Modeling the effect of seal leakage on spontaneous heating in a longwall gob area

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ABSTRACT: Federal regulations provide that mines with a demonstrated history of spontaneous combustion or that are located in a coal seam determined to be susceptible to spontaneous combustion may use a bleederless ventilation system as a spontaneous combustion control measure. Currently, three coal mines in the U.S. are utilizing a bleederless system to prevent spontaneous combustion. In a bleederless ventilation system, one of the headgate entries is used as the tailgate entry of the succeeding panel and is isolated from the gob of the active panel by gob seals constructed in each crosscut inbye the active face. Air is coursed across the face area and outbye in the tailgate entry into a return entry instead of inbye through the gob. As the longwall progresses, some seals may leak. When the headgate entry is ventilated, such as in a Y-type bleederless system, the air leakage through the seals into the gob may lead to spontaneous heating in the gob behind the seals. In this study, a computational fluid dynamics (CFD) model developed in our previous work is used to model the effect of seal leakage on spontaneous heating of coal in longwall gob behind the seal. A single longwall panel using a Y-type bleederless ventilation system was simulated. With typical bleederless ventilation conditions, the simulation results demonstrate that the effect of seal leakage on the spontaneous heating process depends on both seal leakage rate and gob permeability.

1 Introduction

In a longwall gob, spontaneous heating occurs when the heat that is produced by the low temperature reaction of coal left in the gob with oxygen is not adequately dissipated by conduction or convection, resulting in a net temperature increase in the coal mass. Under conditions that favour a high heating rate, the coal attains thermal runaway and a fire ensues. The spontaneous heating of coal in the gob area may not be easily detected. The amount of coal that accumulates in the gob area, the degree of ventilation, and the lack of heat dissipation can combine to give optimum conditions for spontaneous combustion. Although the number of spontaneous combustion fires has remained nearly constant for the last 35 years in the U.S., there is the possibility that the number of spontaneous combustion fires could increase due to growth in the dimensions of longwall panels and due to the exhausting of easily-mined coal beds in the U.S., which results in increased mining of lower rank coals and deeper coal beds. In the U.S., bleederless ventilation systems may be approved by the Mine Safety and Health Administration (MSHA, 2002) to serve as a spontaneous combustion control method in mines with a demonstrated history of spontaneous combustion. Currently, three U.S. coal mines are utilizing bleederless ventilation systems. For a typical bleederless ventilation system, one of the headgate entries is used as the tailgate entry of the succeeding panel and is isolated from the gob of the active panel by gob seals constructed in each crosscut inbye the active face (MSHA, 2002). Air is coursed across the face area and outbye in the tailgate entry into a return entry instead of inbye through the gob. Under a typical bleederless system, the areas most susceptible to spontaneous combustion with this design are immediately behind and around the seals and behind the face shields, due to pressure differentials. Each leakage source can provide oxygen and increase the possibility of spontaneous combustion occurring.

It is difficult to obtain seal leakage rate data from actual underground coal mines because of the difficulty in measuring leakage rates. The Code of Federal Regulation (CFR) requires that all permanent ventilation controls, including explosion-resistant seals, be maintained to serve the purpose for which they were built. NIOSH and MSHA conducted a joint program that evaluated the strength characteristics of proposed explosion-resistant seal designs (Weiss *et al.*, 1993; Stephan & Schultz, 1997). Full-scale seals were constructed and tested in NIOSH's Lake Lynn Laboratory Experimental Mine (LLEM). Post-explosion air leakage characteristics that MSHA deemed acceptable for explosion-resistant seals tested at LLEM are as follows: a) for pressure differentials up to 0.25 kPa (1"wg) leakage must remain below 0.05 m^3/s (100 cfm), b) for pressure differentials up to 0.50 kPa (2"wg) leakage must remain below 0.07 m^3/s (150 cfm), c) for pressure differentials up to 0.75 kPa (3"wg) leakage must remain below 0.10 m^3/s (200 cfm), and d) for pressure differentials exceeding 0.75 kPa leakage must remain below 0.12 m^3/s (250 cfm). Since these studies, new seal regulations have been adopted for seal strength and construction requirements. However, no new seal leakage criteria were included in these regulations. For the purpose of this study, the leakage rates from the previous work were used as guidelines for the model.

