Effect of longwall face advance on spontaneous heating in longwall gob area

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Introduction

In underground longwall coal mines, some coal may be left in the gob, either from the unmined roof or floor coal or from an overlying coal seam that caves into the gob. When exposed to the air, the coal may undergo spontaneous heating, a low temperature coal oxidation. When the heat produced by the low temperature reaction of coal with oxygen is not adequately dissipated by the airflow, it will result in a net temperature increase in the coal mass. Under conditions that favor a high heating rate, the coal attains thermal runaway and a fire ensues. For the period 1990 – 2006, a total of 25 reported fires for underground coal mines in the U.S. were caused by spontaneous combustion (DeRosa, 2004). Although much research has been done in experimental studies and mathematical modeling of spontaneous combustion of coals (Arisoy & Akgun, 1994; Brooks & Glasser, 1986; Carras & Young, 1994; Edwards, 1990; Nordon, 1979; Krishnaswamy et al., 1996; Rosema et al., 2001), most of the research is mainly focused on small coal stockpiles without considering the effect of ventilation air flow. Saghafi et al., (1995, 1997) did numerical modeling of spontaneous combustion in underground coal mines with a back return U-ventilation system, but their work was limited to two dimensions. Balusu et al., (2002) conducted a computational fluid dynamics (CFD) study of gob gas flow mechanics to develop gas and spontaneous combustion control strategies for a highly gassy mine. These strategies include new gob hole designs to ensure that oxygen concentration in the holes was below 4 to 5%, immediately sealing of the crosscut behind the face, and reduction in air velocity on the intake side of the gob.

In order to reduce the fire hazard from spontaneous combustion of coal in gob areas, the National Institute for Occupational Safety and Health (NIOSH) has conducted a series of CFD simulations using coal kinetic data from the former U.S. Bureau of Mines laboratory-scale experimental results (Smith and Lazzara, 1987). Previous CFD models were developed to simulate the spontaneous heating of coals in a two-panel gob area using a bleeder ventilation system with a stationary longwall face (Yuan and Smith, 2007). Parametric studies were then conducted to examine the effects of coal's activation energy, coal surface area, heat of reaction, different ventilation conditions and gob permeability distributions on the spontaneous heating process (Yuan and Smith, 2008a). CFD simulations were also conducted to model the spontaneous heating in longwall gob area using a bleederless ventilation system with a stationary longwall face (Smith and Yuan, 2008). In this paper, CFD modeling of the effect of longwall face advance on the spontaneous heating of coals in a two-panel gob area using a bleeder ventilation system is presented.

Abstract

To reduce fire hazards from spontaneous combustion of coal in longwall gob areas, a series of computational fluid dynamics (CFD) simulations were conducted by the National Institute for Occupational Safety and Health (NIOSH) to model the spontaneous heating of coal in longwall gob areas. The previous modeling results demonstrate that spontaneous heating of coal usually occurred behind the longwall shields and along the face with a bleeder ventilation system. Assuming a stationary longwall face, the spontaneous heating could turn to a spontaneous fire in several days for the most reactive coal under favorable conditions. When the longwall face advances, the spontaneous heating process will be significantly affected. In this study, the effect of longwall face advance on the spontaneous heating in the gob area is investigated using the CFD model developed in previous studies. One longwall panel with a bleeder ventilation system is simulated. The width of the panel is 300 m (984 ft), while the length of the panel is changed between 1,000 to 2,000 m (3,280 to 6,560 ft). The same permeability and porosity profiles are used for gobs with different lengths. The spontaneous heating first develops in the gob when the longwall face is stationary. Then, the face advances at a certain rate. The face advance is simulated as a series of discrete movements, and the effect of the face advance on the maximum temperature developed during the face stoppage is examined.

