Simulation of spontaneous heating in longwall gob area with a bleederless ventilation system

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Introduction

Spontaneous combustion continues to pose a hazard for U.S. underground coal mines, particularly in western mines where the coal is generally of lower rank. Fifteen reported fires for underground coal mines for the period 1990-1999 were caused by spontaneous combustion (DeRosa, 2004), and 10 underground spontaneous combustion fires were reported for the period 2000-2006 (DeRosa, 2007). Spontaneous heating occurs when the heat produced by the low-temperature reaction of coal with oxygen is not adequately dissipated by conduction or convection, resulting in a net temperature increase in the coal mass. Under conditions that favor a high heating rate, the coal attains thermal runaway conditions and a fire ensues. In spontaneous heating events in underground coal mines, large coal masses may be involved. The spontaneous heating of coal in mines often occurs in a gob area and may not be easily detected. The amount of coal that accumulates in these areas and the degree of ventilation can combine to give optimum conditions for spontaneous combustion. In the United States, bleederless ventilation systems may be approved by the U.S. Mine Safety and Health Administration (MSHA) to serve as a spontaneous combustion control method in mines with a demonstrated history of spontaneous combustion. Currently, two U.S. coal mines are using bleederless ventilation systems. Although these bleederless ventilation systems are successful in controlling spontaneous combustion, more research is needed to understand the control mechanism and to optimize bleederless ventilation systems.

Much research has been done in experimental studies and mathematical modeling of spontaneous combustion of coals in outside coal stockpiles, as reviewed by Carras and Young (1994), but little research is available for spontaneous combustion in underground coal mines. Because of the difficulty in conducting full-scale spontaneous combustion tests in underground coal mines, computational fluid dynamics (CFD) modeling has become an important method to study the spontaneous combustion in underground coal mines. Saghafi and coworkers did numerical modeling of spontaneous combustion in underground coal mines with a back return U-ventilation system (Saghafi et al., 1995; Saghafi and Carras, 1997), but their work was limited to two dimensions. Balusu et al. (2002) conducted a CFD study of gob gas flow mechanics to develop gas and spontaneous combustion control strategies for a highly gassy mine. Rosema et al. (2001) also simulated spontaneous combustion using a two-dimensional model.

To understand the fire hazard caused by spontaneous combustion in a gob area, a computational fluid dynamics (CFD) study was carried out by the National Institute for Occupational Safety and Health (NIOSH) to model the spontaneous heating in longwall gob areas under realistic mine ventilation conditions and methane generation rates. In previous NIOSH research, a CFD model was developed to describe the ventilation pathways through the immediate gob under different ventilation schemes (Yuan et al., 2006) and to simulate the spontaneous heating of coals in a two-panel gob area using a bleeder ventilation system (Yuan and Smith, 2007). In this paper, the CFD model was used to study the spontaneous heating of coals in a longwall gob area utilizing a bleederless ventilation system.

Abstract

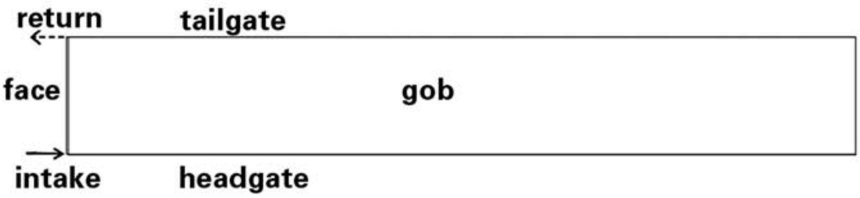
Although only used in a few U.S. longwall mines, bleederless ventilation systems can be an effective spontaneous combustion control method in mines having a demonstrated history of spontaneous combustion. To provide insights for the optimization of bleederless ventilation systems for U.S. underground coal mines, a computational fluid dynamics (CFD) study was conducted to model the spontaneous heating in longwall gob areas using a bleederless ventilation system. A single longwall panel with a bleederless ventilation system was simulated, and typical longwall mine ventilation data were used in the simulations. The permeability and porosity profiles for the longwall gob were estimated using a geotechnical model and were used as inputs for the CFD modeling. The effects of gob permeability and resistance of the collapsed entries on the spontaneous heating were studied. The effectiveness of using nitrogen injection to prevent spontaneous heating in the gob was also examined.[1]