In our previous studies, a CFD model was developed to simulate the spontaneous heating of coal in a longwall gob area using a bleederless ventilation system (Smith & Yuan, 2008). The CFD model was also used to simulate the effect of barometric pressure changes on spontaneous heating in bleederless longwall panel (Yuan & Smith, 2010). Those simulations were conducted without any seal leakages, and the results demonstrate that the area most susceptible to spontaneous heating occurred immediately behind the face shields. The potential for air exchange across a seal due to pressure differential has long been a concern. If methane is present behind the seal, a spontaneous heating could cause a methane ignition and/or explosion. Much research has been conducted on the potential for methane accumulation behind seals, but little research is available in understanding how the seal leakage affects the spontaneous heating of coal in longwall gob area. In this study, the previously developed CFD model is used to model the effect of seal leakage on the spontaneous heating in a longwall gob.

2 CFD Modeling of Spontaneous Heating in the Gob

In this study, an active longwall panel using a Y-type bleederless ventilation system is simulated. Compared with the typical U-type bleederless system, the Y-system keeps the headgate entry ventilated for utilization as the tailgate for the next panel and seals are installed in the headgate entry as the face advances. The seals are accessible for inspection and maintenance but are more exposed for leakage and differential pressure across the seals to develop (Smith *et al.*, 1994). The layout of the panel and the ventilation system, are shown in Figure 1. The simulated gob area is 1,000 m long, 300 m wide, and 10 m high starting from the bottom of the coal seam. The ventilation airways are 2 m high and 5 m wide. In the model, the headgate entry is ventilated and eventually goes to return after passing the back end of the panel. Seals are built between this entry and the active gob. The face is assumed stationary during the simulations.

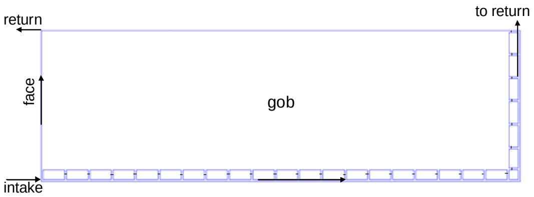

Figure 1 Layout of longwall panel and ventilation system used in simulations.

The chemical reaction between coal and oxygen at low temperatures is complex and still not well understood. In the study, the chemical reaction between coal and oxygen is simplified so that one mole of coal reacts with one mole of oxygen to generate one mole of carbon dioxide and 0.1 mole of carbon monoxide plus the heat of coal oxidation (Smith *et al.*, 1991). The heat generated from coal oxidation is dissipated by conduction and convection, while the oxygen and oxidation products are transported by convection and diffusion. The dependence of the rate of oxidation on temperature and oxygen concentration is 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 pre-exponential factor (in K/s), E is the apparent activation energy (in kJ/mol), 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 $kmol/m^3$).

In the simulation, a 1-meter-thick rider coal seam less than 1 m above a 2-meter-thick main coal seam was considered. The coal source in the model is this rider coal seam that is assumed to cave into the bottom of the gob after the main coal seam is completely mined out. An average coal particle diameter of 10 cm, with a surface-to-volume ratio of 36 m^{-1}, is used in the simulations. A typical bituminous coal with a high spontaneous combustion potential was modeled in this study. The physical and kinetic properties of this coal are listed in Table 1.

Table 1 The physical and kinetic properties of the rider seam coal layer

Coal density	1300	kg/m^3
Coal specific heat	1003.2	J/kg-K
Coal conductivity	0.1998	W/m-K
Heat of reaction	300	kJ/mol-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 permeability and porosity distributions of the gob were based on geotechnical modeling of longwall mining in the Pittsburgh coal seam and the associated stress-strain changes using a FLAC (Fast Lagrangian Analysis of Continua) code (Esterhuizen & Karacan, 2007). For a Pittsburgh coal seam longwall panel, the permeability values in the gob area were estimated to be in a range of 3.0×10^4 to 8.5×10^5 millidarcies (md), while the porosity value is in a range of 0.17 to 0.41 based on the modeling result from FLAC. These values are used as base values in the simulations. 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. The porosity profile in the gob was similar to the permeability profile. It is assumed that these permeability and porosity profiles do not change with the gob height.

A commercial CFD software, FLUENT from Ansys, Inc., was used in this study to simulate 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. Typical ventilation pressures for a U.S. bleederless ventilation system were used in the simulation. The intake airflow rate was 30 m^3/s (64,000 cfm). The pressure was -747 Pa (-3.0"wg) at the intake inlet, -872 Pa (-3.5"wg) at the return outlet.

