Preprint 16-154

CFD STUDIES ON THE PHENOMENON OF GOB BREATHING INDUCED BY BAROMETRIC PRESSURE FLUCTUATIONS

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ABSTRACT

In longwall mines, atmospheric or barometric pressure fluctuations can disturb the pressure balance between the gob and the ventilated working area of the mine, resulting in a phenomenon known as “gob breathing”. Gob breathing triggers a gas flow across the gob and the working areas and may result in a condition where a methane accumulation in the gob flows into the face area forming an explosive mixtures. This paper discusses results of Computational Fluid Dynamics (CFD) modeling carried out to analyze this phenomenon and its impact on the explosive mixture development under a bleeder-ventilated longwall gob panel scheme. Modeling results indicate that the gas inflow and outflow across the gob and the formation of Explosive Gas Zones (EGZs) are directly affected by the barometric pressure changes. Methane gas and EGZs in the gob expand out toward the face and bleeder entries during the falling barometric pressure. Where methane zones interface with mine air, EGZ fringes may form along the face and in the bleeder entries. When the atmospheric pressure increases, an ingression of oxygen into the gob is observed that can also increase EGZs in volume. The findings from this study help assess the methane ignition and explosion risks associated with fluctuating atmospheric pressures.

INTRODUCTION

Methane explosions continue to be a daunting risk for underground coal miners, although the number of related fatalities and injuries in the U.S. coal mining industry has steadily decreased since the establishment of the U.S. Bureau of Mines in 1910. Still, the consequences of a methane explosion are often disastrous with multiple fatalities and property damage often leading to permanent shutdown of the mine.

Methane is formed during the coalification process and is released from the coal seam to the mine atmosphere when the coalbed is disturbed by mining or natural causes such as earthquakes. If not properly diluted by appropriate mine ventilation, this methane may accumulate in the active mine workings and gob areas. Researchers at the Colorado School of Mines have developed numerical models showing how and where explosive methane may accumulate in gob areas. Historical mine explosions appear to show a connection between mine explosions and fluctuating barometric pressure as a result of stormy weather. McIntosh (1957), Boyer (1964), and Kissell et al. (1973) studied the influence of barometric drops on major coal mine disasters in the United States prior to 1970. Their statistical analyses found that a majority of these disasters occurred in the fall and winter months when the barometric pressures were influenced by unstable weather conditions and noted increased methane content in the mine workings during times of falling pressure. Studies conducted by Fauconnier (1992) and Hemp (1994) found similar connections between methane explosions and barometric pressure fluctuations in a majority of gas explosions in South African mines. Ten out of twelve major mine explosions with five or more fatalities in the U.S. after 1970 were found to have occurred during the months of November through April when barometric pressure swings were more abrupt and intense (Lolon et al., 2015).

Despite the fact that fluctuating barometric pressures have been recognized to increase the mine explosion risk, little work has been done to thoroughly study this connection, particularly with regard to EGZs in the gob. The interior atmosphere of the gob remains largely unknown. CFD modeling can predict the atmospheric conditions in the gob as well as their changes during barometric pressure swings.

BAROMETRIC PRESSURE FLUCTUATIONS AS SEASONAL VARIATIONS

Barometric pressure results from periodic tides or oscillations in the atmosphere. These oscillations are triggered by a combination of gravity and thermal forces; the thermal influences are considered more dominant (Lindzen and Chapman, 1969). Solar radiation causes temperature variations, heating the air and reducing its density. In the absence of sun heating, the air cools down, making it denser. Differences in air weight cause pressure changes and air movement. Studies show that fluctuations of atmospheric pressures follow the solar day period (Harris, 1954). In daily records, the atmospheric pressure exhibits maxima and minima that repeat periodically every 24 and 12 hours. The 24-hour harmonic variation is known as the diurnal, while the 12-hour is the semi-diurnal component of the atmospheric pressure. Both components drive harmonic barometric pressure changes under normal weather conditions. Seasonal effects cause these pressure variations to deviate from the periodic rhythms (Lindzen and Chapman, 1969). Observations in South Africa showed that pressure changes associated with cyclonic weather systems were more intense and influential on the mine explosion hazard than the harmonic diurnal and semi-diurnal pressure waves (Fauconnier, 1992).

