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MINE VENTILATION

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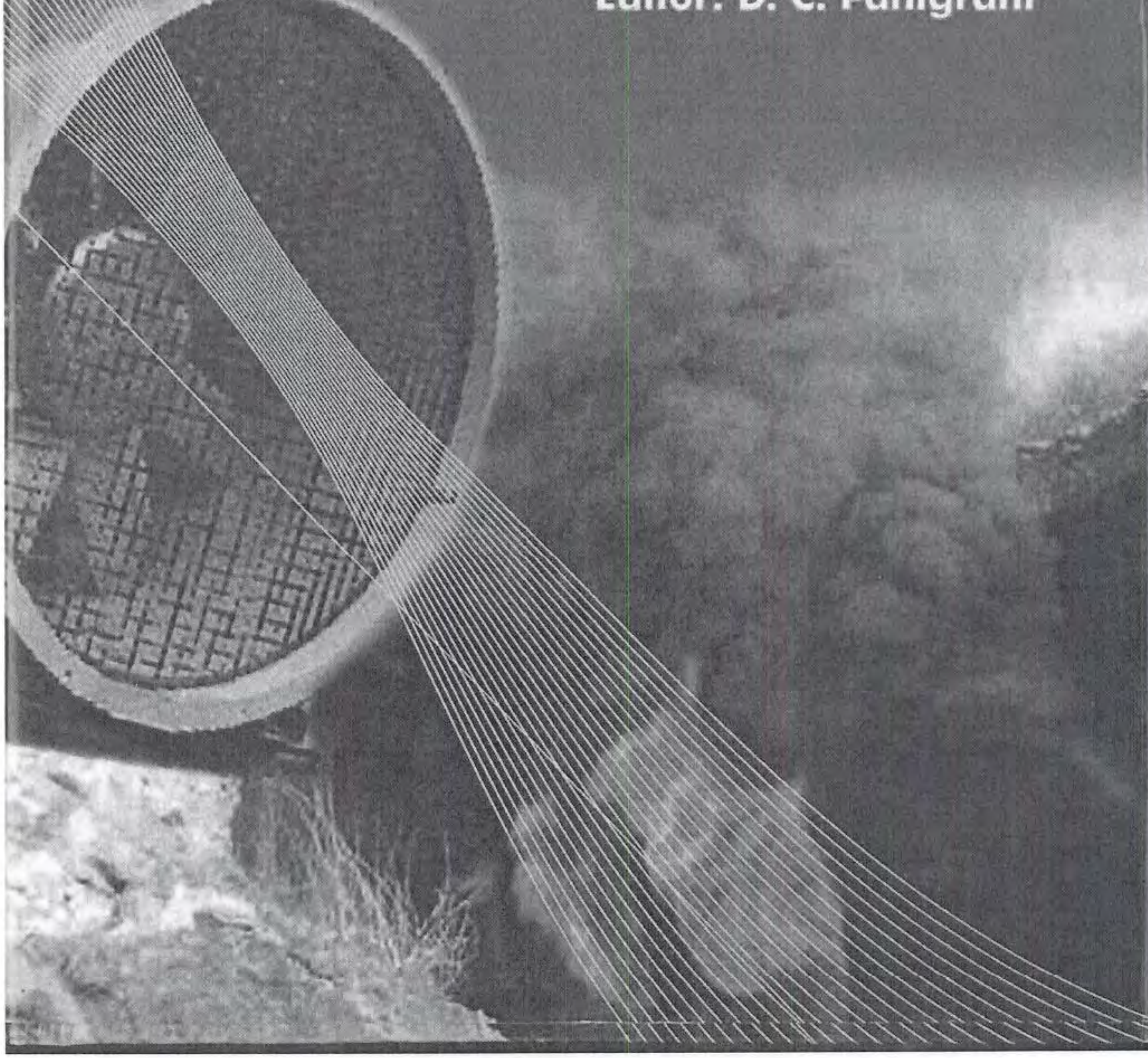

