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MODELING THE EFFECT OF BAROMETRIC PRESSURE CHANGES ON SPONTANEOUS HEATING IN BLEEDERLESS LONGWALL PANELS

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Abstract

Barometric pressure changes affect air density, leading to change in the mass of the gas in the gob. When the barometric pressure decreases, the volume of gas in the gob expands, while the volume of gas contracts when the barometric pressure increases, causing the gob to breathe out and in. Although the concept of gob “breathing” is simple, its effect on spontaneous heating of coal in the gob area is not clear. In this study, computational fluid dynamics (CFD) simulations were conducted to model the spontaneous heating of coal in longwall gob area under measured barometric pressure changes. A single longwall panel using a bleederless ventilation system was simulated. If there is no barometric pressure change, the intake airflow rate is equal to the return airflow rate. When the barometric pressure changes, these two airflow rates are no longer equal, and the difference between the two airflow rates represents the airflow rate the gob breathes in and out. The effect of inflow and outflow of gas on the potential spontaneous heating in the gob was investigated using the CFD model developed in our previous study. The effect of barometric pressure changes on the spontaneous heating was found to be dependent on the gob permeability and the coal oxidation rate. The effect of barometric pressure changes on oxygen concentrations in the gob was also examined.

Introduction

Barometric pressure changes have long been known as a factor that may influence conditions in underground mines. For an underground coal mine, when the barometric pressure changes, it can affect the gas emission not only from the active mining seam, but also from the overlying and underlying strata into the mined coal seam. On the other hand, the barometric pressure changes can also cause leakage into and out of a sealed area or outflow and inflow of an unsealed gob area. In the latter case, the inflow of fresh air into the sealed area or gob area may increase the possibility of a fire or explosion behind the seal or in the gob. The barometric pressure changes can be caused by weather and atmospheric heating and cooling on a daily basis. The weather caused barometric pressure changes are created by storm fronts that are associated with decreasing barometric pressures as they approach, followed by an increasing barometric pressure after they pass. The pressure changes caused by regular atmospheric heating and cooling are responsible for localized changes in barometric pressure, called diurnal pressure changes. These changes occur at approximately the same time each day for a given location. Generally speaking, the barometric pressure changes caused by weather are much bigger than the diurnal pressure changes. Little research has been done to thoroughly study the effect of barometric pressure changes on the gas outflow and inflow in a sealed area or an unsealed gob area. Francart and Beiter [1] investigated the barometric pressure influence in mine fire sealing. They compared the diurnal pressure changes with the measured oxygen concentrations behind a seal and found that the rate of airflow is directly affected by the rate of change in the barometric pressure. They also discussed using the National Weather Service data as a tool for predicting barometric pressure changes. A computer program called Gob Assistant was developed by the U.S. Bureau of Mines to predict air flows into and out of a sealed mine area [2]. The application of this program was limited because the gas concentration was assumed uniform in the gob behind the seal. Fauconnier [3] analyzed 59 major explosions in South African gold and coal mines over a period of 20 years and concluded that diurnal fluctuations in pressure do not have a major influence on the accumulation of gas in the underground workings, but that pressure drops associated with cyclonic weather systems are the major factor contributing to gas explosions in mines. Hemp [4] measured barometric pressure over a period of 26 months to examine the manner in which the barometric pressure changes in the Highveld region of South Africa. He also described the leakage flow into and out of a sealed area based on the observed changes in barometric pressure.

When barometric pressure changes in the unsealed gob area, the absolute pressure in the gob also changes leading to the change of air density. If the longwall face is stationary the gob volume is fixed. The air density change results in a total mass change in the gob. With the barometric pressure decreasing, the density of gas in the gob decreases, while the density of gas increases with the barometric pressure increasing, causing the gob to breathe in and out. When there is no barometric pressure change, the intake airflow is equal to the return airflow, assuming no gas inflows from strata and no gas emission inside the gob. With the barometric pressure changing, these two airflows are no longer equal, and the difference between the two airflows represents the flow rate gob breaths in and out, designated as barometric-induced flow. The outflow and inflow caused by barometric pressure changes affect gas concentrations in the gob, thus affect a potential spontaneous heating in the gob. In this study, the CFD model developed in our previous studies for simulating the spontaneous heating of coals in longwall gob area is used to quantify the outflow and inflow of the gob and examine the effect of barometric pressure changes on the spontaneous heating of coal in the gob area [5, 6].