Gob layout and ventilation system

In a bleederless ventilation system, the previously mined-out panels are usually isolated from the active gob and the remainder of the mine. In this study, only the active panel was simulated. The layout of the panel and the ventilation system is shown in Fig. 1. The simulated gob area is 2,000 m (6,562 ft) long, 300 m (984 ft) wide and 10 m (33 ft) high starting from the bottom of the coal seam. The ventilation airways are 2 m (6.6 ft) high and 5 m (16.4 ft) wide. The ventilation scheme is a simple "U" bleederless ventilation system. In the model, all entries inby the longwall face were treated as though they were collapsed.

FIGURE 1

Layout of longwall panel and ventilation system.



Numerical modeling

A commercial CFD program, FLUENT[2], from Fluent 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 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 permeability and porosity distributions of the gob area were based on geotechnical modeling of longwall mining in the Pittsburgh coal seam and the associated stress-strain changes using Fast Lagrangian Analysis of Continua (FLAC)) code (Esterhuizen and Karacan, 2005). For a Pittsburgh coal seam longwall panel, the permeability values in the gob area were estimated to vary from 3.0 x 10^4 to 8.5 x 10^5 millidarcies (md), while the porosity value varies from 0.17 to 0.41 based on the modeling result from FLAC. Around the perimeter of the gob and immediately behind the face shields, the permeability and porosity values were the largest, while near the center of the gob, these values were the smallest due to compaction. A detailed description of the permeability calculation is given in Esterhuizen and Karacan (2007). The porosity profile in the gob was 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 files do not change with the gob height. The detailed permeability profiles are presented in Yuan and Smith (2007).

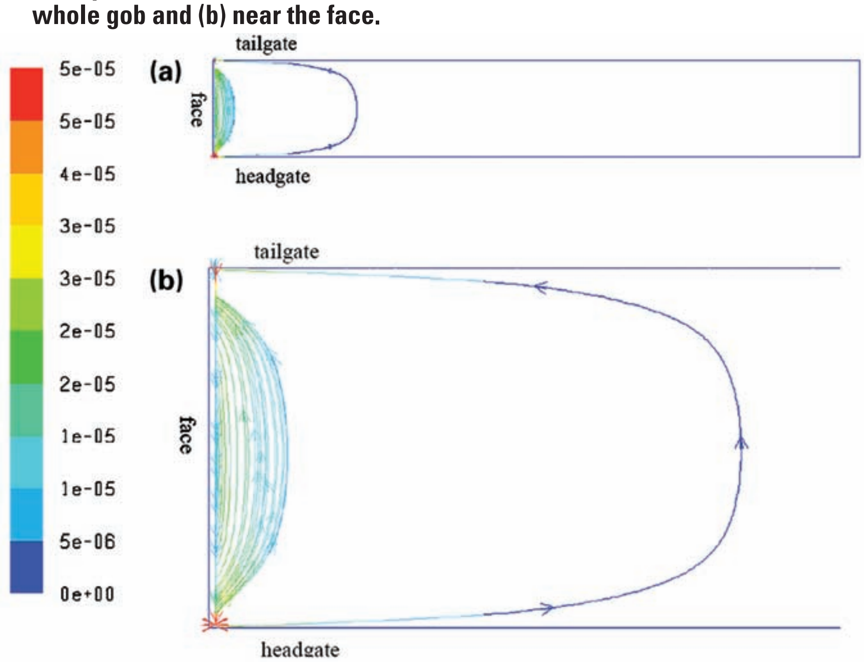
Typical ventilation pressures for the bleederless ventilation system were used in the simulation. The pressure was -76.2 mm (-3 in.) water gauge at the intake inlet and -88.9 mm (-3.5 in.) water gauge at the return outlet. To control the airflow quantity to the longwall face, the wall roughness was adjusted to have a realistic intake airflow rate of 30 m^3/sec (64,000 cu ft/min). A simulation was conducted first without coal oxidation and without methane emissions to obtain a steady-state flow field. Then, simulations with coal oxidation were conducted using the steady-state solution as the initial conditions. The face was assumed stationary during the simulations.