3 Simulation Results and Discussion

The simulation was first conducted without any seal leakage using base values for gob permeability and porosity. The temperature distribution in the gob after 15 days is shown in Figure 2. A small temperature increase of 2 K occurred at the intake corner in the gob. Along the face and immediately after the face shields, there was a slight temperature rise of about 1 K. Simulations were then conducted using seal leakage rates of 0.0047, 0.012, 0.024 and 0.047 m^3/s (10, 25, 50 and 100 cfm). For the purpose of this study, all seals were assumed to have the same leakage rate.

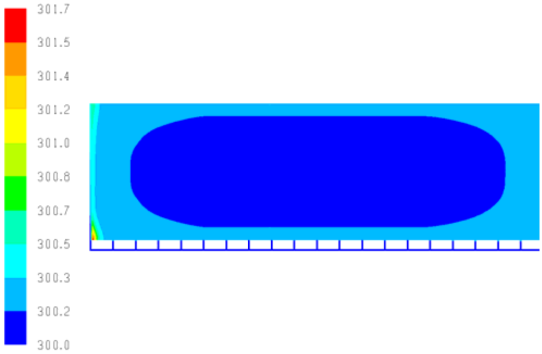

Figure 2 Temperature distribution (K) in the gob after 15 days without any leakage through gob seals.

Figure 3 shows temperature distribution in the gob after 15 days with a leakage rate of 0.0047 m^3/s (10 cfm). The maximum temperature was 308 K at the corner of the back end on the headgate side. Because of leakage at each seal, there was a slight temperature rise of about 2 K behind each seal. Figure 4 shows the temperature distribution in the gob after 15 days with a leakage rate of 0.047 m^3/s (100 cfm). The maximum temperature in this case was 325 K, also observed at the corner of the back end on the headgate side. Because of higher leakage at each seal, the area of temperature rise behind each seal increased, and the magnitude of temperature rise increased to about 15 K above ambient. The maximum temperature histories in the gob with different seal leakage rates are shown in Figure 5. It is clear that with the increase of the leakage rate, the maximum temperature increased, increasing the risk of fire hazard.

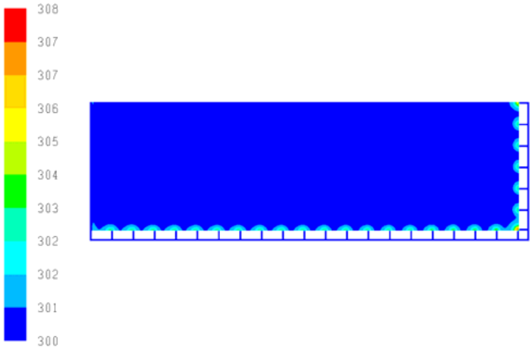

Figure 3 Temperature distribution (K) in the gob after 15 days with a leakage rate of 0,0047 m^3/s.

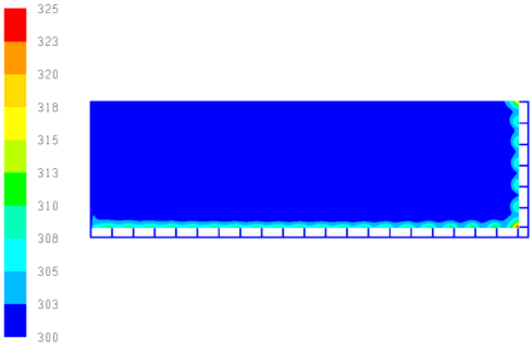

Figure 4 Temperature distribution (K) in the gob after 15 days with a leakage rate of 0.047 m^3/s.

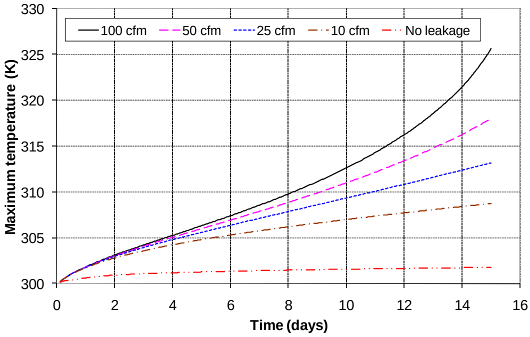

Figure 5 Maximum temperature histories in the gob with different seal leakage rates.