CFD Modeling of Spontaneous Heating in the Gob

In this study, an active longwall panel using a bleederless ventilation system was simulated. The layout of the panel and the ventilation system, shown in Figure 1, are the same as simulated in authors' previous study with the bleederless system [6]. The 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. The ventilation scheme is a simple "U" bleederless ventilation system. In the model, all entries inby the longwall face are treated as though they are collapsed. The face is assumed stationary during the simulations.

The chemical reaction between coal and oxygen at ambient temperatures is complex and still not well understood. In this study, the chemical reaction between coal and oxygen is simplified such that one mole of coal reacting with one mole of oxygen generates one mole carbon dioxide and 0.1 mole carbon monoxide plus the heat of coal oxidation, based on 1988 U.S. Bureau of Mines experimental study [7]. The dependence of the rate of oxidation on temperature and oxygen concentration is expressed in the form [5]:

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

where the chemical reaction rate is defined as the rate of change in the concentrations of the reactants and products, A is the preexponential factor (K/s), E is the apparent activation energy (kJ/mol), R is the gas constant, n is the apparent order of reaction, T is the absolute temperature (°K), and $[O_2]$ is the oxygen concentration (kmol/m^3).

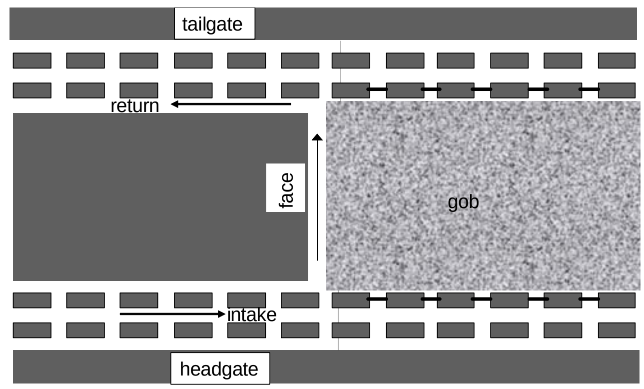

Figure 1. Layout of longwall panel and ventilation system used in simulations

In the simulation, a 1-meter thick rider coal seam less than 1 m above a 2-meter thick main coal seam is 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 [5]. Coal oxidation is an exothermic reaction and the heat generated from coal oxidation is dissipated by conduction and convection, while the oxygen and oxidation products are transported by convection and diffusion. A typical reactive bituminous coal is used in this study with its physical and kinetic properties of this coal listed in Table 1 [6].

Table 1. The physical and kinetic properties of 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 are 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 [8]. For a Pittsburgh coal seam longwall panel, the permeability values in the gob area are 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 are the largest, while near the center of the gob; these values are the smallest due to compaction. The porosity profile in the gob is similar to the permeability profile. It is assumed that these permeability and porosity files do not change with the gob height.

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. Typical ventilation pressures for the bleederless ventilation system were used in the simulation. The intake airflow rate was 30 m^3/s (64,000 cfm). Without barometric pressure change, the pressure was -0.747 kPa (- 3.0 inches water gauge) at the intake inlet, -0.872 kPa (-3.5 inches water gauge) at the return outlet. The recorded typical barometric pressure variations over a 22-day period in western Pennsylvania area, shown in Figure 2, were used in the simulations. It represents the combined effects of both storm fronts and daily natural heating and cooling. The barometric pressure increase and decrease over the standard atmospheric pressure at sea level, 101.3 kPa (29.92 in Hg), were superimposed to both intake inlet pressure and return outlet pressure.