Flow patterns inside the gob

The flow patterns of air inside a gob will have a significant effect on the spontaneous heating of coals, because the oxygen needed for the oxidation is provided by the airflow and the heat generated from the oxidation may be carried away by this airflow. Fresh air flowing into a mine is usually contaminated by strata gas, dust and diesel exhaust, when it moves through the longwall face and into the return or cross the gob. The airflow inside a gob is expected to be three dimensional, with the flow in the vertical direction weaker than in the other two directions due to reduced permeability and pressure gradients. To visualize the flow patterns inside the gob, a virtual horizontal reference surface was created 1 m (3.3 ft) from the bottom of the mined coal seam floor. This was done to compare the results with respect to this horizontal reference surface. Figure 2, (a) and (b), show the flow path lines colored by velocity magnitude in the gob area. The path lines show that flow through the gob itself was mainly concentrated behind the shields. At the headgate side, air leaked through the shields but some flowed back into the face again through the shields near the tailgate side. These flow path lines were generated by releasing 30 massless particles that were evenly distributed along a line that is 1 m (3.3 ft) away and parallel the face shields. The color of the flow path lines represents the velocity magnitude, while the numbers of flow path lines in a certain area represents the amount of the airflow in that area. The single flow line some distance into the panel indicates that the quantity of airflow there is very low. There was no flow line deeper into the gob, indicating the airflow rate is too low to be represented by a single flow line. If more massless particles are released, it will make the flow path lines too crowded to see near the face area. The flow from tailgate to headgate was caused by shock losses. The air velocity ranged between 1 x 10^{-5} to 3 x 10^{-5} m/sec (0.002 to 0.006 ft/min) in the gob near the shields, and there was nearly no flow farther away from the shields into the gob.

FIGURE 2

Flow path lines colored by velocity magnitude (m/s) in gob area: (a) in the whole gob and (b) near the face.



Low-temperature coal oxidation

The low-temperature coal oxidation was simulated the same way as for the bleeder ventilation system, as described in the authors' previous study (Yuan and Smith, 2007). Here, only a brief description is provided.

The chemical reaction between coal and oxygen is simplified as:

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

The detailed chemical structure of coal is not clear and varies with the rank and origin of coal. According to experimental data (Smith et al., 1987), one mole of coal reacting with one mole of oxygen generates one mole carbon dioxide and roughly 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

A is the pre-exponential factor,
E is the apparent activation energy that is the energy needed to initiate a chemical reaction,
R is gas constant,
n is the apparent order of reaction,
T is the absolute temperature and
$[O_2]$ is the oxygen concentration.

In this study, the activation energy and pre-exponential factor data for the most reactive coal of the 24 U.S. coals tested by Smith and Lazzara (1987), designated as No. 80-1, was used to represent the worst-case spontaneous combustion scenario. Schmidt found the value of the apparent order of the reaction (n) is about 0.61 for some U.S. coals (Schmidt and Elder, 1940). The physical and kinetic properties of the coal layer are listed in Table 1.

