to systematically study the characteristics of the outcrop coal fire development under complex ventilation power, as well as interaction process of the ventilation systems, there is need to establish a simplified dynamic model for the process of outcrop coal fire. On this basis, the dynamic models and numerical algorithm can be applied to calculate the influence law of the coal fire burning under the impact of ventilation conditions, so as to provide technical support for the government of the fire area.

Coal fire is one kind of serious disasters. In the research field of coal fire, some researchers have been acquired some mathematical models of the coal fire and the ways of gas emission. A Dip Angle Model (DNM) [1] for semi-infinite solid is deduced to estimate the temperature distribution at different times at places in underground coalbed fire of different diffusivity. But it includes too hypotheses, thus, it doesn't adapt to coal field fire. Bustin [2][3] found the volatile produced in coal combustion area drive coal spontaneous combustion along a certain path by the investigation in Province of British Columbia of Canada. ITC of Holand cooperated with China in the investigation of the northwest area coalfield in China [9]. They proposed fire depth and temperature distribution, which could be acquired by means of heat transfer model, were very important for underground coal fire. Stefan [8] studied the evolution of energy and surface temperature of Wuda coal fire area. A temperature model of goaf spontaneous combustion was set up based on the float coal factor [5]. Based on the convection theory in porous media, Jiejie Huang [7] established a 2D model of underground coal fire and then found the gas convection play an important role in fire area. The author set up a model coupling seepage with thermal dynamics of spontaneous combustion of coalfield outcrop [10]. But the models above do not consider the development of fire area and seepage characteristics in the multi-ventilation power system, and none research has been carried out specifically for the large area coal fire laws.

Under the background of Didao old shaft II outcrop fire area in Jixi city of China, this paper is mainly to research the characteristics of the development in the fire area under the combining effect of the mine ventilation system, air system, coal and rock seepage system, combustion system in fire area, as well as under the impact of changes of ventilation system, so as to provide technical support for ensuring mine safety production.

THE THERMAL DYNAMIC SYSTEM STRUCTURE OF THE OUTCROP COAL FIRE

Overview of fire area: Didao mining area is an old group-shaft mine. There are four production mines, namely, vertical shaft, Shaft III, Shaft IX and Shaft XI. The fire area of the old Shaft II formed in 1982, which now becomes outcrop coalfield fire area with large areas. To suppress the rapid development of spontaneous combustion area, the even air pressure fan is specially set up for the Didao mine to control the spread of the fire area. The conditions of the fire area must be monitored on duty continuously by the specially person. The air current is complex in the range of the old Shaft II fire area, which is shown in Fig.1. There are many gobs, outcrop areas unexploited and small coal mines surrounded. Near the fire area, there is old Shaft II, Shengli shaft, Shaft XI, Shunhexing Coal Mine, Jinshan Coal Mine, etc. Through the field investigation and analysis, the possibility of air supply by Shunhexing Coal Mine and Jinshan Coal Mine is excluded. The Shengli shaft is an inclined shaft with natural ventilation, located in -480m main haulageway, which is directly connected to the underground mine system of the old Shaft II, later connected toward the south west, with the area of Shaft XI. The wall structure in the lower part of the Shengli shaft is incomplete. The space between the old Shaft II and Shengli shaft is the goaf; the Shengli shaft is natural ventilation; the old Shaft II and the Shaft XI are negative-pressure ventilation. Therefore, the old Shaft II fire area is jointly controlled by the surface atmosphere, even air pressure fan of the old Shaft II, negative-pressure main fan of the Shaft XI, and fire pressure. The ventilation system scheme is shown in Fig.2. The mine air in the old Shaft II was measured in 15th, January, 2011, shown in Table 1.

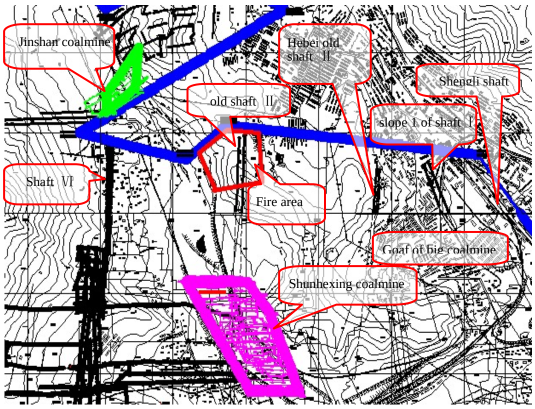


Fig. 1: Mine workings system around the fire area

Table 1 Measured result of mine air in old Shaft II

sampling site	Measuring result /%			
	O_2	CO	CH_4	CO_2
10 m below air branch	18.6300	0.0389	0.0756	1.9780
aidt of fourth level	18.5900	0.0375	0.0834	2.1590
5th level	19.3800	0.0538	0.0264	1.6590
120 m below air branch	19.0200	0.0274	0.0843	1.4600