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NUMERICAL STUDY ON SPONTANEOUS COMBUSTION OF COAL IN U.S. LONGWALL GOB AREAS

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ABSTRACT

In order to reduce fire hazards caused by spontaneous combustion in longwall gob areas, a computational fluid dynamics (CFD) study is being conducted by National Institute for Occupational Safety and Health (NIOSH) to simulate the spontaneous heating of coal in longwall gob areas. A CFD model was first developed to model the spontaneous heating process in a two longwall panel district using a bleeder ventilation system with a stationary longwall face. The spontaneous heating is modeled as the low-temperature oxidation of coal in the gob using kinetic data obtained from previous laboratory-scale spontaneous combustion studies. Heat generated from coal oxidation is dissipated by convection and conduction, while oxygen and oxidation products are transported by convection and diffusion. CFD simulations were then conducted to model the spontaneous heating in longwall gob area with a bleederless ventilation system. A single longwall panel with a bleederless ventilation system was simulated. The effect of gob permeability on the spontaneous heating was also investigated.

KEYWORDS: *Spontaneous combustion; Coal; Longwall gob; Modeling; Ventilation*

1. 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. Approximately 15% of the 164 total reported fires for underground coal mines for the period 1978 – 1990 were caused by spontaneous combustion. For the period 1990 – 2006, totally 25 reported fires for underground coal mines were caused by spontaneous combustion (DeRosa, 2004). The spontaneous heating of coal in underground mines often occurs in a gob area and may not be easily detected. 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. Although much research has been done in experimental study and mathematical modeling of spontaneous combustion of coals, most of the research was mainly focused on small size 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.

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 (Yuan and Smith, 2007; Smith and Yuan, 2008). A CFD model was first developed to simulate the spontaneous heating of coals in a two-panel gob area using a bleeder ventilation system with a stationary longwall face. CFD simulations were also conducted to model the spontaneous heating in longwall gob area using a bleederless ventilation system with a stationary longwall face. In this paper, CFD modeling results for both bleeder and bleederless ventilation systems are presented and the difference between two systems is discussed.

2. GOB LAYOUT AND VENTILATION SYSTEMS

2.1 Bleeder Ventilation System

In the U.S., most underground coal mines utilize a bleeder ventilation system to ventilate the mined out panels and the gob area of the active panel. In our 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. 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. 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 in by the longwall face and the two tailgate entries, respectively, for controlling the bleeder ventilation.

The ventilation conditions used in the simulation were based on a local Pittsburgh coal seam mine's ventilation data. The pressure was -3.0 inches water gauge at the intake inlet, -3.5 inches water gauge at the return outlet, and -11.0 inches water gauge at the bottom of the bleeder shaft. The wall roughness of the ventilation airways was adjusted to have a total intake airflow rate of 87 000 cfm in the active longwall panel. The pressure drops through the two regulators located at the second and third intake entries were also adjusted to have an airflow rate entering onto the face of 60 000 cfm. The pressure drop at regulator 3 was adjusted to have a flow rate at the return of 50 000 cfm, and the flow rate in the entry on panel A's tailgate side was 7 000 cfm by adjusting the pressure drop at the regulator 4.

