

EFFECT OF LONGWALL FACE ADVANCE ON SPONTANEOUS HEATING IN LONGWALL GOB AREA

L. Yuan, NIOSH, Pittsburgh, PA
A. C. Smith, NIOSH, Pittsburgh, PA

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 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, while the length of the panel is changed between 1,000 to 2,000 m. 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.

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.

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 (Ariso & 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 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 4-5%, 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, NIOSH has conducted a series of computational

fluid dynamics (CFD) simulations using coal kinetic data from the former U.S. Bureau of Mines laboratory-scale experimental results (Smith & 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 & 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 & 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 & 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.

GOB LAYOUT AND VENTILATION SYSTEM

In this study, a single longwall panel, 2,000 m long and 300 m wide, with a three-entry bleeder ventilation system is simulated. The layout of the panel and the ventilation system is shown in Figure 1. The original coal seam is 2-m high, and the gob is assumed to be 10-m high starting from the bottom of the coal seam. The ventilation airways are 2 m high and 5 m 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.

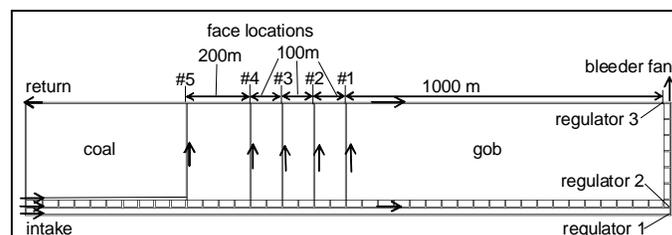


Figure 1. Layout of longwall panel and ventilation system.

The longwall face is originally at location #1, 1,000 m from the start line of the panel. It is assumed that the face advances in a rate of 20 m per day from location #1. The face advances 100 m in 5 days to reach locations #2, #3, and #4, respectively. The face advances 200 m 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 & 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 (CO₂), and water vapor (H₂O).

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:



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

$$\text{Rate} = A[\text{O}_2]^n \exp(-E/RT)$$

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) 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 [O₂] is the oxygen concentration (in kmol/m³).

The value of apparent activation energy, E, of different coals can vary 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 7×10⁵ /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 & Young, 1994), and is about 0.61 for some U.S. coals ((Schmidt & 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-meter thick rider coal seam less than 1 m above the 2-meter 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. 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 & Smith, 2007). In this study, an average coal particle diameter of 10 cm, 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 & 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 FLAC¹ (Fast Lagrangian Analysis of Continua) code. A simple relationship is used to estimate the changes in permeability in the caved rock based on the Kozeny-Carman equation:

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

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

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	73.6	kJ/mol
Pre-exponential factor	1.1×10 ⁷	K/s
Coal particle diameter	10	cm
Initial coal temperature	300 (27)	K (°C)

For a Pittsburgh coal seam longwall panel, the permeability values in the gob area are estimated to vary from 3.0×10⁴ to 8.5×10⁷ 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 5 days, it is assumed that the face moves instantaneously to location #2 and remains there for 5 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. 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.

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

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 (-3.0 inches water gauge) at the intake inlet at the headgate side, -0.87 kPa (-3.5 inches water gauge) at the return outlet at the tailgate side, and -2.2 kPa (-9.0 inches 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 m³/s (87,000 cfm) in the panel. The pressure drops through the two regulators located at the second and third headgate entries were also adjusted to have an airflow rate entering onto the face of 28 m³/s (60,000 cfm). The pressure drop at regulator 3 was adjusted to have a flow rate in the return of 24 m³/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 Figure 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 & 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 5 days. Figure 3 shows the temperature distribution in the gob 5 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 Figure 4, with the maximum temperature at 325 °K (52 °C) after 5 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 5 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.

