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Prediction of Self-Ignition Fire Propagation and Coal Loss in An Inclined Seam

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Abstract: The thermo-chemical processes of coal spontaneous combustion in a practical inclined outcrop seam were investigated in order to understand underground mineral self-ignition, fire propagation, and reserves loss. A heat and mass transfer model of porous coal-bearing stratum was employed, combining convection and radiation with transient exothermic source which is coupled with coal oxidation, oxygen supply, and fuel consumption. It is found that spontaneous combustion firstly occurs under lean oxygen condition and fire development controlled by the reaction heat release in the early oxidation process shifts to oxygen restriction after coal self-ignition. The stratum porosity affects significantly the fire propagation. Fire propagation rate slightly increases as the inclined angle decreases. Compared with indirect surface survey, the predicted reverses loss is more reasonable; and thus, the present model could provide a useful reference to loss estimation in coal fire hazards.

Keywords: Combined heat transfer; Coal fires; Fire propagation; Fuel loss
Nomenclature

\( A \) frequency factor, Hz
\( C_o \) local oxygen concentration, kg/m\(^3\)
\( C_p \) specific heat, kJ/(kg \cdot K)
\( E_a \) activation energy, kJ/mol
\( \bar{g} \) gravitational vector, m/s\(^2\)
\( h \) coal seam thickness, m
\( K \) permeability, m\(^2\)
\( l_d \) dip length of coal seam, m
\( l_s \) strike length of coal seam, m
\( \dot{M} \) coal consumption rate, kt/y
\( O_r \) theoretical oxygen requirement for combustion, kg/kg coal
\( p \) hydrostatic pressure, Pa
\( q \) heat release rate, W/g
\( q_{re} \) heat flux of radiation, W/m\(^2\)
\( Q \) reaction heat, J/g
\( Q_{net} \) net calorific value of coal, MJ/kg
\( R \) gas constant
\( t \) time, s
\( T \) absolute temperature, K
\( \nabla \) seepage velocity, m/s

Greek symbols

\( \beta \) attenuation coefficient, m\(^{-1}\)
\( \sigma \) Stephan-Boltzmann constant
\( \lambda \) thermal conductivity, W/(m \cdot K)
\( \mu \) air dynamic viscosity, Pa \cdot s
\( \rho \) density, kg/m\(^3\)
\( \rho_c \) simulated coal consumption based on oxygen reaction, kg/m\(^3\)
\( \rho_r \)  residual coal density, kg/m\(^3\)
\( \rho_t \)  total consumption of local coal, kg/m\(^3\)
\( \varphi \)  porosity

**Subscripts**

\( s \)  solid material
\( f \)  leakage air

**1. Introduction**

Coal accounts for approximately 30% of total global energy usage, generating 41% of the world’s electricity (Arunachalam and Fleischer, 2008). Coal fires are a serious safety and health hazard in coal-mining countries such as China, the USA, and Australia. A coal seam fire refers to large-area spontaneous combustion of underground coal oxidation caused under natural condition or by human activities. Uncontrolled coal fires consume the coal resources and bring serious problems to the global environment and local ecology, such as atmosphere pollution, damage to soils, contamination to underground water, and consequently the health problems to human beings (Kuenzer et al., 2007). Coal fires are truly a global problem that has attracted increasing attention in recent years.

As one of the top coal producing and consuming countries, China has experienced some worst coal fire disasters, having an annual coal loss of 13.6 million tons. Among all the fire areas, Xinjiang region where reserves the most abundant coal in China suffers the severest coal fires. According to the latest report issued by Xinjiang Coal Fire Fighting Bureau (Tang, 2015), there were 49 coal fire areas in Xinjiang region by the end of 2010, about 8 million tons of coal was burned out each year with a burning area of 9 square kilometers, and the direct economic loss was
nearly one billion RMB every year. For example, the Heshituoluogai coal fire (Xinjiang Coal Field Fire-Fighting Engineering Bureau, 2009) that is currently one of the last three State Key Coal fires in Xinjiang province contains 12 sub-fire areas with total fire area more than 1.4 km$^2$. Every year, the assessed coal loss due to self-combustion exceeds 1.5 million tons and other more than ten times of fuel sources could not be exploited due to the threat of the nearby underground fires. Although many efforts to extinguish coal fires such as water injection and surface covering had been taken place, the coal fires in this region still spread rapidly (Xinjiang Coal Field Fire-Fighting Engineering Bureau, 2010). It is hard to reveal the dynamical combustion loss of underground coal fire and catch the invisible combustion propagation accurately.