GOB layout and ventilation system

In this study, a single longwall panel, 2,000-m- (6-560-ft-) long and 300-m- (984-ft-) wide, with a three-entry bleeder ventilation system is simulated. The layout of the panel and the ventilation system is shown in Fig. 1. The original coal seam is 2-m- (6.5-ft-) high, and the gob is assumed to be 10-m- (33-ft-) high starting from the bottom of the coal seam. The ventilation airways are 2-m- (6.5-ft-) high and 5-m- (16-ft-) wide. This scheme and the panel dimensions are typical of longwall mines operating in the Pittsburgh coal seam in Northern Appalachian Basin. The bleeder entries at the back end of the gob are modeled as one entry connecting to the bleeder fan. Three regulators are located at the end of the second and third headgate entries and the tailgate entry, respectively, for controlling the bleeder ventilation.

The longwall face is originally at location #1, 1,000 m (3,280-ft-) from the start line of the panel. It is assumed that the face advances in a rate of 20 m/d (65 ft/day) from location #1. The face advances 100 m (328 ft) in five days to reach locations #2, #3 and #4, respectively. The face advances 200 m (656 ft) in 10 days to reach location #5.

Low temperature coal oxidation

The chemical reaction between coal and oxygen at low temperatures is complex and still not well understood. Generally, three types of processes are believed to occur in low temperature coal oxidation (Carras and Young, 1994), including physical adsorption; chemical adsorption, which leads to the formation of coal-oxygen complexes and oxygenated carbon-species; and oxidation, in which the coal and oxygen react with the release of gaseous products, typically carbon monoxide (CO), carbon dioxide (CO_2) and water vapor (H_2O).

The moisture content of coal can play an important role in the low temperature coal oxidation process. The interaction between water vapor and coal can be exothermic or endothermic, depending on whether the water condenses or evaporates. Sondreal and Ellman (1974) reported that for dried lignite, the rate of temperature increase due to the adsorption of water increased with the moisture content up to a value of 20% water (by mass) and then decreased with further increasing moisture content. Smith and Lazzara (1987) found that the effect of the moisture content of the air on self-heating process was also dependent on coal rank and temperature.

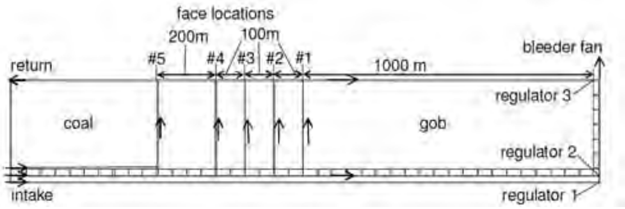
In this study, the effect of water vapor is not considered, and the chemical reaction between coal and oxygen is simplified as:

$$\text{Coal} + O_2 \rightarrow CO_2 + 0.1CO + \text{heat}$$

The detailed chemical structure of coal is not clear and is believed to vary with the rank and origin of coal.

FIGURE 1

Layout of longwall panel and ventilation system.



According to experimental data (Smith et al., 1991), one mole of coal reacting with one mole of oxygen generates one mole carbon dioxide and 0.1 mole carbon monoxide plus heat at the early stage of coal oxidation. The dependence of the rate of oxidation on temperature and oxygen concentration can be expressed in the form:

$$\text{Rate} = A[O_2]^n \exp(-E/RT)$$

where the chemical reaction rate is defined as the rate of change in the concentrations of the reactants and products, A is the preexponential factor (in K/s), E is the apparent activation energy (in kJ/mol) that is the energy needed to initiate a chemical reaction, R is the gas constant, n is the apparent order of reaction, T is the absolute temperature (in °K), and $[O_2]$ is the oxygen concentration (in kmol/m^3).

The value of apparent activation energy, E, of different coals can very between 12 and 95 kJ/mol. The preexponential factor, A, depends more on coal rank and measurement method, and has a typical value between 1 and 7×10^5 /s. The value of the apparent order of the reaction, n, in low-temperature oxidation studies of coal and other carbonaceous materials has been shown to vary from ~0.5 to 1.0 (Carras and Young, 1994), and is about 0.61 for some U.S. coals (Schmidt and Elder, 1940).

The coal source in the gob can be coal left from the mined coal seam or other overlying coal seams. In this study, the Pittsburgh coal seam was considered, with a 1-m- (3.3-ft-) thick rider coal seam less than 1-m- (3.3-ft-) above the 2-m- (6.6-ft-) thick main coal seam. The coal source in the model is this rider coalbed that is assumed to cave into the gob after the main coal seam is completely mined out.