3.1 Effect of Gob Permeability

Gob permeability has a strong effect on gas flow in the gob. It is important to examine the effect of gob permeability on the spontaneous heating of coal with different leakage rates. CFD simulations were conducted at the same seal leakage rates with the gob permeability increased 100 times from its base value. Figure 6 shows temperature distribution in the gob after 15 days without any leakage through the gob seals. The maximum temperature was 319 K. Temperature increases were observed at the intake corner in the gob and immediately behind the face shields. Figures 7 and 8 show the temperature distributions in the gob after 15 days with the seal leakage rates of 0.0047 and 0.047 m^3/s (10 and 100 cfm), respectively. At the leakage rate of 0.0047 m^3/s (10 cfm), the maximum temperature was still 319 K at the inbye corner of the intake in the gob. Because of leakage at each seal, there was again a slight temperature rise behind each seal. At the leakage rate of 0.047 m^3/s (100 cfm), the maximum temperature was 324 K, but at the outbye corner of the back end on the headgate side. The temperature increases were similar to the results with the base value permeability. Because of higher leakage at each seal, the area with a slight temperature rise behind each seal increased. It should be pointed out that the major difference between the two leakage rates with the gob permeability increased 100 times is the location of the maximum temperature. The maximum temperature occurred at the intake corner at the leakage rate of 0.0047 m^3/s (10 cfm), while it occurred at the corner of the back end on the headgate side at 0.047 m^3/s (100 cfm). The maximum temperature histories in the gob with permeability increased 100 times under different seal leakage rates are shown in Figure 9. It is clear that with the increase of the leakage rate from 0 to 0.023 m^3/s (50 cfm), the maximum temperature increased insignificantly. Only with the leakage rate of 0.047 m^3/s (100 cfm) did the maximum temperature rise become significant.

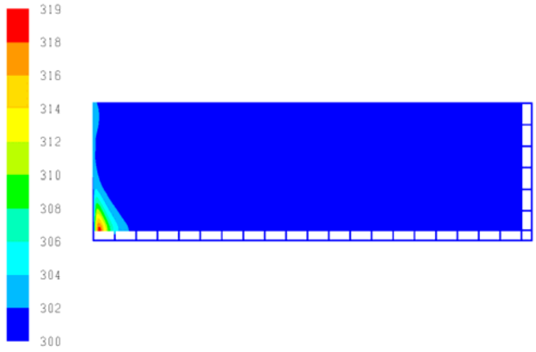

Figure 6 Temperature distribution (K) in the gob with permeability increased 100 times after 15 days without any leakage through gob seals.

Figure 10 compares maximum temperature histories in the gob with different gob permeability for the seal leakage rates of 0.047 and 0.0047 m^3/s (100 and 10 cfm). It is interesting to note that the maximum temperature in the gob with the gob permeability increased 100 times was nearly the same as that with the original gob permeability under the 0.047 m^3/s (100 cfm) seal leakage rate. On the other hand, the maximum temperature in the gob with the gob permeability increased 100 times was much higher than that with the original gob permeability under the 0.0047 m^3/s (10 cfm) seal leakage rate. This indicates that with a higher seal leakage rate (0.047 m^3/s), the gob permeability had little effect on the maximum temperature in the gob. Whereas with a lower seal leakage rate (0.0047 m^3/s), the larger gob permeability resulted in the higher maximum temperature in the gob.

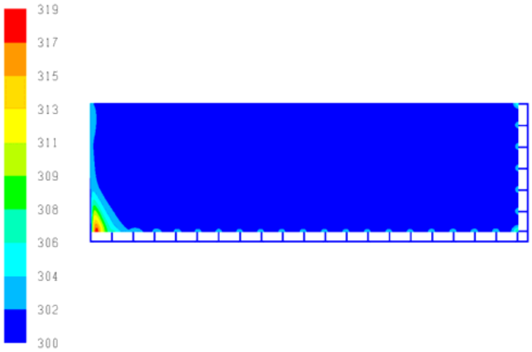

Figure 7 Temperature distribution (K) in the gob with permeability increased 100 times after 15 days with the seal leakage rate of 0.0047 m^3/s.

