Effects of ventilation and gob characteristics on spontaneous heating in longwall gob areas

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ABSTRACT: In the U.S. coal mining industry, most spontaneous combustion fires occur in longwall or worked-out gob areas. In order to reduce the fire hazard caused by spontaneous combustion, it is important to understand how ventilation and gob characteristics affect the spontaneous heating process. Given the difficulty to conduct field tests in such an environment, a computational fluid dynamics (CFD) study was conducted to investigate the effects of ventilation and gob characteristics on the spontaneous heating process in longwall gob areas. Two longwall panels with a bleeder ventilation system were simulated. The spontaneous heating is modeled as the low-temperature oxidation of coal in the gob using the Arrhenius rate law and kinetic data obtained from previous laboratory-scale studies. The heat generated from the spontaneous heating is transported by convection and conduction, and oxygen and the oxidation products are transported by convection and diffusion. Unsteady state simulations were conducted with different ventilation conditions and gob permeability distributions. The ventilation parameters varied in the simulations are the pressure at the bottom of the bleeder shaft and regulator resistance in the second entry inby the longwall face.

1 Introduction

Spontaneous combustion continues to pose a hazard for the U.S. underground coal mines. Approximately 17% of the 87 total reported fires for underground coal mines for the period 1990–1999 were caused by spontaneous combustion (DeRosa, 2004). The risk of an explosion ignited by a spontaneous combustion fire is also present in those mines with appreciable levels of methane emissions. In fact, three of the mine fires from the reported period resulted in subsequent methane explosions. Spontaneous combustion occurs when the heat that is 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 and a fire ensues. The spontaneous combustion potential of coals can be evaluated qualitatively in a laboratory using one of four commonly used methods: adiabatic calorimetry, isothermal calorimetry, oxygen sorption, and temperature differential methods. Although laboratory results are valuable, their extrapolation to the mining environment has not been completely successful because of complicated scaling effects that cannot be reproduced in small-scale experiments. In actual spontaneous heating events in coal mines, much larger coal masses may be involved. The spontaneous heating of coal in mines often occurs in a gob area and is not 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. Although much research has been done in experimental studies and mathematical modeling of spontaneous combustion of coals (Carras and Young, 1994), most of the research was focused on small coal stockpiles. 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 CFD study of gob gas flow mechanics to develop gas and spontaneous combustion control strategies for a highly gassy mine. Singh et al. (2002) developed a risk management plan for Australian mining operations in seams prone to spontaneous combustion.

In order to reduce the fire hazard caused by spontaneous combustion in a gob area, a computational fluid dynamics (CFD) study was carried out by 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 examine the effects of changing ventilation parameters and gob characteristics, such as its permeability distribution, on spontaneous heating in longwall gob areas.

2 Gob Layout and Ventilation System

A typical longwall district in an underground coal mine may consist of multiple panels. These panels are typically ventilated using bleeder fans to ventilate the mined out panels and the gob area of the active panel. In this study, this situation is simulated with two panels, one as a mined-out panel and the other one as an active panel, utilizing a bleeder system ventilated by a bleeder fan. The layout of the two panels and the ventilation system is shown in Figure 1. Each simulated gob area is 2,000 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. Panel A represents the completed panel, while panel B represents the active one. The ventilation scheme uses a three-entry gateroad system. This scheme and the panel dimensions are typical of longwall mines operating in the Pittsburgh coal bed of the Northern Appalachian Coal Basin. In the model, it is assumed that the middle entry between panel A and B and an entry on panel A's tailgate side are partially open. All crosscuts between the first and second entries inby the longwall face on the headgate side of panel B are open. For modeling purposes the bleeder entries at the back end of the gob are represented as one entry connecting to the bleeder fan. Four regulators are located at the end of the second and third entries inby the longwall face and the two tailgate entries, respectively, for controlling the bleeder ventilation.