FIGURE 2

Temperature distribution (K) after 20 days with longwall face at location #1.

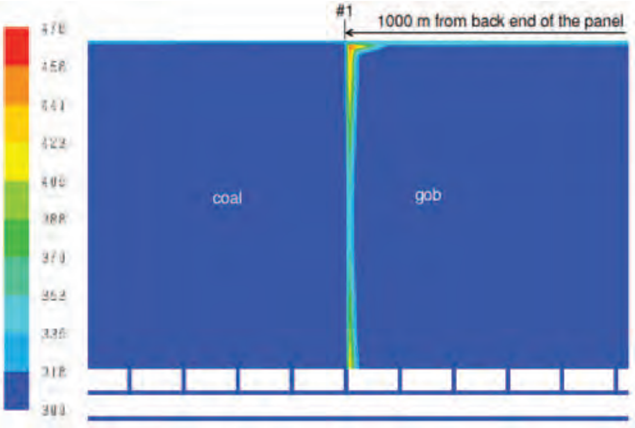


FIGURE 3

Temperature distribution (K) after five days with longwall face at location #2.

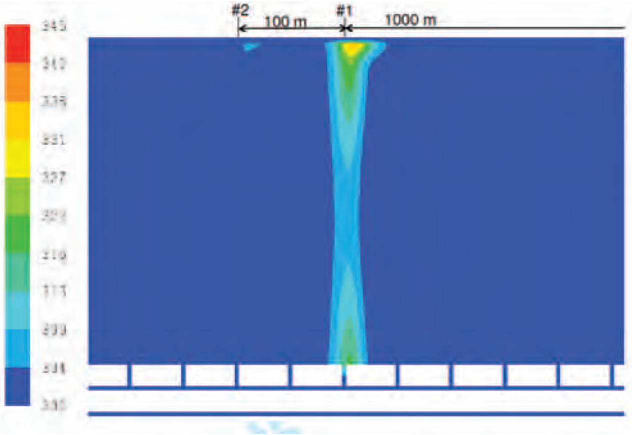


Table 1

The physical and kinetic properties of the coal layer.

Coal density	1,300	kg/m^3
Coal specific heat	1,003.2	J/kg-K
Coal conductivity	0.1998	W/m-K
Heat of reaction	300	$kJ/mol\text{-}O_2$
Activation energy	73.6	kJ/mol
Pre-exponential factor	1.1×10^7	K/s
Coal particle diameter	0.1	m
Initial coal temperature	300 (27)	°K (°C)

The oxidation of coal occurs on both external and internal micro pore surfaces. It is difficult to define a coal particle size distribution in the coal layer in the gob area because of the large gob size. The parameter that affects the heat generation and dissipation during the spontaneous heating process is the coal surface area available in a unit volume, or surface-to-volume ratio. The effect of coal surface area on spontaneous heating was investigated in the previous study (Yuan and Smith, 2007). In this study, an average coal particle diameter of 10 cm (4 in.), with a surface-to-volume ratio of 36 m^{-1}, is used in the simulations. The heat generated from oxidation is dissipated by conduction and convection, while the oxygen and oxidation products are transported by convection and diffusion.

It is well known that the kinetic properties of coal oxidation have a major effect on the spontaneous heating process. Because the effect of coal kinetic properties on the spontaneous heating has been studied in the previous work (Yuan and Smith, 2008b), only a typical reactive bituminous coal was presented in this study. The physical and kinetic properties of this coal are listed in Table 1.

Estimation of GOB permeability

The permeability and porosity distributions of the gob areas are based on geotechnical modeling of longwall mining and the associated stress-strain changes using fast lagrangian analysis of continua (FLAC) code. A simple relationship is used to estimate the changes in permeability in the caved rock based on the Kozeny-Carman equation:

$$k = f\left(\frac{n^3}{(1-n)^2}\right) \tag{1}$$

where n is the porosity, k is the permeability, and f is a function.