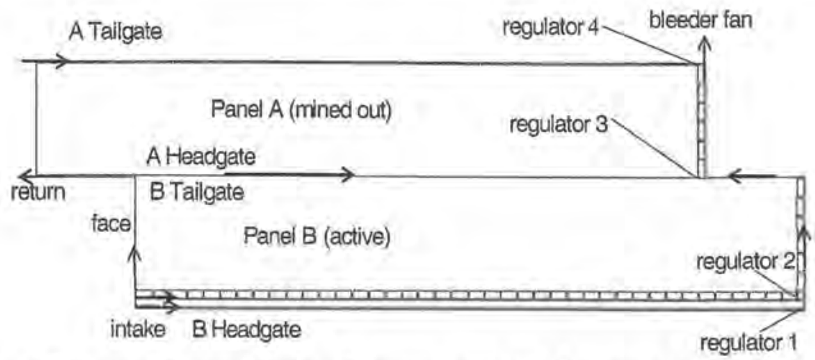

Figure 1: Layout of two longwall panels with a bleeder ventilation system

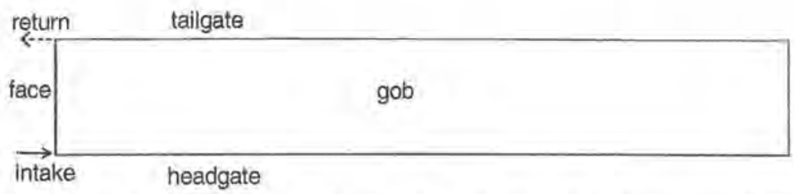

Figure 2: Layout of single longwall panel with a bleederless ventilation system

2.2 Bleederless Ventilation System

In the U.S., bleederless ventilation systems may be approved by the Mine Safety and Health Administration (MSHA) 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. In a bleederless ventilation system, the previously mined-out panels are usually isolated from the active gob and the remainder of the mine. In our study, only the active panel was simulated. The layout of the panel and the ventilation system is shown in Figure 2. The simulated gob area is also 2 000 m long, 300 m wide and 10 m high. The ventilation airways are 2 m high and 5 m 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.

Typical ventilation pressures for the bleederless ventilation system were used in the simulation. The pressure was -3.0 inches water gauge at the intake inlet, -3.5 inches water gauge at the return outlet. To control the air flow quantity to the longwall face, the wall roughness was adjusted to have a realistic intake airflow rate of 64 000 cfm.

3. MODELING LOW-TEMPERATURE COAL OXIDATION

A detailed description of the low temperature coal oxidation process used in these simulations is described in our previous study (Yuan and Smith, 2007). Here, only a brief description is provided. The chemical reaction between coal and oxygen is simplified as:

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

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.*, 1991), 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 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, 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. The activation energy and pre-exponential factor were measured using an adiabatic heating oven (Smith and Lazzara, 1987). 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, and is about 0.61 for some U.S. coals.

The coal source for spontaneous heating can be coal left from the mined coal seam or other overlying or underlying coal seams. In our study, a 2-m-thick main coal seam was considered, with a 1-m-thick rider sequence 1 m 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 oxidation of coal will occur on any available coal surface. Surface area available for coal oxidation in a unit volume, or surface-to-volume ratio, is calculated based on coal particle size and gob porosity. The physical and kinetic properties of the coal used in the simulation are listed in Table 1.

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

4. NUMERICAL MODELING

A commercial CFD program, FLUENT[1], 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.

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

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 FLAC (Fast Lagrangian Analysis of Continua) code. For a Pittsburgh coal seam longwall panel, the permeability values in the gob area were estimated to vary from 3.0×10^4 to 8.5×10^5 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.

5. SIMULATION RESULTS AND DISCUSSION

The flow patterns inside a gob 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. 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. Steady-state simulations were first conducted without coal oxidation to determine the flow patterns in the gob. Figure 3 shows the flow path lines colored by velocity magnitude in the two gob areas with the bleeder ventilation system. 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 1.5×10^{-4} to 2.5×10^{-4} m/s (0.03 to 0.05 fpm) near the back end of panel B.

The flow path lines colored by velocity magnitude in the gob area for the bleederless ventilation system are shown in Figure 4. 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. The air velocity ranged between 1.0×10^{-5} to 3.0×10^{-5} m/s (0.002 to 0.006 fpm) in the gob near the shields, and there was nearly no flow farther away from the shields into the gob.