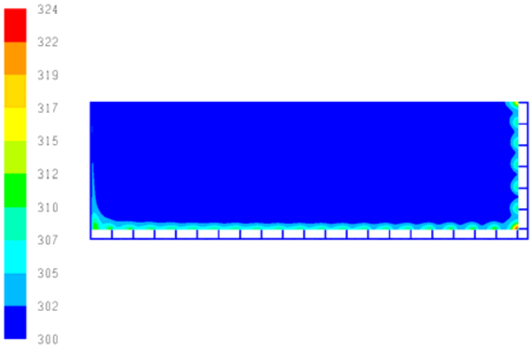

Figure 8 Temperature distribution (K) in the gob with permeability increased 100 times after 15 days with the seal leakage rate of 0.047 m^3/s.

3.2 Effect of the Number of Leaking Seals

Under actual mining conditions, the leakage rate for each seal may be different. As the longwall progresses, some seal leakage may increase. In order to examine the effect of the number of leaking seals on the spontaneous heating of coal in the gob, a CFD simulation was conducted with only one seal, the closest to the back end of the panel leaking. Figure 11 shows the temperature distribution in the gob after 15 days with a leakage rate of 0.047 m^3/s (100 cfm) at that seal. The maximum temperature was 312 K behind the seal. This compares to a maximum temperature of 325 K at the corner of the back end of the panel on the headgate side with leakage behind all seals, as shown in Figure 4. Figure 12 shows the temperature distribution in the gob after 15 days with two seals leaking at a rate of 0.047 m^3/s (100 cfm). The maximum temperature was 312 K behind both seals, indicating that under this condition, the leakage from a neighbouring seal does not affect heating behind a seal. The location of the hot spot and the higher maximum temperature shown in Figure 4 was apparently caused by the combined effect of two seals together at the headgate side corner of the back end of the panel that allowed for short-circuiting of the ventilation flow.

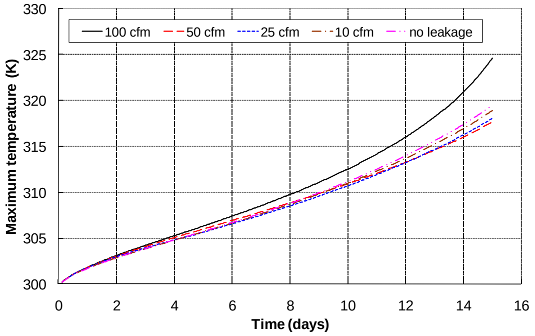

Figure 9 Maximum temperature histories in the gob with permeability increased 100 times under different seal leakage rates.

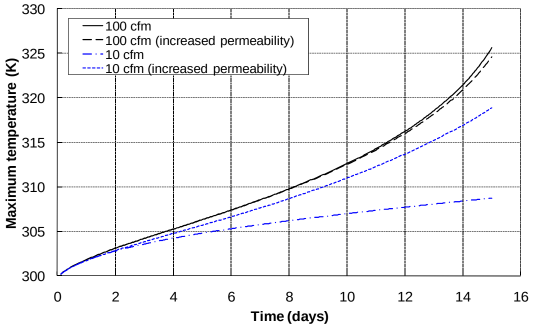

Figure 10 Maximum temperature histories in the gob with different gob permeability for the seal leakage rates of 0.047 and 0.0047 m^3/s.

Simulations were also conducted with one and two seals leaking when the gob permeability was increased 100 times from the base value. Figure 13 shows the temperature distribution in the gob after 15 days with only one seal leaking at the rate of 0.047 m^3/s (100 cfm) with the gob permeability increased 100 times. The maximum temperature was 319 K at the intake corner of the gob. The seal leakage caused some temperature rise, but was much lower than the maximum temperature at the intake corner. Figure 14 shows the temperature distribution in the gob after 15 days with two neighbouring seals leaking at the rate of 0.047 m^3/s (100 cfm) with the gob permeability increased 100 times. The maximum temperature was still 319 K at the intake corner of the gob. Some temperature increase was observed behind the seals but the temperature rise was similar behind both seals, indicating again that the leakages from neighbouring seals did not affect each other.

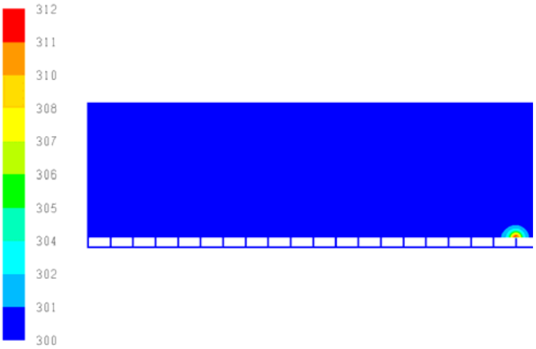

Figure 11 Temperature distribution (K) in the gob after 15 days with the leakage rate of 0.047 m^3/s at one seal.