Previous studies have pointed out that a coal fire is a multidisciplinary physical and chemical process incorporating coal-oxygen reactions, seepage flow and gas dispersion, and combined heat and mass transfer (Shao et al., 2014; Wactawik, 1998; Shi et al., 2017). Coal fire research mainly involves two aspects: 1) the mechanism of fire ignition and development, focusing on the causes of coal fire and combustion evolution (Wang et al., 2013; Rosema et al., 2001) and 2) the controlling technologies, including fire area detection, monitoring, and extinguishing methods and materials (Wang et al., 2015; Chatterjee, 2006; Song et al., 2017). Thermodynamic characterization of self-combustion is important because of its role in revealing the mechanism of fire propagation and fuel consumption as well as scientifically evaluating the environmental impacts (Su et al., 2016).

To prevent and control coal fires, laboratory-scale works (Jones et al., 1998; Zarrouk and O'Sullivan, 2006; Jin et al., 2015) have been conducted to obtain coal oxidation and combustion properties including physical and chemical adsorption
mechanism, equations of coal and oxygen reactions and kinetic parameters. Though such studies help understand combustion characteristics (Küçük et al., 2003; Yuan et al., 2017a), it is hard to describe the real process of large-scale underground coal fires by using the theory of coal oxidation directly, because the laboratory-scale results could not be transferred to simulating model of spontaneous combustion process uncritically. In fact, coal combustion or heat release in field is not only determined by reaction rate but also limited by local oxygen supply and transport (Shi et al., 2015). That means that the quantitative correlation between oxygen requirements and fuel consumption needs to be considered in estimating the real process of coal combustion under these aforementioned conditions (Qin et al., 2012).

To characterize the thermodynamic processes of fire propagation and predict coal reserves loss in large scale, a numerical study is carried out in this treatise. First, the dependence of heat release rate from coal oxidation on oxygen supply is investigated. Then a coal and oxygen consumption model is established with the quantitative correlation between theoretical oxygen requirements and coal elements. Based on the principles of heat and mass transfer in a porous medium, a combined heat transfer model for underground combustion coal fire is established with appropriate boundary and initial conditions as well as thermo-chemical and physical parameters. The development of fire history is traced and the consumptions of coal reserves and oxygen are analyzed at different fire stages. In addition, parametric studies of influencing factors such as inclined angle and porosity are conducted. Finally, we take into account a typical coal fire in the Heshituoluogai fire areas in Xinjiang region, China, and the coal loss and advancing rate of fire front are predicted and compared with field survey results from indirect methods.
2. Theory and Simulation Model

2.1 Spontaneous combustion and coal consumption

Fuel consumption rate and heat release intensity of coal spontaneous combustion have crucial influence on sustainable burning in coal fire development. Both factors are regarded as an inner motive power for fire front propagation. According to the kinetics theory of coal oxidation (Schmal et al., 1985), the exothermal capacity of coal is related to the reaction rate as:

\[ q(T) = Q A e^{-E_a / RT} \]  (1)

where \( q(T) \) is the heat release rate per unit mass at absolute temperature \( T \), \( R \) is the universal gas constant, \( E_a \), \( A \) and \( Q \) are the activation energy, the frequency factor and reaction heat, respectively. These kinetic parameters could be obtained by oxidation measurements in laboratory scale (Garcia et al., 1999; Wang et al., 2017a). Integrating the exothermal capacity through the whole reaction process from ambient temperature to burnout, the total heat release or net calorific value of coal \( Q_{net} = \int q(T) dT \) could be estimated. Between an interval time \( \Delta t \) with varying temperature, the amount of coal consumption reads

\[ \rho_t = \rho_s \int_t^{t+\Delta t} q(T) dT / Q_{net} \]  (2)

where \( \rho_s \) represents the true related density of local solid fuel.

It should be pointed out that this value is the theoretical fuel consumption under sufficient oxygen in the reaction. Unlike laboratory conditions with stable and continuous oxygen supply, however, the real situation of underground coal combustion is that oxygen supply vis-à-vis rich occurrences of fuel in the coal seam usually do not guarantee complete burning in a fire zone, i.e., oxygen supply or transport is a limiting factor in practical coal oxidation regime and the results from lab-scale measurements might not be uncritically transferred to simulate spontaneous
combustion process of underground coal fires.

The theoretical oxygen requirement \( O_r \) for complete combustion as kg/kg coal can be obtained in one step following the overall combustion equation as (Mazumdar, 2000):

\[
O_r = 0.08(C/3 + H) + 0.01(S - O)
\]  

(3)

where, C, H, S and O denote the usual notations for carbon, hydrogen, sulfur and oxygen weight percentages (wt%) in a coal on the dry mineral matter free basis, respectively. The critical fuel consumption related to the theoretical oxygen requirement can be regarded as \( C_o/O_r \), where \( C_o \) in kgm\(^{-3}\) is the local oxygen concentration determined by gas diffusion and component producing or consuming rate. Considering oxygen supply as a potential limiting factor, the local coal consumption within \( \Delta t \) in a field circumstance will be

\[
\Delta \rho_l = \min(\rho_t, \frac{C_o}{O_r})
\]  

(4)

The total consumption of local coal in the seam could be obtained by accumulating the local coal consumptions as \( \rho_l = \sum_0^t \Delta \rho_l \). Meanwhile, along with the fuel consumption, the density of the remaining or residual coal left in the seam which decreases gradually till the coal burns out is easily obtained as \( \rho_r = \rho_s - \rho_l \).