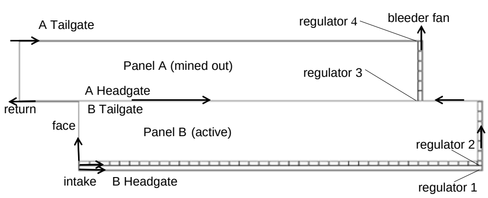


Figure 1. Layout of longwall panels and ventilation system.

3 Low Temperature Coal Oxidation

The chemical reaction between coal and oxygen at low temperatures is complex. Generally, three types of processes are believed to occur (Carras and Young, 1994). These are: (i) physical adsorption; (ii) chemical adsorption which leads to the formation of coal-oxygen complexes and oxygenated carbon-species; and (iii) 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. The interaction between water vapor and coal can be exothermic or endothermic depending on whether the water condenses or evaporates. Smith and Lazzara (1987) found that, initially, the rate of temperature rise depends on the heat-of-wetting. Later the heating curves pass through an inflection point, in which neither the heat-of-wetting mechanism nor the oxidation mechanism dominates. In the final phase, the oxidation mechanism dominates. Smith and Glasser (Smith and Glasser, 2005) concluded that adsorption of water vapor does not in itself compete with the low-temperature oxidation in terms of 'heat generation', but appears to speed up the oxidation rate, and possibly plays a catalytic role.

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

$$\text{Coal} + O2 \rightarrow CO2 + 0.1CO + \text{heat}$$

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:

$$\text{Rate} = A[O_2]^n \exp(-E / RT) \qquad (1)$$

Where:
A = preexponential factor (/s)
E = apparent activation energy (kJ/mol)
R = gas constant (kJ/mol-K)
n = apparent order of reaction
T = absolute temperature (K)
[O2] = oxygen concentration (kmol/m^3)

The value of apparent activation energy, E, of different coals can very between 12 and 95 kJ/mol. The pre-exponential factor, A, depends more on coal rank and measurement method, and has a typical value between 1 and 7×10^5 /s. 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. 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 physical and kinetic properties of the coal layer are listed in Table 1.

In order to simulate the spontaneous heating of coal in longwall gob areas, 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, the Pittsburgh coal seam was considered, with a 1-m-thick Pittsburgh rider coal sequence less than 1 m above the main coal seam. The rider coal sequence was modeled as caving into the gob after the main coal seam was completely mined out. Figure 2 shows the cross section of two longwall panels with the caving coal layer at the bottom of the gobs. 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 both external and internal pore surfaces. The reaction rate of spontaneous heating of coal in coal stockpiles was found to be related to the external surface area for nonporous coal particles with small pore diameters, and weakly related or not related to particle size for small porous coal particles with larger pore diameters. 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 surface-to-volume ratio used in the simulations is 36/m, which is equivalent to an average coal particle diameter of 10 cm. The heat generated from oxidation will be dissipated by conduction and convection while the oxygen and oxidation products are transported by convection and diffusion.

Table 1. The physical and kinetic properties of the 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	66.5	kJ/mol
Pre-exponential factor	6×10^4	/s
Coal particle diameter	10	cm
Initial coal temperature	300	K

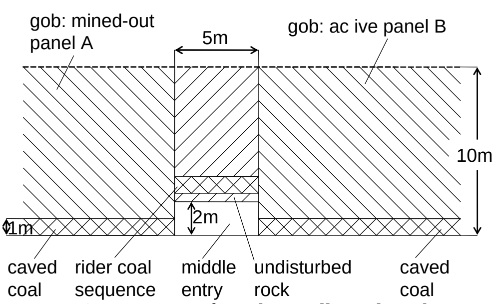


Figure 2. Cross section of two longwall panels with caving coal layer.