For a Pittsburgh coal seam longwall panel, the permeability values in the gob area are estimated to vary from $3.0\text{x}10^4$ to $8.5\text{x}10^5$ millidarcies (md), while the porosity value varies from 0.17 to 0.41. The permeability and porosity distributions in the gob are not uniform. Around the perimeter of the gob and immediately behind the face shields, the permeability and porosity values are the largest, while near the center of the gob, these values are the smallest due to compaction. A detailed description of permeability calculation is given in Esterhuizen and Karacan (2007). These permeability and porosity distributions are used as input for the CFD program. The porosity profile in the gob is similar to the permeability profile, except the maximum and minimum values are 0.41 and 0.17, respectively. It is assumed that these permeability and porosity profiles do not change with the gob height.

Simulation of face advance

When the face is continuously moving, the gob volume is expanding. Since the gob permeability and porosity distributions are non-uniform and affected significantly by the face advance, the continuous gob advance will result in continuous changes of permeability and porosity distributions in the gob. Although it is possible to model the continuous face movement, it is difficult to model this face movement process with the continuous changing gob permeability and porosity. In this study, the face advance is simulated as a series of discrete movements. Instead of simulating the continuous face movement from location #1 to location #2 in five days, it is assumed that the face moves instantaneously to location #2 and remains there for five days. This method is repeated for the moves to location #3, #4 and #5. At location #5, the face remains for 10 days because the distance between location #4 and #5 is 200 m (656 ft). Each time the face moves to a new location, the similar permeability and porosity profiles are applied to the new gob. Although this approximation method does not simulate the exact face movement, it still captures the nature of the dynamic face movement.

Numerical modeling

A commercial CFD software, FLUENT from Ansys, Inc., was used in this study to simulate the gas flow and spontaneous heating in the longwall gob areas. The gas flow in the longwall mine gob area was treated as laminar flow in a porous media using Darcy's law, while the gas flow in the ventilation airways was simulated as fully developed turbulent flow. The physical model and mesh for the CFD simulation were generated using the mesh generator software, GAMBIT, from Ansys, Inc.

The boundary conditions for ventilation pressures used in the simulation were also obtained from a local Pittsburgh coal seam mine's ventilation data. The pressure was -0.75 kPa (-3 in. water gauge) at the intake inlet at the headgate side, -0.87 kPa (-3.5 in. water gauge) at the return outlet at the tailgate side and -2.2 kPa (-9 in. water gauge) at the bottom of the bleeder shaft. Typical ventilation airflow rates for the Pittsburgh coal seam mines were used. The wall roughness of the ventilation airways was adjusted to have a total intake airflow rate of 41 m^3/s (87,000 cfm) in the panel. The pressure drops through the two regulators located at the second and

FIGURE 4

Temperature distribution (K) after five days with longwall face at location #3.

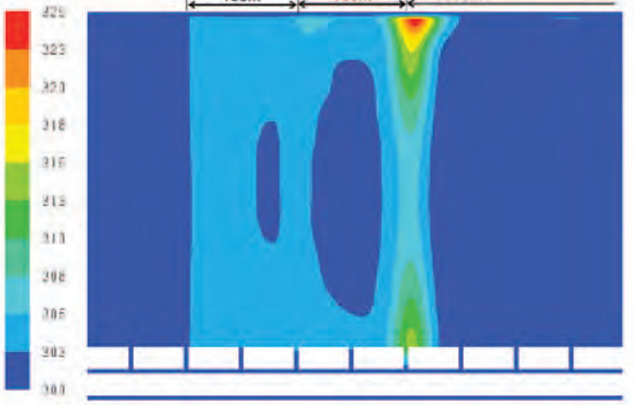


FIGURE 5

Temperature distribution (K) after five days with longwall face at location #4.