2.2 Combined heat and mass transfer model

The combined heat and mass transfer model of underground coal fire is referred to the theory of transport phenomena in a porous medium (Rashad et al., 2014; Wang et al., 2016; Huang et al., 2017). For the mixed media consisted of gas and solid materials, two-phase heat transfer equations should be established. For air leakage through the pore structure, ignoring the heat source and air expansion work, the transient heat transfer equation for the gas phase is written as

\[
\varphi \rho_f C_{pf} \frac{\partial T_f}{\partial t} + \rho_f C_{pf} \vec{v} \cdot \nabla T_f + \varphi \nabla \cdot (q_f) = 0
\]  

(5)
where $\rho_f$, $C_p$ and $\bar{V}$ are the density, specific heat and seepage velocity of fluid, respectively, $\varphi$ is the porosity, $q_f (= -\lambda_f \nabla T_f - h(T_f - T_s) + \bar{q}_{re})$ is the total heat flux in the fluid including thermal conduction, convection, and radiation (Guo and Hunter; 2013).

In the same way, the heat equation for the solid phase is described as

$$(1 - \varphi)\rho_s C_{ps} \frac{\partial T_s}{\partial t} + (1 - \varphi)\nabla \cdot (q_s) = (1 - \varphi)\rho_r q(T_s)$$

where $\rho_s$ and $C_{ps}$ are the density and specific heat of coal or rock, respectively, $q_s (= -\lambda_s \nabla T_s - h(T_s - T_f) + \bar{q}_{re})$ is the total heat flux in solid, and $\rho_r q(T_s)$ is the reaction heat source.

Under the assumption of thermal equilibrium between the solid matrix and gas, the temperature is the same for both the gas and solid materials. Therefore, combining these two heat equations, the two-phase energy equation is formulated as:

$$[(1 - \varphi)\rho_s C_{ps} + \varphi \rho_f C_{pf}] \frac{\partial T}{\partial t} + \rho_f C_{pf} \bar{v} \cdot \nabla \bar{T} = \nabla \cdot (\lambda_e \nabla T - \bar{q}_{re}) + (1 - \varphi)\rho_r q(T)$$

where $\lambda_e (= [(1 - \varphi)\lambda_s + \varphi \lambda_f])$ and $\bar{q}_{re}$ are defined as the effective conductive coefficient and radiation heat flux, respectively (Yuan et al., 2017b).

Furthermore, Darcy’s law for seepage air flow through the porous coal and rock strata (Liu et al., 2016) is assumed:

$$\bar{v} = \frac{K}{\mu} (\nabla p - \rho_f \bar{g})$$

where $K$ in m$^2$ is permeability in porous coal or rock, $\mu$ is air dynamic viscosity and set to be $1.8 \times 10^{-5}$ Pa•s, $p$ is hydrostatic pressure in Pa, and $\bar{g}$ is the gravitational vector. Here, the local permeability in the collapsed zone is directly determined by relevant porosity $\varphi$ varying from 0.1 to 0.4 (Zeng et al., 2015) as follows:

$$K = \frac{K_0}{0.241} \left[ \frac{\varphi^3}{(1-\varphi)^2} \right]$$
where the initial permeability, $K_0$, is given a value of $10^{-10}$ m$^2$.

2.3 Simulation setup

2.3.1 Physical and simulation model

In this study, a 2-D model in an inclined outcrop seam of Heshituoluogai coal fires in Xinjiang Regime, China (Xinjiang Coal Field Fire-Fighting Engineering Bureau, 2010) is taken into consideration. As shown in Fig. 1, after original mining in the dip direction at a lower level in the seam, an open and long-strip type goaf along the strike direction is left when coalmine shutdown and then the upper seam is exposed to the leakage air. When the coal temperature rose caused by oxidation, self-ignition would occur almost at the same time through the whole seam in the strike direction and then fire would advance towards the outcrop gradually. Since the fire propagating rate in the strike direction is much greater than that in the dip direction which can be regarded as infinite, the physical model of underground combustion system can be simplified as a 2-D section perpendicular to the seam strike including a subsidence roof, an inclined seam, an opened area of goaf, and an original rock floor.