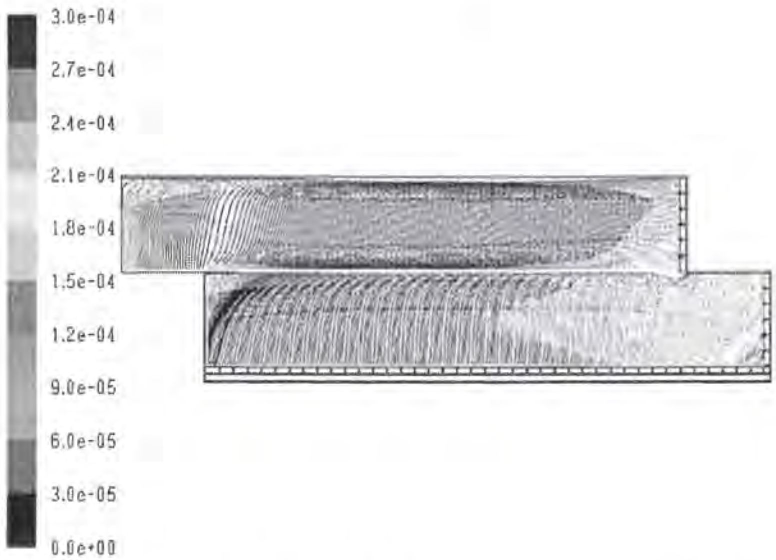

Figure 3: Flow path lines colored by velocity magnitude (m/s) in gob areas for the bleeder ventilation system

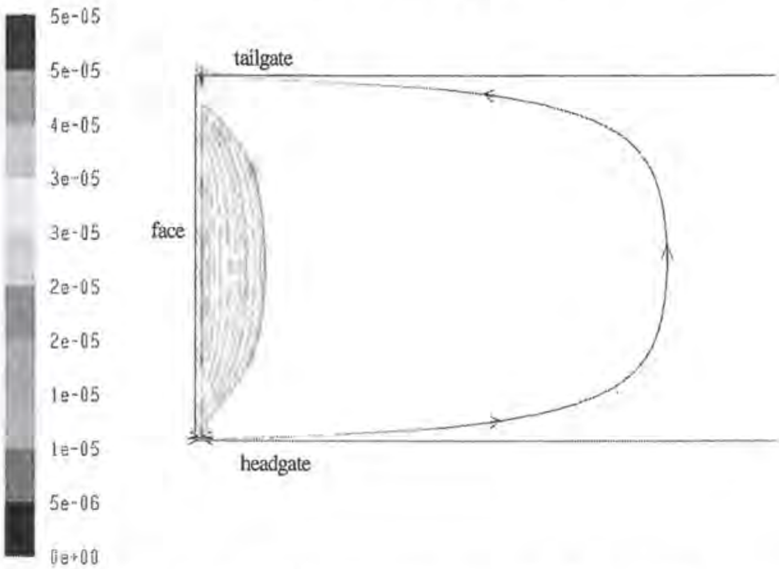

Figure 4: Flow path lines colored by velocity magnitude (m/s) in gob area for the bleederless ventilation system

Unsteady state simulations were then conducted to model coal oxidation. Figure 5 shows the temperature distribution in the two panels with the bleeder ventilation system after about 9 days. It is apparent that temperature increases only occurred in three areas. 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. There was very little or no temperature rise in areas other than areas I, II and III. This is because nearly all the oxygen was consumed by coal oxidation at the periphery of the gob areas and little or no oxygen was available inside the gobs. 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.