To simulate the spontaneous heating of coal in longwall gob area, the source of coal needs to be defined. The coal source can be coal left from the mined coal seam or other overlying or underlying coal seams. In this study, a 2-m- (6.6-ft-) thick main coal seam was considered with a 1-m- (3.3-ft-) thick rider sequence 1 m (3.3 ft) above the main coal seam. The rider seam was modeled as caving into the bottom of the gob after the main coal seam was completely mined out. The coal pillars remaining along the perimeter of the gob were also considered as a coal source. The oxidation of coal will occur on any available coal surface including external and internal 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. An average coal particle diameter of 100 mm (4 in.) and a surface-to-volume ratio of 36 m^{-1} were used in the simulations. The heat generated from oxidation will be dissipated by conduction and convection while the oxygen and oxidation products are transported by convection and diffusion.

Methane emission

Methane emission was also considered in the simulation because it affects the oxygen concentration distribution in the gob. Generally, the U.S. mines using bleederless ventilation systems liberate very little methane. The methane emission rate for one of these mines is about 1,840 m^3/d (65,000 cu ft/day) (MSHA, 2002). This value was used for methane emission from the overlying rider coal seam that caved into the bottom of the gob in this study, and the emission was assumed to reduce linearly with the distance away from the face towards the back end of the panel. These values were entered into FLUENT using C subroutines. If the same methane emission rate is maintained, the gob will eventually be full of methane. However, the time to reach this steady state could be several months long. Additionally, the coal oxidation is taking place. In this study, the methane emission and oxidation were assumed to start at the same time, which is closer to real situation and also represents the worst-case scenario. Figure 3 shows the steady-state methane concentration distribution in the gob. The methane concentration was 100 percent, except for the area close to the face.

Table 1

The physical and kinetic properties of the coal layer.

Property	Units	Value
Coal density	kg/m^3	1,300
Coal specific heat	J/kg-K	1,003.2
Coal conductivity	W/m-K	0.1998
Heat of reaction	kJ/mol-O_2	300
Activation energy	kJ/mol	66.5
Pre-exponential factor	K/s	1.9×10^6
Coal particle diameter	mm	100
Initial coal temperature	K	300

Simulation results and discussion

Spontaneous heating can begin at ambient temperature when coal is exposed to oxygen. As the coal oxidizes, 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, or a thermal runaway. The time to reach a thermal runaway is called the induction time. When the coal temperature reaches 500° K (440° F), the spontaneous heating mechanism changes to rapid combustion

FIGURE 3

Steady-state methane concentration distribution in the gob (1 = 100 percent).

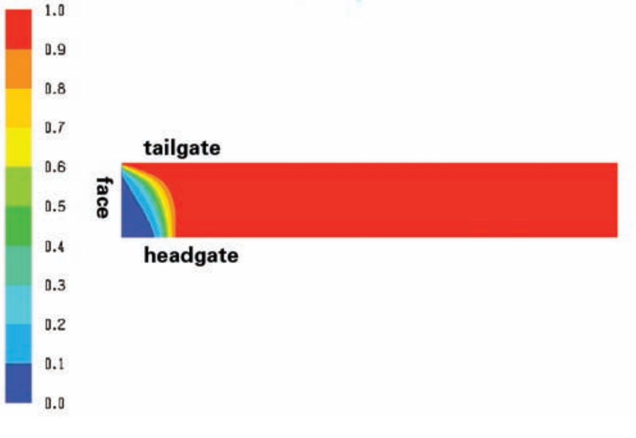
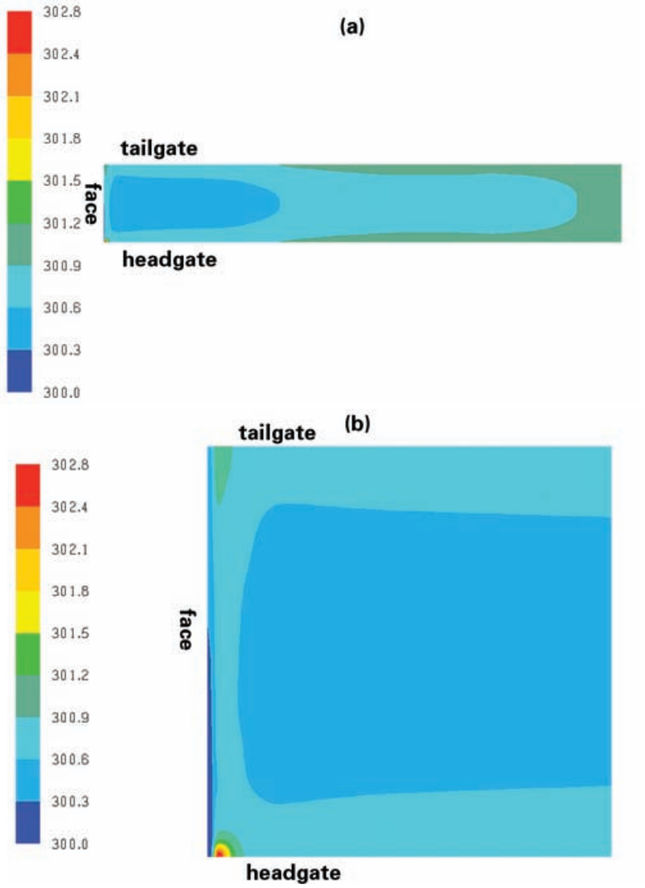