![Figure 1. Simulation model of a coal-bearing stratum with inclined seam and mesh map.](image)

Based on the geological and uncovering conditions in the coal field, the horizontal scale of the simulation strata is set to be 200 m and the whole height from
surface to bottom is assumed as 80 m; the thickness of occurrence inclined seam is 8 m and the averaged angle between the dip and horizontal direction approximates 18°; the bottom corner of the coal seam is set at 190 m in the horizontal direction and 60 m in the buried depth. In addition, for the inclined mining seam, goaf roof bends and subsides occur under self and overburden gravity resulting in cAVING zone. When the tensile stress in the rock exceeds the ultimate strength, capping stratum will move downward and there exists a near-vertical fracture belt providing an air-leaking channel in the subsidence roof.

2.3.2 Initial and boundary conditions

Initial and boundary conditions need to be defined for the temperature, pressure, and gas components. For the temperature, Dirichlet condition is applied for the bottom boundary in which the temperature is assumed 300 K invariably, and Neumann condition is considered on both sides of the simulation domain and the diffusive flux of thermal energy is assumed zero. Robin boundary condition is applied for the top considering convective heat transfer between the rock and the ambient air. The ambient temperature and convective heat transfer coefficient are assumed 300 K and 10 Wm\(^{-2}\)K\(^{-1}\), respectively. For the air pressure, it is assumed to be a reference value for all the boundaries under Dirichlet condition. For the leakage air, the no-slip condition is applied at the bottom and both sides. At the top surface, there exists a fracture belt in the overlying rock where air seeps into the seam through the leakage channel and the other part of the surface is regarded as seepage exit through the overlying rock and soils.

Moreover, an initial temperature at 300 K with hydrostatic pressure distribution is assumed for all the zones in the strata. The relevant pressure referred to standard barometric pressure of 101,325 Pa is directly determined by local
geopotential energy at a certain depth. In addition, the initial air density of 1.18 kgm$^{-3}$ at 300 K with oxygen content of 21 vol.% is set in the goaf as well as in the fracture channel.

2.3.3 Other parameters

Coal fire process is obviously influenced by the physical and mechanical properties (such as density, porosity, permeability, compressive strength) and thermochemical parameters (such as thermal conductivity, heat capacity, reaction rate, heat release) of the coal seam and surrounding rock. In the present study, the main parameters based on the field conditions in the Heshituoluogai fire areas are listed in the followings.

For the chemical properties of coal sample from the fire region, the values of kinetic parameters $Q_A$ and $E_a$ in Eq. (1) could be derived by TG-DSC test (Li et al., 2014) so that the heat release can be determined. Here, a two-stage model is involved in the heat source model (Wang et al., 2017b). For the local coal, the parameters $Q_A$ and $E_a$ below and above the critical temperature $T_s$ at 598 K are $3.4 \times 10^5$ and $1.21 \times 10^6$ W/g, 57.3 and 66.1 kJ/mol, respectively, while the measured ignition temperature reads 725 K. Then, the averaged contents of C, H, O and S elements in the coal sample are obtained as 70.39, 4.39, 23.78 and 0.3 wt% by elemental analysis, respectively, so that the theoretical oxygen requirement for the coal combustion is recorded as 1.993 kg/kg coal by using Eq. (3) with net calorific value of 25.16 MJkg$^{-1}$.

For the geological parameters, the averaged true relative density of local coal is 1340 kgm$^{-3}$ and the surrounding rock density in roof or floor stratum mainly consisted of sandstone is set to be 2300 kgm$^{-3}$. In the simulation, the porosity in the inclined coal seam, subsidence roof, and rock floor is set to be 0.2, 0.1 and 0.02,
respectively. Considering the burned out area in the coal seam where could be filled with the collapsed roof rock, for simplicity, the local porosity along the dip direction in the coal outcrop is regarded as a constant throughout the whole approach.

For the thermo-physical parameters, the specific heat capacity of rocks and air is assumed as 2.0 and 1.0 kJkg$^{-1}$K$^{-1}$, respectively; the thermal conductivity of coal, rock, and air is set to be 0.2, 2.0, and 0.023 Wm$^{-1}$K$^{-1}$, respectively. In addition, according to the previous simulating methods of combined conduction-convection-radiation heat transfer in porous medium (Sun et al, 2016; Yuan et al., 2016), the diffusion approximation is applied for the radiation heat in the coal/rock bed such that
\[ \overline{q_{re}} = -(16\sigma T^3/3\beta) \nabla T , \]
in which \( \sigma (= 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}) \) is the Stephan-Boltzmann constant, and \( \beta \) assumed as 100 m$^{-1}$ is the attenuation coefficient of the coal and rocks.