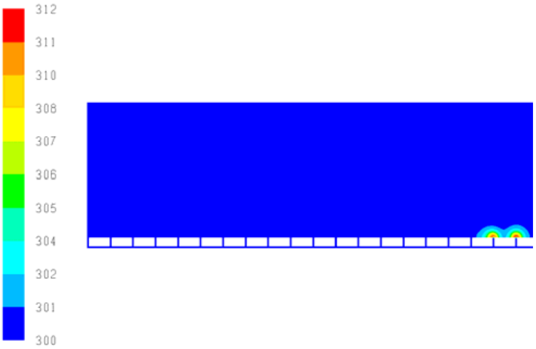

Figure 12 Temperature distribution (K) in the gob after 15 days with the leakage rate of 0.047 m^3/s at two seals.

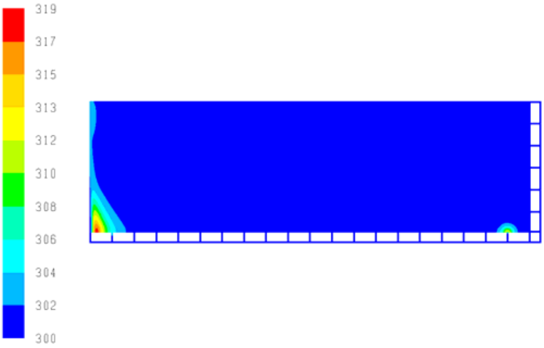

Figure 13 Temperature distribution (K) in the gob with permeability increased 100 times after 15 days with the leakage rate of 0.047 m^3/s at one seal.

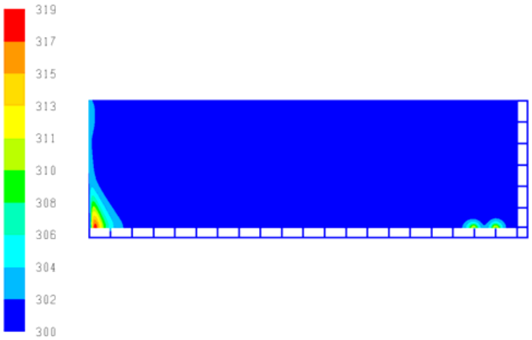

Figure 14 Temperature distribution (K) in the gob with permeability increased 100 times after 15 days with the leakage rate of 0.047 m^3/s at two seals.

4 Conclusions

CFD simulations were conducted to investigate the effect of seal leakage on spontaneous heating of coal in longwall gob area. Simulation results demonstrate that under typical bleederless ventilation conditions, with the increase of leakage rate from 0.0047 to 0.047 m^3/s (10 to 100 cfm), the maximum temperature in the gob increased, and the maximum temperature occurred at the headgate side corner at the back end of the panel. When the gob permeability was increased 100 times, with the leakage rate of 0.0047 m^3/s (10 cfm), the maximum temperature was the same as without seal leakage, while with the leakage rate of 0.047 m^3/s (100 cfm), the maximum temperature was higher and at the headgate side corner at the back end of the panel. With the increase of the seal leakage rate from 0 to 0.023 m^3/s (50 cfm), the maximum temperature increased insignificantly. Only with the leakage rate of 0.047 m^3/s (100 cfm) did the maximum temperature rise become significant.

With a high leakage rate (0.047 m^3/s), the gob permeability had little effect on the maximum temperature in the gob, while with a low seal leakage rate (0.0047 m^3/s), the larger gob permeability resulted in the higher maximum temperature in the gob. Simulations also revealed that when only one or two seals were leaking, the maximum temperature occurred around the seal. However, with the gob permeability increased 100 times and only one or two seals leaking, the maximum temperature was still at the intake corner in the gob. The neighbouring seal leakages did not affect each other.

These results show that complex interactions between pressure differentials and gob permeability at different locations in the gob cause ventilation pathways to change in reaction to these dynamic processes. These interactions are highly dependent on gob permeability and seal leakage rates. This study indicates that CFD modeling can be used to investigate these interactions. Future studies will be conducted to obtain data to verify the model results.

Disclaimer: The findings and conclusions in this paper 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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