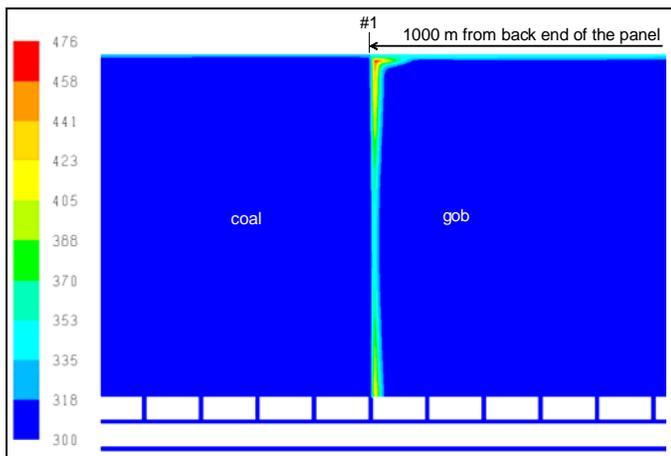


Figure 2. Temperature distribution (K) after 20 days with longwall face at location #1.

After the face was at location #5 for 10 days, the maximum temperature (315 °K (42 °C)) in the gob area was still at the tailgate corner of location #1, as shown in Figure 6. The temperature decrease was just 5 degrees, compared with the maximum temperature when the face was at location #4. This is summarized in Figure 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.

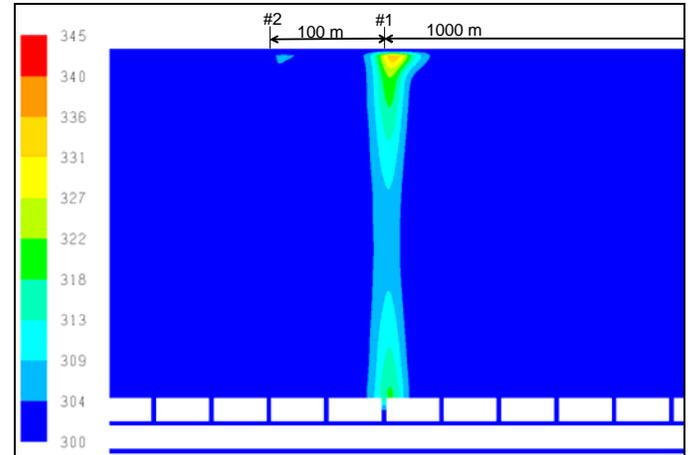


Figure 3. Temperature distribution (K) after 5 days with longwall face at location #2.

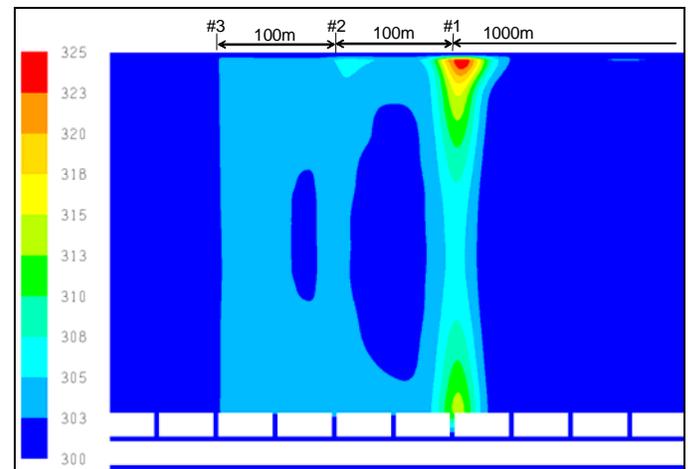


Figure 4. Temperature distribution (K) after 5 days with longwall face at location #3.

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 proceeding into a thermal runaway. As shown in Figure 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.