2.3.4 Numerical method and mesh-independence validation

The finite difference method with implicit scheme is applied to solve the set of differential equations and the additional source term method is utilized to discretize the boundary conditions. A rectangular gridding system is carried on the simulation domain. Grid independence study has been implemented to find out an appropriate grid size from the test of four different sets of grid: 50×20, 100×40, 200×80, and 400×160. It has been found that the simulated temperature distribution at 30th year with the 200×80 grid is extremely close to these results of 400×160 grid as shown in Fig. 2. When the coarse meshes (50×20 or 100×40) are employed, significantly lower temperature is obtained probably due to the omission of the original ignition in the seam under the large intervals. Therefore, the grid of 200×80 is used for the entire calculations thereafter. In such a grid, the grid space in both directions is 1 m.
Figure 2. Comparison of simulated temperature distributions along the dip direction with different grid levels.

3. Results and Discussion

Based on the numerical method and physical model established, combined heat and mass transfer for coal fire development under spontaneous combustion condition is simulated. The history of coal fires as well as surface heat anomalies are firstly evaluated in the large-scale stratum with an inclined coal seam. Then, detailed analyses for the interactions between coal oxidation and ignition, oxygen and fuel consumption, and fire propagation are implemented during different periods in the fire development. Finally, comparative studies of two influencing factors – the dip angle of outcrop seam and the stratum porosity - on fire propagation are performed.

3.1 Coal fire development

To reveal the thermodynamic process of the subsurface coal fire development, Fig. 3 shows the simulated temperature contours in the 2-D strata with outcrop coal seam at different fire stages. Aiming to emphasize the development of self-combusting, the cut-off of maximum temperature isoline is 800K in this figure which is beyond the ignition point. It should be noticed that it does not mean the maximum temperature is just 800K.
Figure 3. Simulated temperature contours in coal fire history.

The results show that the temperature in the coal and surrounding rock stays at a low level for a very long time up to the 12th year after the seam uncovering due to the tiny heat release from oxidation reaction or chemisorption. In this early period, with oxygen seeping into the coal gradually in the dip direction, the oxidations perform through the whole seam. Then, the accumulated heat at the seam bottom achieves the ignition temperature in the 12th year and a stable flame occurs. From the
start of ignition, the heat diffuses from the seam into the upper rock rapidly and the combustion or high temperature zone expands sharply but the temperature at the rest seam near the outcrop is close to the ambient value without oxygen supply. During the period from the 12th year to 15th year, the hotspot enlarges but there is no apparent movement of combustion center yet. After that, the fire starts to advance towards the seam outcrop, as clearly illustrated in the contours from the 20th year to the 30th year. The propagation rate of the fire front reads about 40m every five years or about 8 m per year.

3.2 Oxygen and fuel consumption

In order to reveal the self-ignition and fire propagation in the coal seam, especially the relationships among the combustion, oxygen and coal consumption, the coal fire development is divided into two periods, i.e., early ignition and stable combustion. Here, all the presented results, in sections 3.2 and 3.3, are collected on the centerline of coal seam along the dip direction. The zero point is set at the interface between the goaf and coal seam, while the positive direction towards to the coal outcrop as shown in Fig. 1.

In the first period, the temperature, oxygen content, and local coal consumption (divided by original coal density) distributions from the first to 11th year after coal opening up are plotted in Figs. 4-6, respectively. It is seen from Fig. 4 that after the coal opens up, the seam temperature gradually and slowly rises with the coal oxidation process. The temperature is lower at the interface between the goaf and seam than in the inner area nearby due to the convective heat transfer to the downstream caused by leakage air until the 8th year. After that, the temperature at about 12 m in the dip direction goes beyond the critical temperature and combustion starts. Noticing the same position and time in Fig. 5, it is seen that the initial ignition
is under insufficient oxygen condition (about 15 vol.%). The initial combustion spot moves up and down in the following years. In the 11th year, the coal temperature along the whole seam drops to under the ignition critical value except in the area near the goaf.

Figs. 5 and 6 further illustrate this non-monotonic variation in terms of oxygen and coal consumptions. Before the 8th year, the oxygen supply with the leakage air could match the oxygen requirement of coal reaction at low temperature such that the oxygen content is linearly decreasing in the dip direction with synchronous oxidizing through the coal seam. In the meantime, stable fuel consumption along the whole seam by coal chemisorption exists due to enough oxygen supply. Comparing the variations in Figs. 4 and 6, it can be found that the local coal consumption at any time varies up and down with local temperature. This consistency could be explained by reaction mechanism, in other words, the self-heating process in the early stage is entirely controlled by coal oxidation model presented as Eqs. (1) and (2). Meanwhile, in the oxygen rich state, the model incorporating Eqs. (3) and (4) has not been applied in the simulation. Thus, it indicates that, during this stage, the thermodynamic process of spontaneous combustion is dominated by reaction rate and heat release of coal oxidation.