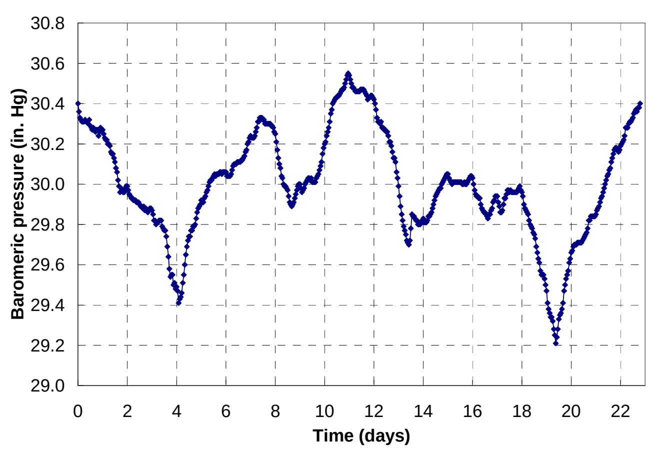

Figure 2. Barometric pressure changes used in simulations

Simulation Results and Discussion

A base case CFD simulation was conducted using the barometric pressure data shown in Figure 2. Figure 3 shows the barometric-induced flow under the barometric pressure changes. The positive value indicates the inflow while the negative one indicates the outflow. From the beginning to Day 4, the barometric pressure decreased from 30.4 to 29.4 in Hg causing the maximum outflow rate of 0.26 kg/s (450 cfm). The maximum inflow rate was about 0.15 kg/s (260 cfm). The simulated maximum temperature from spontaneous heating of coals in the gob is shown in Figure 4. To demonstrate the difference caused by the barometric pressure changes, the maximum temperature simulated without barometric pressure change is also shown in Figure 4. It can be seen that the maximum temperature change followed closely with barometric pressure variations: the former decreased as the pressure decreased; vise versa is also true.

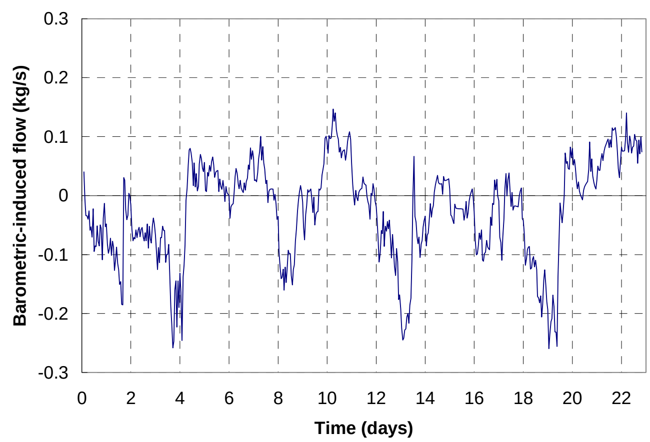

Figure 3. Barometric-induced flow for the base case

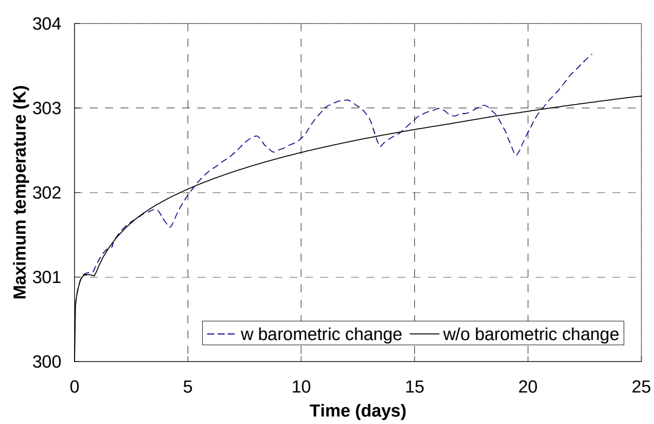

Figure 4. Maximum temperatures (K) in the gob versus time with and without barometric pressure changes

As the barometric pressure decreased, the gob breathed out, and therefore less oxygen was available for coal oxidation. On the other hand, as the barometric pressure increased, the gob breathed in, more oxygen was available for coal oxidation. Figure 5 shows the contours of oxygen concentration in the gob at 19.5 days and 22.5 days, respectively. From 19.5 days to 22.5 days, the barometric pressure increased from 29.33 to 30.33 in Hg, causing the gob to breathe in. It is evident that at 22.5 days, higher oxygen concentration was available at the headgate corner of the gob as compared to 19.5 days.