The Köppen climate system (Köppen and Wegener, 1924) classifies the North America as well as the southern region of Africa and most of Europe to be in the Mid-Latitude climate zone as shown in Figure 1 (Pidwirny, 2006). Countries located in this zone will experience “frontal cyclones” that exist as the result of interaction between warm tropical and cold artic fronts. These cyclones, that are associated with freezing rain, hail, snow, and storms, tend to be most disruptive during winter months and cause disturbance to the normal barometric pressure changes (Pidwirny, 2006). Barometric pressures may rapidly decrease as a storm approaches and then rise again after it passes, causing much greater pressure swings than normal daily fluctuations. For comparison, normal barometric pressure changes due to diurnal fluctuations range 300 – 400 Pa in 24-hr period, while severe storms can result in fluctuations of 3,400 – 6,800 Pa over the course of 2 to 10 hours (Zipf and Mohamed, 2010).

Since frontal cyclones primarily occur around late fall and winter seasons, researchers have observed more abrupt changes of barometric pressure between November and April than during other months of the year (Boyer, 1964; Hemp, 1994; Wasilewski, 2014; and Lolon et al., 2015).

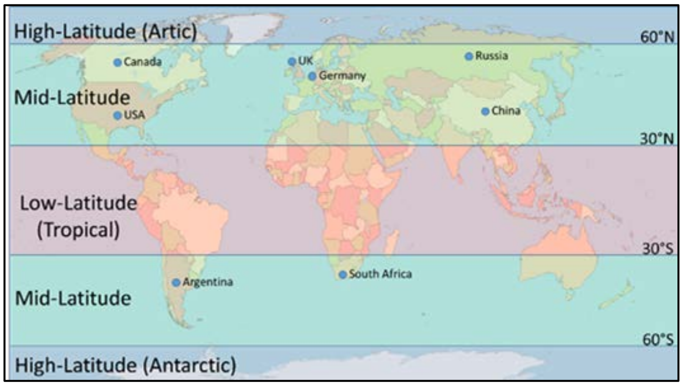

Figure 1. Köppen Classification climate system (drawn based on data from Pidwirny, 2006).

GOB BREATHING AND ATMOSPHERIC PRESSURE FLUCTUATIONS

The phenomenon of gob breathing can be simply explained by the ideal gas equation, given below (where P is pressure, V is gas volume, n is gas mole, R is 8.314 J K^{-1} mol^{-1}, and T is the absolute temperature).

$$PV = nRT$$

The equation states that the mole of a gas present in a domain (e.g. gob) is directly proportional to the absolute pressure. As a gob breathes, the changes of gas volume are inversely proportional with the change of barometric pressure. For a bleeder ventilated, unsealed gob, this volume change allows a certain amount of gases to flow across the boundaries between the gob and the active working areas. The equation above can be rewritten in terms of the mass flow rate, $\dot{m}$, and pressure change rate, dP/dt, as follows:

$$\dot{m} = \frac{dm}{dt} = \frac{V}{RT}\frac{dP}{dt}$$

When the atmospheric pressure rises or falls, the ambient pressure of the active working areas will change almost instantaneously (Stevenson, 1968; Wasilewski, 2014). In contrast, the gob pressure will change more slowly because the porous gob material slows gas flow and pressure wave propagation. The slower response of the gob pressure to the outside changes causes a time lag.

Figure 2 shows a simplified schematic of pressure conditions that occur in the gob and bleeder entries during barometric pressure fluctuations. The red line represents the gob pressure while the blue line indicates the absolute pressure at a given point in the bleeder system. A bleeder system is designed to exhaust methane to the surface via a bleeder shaft or other dedicated return airway. By design, the bleeder pressure, indicated by the blue line in Figure 2, is lower than the gob pressure indicated by the red line. During times of steady barometric pressure, the pressure difference between these two lines is constant and denoted by ΔP_s. When the barometric pressure changes at t_0, the bleeder pressure responds immediately. The gob pressure responds after a certain time lag. Due to restricted flow in the porous regions of the gob, the rate of gob pressure change is slower than the rate of bleeder pressure change, making the slope of the red line flatter than that of the blue line.