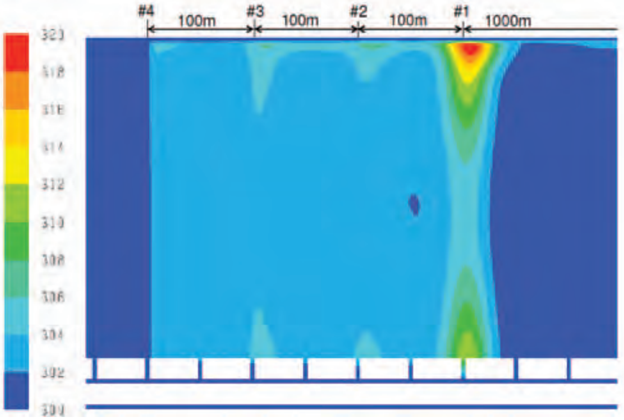
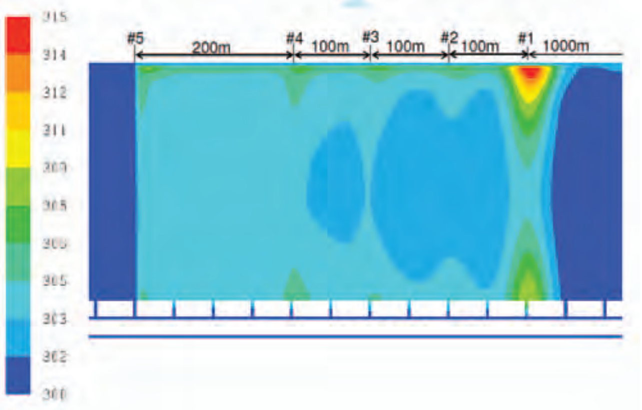


FIGURE 6

Temperature distribution (K) after 10 days with longwall face at location #5.



third headgate entries were also adjusted to have an airflow rate entering onto the face of 28 m^3/s (60,000 cfm). The pressure drop at regulator three was adjusted to have a flow rate in the return of 24 m^3/s (50,000 cfm).

Results and discussion

The longwall face was assumed to be stationary at location #1. Simulations of spontaneous heating of coals with the stationary face at location #1 for 20 days were conducted, and the temperature distribution in the gob area is shown in Fig. 2. After 20 days, the maximum temperature was 476° K (203° C), occurring in the gob area at the tailgate corner of location #1. As shown in the previous simulations (Yuan & Smith, 2007 and 2008a), the temperature rise in the gob mainly occurred immediately behind the longwall shields and along the face. There was also a small temperature rise at the corner of the gob near the bleeder fan, approximately 350° K (77° C), because of higher airflow velocity. The face was then moved to location #2 and stayed there for five days. Figure 3 shows the temperature distribution in the gob five days after the face arrived at location #2. The maximum temperature at the tailgate corner of location #1 decreased from 476° K (203° C) to 345° K (72° C). Because of face advance to location #2, the permeability and porosity along the face area of location #1 decreased, leading to less airflow through this area. Therefore, the temperatures along the face of location #1 decreased. It is worthwhile to note that a temperature rise also occurred along the new face at location #2. When the face was moved to location #3, the temperatures along the face area of location #1 continued to decrease, as shown in Fig. 4, with the maximum temperature at 325° K (52° C) after five days. This occurred because of a further reduction in permeability and porosity in that area. At the same time, the temperatures increased several degrees along the new face at location #3. Figure 5 shows the temperature distribution in the gob five days after the face moved to location #4. The maximum temperature along the face of location #1 further decreased to 320° K (47° C), while temperature rise occurred along the new face.

After the face was at location #5 for 10 days, the maximum temperature (315° K or 42° C) in the gob area was still at the tailgate corner of location #1, as shown in Fig. 6. The temperature decrease was just 5°, compared with the maximum temperature when the face was at location #4. This is summarized in Fig. 7, which shows the maximum temperature change in the gob versus time with the face movements. It should be pointed out that this maximum temperature was always at the tailgate corner of face location #1. The maximum temperature decrease exhibits three different stages. The first stage was a fast temperature decrease, then a moderate temperature decrease, followed by a slow temperature decrease. Interestingly, the change from the fast decrease stage to the moderate decrease stage occurred when the face was at location #2, while the change from the moderate decrease stage to the slow decrease stage occurred when the face was at location #3. When the face was at location #5, the maximum temperature was also in the slow decrease stage as the face was at location #4, indicating that the face locations had little effect on the maximum temperature decrease once it was in slow decrease stage.