FIGURE 4

Temperature distribution (K) in the gob after 20 days: (a) in the whole gob and (b) near the face.



(Babrauskas, 2003). Therefore, the simulations focused on the self-heating mechanism at temperatures below 500° K (440° F).

Figure 4, (a) and (b), show the temperature distribution in the gob after 20 days. The maximum temperature at that time was only 302.8° K (85.4° F). The maximum temperature rise, 2.8° K (5° F), occurred in the corner of the gob between the face and the intake entry. There was very little or no temperature rise in the other areas. This is because oxygen was nearly all consumed by coal oxidation in the gob, as shown in Fig. 5. Only at the intake corner was enough oxygen supplied to maintain the spontaneous heating. This is much different from the case with a bleeder ventilation system, where temperature rise occurred along the face and behind the shields in the gob (Yuan and Smith, 2007). At any given time over the simulation, there existed a maximum temperature somewhere in the gob area. From a fire safety point of view, this maximum temperature represents the worst-case scenario. Hereafter, this temperature is referred to as the maximum temperature in the gob at a given time. Figure 6 shows the maximum temperature versus time histories from the simulation compared with the case with the bleeder ventilation system. With the bleederless system, the maximum temperature was 302.8° K (85.4° F) after 20 days, while the maximum temperature reached 500° K (440° F) in eight days in the bleeder system simulation. The maximum temperature occurred at the corner on the headgate side for the bleederless system, while it occurred along the face and behind the face shields for the bleeder system.

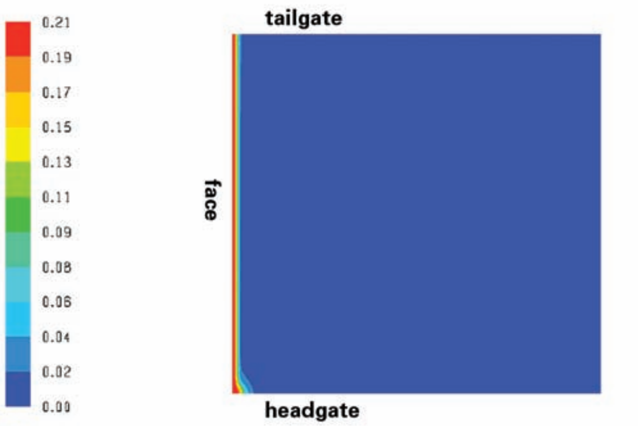
Effect of gob permeability. The gob permeability has a major effect on the spontaneous heating in the gob because it affects the quantity of air flowing into and through the gob. To examine the effect of the gob permeability on the spontaneous heating for the bleederless system, a simulation was conducted with the permeability increased 100 times. Figure 7 shows the maximum temperature versus time histories for the increased permeability simulations for the bleederless and bleeder systems. With the increased permeability, the maximum temperature reached 500° K (440° F) in about 22 days compared to only a 2.8° K (5° F) rise in the previous simulation for the bleederless system. Additionally, the induction time for the bleederless system simulation was reduced by 14 days compared with the bleeder system simulation. It should be noted that with the permeability increased 100 times, the temperature rise only occurred at the corner of the intake entry, shown in Fig. 8.