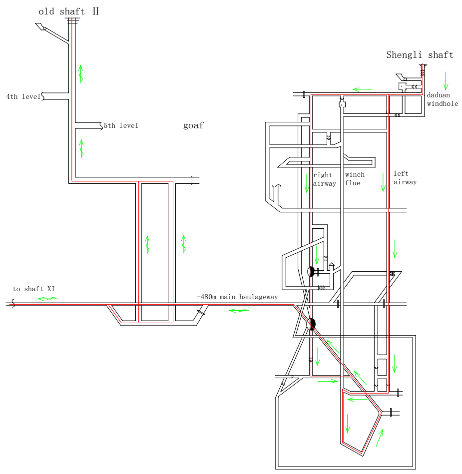


Fig. 2: Ventilation system scheme around the fire area

Characters of the thermal dynamic system of outcrop coal fire: The coal bed outcrop forms fire area is the result of synthetical influence of atmosphere system, rock system and mine ventilation system. After the outcrop fire area formed, the dynamic system of oxygen supply, combustible component of the coal bed, gas emissions to the atmosphere must be formed. After the formation of the thermal dynamic system of outcrop coal fire, the combustion of coal seam will maintain under the condition of continuous oxygen supply. The thermal dynamic system of outcrop coal fire is to circulate under interaction of atmospheric oxygen supply, oxygen supply of the ventilation air leakage, smoke dissipation and heat dissipation of the rock. According to the specific characters of the old shaft II fire area, the thermal dynamic system of the outcrop coal fire near the old Shaft II include three parts, namely subsystem of oxygen supply, subsystem of combustion and subsystem of combustion gas exhaust, which are shown in Fig. 3.

The subsystem of oxygen supply typically includes the oxygen supply of outside air leakage through coalbed outcrop, air leakage through fracture or fault of overburden rock, and the gob air leakage, as well as through the slow seepage of the coal and rock porous medium. The fire area of the old shaft II contains two ways to supply oxygen through outcrop and gob.

The subsystem of combustion is a part of chemical reaction of the coal fire, receiving the oxygen supplied by the subsystem of oxygen supply, and producing combustion products.

The subsystem of combustion gas exhaust includes combustion products inject through the fracture of rock and overburden, smoke outflow through mine ventilation system, slowly seepage through the coal and rock porous medium. The fire area of the old Shaft II contains all the exhaust ways above.

In the three subsystems above, the subsystem of combustion, and surface atmosphere system and goaf air leakage system constitute difference of thermal pressure, and constitute negative pressure on gas leakage to pull oxygen supply. The exhaust system constitutes positive pressure, so that the gas can be exhausted by the subsystem of exhausting combustion gas.

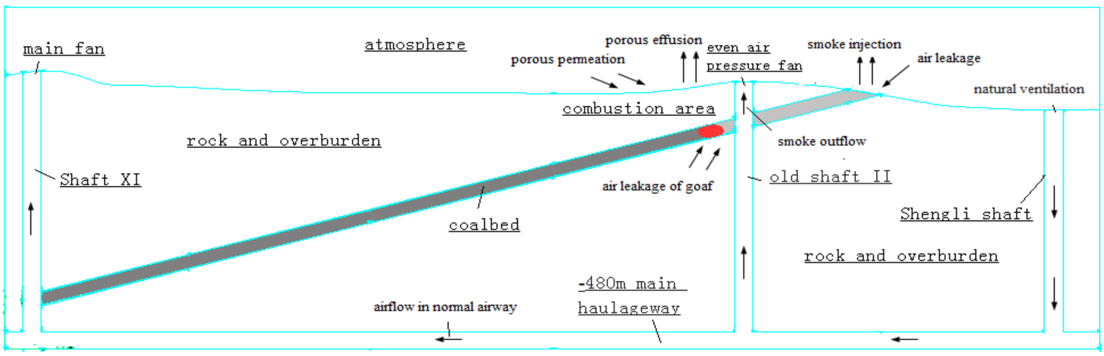


Fig. 3: Simplified graph of the thermal dynamic system in the outcrop fire area of old Shaft II