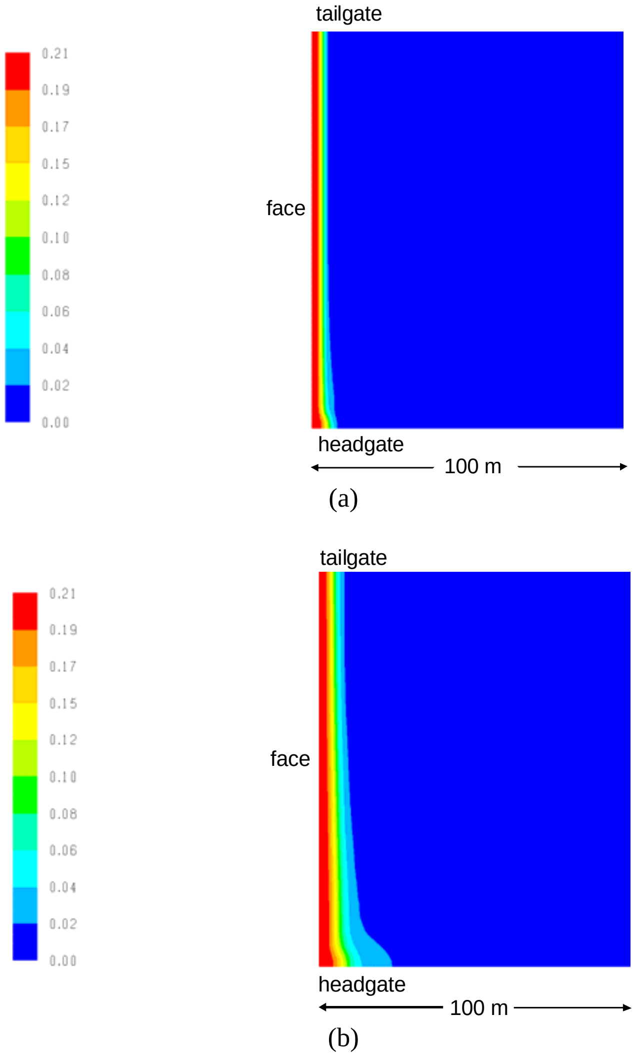

Figure 5. Oxygen concentration distribution in the gob at two different times: (a) 19.5 days (b) 22.5 days

To quantitatively examine the oxygen concentration variation caused by the barometric pressure changes, oxygen concentrations along a line 3 m from the gob perimeter on the headgate side are plotted in Figure 6 for 19.5, 20.5, 21.5 and 22.5 days, respectively. It is clear that as the barometric pressure increased, more oxygen was breathed into the gob, which resulted in the higher temperature. Figure 7 shows oxygen concentrations along the 3-m line for 18, 18.5, 19 and 19.5 days, respectively. From 18 days to 19.5 days, oxygen concentration at the headgate corner decreased as the barometric pressure decreased from 29.96 to 29.33 in Hg. As the coal oxidation was taking place at the same time, this oxygen concentration decrease was a combined effect of both barometric pressure decrease and coal oxidation.

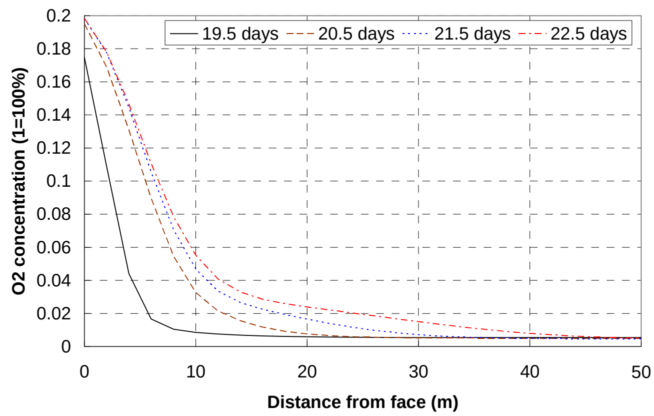

Figure 6. Oxygen concentration along the 3-m line in the gob from 19.5 to 22.5 days