When the temperature around 12m in the dip direction exceeds the ignition temperature at the end of the 8th year, the local oxygen consumption sharply increases with the occurrence of severe reactions of fuel combustion near there. And then, this dramatic change causes a rapid drop in the local oxygen concentration and the lean oxygen environment occurs after the initial ignition. Without oxygen supply, the remaining coals stop reaction around the ignition point after the 9th year except the coals near the interface between the seam and goaf where combustion continues under
enough oxygen supply from the fractures.

Figure 4. Temperature distributions during the early oxidation stage in the coal seam.

Figure 5. Oxygen content profiles during the early oxidation stage in the coal seam.

Figure 6. Fuel consuming variations during the early oxidation stage in the coal seam.
When the bottom coals burnout after the 11th year, the oxygen starts to seep into deep seam and re-ignitions occur in the original combustion zone, so that the combustion state changes from the early oxidation to the stable development. Figs. 7-9 plot the temperature, oxygen content, and local coal consumption distributions in the dip direction at the 15th, 20th, 25th, and 30th year, respectively. It is seen from Fig. 7 that the maximum temperature at different times ranges from about 950 K to 1100 K while the interval between any two successive peaks stays at a relatively fixed value. The combustion zone moves towards the outcrop with a stable rate of fire propagation.

Looking at the oxygen content and local fuel consumption profiles in Figs. 8 and 9, a step variation along the seam dip appears for both. The position of entire coal loss falls a little bit behind the position of oxygen content decreasing. This synchronous changing means that the oxygen supply is the dominant factor for the fire propagation in this 2nd stage of stable combustion. Due to very fast reaction kinetics at high temperature, immediate consumption of oxygen takes place around the combustion center. Combustion will only proceed when the gas transport provides sufficient oxygen.

![Temperature distributions in the coal seam in the second combustion stage.](image)
Figure 8. Oxygen content profiles in the dip direction in the second combustion stage.

Figure 9. Local fuel consuming variations along the coal seam in the second combustion stage.

3.3 Geological influences

Geological factors such as inclined angle of dip and porosity in the coal seam have significant influences on the fire development. Fig. 10 plots the simulated temperature distributions along the seam dip with three different inclined angles in the 30th year since the coal opened up. It is seen that the combustion peak at the smallest inclined angle of 6° is slightly in front of the peaks of other two angles towards the outcrop and the hotspots zone is also larger than the other two cases. It indicates that when the inclined angle decreases from 18° to 6°, the fire propagation rate becomes a little bit fast. This phenomenon is due to the enlarged contact area between the coal
and oxygen at the same horizontal level with lower inclined angle, then more heat of coal reaction releases at early oxidizing stage.

Figure 10. Simulated temperature distributions at different dip angles.

To inspect the effect of porosity, three different porosity values of 0.2, 0.15 and 0.1 in the outcrop coal seam are assumed, and the other regions keep their porosity invariably. Comparative results are drawn in Figs. 11 and 12, and the colorful rectangles denote the positions and widths of combustion zones along the dip direction where the temperatures achieve ignition point under different porosity conditions involved in the simulation. It is seen in Fig. 11, in the 10th year, the width of combustion zone near the seam bottom reports 9m, 11m and 10m for porosity of 0.2, 0.15 and 0.1, respectively. Detailed comparison demonstrates the temperature peaks represented as maximum values within the combustion zones stay at the same position of 4m in the dip direction. It means at the early oxidizing stage, enough oxygen supply lead the processes of coal oxidation and heat release are independent of coal porosity. But when it is in the stable state of fire development in the 30th year (cf. Fig. 12), the differences between the combustion zones are much more obvious, in which the central position of fire for porosity of 0.2, 0.15 and 0.1 is observed at about 115m, 87 m and 58 m in the dip direction, respectively. In this circumstance, it illustrates that the reactions are entirely controlled by the oxygen supply which determined by the leakage flow, so the higher porosity with higher seepage velocity in the porous
medium results in more oxygen transfer and a faster rate of fire propagation.

Figure 11. Combustion zones in the 10th year at different porosity values for the seam.

Figure 12. Combustion zones in the 30th year at different porosity values for the seam.