4 Estimation of Gob Permeability

The permeability and porosity distributions of the gob areas were based on geotechnical modeling of longwall mining in the Pittsburgh coal seam and the associated stress-strain changes using FLAC[1] (Fast Lagrangian Analysis of Continua) code (Esterhuizen and Karacan, 2005). In FLAC modeling, mining was simulated in increments, starting from one side of the grid and advancing to the other side. Extraction of the coalbed was modeled by removing elements over the height of the coalbed. The process of gob formation was modeled by first deleting rock elements in the roof of the coalbed, so that they are stress relieved, followed by inserting gob properties in these elements. Gob properties were also inserted in previously mined coalbed elements, so that the gob filled the mined void. In the gob caved area, the re-compaction of the caved rock has a significant effect on its permeability. Stress changes in the rock in the gob cause changes in the fracture apertures which then impact the permeability. Immediately behind the advancing face, the caved rock is loosely stacked and has an estimated porosity of approximately 0.4. As the mining face advances away from this caved rock, the weight of the overburden gradually increases and re-compacts the caved rock. This loading or stress in the caved material increases exponentially, until the full overburden load is supported by the caved material. The re-compaction, estimated with the FLAC model's assigned strength and mechanical properties of the gob material, results in a reduction in the void space within the broken rock rubble and, therefore, significant changes in permeability. A simple relationship was used to estimate the changes in permeability in the caved rock based on the Kozeny-Carman equation:

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

Where:
n = porosity
k =permeability (m^2)

For a Pittsburgh coal seam longwall panel, the permeability values in the gob area were estimated to vary from $3.0\text{x}10^{-11}$ to $8.5\text{x}10^{-10}$ m^2, while the porosity value varies from 0.17 to 0.41. 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 permeability calculation is given in Esterhuizen and Karacan (2007). The same profile was also applied to panel B. The porosity profiles in the two panels were similar to those permeability profiles 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. The detailed permeability profiles were described by Yuan and Smith (2007).

5 Numerical Modeling

A commercial CFD program, FLUENT, from Fluent, Inc., was used in this study to simulate the air flow and spontaneous heating in the longwall gob areas. The air flow in the longwall gob area was treated as laminar flow in a porous media using Darcy's law, while the air flow in the ventilation airways was simulated as fully developed turbulent flow.

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

Methane emission was also considered in the simulation because it affects the oxygen concentration distribution in the gob. Methane is continually liberated from the face and from the overlying rider coal seam reservoir. The methane from the overlying coal seam reservoir is assumed to be released uniformly along the border between the gob and the reservoir. Using ventilation data from a local Pittsburgh coal seam mine, the amount of methane released from the reservoir in this simulation is 0.13 m^3/s for panel B and 0.024 m^3/s for panel A. The methane emission rate from the face to the panel B is 0.014 m^3/s. These data were entered into FLUENT using C subroutines.

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 -747 Pa (-3.0 in.) at the intake inlet, -872 Pa (-3.5 in.) at the return outlet, and -2739 Pa (-11.0 in.) at the bottom of the bleeder shaft. The wall roughness of the ventilation airways was adjusted to have a total intake airflow rate of 41 m^3/s in the active longwall panel. The pressure drop through the two regulators located at the second and third entries inby the longwall face were also adjusted to have an airflow rate entering onto the face of 28 m^3/s. The pressure drop at regulator 3 was adjusted to have a longwall face return airflow rate of 24 m^3/s and 4.7 m^3/s airflow reporting to the bleeder system for the active panel. The flow rate in the entry on panel A's tailgate side was 3.3 m^3/s by adjusting the pressure drop at regulator 4.

A simulation was conducted first without coal oxidation to obtain steady state flow field and gas distributions. Then, the unsteady simulation with coal oxidation was conducted using the steady state solution as the initial conditions. The face was assumed stationary during the simulation.