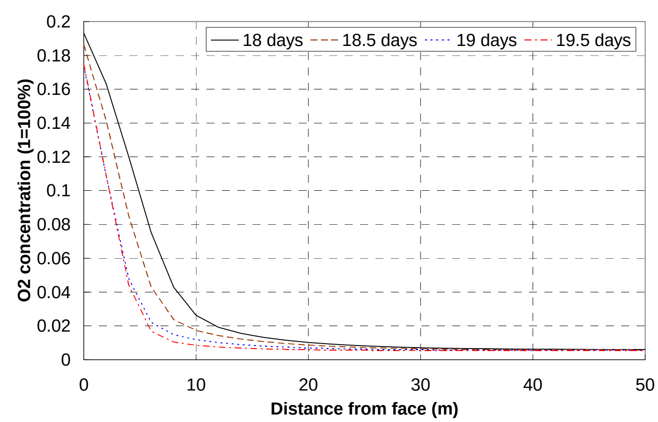

Figure 7. Oxygen concentration along the 3-m line in the gob from 18 to 19.5 days

As demonstrated in the previous study [6], the gas flow inside the gob was significantly affected by the gob permeability. To examine the effect of gob permeability on the barometric-induced flow, CFD simulation was conducted with the gob permeability increased 100 times. Figure 8 shows the barometric-induced flow for this case. The maximum outflow rate was about 1.0 kg/s (1,730 cfm), while the maximum inflow rate was about 0.90 kg/s (1,557 cfm). These maximum outflow and inflow rates were much higher than those in the base case because of smaller resistance in the gob. The maximum temperature in the gob with and without barometric pressure changes under increased gob permeability is shown in Figure 9. As discussed in the previous paper [6], when the gob permeability was increased 100 times, the maximum temperature from spontaneous heating reached 500 °K in about 22 days without barometric pressure changes. However, with barometric pressure changes, the maximum temperature became slightly lower most of the time, not following the trend of barometric pressure changes. This indicates that the effect of barometric pressure on spontaneous heating is different with the increased gob permeability. Figure 10 shows the oxygen concentrations along the 3-m line for the case with the gob permeability increased 100 times at 19.5, 20.5, 21.5, and 22.5 days, respectively. As the barometric pressure increased from 19.5 days to 22.5 days, oxygen concentration at the headgate corner decreased. This may be caused by a faster coal oxidation rate. Although air was breathed in during this period, more oxygen was consumed by the coal oxidation than that added by air breathed in. In the base case, however, oxygen consumed by coal oxidation was less than that breathed in, so oxygen concentration at the headgate corner increased with time. This faster coal oxidation rate was supported by the higher oxygen concentration. Figure 11 shows the oxygen concentration along the 3-m line at 19.5 days for both cases. It is evident that the oxygen concentration was higher in the case with increased gob permeability compared with the base case. The higher oxygen concentration resulted in faster coal oxidation rate, and thus higher temperature at 19.5 days as shown in Figure 12. At 19.5 days, the maximum temperature along the 3-m line reached nearly 350 K, while it was only about 302 K in the base case.

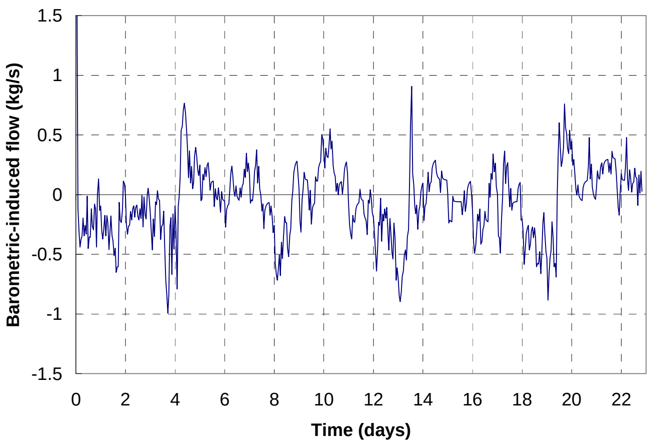

Figure 8. Barometric-induced flow for the case with permeability increased 100 times