MATHEMATICAL MODEL OF THE THERMAL DYNAMIC SYSTEM OF OUTCROP COAL FIRE

Combustion subsystem: In the process of outcrop coal fire, the reaction of coal with oxygen belongs to insufficient oxidation. Outcrop coal fire often occurs under the environment with appropriate humidity, oxygen supply and heat generation. Due to the complexity of the oxidation process of outcrop coal, details of reaction should be omitted in description of the combustion process of the outcrop coal. The oxidation process of the outcrop coal can be simplified into four sub-processes, namely, precipitation of the volatile and remaining C, reaction of the volatile and O_2, reaction of C and O_2, reaction of CO and O_2, namely:

$$\begin{aligned}
&coal \to volatile + remaining \quad \mathrm{C} \\
&volatile + a_1 O_2 \to a_2 CO_2 + a_3 H_2 O \\
&(1+m)C + (m+1/2)O_2 \to CO + mCO_2 \\
&2CO + O_2 \to 2CO_2
\end{aligned} \tag{1}$$

Where: a_1, a_2, a_3 are the coefficients reflected are different according to different levels of volatile, for example, the high volatiles are respectively 1.598,1,1.417, the low volatiles are respectively 2.979, 1, 4.17, and the general volatiles are respectively 1.706, 1, 1.543 [6]; m is an undetermined coefficient, and its value is affected by temperature, oxygen concentration and environmental pressure.

The speed of oxidation reaction in the combustion process of the outcrop coal meets the Arrhenius law [1], which is established based on the rate equation of the oxygen consumption of outcrop coal in the fire area through reaction law of Arrhenius.

$$\dot{r} = \rho_1 \frac{\rho_s}{\rho_{10}} \frac{C_{ps}}{Q} (1-\phi) k_0 e^{-\frac{E}{RT}} \tag{2}$$

Where: ρ_1 is density of oxygen, kg.m^{-3}; ρ_s is density of coal, kg.m^{-3}; Cp_s is specific heat of coal, J.K^{-1}; Q is coal-oxygen reaction heat (equal to 300KJ.mol^{-1}O$_2$). Φ is porosity, 1-Φ ensures no reaction in the non-flammable coal area, thus, there is no oxygen consumption; k is reaction rate constant, (mol.m^{-3})$^{1-n}$s^{-1}; n is a reaction order, if necessary, the time unit (s) can be replaced by min or h; k_0 is frequency factor, with its unit same as k; E is activation energy, J.mol^{-1}; R is universal gas constant, R = 8.315J.mol^{-1}.K^{-1}; T is temperature, K.

Oxygen supply subsystem of atmospheric seepage: In the outcrop fire area, the way of oxygen supply by the fracture and faults belongs to pore-fissure media seepage. The transportation of gas in coal and rock media can be decomposed into two parts: one is the gas molecules move with the whole system according to the average flow velocity; the other is molecular diffusion and mechanical diffusion relative to the mean movement due to the gradient of the molecular concentration. According to the principle of mass conservation, considering the gravity, the gas seepage in the outcrop meets Darcy law, and all chemical reactions are carried out in the coal matrix, and thus the equation of the seepage flow of the component i can be established.

Pore

$$\frac{\partial}{\partial t}(\phi_1 \rho_1 C_{i1}) + \nabla \bullet \left[-\frac{K_1}{\mu_1} \rho_1 C_{i1} (\nabla P_1 + \rho_1 g \sin\varphi) \right] + \gamma_i + S_{i1} = 0 \tag{3}$$

Fracture

$$\frac{\partial}{\partial t}(\phi_2 \rho_2 C_{i2}) + \nabla \bullet \left[-\frac{K_2}{\mu_2} \rho_2 C_{i2} (\nabla P_2 + \rho_2 g \sin\varphi) \right] - \gamma_i = 0 \tag{4}$$

Where: C_{i1} is mass fraction of component i in the pore; C_{i2} is mass fraction of gas component i in the fracture; γ_i is exchange amount of component i in the pore and component i in the fracture; S_i is generation or disappearance amount of component i in the pore; Φ_1 is porosity in the non-fractured area or non-fault area of the coal and rock; Φ_2 is porosity in the fractured area or fault area of the coal and rock; ρ is density, kg.m^{-3}; K_1 is permeability of the pore; K_2 is permeability of the fracture. S_{i1} in the equation can be obtained according to dynamic analysis of the relevant chemical reactions, such as the generation of volatile and oxygen consumption, etc.