After the barometric pressure has stabilized at t_1, the bleeder pressures remains constant while the gob pressure continues adjusting until the difference ΔP_s above the bleeder pressure is reached.

Due to this time lag, the difference, ΔP_b between gob and bleeder pressure varies during barometric pressure changes. Methane outflow from the gob to the bleeder is driven by the resultant pressure gradient or the difference between the red and blue lines in Figure 2. When the barometric pressure drops (Figure 2a), methane outgassing is driven by the total pressure gradient of $\Delta P_s + \Delta P_b$. In this case, the pressure difference causes gob to breathe out and release additional methane and air from the gob into the bleeders. When the barometric pressure rises (Figure 2b), the resultant gradient of reduces the methane outflow. During large barometric changes, ΔP_b can exceed ΔP_s, causing bleeder air to push into the gob. In Figure 2b, this is indicated where the blue line crosses above the red line. This is when the gob breathes in and oxygen-rich air ingresses into the gob, creating EGZs along the fringes.

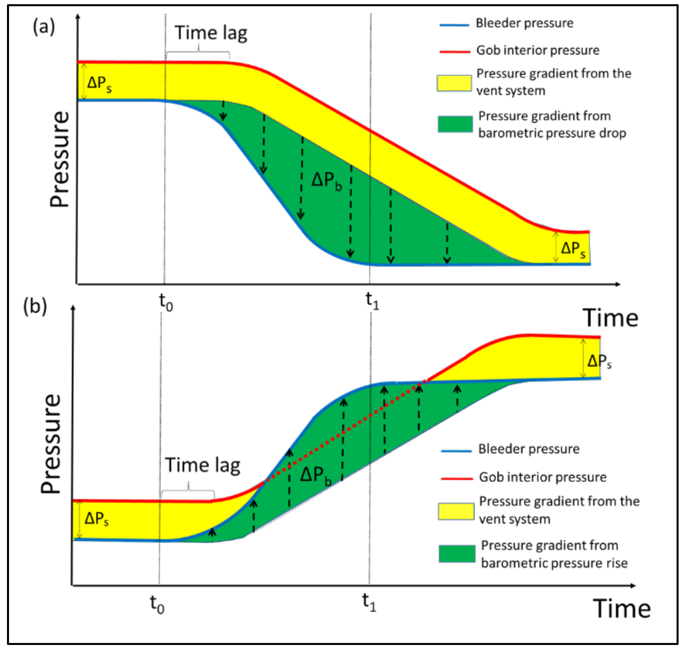

Figure 2. Pressure conditions for "gob breathing" phenomenon during (a) falling and (b) rising barometric pressures.

CFD MODEL DESCRIPTION AND PARAMETERS

A 3-D bleeder ventilation model, was developed using the Ansys Fluent® CFD program. Figure 3 shows the ventilation schematic and bleeder entry geometry. The model is 10,200-ft (3,100 m) long, 1,200-ft (380 m) wide, and 130-ft (40 m) high, which includes a 40-ft (13 m) high rubble zone of the gob. The gob porosity distribution was computed from a geomechanical model in FLAC3D® which was validated against subsidence data (Marts et al., 2014). The permeability was calculated using the Carman-Kozeny equation. The gob in this study has a porosity ranging from 10% to 50% and a permeability of 1.45 x 10^{-5} to 2.0 x 10^{-7} m^2.

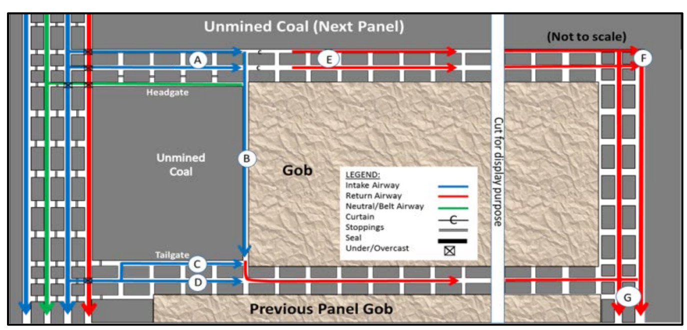

Figure 3. A typical bleeder panel layout and airflow requirement used in this study.