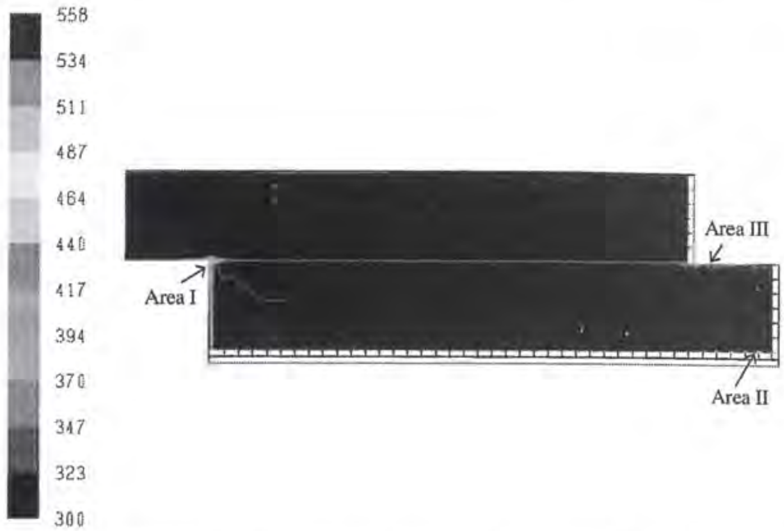

Figure 5: Temperature distribution (K) in gob areas with the bleeder system after 9 days

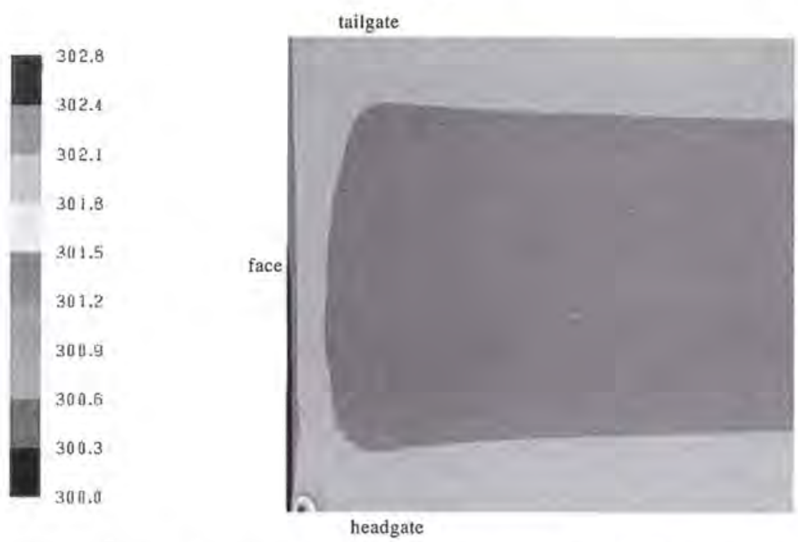

Figure 6: Temperature distribution (K) in gob area with the bleederless system after 20 days

Figure 6 shows the temperature distribution in the gob with the bleederless ventilation system after 20 days. The maximum temperature at that time was only 302.8 K. The maximum temperature rise, 2.8 degree K, 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 the oxygen was nearly all consumed by coal oxidation at the intake corner of the gob. This is much different from the case with a bleeder ventilation system where a temperature increase was observed along the face and behind the shields in the gob. Figure 7 shows the maximum temperature versus time histories from the simulation for both bleeder and bleederless ventilation systems. With the bleederless system, the maximum temperature was only 302.8 K after

20 days, while the maximum temperature reached 500 K in 8 days with the bleeder ventilation system.

The gob permeability also has a major effect on the spontaneous heating in the gob because it affects the quantity of air flowing into and through the gob. In order to examine the effect of the gob permeability on the spontaneous heating, simulations were conducted with the permeability increased 100 times for both ventilation systems. Figure 8 shows the maximum temperatures versus time histories for the increased permeability simulations for both bleeder and bleederless systems. With the increased permeability, the maximum temperature reached 500 K in about 22 days compared to only 2.8 degree K temperature 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.