Subsystem of heat dissipation of coal and rock and overburden: Coal and rock above the outcrop coal fire plays a major role to dissipate heat to the atmosphere. The heat dissipation capacity through this channel plays a certain role in the hold time of the fire area. For the heat released by the reaction of coal fire, on the one hand, due to temperature difference in the outcrop, the head can be transferred by heat conduction; on the other hand, due to existence of the gas seepage in the coal and rock, parts of energy can be brought out by gas discharged. Assuming the heat generated by the combustion transferring in the outcrop meets Fourier heat transfer law, the effective thermal conductivity of coal and rock in the direction of depth and horizon are [11]

$$\lambda_r = \lambda_0 + 0.1 \mathrm{Re}\,\mathrm{Pr}\,\lambda_g \tag{5}$$

$$\lambda_z = \lambda_0 + 0.5 \mathrm{Re}\,\mathrm{Pr}\,\lambda_g \tag{6}$$

Where: λ_r is effective thermal conductivity in the depth direction of the fire area; λ_z is effective thermal conductivity in the horizontal direction; Re is local Reynolds number; Pr is Prandtl number, Pr = μC_p / λ_g; μ is coefficient of gas dynamic viscosity; C_p is heat capacity of gas; λ_g is thermal conductivity of the gas under the temperature of T, $\lambda_g = \lambda_{g0}\sqrt{T/T_0}$; r is vector in the depth direction; z is vector in the horizontal direction; λ_0 is effective thermal conductivity in non-fluid flow area, $\lambda_0=\lambda_g(\lambda_s/\lambda_g)^{\alpha}$; α is coefficient, α=0.28-0.757log$_{10}$(Φ)-0.057log$_{10}$(λ_s/λ_g); λ_s is thermal conductivity of the solid skeleton; T_0 is ambient temperature.

According to the heat transfer law, the equation of the temperature field in coal and rock under the fire pressure is

$$\frac{\partial T}{\partial t} + v_z\frac{\partial T}{\partial z} + v_r\frac{\partial T}{\partial r} = \frac{\lambda_z}{\phi\rho C_p}\cdot\frac{\partial^2 T}{\partial z^2} + \frac{\lambda_r}{\phi\rho C_p}\cdot\frac{\partial^2 T}{\partial r^2} - \frac{\partial T_s}{\partial t}\cdot\frac{1-\phi}{\phi} + \frac{\dot{r}Q}{\rho C_p \phi} \tag{7}$$

Subsystem of gas discharge: The process of gas discharge can be divided into three ways, namely, porous seepage, smoke injection and smoke outflow. The first two ways appear in the exchange between coal and rock and the atmosphere. The third way appears in the exchange between the fire area and mine ventilation system. No matter which way of discharge, they shall appear under the condition of the existence of pressure difference and concentration difference between the fire area and environment or mine ventilation. That is to say, if there is pressure difference or concentration difference, the exchange of the gas component appears, in which the function of pressure difference is greater than the concentration difference, which is a main reason to cause the combustion gas discharge in the outcrop coal fire.

The pressure condition in the outlet of combustion gas discharge in the fire area is

$$P\big|_s = P_0 + 1/2\rho\big|_s w^2 \tag{8}$$

Where: s is boundary of fire area and the atmosphere or ventilation system; P_0 is surface atmospheric pressure or ventilation boundary pressure, Pa; w is surface atmospheric wind speed or air flow velocity of the mine ventilation, m.s^{-1}.

Assuming the gas density $\rho|_s$ meets the equation of the ideal gas state, there is

$$\rho\big|_s = \frac{P|_s}{P_0}\cdot\frac{T_0}{T_1} \tag{9}$$

and $T|_s=T_1$

Where: T_0 is atmospheric temperature or the air temperature in the ventilation system, K.