6 Flow Patterns Inside The Gob

The flow patterns 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 air flow, and the heat generated from the oxidation may be carried away by the air flow. Fresh air flowing into a mine is contaminated by strata gas, dust and diesel exhaust etc. when it moves through the longwall face and into the return or across the gob. The air flow inside a gob is expected to be three dimensional with the flow in the vertical direction being weaker than in the other two directions due to reduced permeability and pressure gradients. In order to visualize the flow patterns inside the gob, a virtual horizontal reference surface was created 1 m from the bottom of the mined seam floor. Comparison of model results is with respect to this horizontal reference surface. Figure 3 shows the flow path lines colored by velocity magnitude in the two gob areas. The path lines indicate that the flow was mainly from the headgate side to the tailgate side in the two panels. At the face, air entered into the gob through the face shields and the tailgate area and flowed to the middle entry between the two panels. The higher velocities of air traveling through the gob itself were between 1.5x10-4 to 2.5x10-4 m/s (0.03 to 0.05 fpm) near the back end of panel B. Figure 4 shows the oxygen distribution in the two panels for a steady-state case considering methane emissions but no coal oxidation. For this condition, the oxygen concentration was at 21% in most of mined-out panel A. In the active panel, B, the oxygen concentration close to the entry inby the longwall face was below 21% because of methane emissions from the overlying coal seam reservoir. The pressure drops at the regulators and air quantities in each entry for the base case simulation are listed in Table 2.

Table 2. Pressure drops at the regulators and air quantities in each entry for the base case simulation.

Pressure drop at regulator 1	1942	Pa
Pressure drop at regulator 2	1743	Pa
Pressure drop at regulator 3	448	Pa
Pressure drop at regulator 4	1594	Pa
Airflow at longwall face	28	m^3/s
Airflow at return	24	m^3/s
Airflow at regulator 1	5.7	m^3/s
Airflow at regulator 2	3.8	m^3/s
Airflow at regulator 3	6.6	m^3/s
Airflow at regulator 4	3.3	m^3/s
Airflow at bleeder fan	21	m^3/s

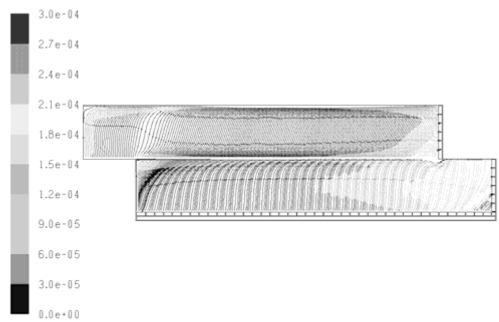


Figure 3. Flow path lines colored by velocity magnitude (m/s) in gob areas.

7 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 thermal runaway. The time to reach a thermal runaway is called the induction time. When the coal temperature reaches about 500 K (227 C), the spontaneous heating mechanism changes to rapid combustion (Babrauskas, 2003). So the simulations were focused on the self-heating mechanism at temperatures below 500 K.

Simulation of spontaneous heating of coals was first conducted with the boundary conditions described in the

Numerical Modeling section, and it was used as the base case. The simulations were then conducted using different ventilation conditions and permeability distributions, and the results were compared with those from the base case. Figure 5a shows the temperature distribution in the two

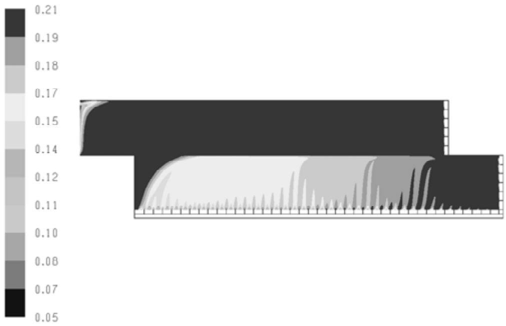
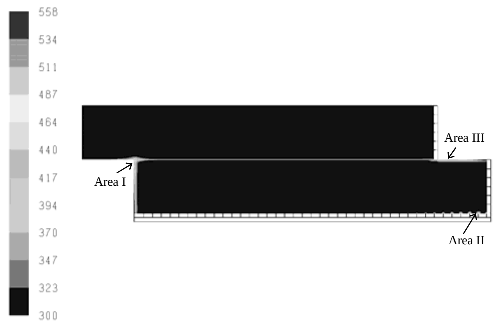


Figure 4. Contours of oxygen concentration (1=100%) in gob areas without coal oxidation.

panels after about 9 days for the base case. It is apparent that temperature increases occurred in three areas. These areas appeared more apparent in digital figures than in printed figures. Area I is the area close to the active tailgate and around the return. Area II is the area nearby the crosscuts close to the back end of the active panel B, and area III is around the middle entry at the back end of the mined-out panel A. Figure 5b shows the temperature increases in area I. There was very little or no temperature rise in areas other than areas I, II and III. This is because all oxygen was nearly consumed by coal oxidation at the periphery of the gob areas and no oxygen was available inside the gobs, as shown by the oxygen concentration in Figure 5c. The rate of temperature rise in three areas was also different. At any given time during 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 as the maximum temperature in the gob at a given time.