Effect of resistance at collapsed entries. In this study, all entries inby the longwall face were treated as though they were collapsed, and the permeability and porosity at these areas were calculated using FLAC program. This represents a full compaction situation for these areas with large resistances. In reality, these entries may remain partially open and have much lower resistance, especially at the early stage of the panel life. It is important to simulate spontaneous heating with lower resistance value at these entries. A simulation was conducted with the permeability of the collapsed intake entry, backend entry and return entry set at 7 x 10^9 md, which was the value chosen for the middle entry in our previous simulation with the bleeder ventilation system (Yuan and Smith, 2007). Figure 9 shows the temperature distribution in the gob after 20 days from the simulation. The temperature rise still occurred at the corner of the intake entry but no longer directly behind the shields. The temperature rise, instead, occurred along the intake entry, because of lower resistance in the intake entry. The maximum temperature was about 315° K (107° F) after 20 days, compared to 302.8° K (85.4° F) for the case shown in Fig. 4, indicating a slightly higher rate of maximum temperature rise.

Effect of nitrogen injection. Although the bleederless ventilation system appears to significantly reduce the rate

FIGURE 5

Oxygen concentration distribution in the gob after 20 days (1 = 100 percent).



of maximum temperature rise in the gob compared to the bleeder system, a thermal runaway could still occur under favorable gob conditions such as a high permeability and a reactive coal, as shown in Fig. 7. Certain types of control methods may be needed to reduce the hazard from spontaneous combustion fires. One method is nitrogen inertization in which nitrogen is injected into the gob to reduce the oxygen concentration to a value that cannot sustain coal oxidation. This method has been effectively used at the San Juan coal mine with a bleederless ventilation system (Bessinger et al., 2005). In Australia, CFD modeling and field tests were conducted to optimize inertization strategies to prevent heatings and fires in longwall gobs (Balusu et al., 2006).

Using the simulation conditions and a pre-exponential factor of 3.8 x 10^6 K/s, which resulted in the temperature distribution shown in Fig. 8, the nitrogen was injected at the corner of the intake entry at nitrogen flow rates of 0.236 and 0.472 m^3/s (500 and 1,000 cu ft/min). This served to dilute the oxygen concentration of the air flowing into the corner of the gob. Figure 10 shows the maximum temperature versus time histories with nitrogen injections compared with no nitrogen injection for the case. For the 0.236 m^3/s (500 cuft/min) injection rate, the induction time was increased about two days, and the time to reach 500° K (440° F) was significantly increased. With the 0.472 m^3/s (1,000 cu ft/min) injection rate, the induction time was increased about five days, and the maximum temperature reached only 472° K (390° F) after 30 days. The location of the maximum temperature rise with nitrogen injection remained near the corner of the intake entry, the same as without nitrogen injection. As shown in Fig. 11, nitrogen was forced to flow in the direction of ventilation air at the corner of the intake entry. More work is needed to study how to effectively prevent spontaneous heating of coal at the corner of the intake entry using nitrogen injection.

It should be pointed out that the ventilation system used in this study was an exhaust system. With the exhaust system, the exhaust fan sucks air from the face and the gob. A blowing system can also be used with the bleederless ventilation system. With the blowing system, air is blown into the face and the gob. This can pressurize the gob to some extent and push gases away from the face. The detailed implication of the blowing system on coal spontaneous heating process in the gob will be investigated in our future study.