Subsystem of the oxygen supply by goaf air leakage: The air current in goaf belongs to air leakage in the loose coal. The velocity of the air leakage current in the loose coal of the goaf is very small. Therefore, the fluid state with the loose coal to supply oxygen to the fire area is laminar flow. The main gas component in the goaf is air. The density of the air leakage flow in the loose media of the goaf changes little, with tiny temperature changes. According to Darcy's law, and assuming that seepage in the loose coal of the goaf is isotropic, the air leakage in the goaf can be expressed as

$$\sum_i \frac{\partial}{\partial x_i}\left(k\frac{\partial P}{\partial x_i}\right) = 0 \tag{10}$$

Ignoring of the effect of the oxygen adsorption and consumption, the oxygen concentration in the loose coal of the goaf is

$$\frac{dC_{ox}}{dt} + \sum_i Q_{xi}\frac{dC_{ox}}{dx_i} = \sum_i D_{xi}\frac{d^2 C_{ox}}{dx_i^2} \tag{11}$$

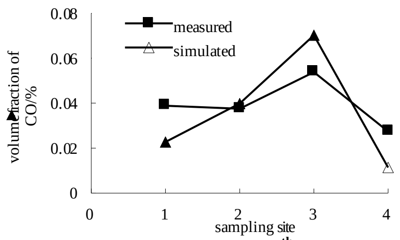
Where: Q_{xi} is intensity of air leakage at x_i direction; k is absolute permeability, m^2, $k=K.\mu$, K is permeability coefficient of loose medium, $m^3.s.kg^{-1}$; D is diffusion coefficient of oxygen, $m^2.s^{-1}$, in the goaf, $D = 2.88 \times 10^{-5}$.

It should be noted that, if the vertical distance between the goaf and the fire area is far, the effect of the air flow in the distant location is similar to the atmosphere seepage model of the outcrop due to the gradual compaction in the goaf. That is to say, the effect of the seepage of the fracture and pore meets the law described by the atmosphere seepage equation.

SEEPAGE CHARACTERS OF OUTCROP COAL FIRE UNDER THE IMPACT OF THE MULTI-VENTILATION POWER

Overview and simulation parameters of the fire area of the old Shaft II: In order to analyze the development state of the outcrop coal fire under the action of even air pressure fan of the old Shaft II, negative-pressure main fan of the Shaft XI, nature ventilation of the Shengli shaft, as well as the development changes after the even air pressure fan of the old Shaft II stops working, the three shafts and the coal and rock between them are selected for numerical analysis. At the same time, some atmospheric area also is added for simulation. The wind speed on the atmospheric surface shall be controlled by the inlets on the left and right sides. The velocity inlet or pressure outlet shall be selected according to the wind direction. The atmosphere above the boundary is the pressure outlet, maintaining an standard atmospheric pressure. Rock and coal seam are considered as a single porosity and permeability. The porosity of rock is 0.03, and the permeability is 0.03; the porosity of coal is 0.25, and the permeability is 10. The thickness of the coal bed is 1.5m, an average of the coal volatile content is 35%, ash content is 3%, moisture content is 4.6%, the fixed carbon content is 57.4%, and the calorific value is 29000KJ/kg.

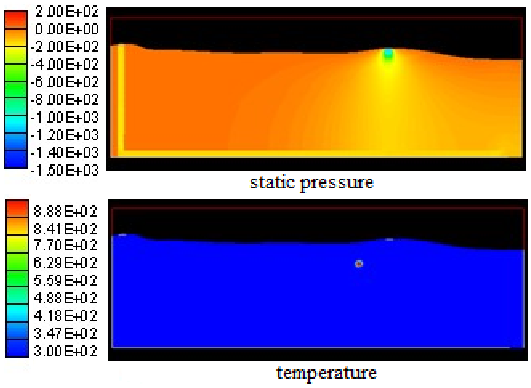
Comparison between simulated results with measured data: Fig. 4 is the comparison of concentration of CO between simulated results and measured results. It shows that the volume fraction of CO simulated close to measured data, and so, it validates the mathematical model of the thermal dynamic system of outcrop coal fire.



1-10 m below air branch; 2- aidt of fourth level; 3- 5th level; 4-120 m below air branch

Fig. 4: Comparison of concentration of CO between simulated results and measured results

Seepage characters near the fire area under the combined effects of natural ventilation, even air pressure fan and main fan of mine: Fig.5 is the distribution of the static pressure field, temperature field, velocity field and CO concentration field when there is fire area from the old Shaft II to Shaft XI. It can be shown that, under the impact of the negative-pressure fan of the old Shaft II and Shaft XI, the static pressure field in the coal and rock is controlled by negative pressure; the high-temperature region is confined near the fire source. Because of the even air pressure effect of the old Shaft II fan, the air flow velocity in the position connected the shaft of old Shaft II and -480m main haulageway is very low. Under the action of fire pressure, the gas seepage velocity increases, but the overall gas velocity in coal and rock is low. Due to the pumping action of the fan of the old Shaft II, most of the gas is discharged through an old Shaft II. There is no product in the position below 5th level, which is the same as the actual measurement and observation in the fire area. Simulation results show that the even air pressure fan of the old Shaft II plays a significant positive role in the development of the Shaft XI under control of fire.