Spontaneous heating can begin at ambient temperature when coal is exposed to oxygen. As the self-heating proceeds, the coal temperature increases slowly. The temperature rise usually consists of two stages. The first stage is a slow temperature rise while the second one is a fast temperature rise. The start of the second stage is also called thermal runaway. The time to reach a thermal runaway is called induction time. When the coal temperature reaches about 500° K (227° C), the spontaneous heating mechanism changes to rapid combustion (Babrauskas, 2003). So it is important to prevent the spontaneous heating from

FIGURE 7

Maximum temperature (K) versus time histories: longwall face began to advance when the maximum temperature reached 476° K.

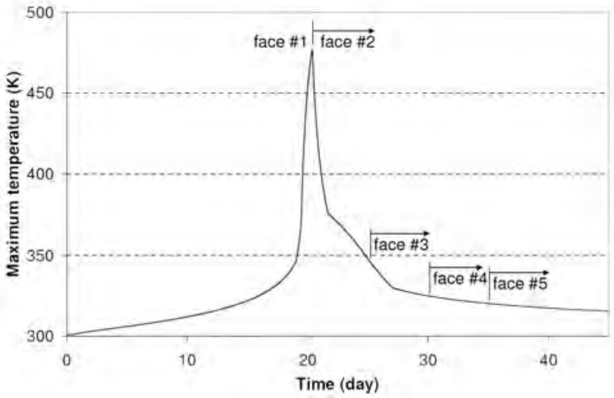
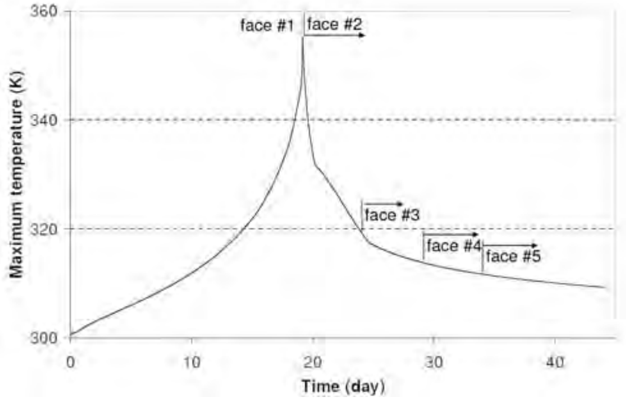


FIGURE 8

Maximum temperature (K) versus time histories: longwall face began to advance when the maximum temperature reached 350° K.



proceeding into a thermal runaway. As shown in Fig. 7, the thermal runaway occurred when the coal temperature reached about 350° K (77° C) under conditions studied here. Additional simulations were conducted that moved the face to location #2 when the maximum temperature at the tailgate corner of face location #1 reached about 350° K (77 °C). Figure 8 shows the maximum temperature change in the gob versus time. The maximum temperature decrease still went through three stages, indicating the value of the initial maximum temperature did not affect the pattern of maximum temperature decrease. However, these results show that by moving the face, which effectively changes the permeability of the coal in the heated area, the spontaneous combustion can be controlled. This also demonstrates the effect of face advance rate on the spontaneous combustion process.

Conclusions

CFD simulations were conducted to investigate the effect of longwall face advance on spontaneous heating of coals in longwall gob area. Simulation results demonstrate that under typical three-entry bleeder ventilation conditions, face advance can quickly reduce the maximum temperature in the gob developed during face stoppage. The maximum temperature decrease follows three stages: fast decrease, moderate decrease and slow decrease. Once the maximum temperature is in the slow decrease stage (below 330° K (57° C) in this study), the face advance no longer has a significant effect. It is also found that the value of the maximum temperature prior to the face advance has no effect on the pattern of maximum temperature decrease. Although the continuous face advance was simulated as a series of discrete movements, the results show the main features of the dynamic face advance. More research is needed to further improve the modeling of face advance in the future.

Because of the complexity of the problem and lack of field data for gob permeability and porosity distribution, the results reported here are valid only for the permeability and porosity data used in this study with the longwall panel setup and ventilation conditions stated in the paper.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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