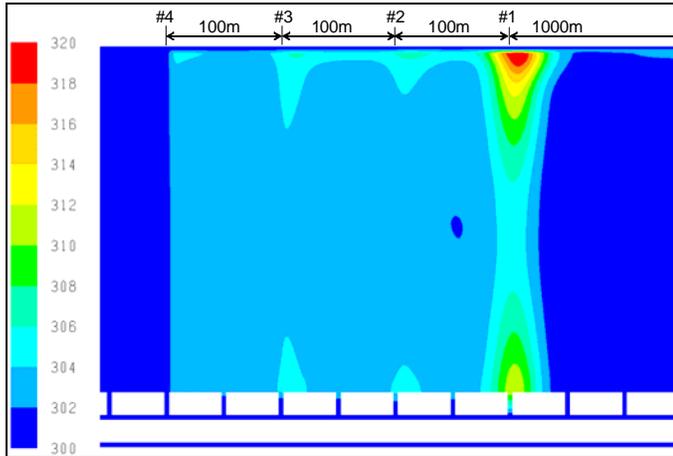


Figure 5. Temperature distribution (K) after 5 days with longwall face at location #4.

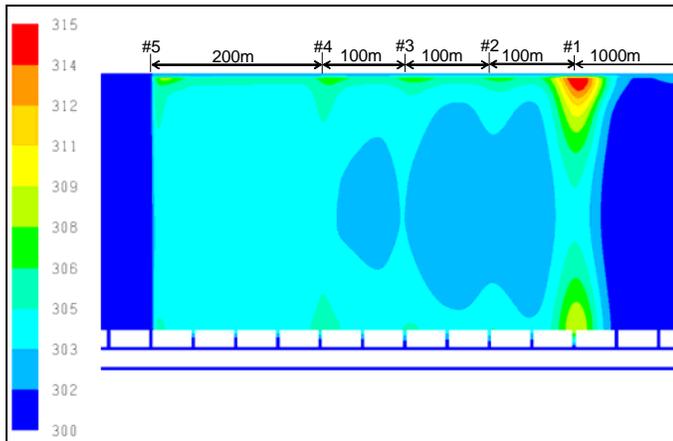


Figure 6. Temperature distribution (K) after 10 days with longwall face at location #5.

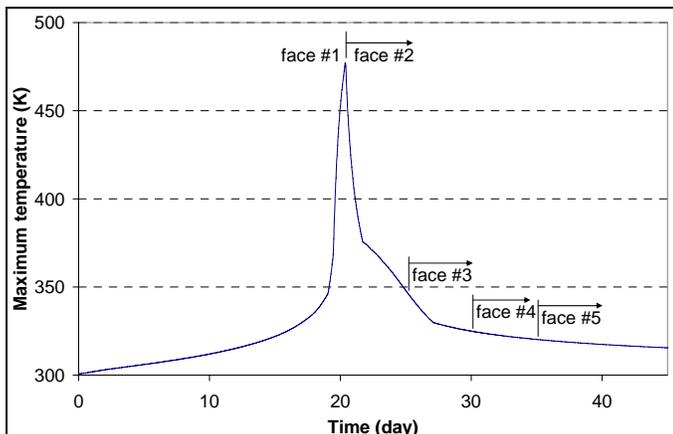


Figure 7. Maximum temperature (K) versus time histories: longwall face began to advance when the maximum temperature reached 476 °K.

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, that 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 modeling of face advance in the future.

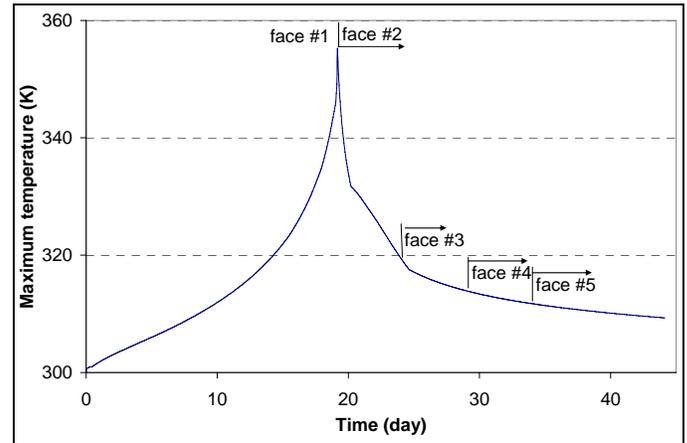


Figure 8. Maximum temperature (K) versus time histories: longwall face began to advance when the maximum temperature reached 350 °K.