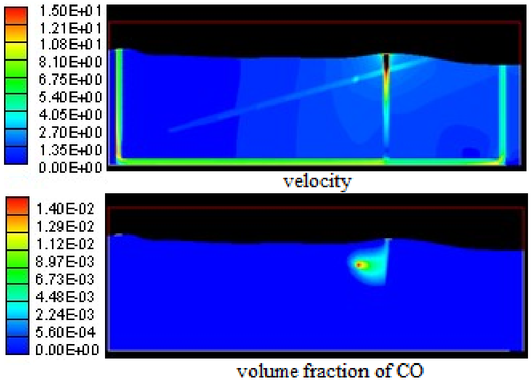


Fig. 5: Static pressure field, temperature field, velocity field and CO concentration field when the fan of old Shaft II starts

Characters of the fire area after stopping even air pressure fan and the impact on work safety: Fig.6 shows the outcrop field variation characters after stopping even air pressure fan of old Shaft II. The figure shows that the pressure in the outcrop fire area is redistributed as stopping the even pressure fan of the old Shaft II. The negative pressure in the fire source is much smaller than that of operating the fan of the old Shaft II. Larger negative pressure appears in the position of -480m main haulageway connected old Shaft II and Shengli shaft. After stopping the even pressure fan, some combustion products of the fire area flow into -480m main haulageway, thus, posing an impact on work safety of the area of Shaft XI. Correspondingly, the velocity field shall also be redistributed, the original higher air speed in the area of the old Shaft II disappears, the wider range of the seepage in the coal and rock of the old Shaft II reduces, and the seepage velocity decreases.

Based on the above analysis, as stopping the fan of old Shaft II can decrease the seepage velocity and range of gas in coal and rock, and the development of the fire area decreases to some extent. Due to the disappearance of the bumping action of the even pressure fan, part of combustion product in the fire area flow to the working area of the Shaft XI, posing a direct threat to work safety. Therefore, it is necessary to take some measures if stop the fan of old Shaft II directly. It is recommended to add automatic air door and CO sensor in the space between the old Shaft II and Shaft XI in -480m main haulageway, so as to monitor the fire area influence on work safety momentarily.

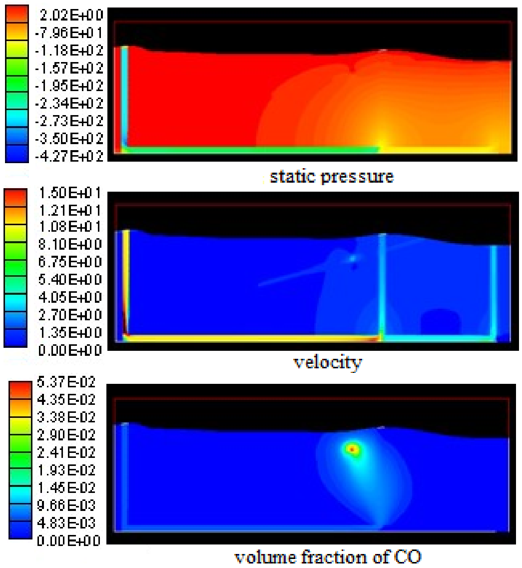


Fig. 6: Pressure field, velocity field and CO concentration field of coal fire after stopping the even pressure fan of old Shaft II

CONCLUSION

Based on the analysis of the structure of thermal dynamic system of the outcrop coal fire, the thermal dynamic mathematical model of the outcrop coal fire under the control of multi-ventilation power system is set up. Then, the field variation characters in the fire area of the Didao old Shaft II under the control of ventilation, and the impact of stopping the even pressure fan ventilation system of the old Shaft II on the development of the outcrop fire area are carried out by numerical simulation. Last, some measures are proposed to assurance the fire area security after stopping the fan in the old Shaft II.

Acknowledgment
We kindly acknowledge financial support bythe national science foundation of China Program (No.U1261214, 51304211).

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