4. Field data

Heshituoluogai coal fires are located in the Hoboksar Mongol Autonomous County, northwest of the Junggar Basin. There are 12 sub-fire areas caused by improper mined post-processing, distributed in a range of 57 km² as drawn in Fig. 13. The earliest coal fires occurred in the 1ª, 2ª and 3ª fire areas in 1968; and then during the period from 1968 to 1990, other six fire areas were observed. The 8ª area, ignited in September 2008, is the latest coal fire. Since 2000, the county government has repeatedly and costly operated fire extinguishing many times, but the fires have not been controlled due to lack of both water supply near the fire areas and the effective extinguishing methods. Instead, the advancing rate of the fire front accelerates with the expansion of leakage channel in the underground burning body.
Among these 12 sub-fire areas, the 5th fire area has the greatest impact on coalmine safety production. It is about 130 m apart from No. 9 well belonging to Xuzhou Mining Group Co., LTD in southeast. Since the mining level of the well is a few meters higher than the burning bottom of the fire area, the well has been seriously threatened by the rapid movement of self-combustion. To this end, the in-situ study presented here was conducted in the 5th fire area. This fire area started burning in 1986, due to the spontaneous combustion of coal in the abandoned mine goaf after the old mine shutdown which was built in 1965 with 7 wells. The underground goafs of wells No. 3 to 6 were fully connected and the spontaneous combustion was firstly observed in well No. 5 where the gas temperature passed 38°C and carbon monoxide was found in the roadway. All the wells closed in 1986 and fire features at surface upper the No. 4 and 6 wells were identified in the following years.

The 5th fire area is located at about 7 km southwest of the town of Heshituoluogai, next to the G217 National Road (cf. Fig. 13). The center point coordinates of the fire area are located at 85°, 58 min east longitude and 46°, 27 min north latitude. During the field survey in 2011 year, control survey of the fire area was based on the national four degree points WQN, 125, 128 and 83409, control network was set by using GPS static mode with the fitting elevation. According to a surface temperature survey, the northern area has a higher surface temperature, and the highest temperature measured on the surface is 674K (cf. Fig. 13). In addition, through the temperature reconstruction, the temperature range of fire area by infrared measurement is 23°C to 160°C with a zonal distribution of high temperatures.
Figure 13. Area chart of Heshituoluogai coal fires, surface temperature map and infrared image in the 5th fire area.

The geologic units covering of the 5th fire area consist of Devonian, Carboniferous, Jurassic, Tertiary and Quaternary. The coal-bearing stratum is the
upper Badaowan Formation of the Lower Jurassic \( (J_1B^2) \). The thickness of the stratum varies from 109.61 to 221.54 m with an average value of 161.22 m. There are 8-12 coal seams contained in the Badaowan Formation, numbered from the bottom \( A_1 \) to \( A_{12} \). All of the 12 coal seams are long-flame or jet coal (brand CY41) with weak caking index. The main recoverable and combustion coal seams are \( A_2 \), \( A_3 \) and \( A_4 \) with stable development district and the rest seams are unrecoverable or local minable. The average thickness of all the coal seams is 12.12 m with coal-bearing coefficient of 8.20\%. Some portions of the seams \( A_2 \) and \( A_3 \) merge into one layer and \( A_4 \) is very close to the other two seams. Therefore, these three seams are regarded as one layer in the present simulation with an average total thickness of 7.99 m, strike direction of 27° and dip angle of 18° (cf. Fig. 13). The strike length of the coal outcrop is 497 m approximately by surface prospecting in the 5th fire area. The relative density of coals sampling from \( A_2 \), \( A_3 \) and \( A_4 \) are 1410, 1320 and 1300 kgm\(^{-3}\), respectively; thus, an averaged value of 1340 kgm\(^{-3}\) is employed in the simulation. Then, the fire bottom or worked-out floor is 738 m from the seal level and the surface elevations vary from 798 m to 808 m. Therefore, the buried depth of seam bottom is about 60 m and the length of outcrop seam in the dip direction is 185 m in the present simulation. Considering a plate of coal seam, the total occurrence in the whole outcrop is about 986 kilotons. Other thermal, chemical and physical parameters employed in the evaluation follow the settings in Section 2.3.3. The local consumption of coal described in Eq. (4) along the outcrop seam is calculated, and integrated with the seam thickness \( h \), dip length \( l_d \) and strike length \( l_s \) (set to be a constant) to derive the total loss history of coal self-combustion as kt/y. Thus, the time-dependent coal consumption rate in the whole seam could be obtained as

\[
\dot{M} = l_s \iint \Delta \rho_i dh dl_d
\]  
(10)
Fig. 14 plots the annual coal consumption from 1987 after the old mine shutdown in the year 1986 until 2010. The original reserves loss by self-combustion read 460 tons in 1987 and then it increased to about 3 kilo tons around the year 1994 due to the original oxidation and ignition at early oxidizing stage. After that, the combustion was restrained under lean oxygen supply for a long time so that the annual fuel consumption stayed a lower level in the following several years until 2003. In the next year, the coal loss was dramatically enlarged to about 10 kilo tons, and continuously increased to around 60 kilo tons in 2006.