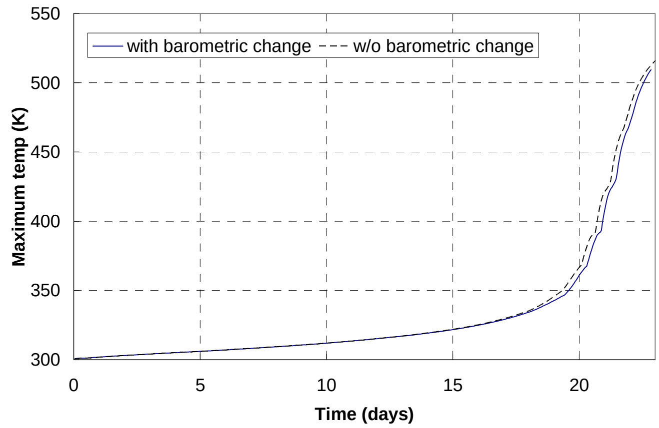

Figure 9. Maximum temperatures (K) in the gob versus time with and without barometric pressure changes: gob permeability increased 100 times

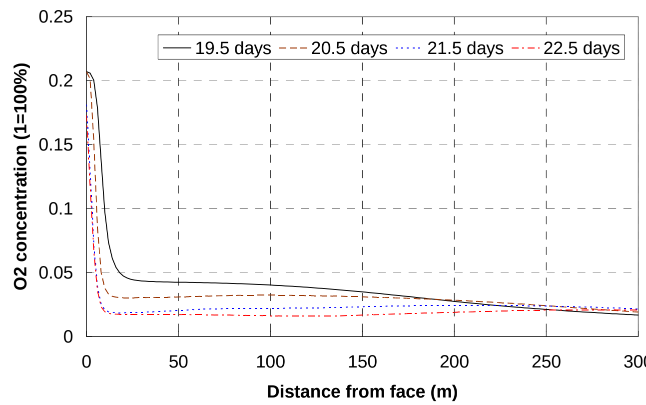

Figure 10. Oxygen concentration along the 3-m line in the gob for the case with permeability increased 100 times

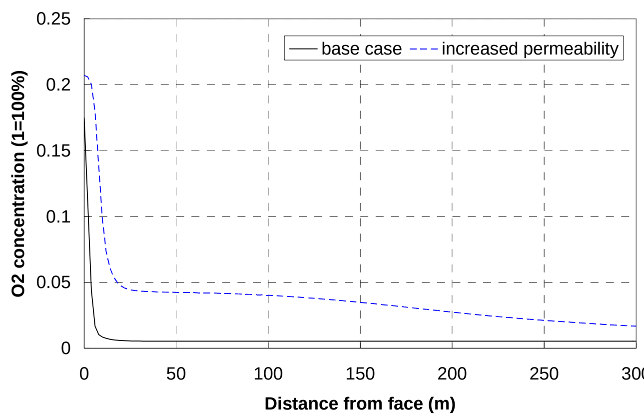

Figure 11. Comparison of oxygen concentrations along the 3-m line in the gob for the base case and the case with permeability increased 100 times

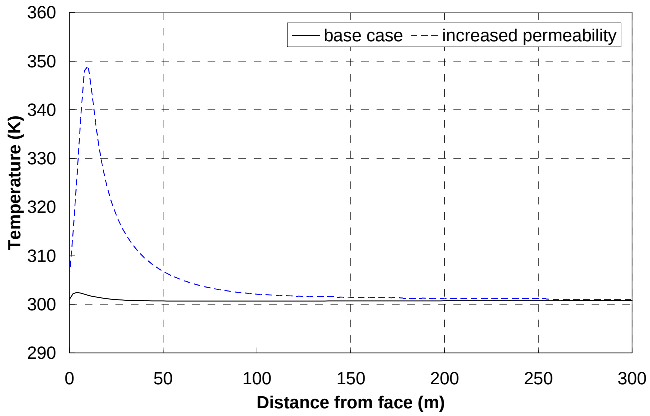

Figure 12. Comparison of temperatures along the 3-m line in the gob for the base case and the case with permeability increased 100 times