7.1 Effect of Pressure at the Bottom of Bleeder Shaft

Three simulations were conducted with different pressures at the bottom of the bleeder shaft: -1743 Pa (-7 in.), -3735 Pa (-15 in.) and -4980 Pa (-20 in.) to determine the effect of gob pressure differential on the spontaneous heating process. The pressure used in the base case was -2739 Pa (-11 in.). Figure 6 shows the maximum temperature obtained somewhere in the gob versus time for the three pressures compared with the base case. The general trend is that with the lower pressure at the bottom of the bleeder shaft, the rate of the maximum temperature rise increased. This is probably because the lower pressure in the bleeder system increases the pressure differential across the gob which increases the velocity and therefore quantity through the gob. With the pressure increased to -1743 Pa (-7 in.), the induction time increased about half a day compared with the base case. When the pressure was decreased to -3735 Pa (-15 in.), the induction time was nearly the same as the base case, but the temperature rise rate increased greatly in the second stage. With the pressure decreased to -4980 Pa (-20 in.), the rate of temperature rise just increased slightly compared with -3735 Pa (-15 in.) pressure, indicating enough oxygen was supplied by the ventilation to sustain the spontaneous heating process with the pressure of -3735 Pa (-15 in.) under the simulated conditions.



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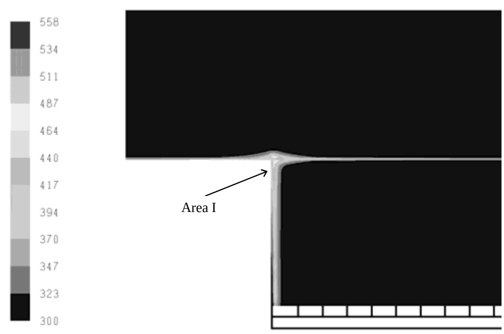

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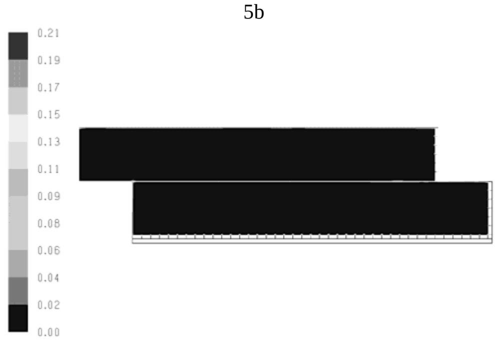

5c

Figure 5. Temperature and oxygen concentration distributions for the base case after 9 days. 5a: temperature in entire gob (K); 5b: temperature in area I (K); 5c: oxygen concentration (1=100%).

7.2 Effect of Resistance in the Second Entry inby The Longwall Face

Figure 7 shows the effect of resistance of regulator 2 on the spontaneous heating process in the gob. The pressure drop at regulator 2 was about 1743 Pa (7 in.) in the base case. It was increased to about 3735 Pa (15 in.) in one case by increasing the resistance at the regulator, and was decreased to about 187 Pa (0.75 in.) in another case by decreasing the resistance. Results show that with the increase of resistance at regulator 2, more air was pushed into the gob, thus the rate of maximum temperature rise increased. With the decrease of the resistance at regulator 2, less air was moving into the gob, leading to longer induction time for the spontaneous combustion, about two days, compared to the base case. Because of lower total levels of oxygen provided to the gob through the second entry inby the longwall face, the spontaneous heating in area II nearly disappeared, as shown in Figure 8.