FIGURE 8

Temperature distribution (K) in the gob with gob permeability increased 100 times.

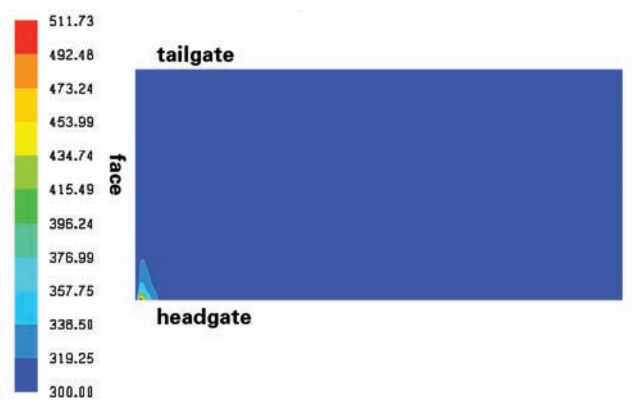


FIGURE 6

Maximum temperature (K) versus time histories.

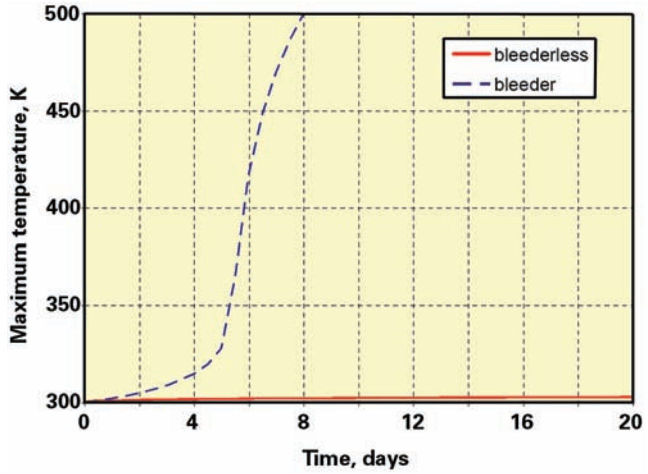
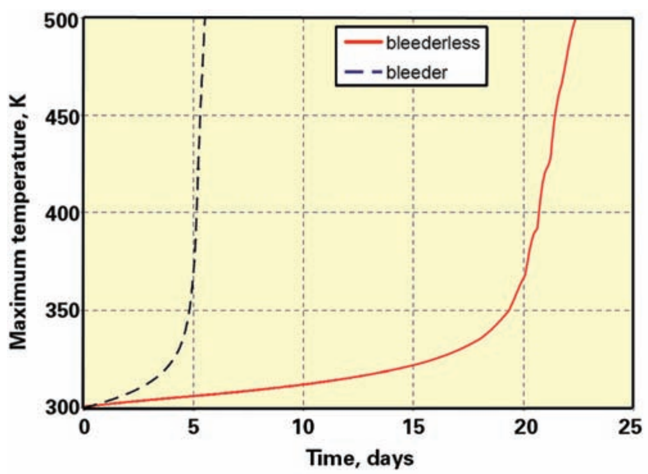


FIGURE 7

Maximum temperature (K) versus time histories with gob permeability increased 100 times.



Conclusions

CFD simulations were conducted on the spontaneous heating of coal in the gob area of a longwall panel with a bleederless ventilation system. In these simulations, the longwall face was stationary. The effects of gob permeability and resistance of the collapsed entries on the spontaneous heating in the gob were investigated. Simulation results demonstrate that under typical ventilation conditions, the bleederless system would greatly reduce the rate of temperature rise in the gob compared with the bleeder system. With the bleeder system, the temperature rise occurred along the face and behind the shields in the gob, while with the bleederless system, the temperature rise occurred only at the corner of the intake entry.