These simulation results indicate that the influence of barometric pressure changes on spontaneous heating was influenced by the gob permeability that determines the outflow and inflow rates. With the higher inflow rate caused by the increased gob permeability, the coal oxidation reaction rate was faster, leading to higher temperature. The spontaneous heating then consumed more oxygen than added by the gob inflow. The effect of barometric pressure changes on spontaneous heating was a slightly lower maximum temperature. The reason for this lower maximum temperature is that during the first decrease period (4 days), the maximum temperature with the barometric pressure change became slightly lower than that without the barometric pressure change. As the barometric pressure increased after first four days, the continuous inflow of air had no effect on the spontaneous heating, probably because enough oxygen was already available for coal oxidation. As the barometric pressure decreased again, the maximum temperature decreased slightly again. This trend continued with time, resulting in apparently lower maximum temperature most of the time.

To examine the effect of coal oxidation on the oxygen concentration in the gob, additional simulation was conducted by turning off coal oxidation at 19.5 days in the increased gob permeability case. Figure 13 shows the oxygen concentration along the 3-m line in the gob at 19.5, 20.5, 21.5 and 22.5 days, respectively. It is obvious that the oxygen concentration increased quickly at the headgate corner form 19.5 days to 22.5 days when the gob was breathing in. Because there was no oxygen consumption by the coal oxidation, the oxygen concentration increased quickly with the time, indicating that the net effect of the barometric pressure changes also depends on the coal oxidation rate.

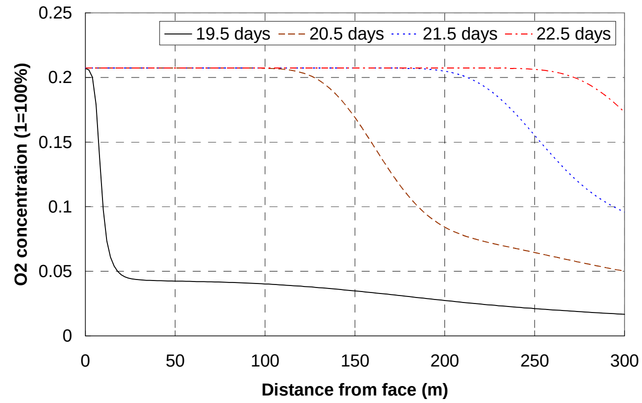

Figure 13. Oxygen concentration along the 3-m line in the gob for the case with permeability increased 100 times from 19.5 to 22.5 days: reaction turned off at 19.5 days

Conclusions

CFD simulations were conducted to investigate the potential effect of barometric pressure changes on spontaneous heating of coal in a bleederless longwall gob area. Simulation results demonstrate that under typical bleederless ventilation conditions, the maximum temperature from the spontaneous heating in the gob was affected by the barometric pressure changes, although not significantly. As the barometric pressure decreased, the oxygen concentration at the headgate corner was reduced and the maximum temperature became lower, while as the barometric pressure increased, the oxygen concentration at the headgate corner was increased and the maximum temperature became higher. However, this effect became quite different when the gob permeability was increased 100 times. Under the increased gob permeability, the barometric pressure changes resulted in higher outflow and inflow rates. As the barometric pressure increased, the oxygen concentration at the headgate corner continually decreased, probably because of faster rate of coal oxidation. The maximum temperature became slightly lower than that without barometric pressure changes. The net effect of barometric pressure changes on the spontaneous heating depends on the gob permeability and the coal oxidation rate.

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. Cooperation with U.S. coal mines to validate our modeling on spontaneous heating in the longwall gob area is greatly needed in our future study.

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