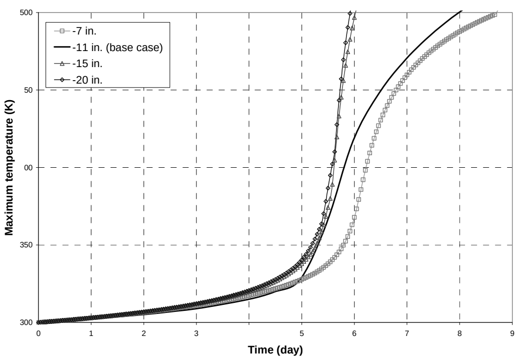

Figure 6. Simulated maximum temperature-time histories in gobs for different pressures at bottom of bleeder shaft.

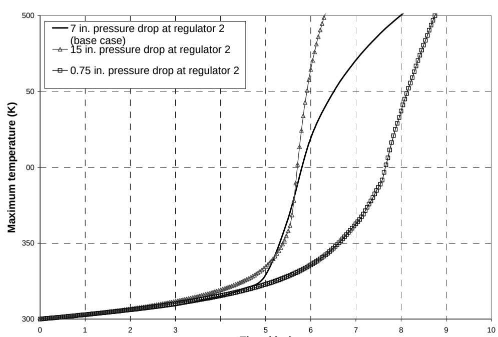

Figure 7. Simulated maximum temperature-time histories in gobs for different pressure drops at regulator 2.

7.3 Effect of Gob Permeability

The gob permeability has a major effect on the spontaneous heating in the gob because it affects the quantity of oxygenated atmosphere air flowing into the gob. In order to examine the effect of gob permeability, the permeability distribution for the base case was increased 10 times, decreased 10 times, decreased 100 times, and increased 100 times, respectively, in the simulations.

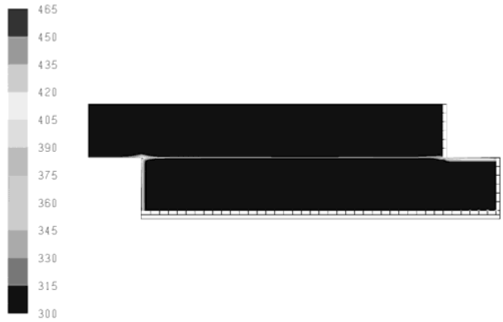

Figure 8. Temperature distributions in the gob areas after about 9 days (with 0.75 in. pressure drop at regulator 2).

Figure 9 shows the maximum temperature versus time histories in the gobs for the four different permeability distributions compared with the base case. With the permeability increased 10 times, the induction time was reduced about half a day and the rate of temperature rise increased at the second stage. When the permeability was increased 100 times over the base case, the induction time was nearly the same, but a slightly faster rate of temperature rise compared with the 10 times increase. When the permeability was decreased 10 times and 100 times, respectively, the two maximum temperature rise curves were nearly overlapped, indicating that further decrease of permeability had no effect on the rate of maximum temperature rise. The induction times for these two cases were increased about 2.5 days compared with the base case. When the permeability was decreased 10 times and 100 times, respectively, there was no temperature rise in area II, probably because of insufficient amount of oxygenated atmosphere into the gob. This is shown in Figure 10 for 10 times decrease.

8 Conclusions

CFD simulations were conducted to investigate the effects of ventilation parameters and gob permeability on the spontaneous heating in longwall gob areas. Simulation results demonstrate that under typical three-entry bleeder ventilation conditions, increasing the pressure differential across the gob area increased the rate of maximum temperature rise in the gob. However, the increase had no effect on the induction time. Conversely, decreasing the pressure differential across the gob increased the induction time while the rate of maximum temperature rise did not change significantly. With the increase of permeability, the induction time was decreased, while decrease of permeability increased the induction time. The results indicate that spontaneous combustion thermal runaway can be delayed through reducing the pressure differential across the gob or reducing the resistance at regulator 2 while still maintaining methane concentrations at different check points under allowable concentrations in the bleeder system.

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 longwall panel setup and the permeability and porosity data used in this study, in addition to the ventilation conditions stated in the paper.