There are two indirect methods in field study, which could roughly estimate the loss of reserves. One is the gas production tracing (Wang and Chen, 2015) and the other is surface heat evaluation (Fierro et al., 1999). For the first method, the tests of gas sampling and point positioning are operated in field synchronously. NOVAH8 gas monitor was employed in the measurement, and the precisions of gas concentration and velocity are 0.1 PPM and 0.1 m/s, respectively. After observing all the gas exhaust vents at the surface of fire area, gas emissions could be determined by multiplying the gas concentration, flow velocity, and crack area. According to the greenhouse gas emissions, the oxygen consumption could be revised and the fuel loss is calculated by theoretical oxygen requirement mentioned in section 2.1. Based on the field data in 2010, the carbon dioxide emission each year from the Hestuoloogai fire area approximates 2.2 million tons and it reads about 128.3 kilo tons in the 5th fire area. The speculative annual loss of coal reserves in 2010 is 46.8 kilo tons.

Based on the thermal equilibrium theory, the evaluation process for combustion loss of coal reserves in fire area is described below. The hot points at surface are identified firstly by using the surface temperature measurement and the temperature contour is delineated by the Surfer software. Then, the areas with
different temperatures are counted and the heat release into the atmosphere every year for each temperature level is determined according to the coefficient of heat transfer depending on the difference between surface temperature and the annual averaged air temperature of the fire area region. Summing these values up, the total heat release could be obtained. Dividing it by the net calorific value of coal, the annual loss of coal reserves is determined. In this way, according to the detailed prospecting data reported by Xinjiang Coal Fire Fighting Bureau (Xinjiang Coal Field Fire-Fighting Engineering Bureau, 2010), the total area of fire delineation approximates 84,013m² with annual combustion loss of 95.5 kilo tons.

Back to the simulation results in Fig. 14, the simulated annual coal loss in 2010 is 57.9 kilo tons and the averaged value from 2006 to 2010 is 58.3 kilo tons. This loss of reserves is less than the field value evaluated by the heat release but higher than that revised from gas emission. In fact, the field estimation method with heat release often exaggerates the temperature range, especially the hotspots lead to an enlarged result. On the contrary, the prediction by the gas emissions misses the residual carbon left in the seam and a small amount of gases exhausting from the soils; and it may present a smaller result. Comparing the simulation with these two indirect observations, it may conclude that the simulated results are closer to the true values and the present simulation could be an effective method for coal loss estimation in coal fire development.

Based on Eq. (10), the accumulated reserves loss or total coal loss in the fire area after the seam opened up could be easily obtained as $M = \sum_0^t \dot{M}$. As shown in Fig. 15, it indicates that the total coal loss till 2010 is more than 350 kilo tons. Meanwhile, the simulated propagation rate of coal fire varies from 8 m to 13 m per year in the last five years with an average rate of 10.8 m per year based on the
simulation. Considering the rest coals in the outcrop seam and the movement of combustion front, it is predicted that the occurrence reserves in the whole outcrop will be entirely consumed by the end of year 2022 or 2023.

Figure 14. The simulated annual consumption of coal reserves from 1987 to 2010 and comparison with field data in 2010.

Figure 15. The simulated accumulated coal loss and fire propagation rate from 1987 to 2010.

5. Conclusions

This work focuses on predicting loss of coal reserves and fire propagation in coalfield fire areas. In combination with correlations between coal/oxygen
consumption and reaction heat release, a heat and mass transfer model for inclined outcrop seam in porous coal-bearing strata with transient exothermic source term is established and employed for the modeling. The simulation model is based on the real process in the fifth fire area of Heshituoluogai coal fires in Xinjiang, China. The main conclusions are drafted below.

(1) By tracing the variation of temperature along the long-term history of coal fire, it is found that at the beginning of 12th year after the seam uncovering, the coal temperature experiences a slight increasing due to the weak oxidation. When the accumulated heat causes the coal ignition with continuous oxygen supply, the combustion zone rapidly enlarges and starts to advance towards the seam outcrop in the strata, and the movement rate of the fire front keeps constant at about 8 m per year from the 20th year.

(2) The combustion or heat release rate is controlled by reaction kinetics at low temperature due to the slower oxygen consumption at the early oxidation stage. The reaction becomes very fast at high temperature and the oxygen transport controls the overall combustion rate after the 12th year.

(3) The fire moves faster with lower inclined angle at 6° at the stable combustion stage in the 30th year. The width of the combustion zones and temperature peaks with different porosities are near the same, which reveals the independence of coal porosity to the heat release at the early oxidation stage. The propagation rate of combustion zone at the 30th year obviously reduces when the stratum porosity decreases.

(4) In comparison with field survey, the simulated result is slightly higher than the gases emission evaluation but lower than the surface heat deduction. The analyses show that the simulation model could predict coal loss more reasonably. The averaged
annual coal loss from 2006 to 2010 for the fifth fire area of Heshituoluo coal fires is simulated as 58.3 kilo tons and the averaged fire propagation rate is 10.8 m per year. With these data, the whole outcrop seam loss is predicted to occur at year 2022 or 2023.

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