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.

REFERENCES

1. Arisoy, A. and Akgun, F. (1994), "Modeling of spontaneous combustion of coal with moisture content included", *Fuel*, 73: 281-286.
2. Babrauskas, V. (2003), *Ignition Handbook*, Fire Science Publishers, Issaquah, WA.
3. 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 Spon com control strategies at a highly gassy mine", *Coal and Safety*, No.20, pp. 35-45.
4. Brooks, K. and Glasser, D. (1986), "A simplified model of spontaneous combustion in coal stockpiles", *Fuel*, 65: 1035-1041.
5. 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.
6. DeRosa, M., (2004), "Analysis of mine fires for all U.S. underground and surface coal mining categories, 1990-1999", NIOSH Information Circular 9470.
7. Edwards, J.C. (1990), "Mathematical modeling of spontaneous heating of a coalbed", Report of Investigations 9296, U.S. Bureau of Mines.
8. 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”, SME 2007 Annual Meeting, Denver.

9. Krishnaswamy, S., Agarwal, P. and Gunn, R. (1996), “Low-temperature oxidation of coal 3. Modeling spontaneous combustion in coal stockpiles”, *Fuel*, 75: 353-362.
10. Nordon, P.A. (1979), “A model for the self-heating reaction of coal and char”, *Fuel*, 58: 456-464.
11. Rosema, A., Guan, H. and Veld, H. (2001), “Simulation of spontaneous combustion, to study the causes of coal fires in the Rujigou Basin”, *Fuel*, 80:7-16.
12. Saghafi, A., Bainbridge, N.B. and Carras, J.N. (1995), “Modeling of spontaneous heating in a longwall goaf”, *Proceedings of the 7th US Mine Ventilation Symposium*, pp. 167-172.
13. Saghafi, A. and Carras, J.N. (1997), “Modeling of spontaneous combustion in underground coal mines: application to a gassy longwall panel”, *Proceedings of the 27th International Conference of Safety in Mines Research Institute*, pp. 573-579.
14. Schmidt, L.D. and Elder, J.L. (1940), “Atmospheric oxidation of coal at moderate temperatures”, *Industrial and Engineering Chemistry*, 32:249-256.
15. Smith, A.C. and Lazzara, C.P. (1987), “Spontaneous combustion studies of U.S. coals”, *Report of Investigations 9079*, U.S. Bureau of Mines.
16. Smith, A.C., Miron, Y. and Lazzara, C.P. (1991), “Large-scale studies of Spontaneous combustion of coal”, *Report of Investigations 9346*, U.S. Bureau of Mines.
17. Smith, A. C. and Yuan, L (2008), “Simulation of spontaneous heating in longwall gob area with a bleederless ventilation system”, 2008 SME Annual Meeting, Feb. 24-27, Salt Lake City, UT, Preprint 08-043.
18. Sondreal, E.A. and Ellman, R.C. (1974), “Laboratory determination of factors affecting storage of North Dakota lignite”, *Report of Investigations 7887*, U.S. Bureau of Mines.
19. Yuan, L. and Smith, A. C. (2007), “Computational fluid dynamics modeling of spontaneous heating in longwall gob areas”, 2007 SME Annual Meeting, Feb. 25-28, 2007, Denver, Colorado, Preprint 07-101.
20. Yuan, L. and Smith, A. C. (2008a), “Effects of ventilation and gob characteristics on spontaneous heating in longwall gob areas”, *Proceedings of the 12th U.S./North American Mine Ventilation Symposium*, pp. 141-147, Reno, NV, June 9-11.
21. Yuan, L. and Smith, A. C. (2008b), “Numerical study on effects of coal properties on spontaneous heating in longwall gob areas”, *Fuel*, 87: 3409–3419.