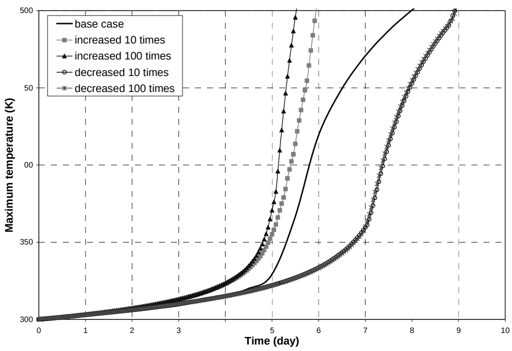

Figure 9. Simulated maximum temperature-time histories in gobs for different gob permeability distributions.

Figure 10. Temperature distributions in the gob areas after about 9 days (with permeability decreased 10 times).

9 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.

References

Babrauskas, V., 1978, *Ignition Handbook*, pp 720-723 (Fire Science Publishers: Issaquash, WA).

Balusu, R., Deguchi, G , Holland, R., Moreby, R., Xue, S , Wendt, M. and Mallett, C., 2002, Goaf gas flow mechanics and development of gas and Sponcom control strategies at a highly gassy mine, *Coal and Safety*, 20: 35-45.

Carras, J.N. and Young, B.C., 1994, Self-heating of coal and related materials: models, application and test methods, *Progress in Energy and Combustion Sciences*, 20: 1-15.

DeRosa, M., 2004, Analysis of mine fires for all U.S. underground and surface coal mining categories, 1990-1999, *NIOSH Information Circular* 9470.

Esterhuizen, G. S. and Karacan, C.Ö., 2005, Development of Numerical Models to Investigate Permeability Changes and Gas Emission Around Longwall Mining Panels, in *Proc. AlaskaRocks 2005, 40th US Symposium on Rock Mechanics*, Anchorage, Alaska, 25-26 June.

Esterhuizen, G. S. and Karacan, C.Ö., 2007, A methodology for determining gob permeability distributions and its application to reservoir modeling of coal mine longwalls, *Preprint of SME 2007 Annual Meeting*, Denver, CO.

Saghafi, A., Bainbridge, N.B. and Carras, J.N., 1995, Modeling of spontaneous heating in a longwall goaf, in *Proceedings of the 7th US Mine Ventilation Symposium*, pp. 167-172.

Saghafi, A. and Carras, J.N., 1997, Modeling of spontaneous combustion in underground coal mines: application to a gassy longwall panel, in *Proceedings of the 27th International Conference of Safety in Mines Research Institute*, pp. 573-579.

Schmidt, L D. and Elder, J.L., 1940, Atmospheric oxidation of coal at moderate temperatures, *Industrial and Engineering Chemistry*, 32:249-256.

Singh, R.N , Shonhardt, J.A. and Terezopoulos, N., 2002, A new dimension to studies of spontaneous combustion of coal, *Mineral Resources Engineering*, 11(2): 147-163.

Smith, M.A. and Glasser, D., 2005, Spontaneous combustion of carbonaceous stockpiles. Part II: Factors affecting the rate of the low-temperature oxidation reaction, *Fuel* , 84: 1161-70.

Smith, A.C. and Lazzara, C.P., 1987, Spontaneous combustion studies of U.S. coals, *Report of Investigations 9079*, U.S. Bureau of Mines.

Smith, A.C., Miron, Y. and Lazzara, C.P., 1987, Large-scale studies of Spontaneous combustion of coal, *Report of Investigations 9346*, U.S. Bureau of Mines.

Yuan, L., Smith, A.C., and Brune, J.F., 2006, Computational Fluid Dynamics Study on the Ventilation Flow Paths in Longwall Gobs, in *Proceedings of the 11th U.S./North American Mine Ventilation Symposium*, University Park, PA.

Yuan, L. and Smith, A.C., 2007, Computational fluid dynamics modeling of spontaneous heating in longwall gob areas, *Preprint of SME Annual meeting*, Denver, CO.