With the increased permeability, the induction time to thermal runaway was reduced by 14 days. When the collapsed entries had a lower resistance, the temperature rise occurred still at the corner of the intake entry, but no longer directly behind the shields, instead along the intake entry. The rate of maximum temperature rise was also slightly increased. Nitrogen injection at the corner of the intake entry appears to increase the induction time of the spontaneous combustion, but the optimum locations and flow rates of nitrogen injections need to be determined in future simulations.

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. ■

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FIGURE 9

Temperature distribution (K) in the gob with a lower resistance in collapsed entries.

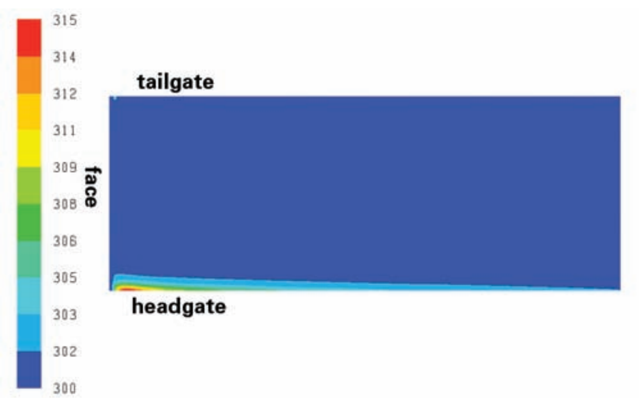


FIGURE 10

Effect of nitrogen injection on the maximum temperatures in the gob.

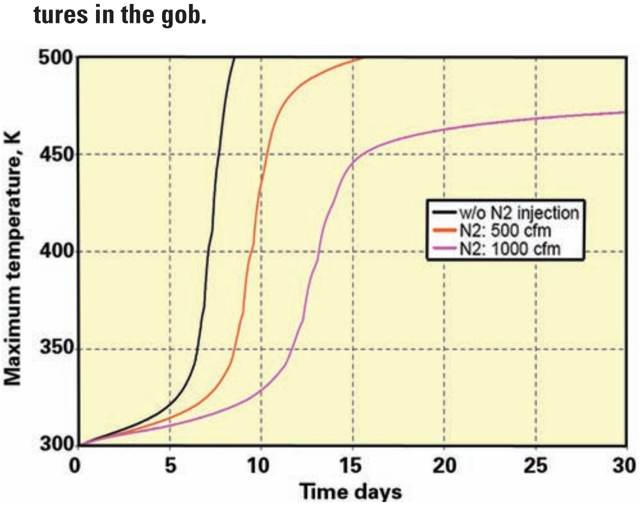
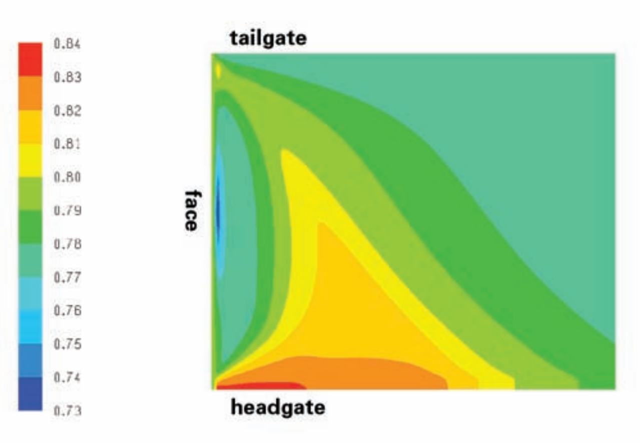


FIGURE 11

Nitrogen concentration distribution in the gob after 20 days with nitrogen injection rate of 0.236 m³/s (500 cuft/min) (1 = 100 percent).



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Footnotes

[1]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.

[2]Reference to a specific product is for informational purposes and does not imply endorsement by NIOSH.