6. CONCLUSIONS

CFD simulations were conducted to investigate the spontaneous heating of coals in longwall gob areas with both bleeder and bleederless ventilation systems. The spontaneous heating hazards of different coals were strongly dependent on mine ventilation conditions. Under typical three-entry bleeder ventilation conditions, simulations confirmed the existence of a critical velocity zone behind the shields in the gob, and showed the existence of other critical velocity zones in both the active panel and the mined-out panel. 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, and the temperature rise occurred only at the corner of the intake entry with the bleederless system. For the bleederless system with the increased permeability, the induction time to thermal runaway was reduced significantly.

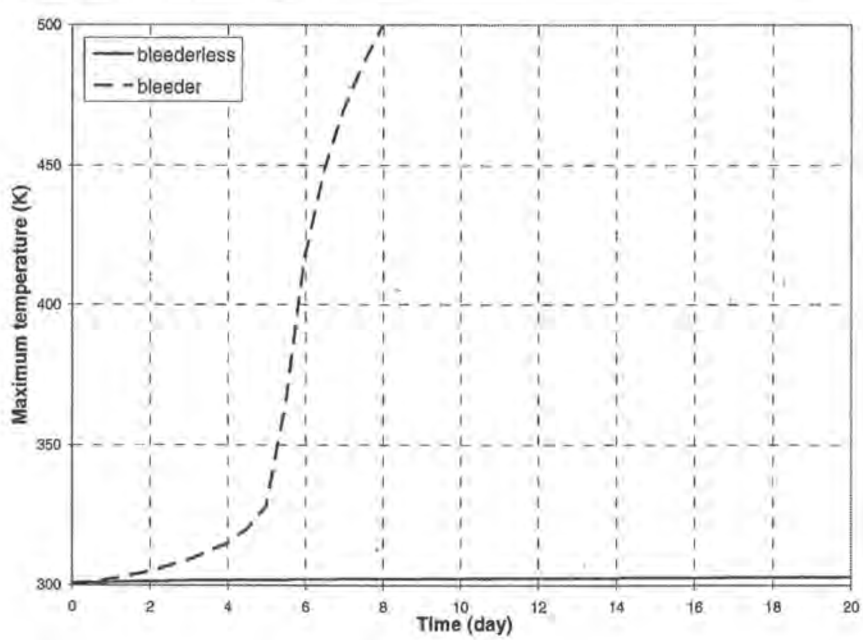

Figure 7: Maximum temperatures (K) versus time histories for both ventilation systems

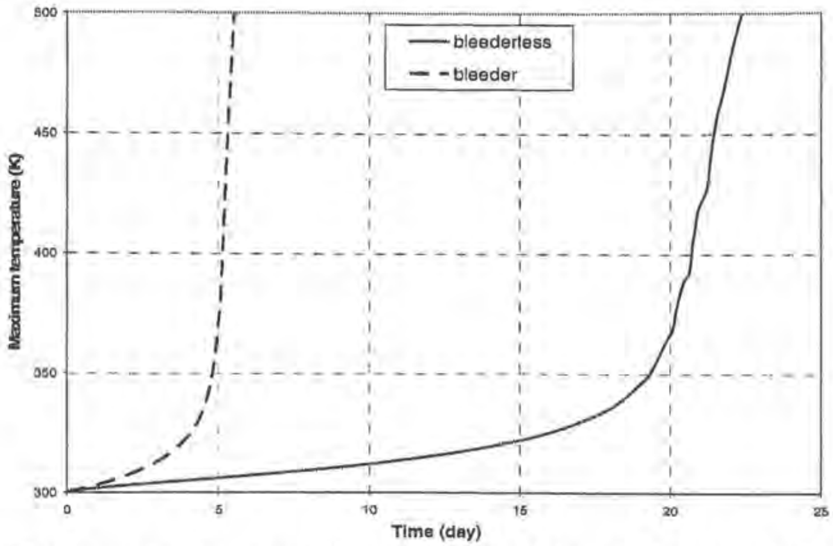

Figure 8: Maximum temperature (K) versus time histories with gob permeability increased 100 times for both systems

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