Table 1 shows the air flow parameters used in this model. A total of 95,000 cfm (44.8 m^3/s) was supplied to the panel at Point A, of which 75,000 cfm (35.4 m^3/s) were coursed the longwall face at Point B and the remaining 20,000 cfm (9.4 m^3/s) went to the inby headgate at Point E. The outby tailgate entries supplied another 10,000 cfm (4.7 m^3/s) into the panel at Points C and D. A total of approximately 105,000 cfm (49.5 m^3/s) was directed out through the bleeder return at point G.

Table 1. Air flow requirement for the base case.

Measurement Point	Flow rate (Q)	
	m^3/s	1000 ft^3/min
A	44.8	95
B	35.4	75
C	2.4	5
D	2.4	5
E	9.4	20
F	~4.8	10
G	~49.5	105

Pressure boundary conditions were assigned to all inlets and outlets. The model simulates an exhaust ventilation system with -4,980 Pa (20 in. w.g.) at the bleeder return (point G). Pressure values at other intakes and outlets were varied to represent the flow rates shown in Table 1. The pressure drop across the panel was approximately 70 Pa (0.28 in. w.g.). The ventilation parameters were chosen to represent conditions at a cooperating longwall mine in the western U.S. The model incorporates regulators near the startup room on the headgate side (point F) to control air flow to the bleeder entries. The methane flows into the model from a rider coalbed above the seam mined.

The impact of gob breathing under fluctuating barometric pressures is analyzed by observing the formation, volume changes and movements of EGZs in the gob. The diagram in Figure 4 illustrates the explosibility of the methane-air mixture, based on the Coward's triangle (Gilmore et at., 2015). Red shading denotes explosive gas mixtures or EGZs, yellow is fuel-rich inert and green is fuel-lean inert. Blue denotes fresh air and inert mixtures with less than 4% methane. These color codes are used as the reference for Figures 5 through 7.

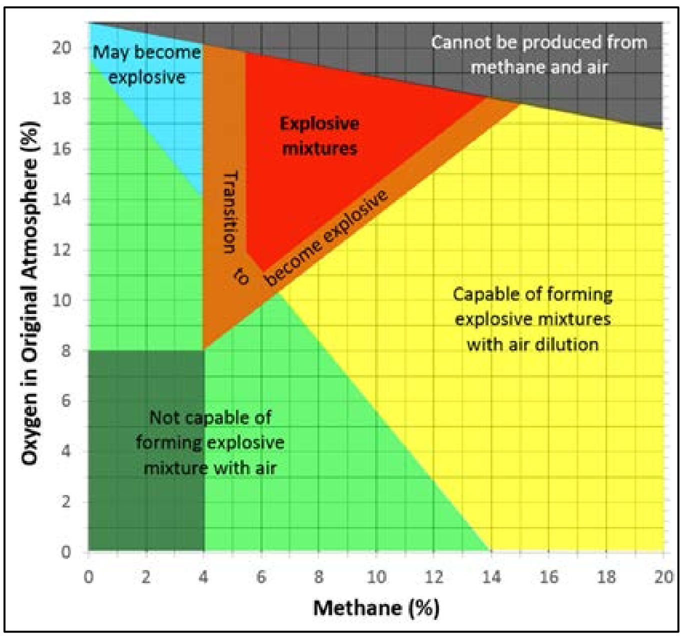

Figure 4. Explosibility diagram of methane and air mixture (redrawn from Gilmore et al., 2015).

SIMULATION OF BAROMETRIC PRESSURE FLUCTUATIONS

Figure 5 illustrates the EGZ formation in the gob under stable, base case conditions. The plan view shows the gob gas composition 1.5 m above the mine floor or bottom of the coal seam. There is a contiguous EGZ fringe along all sides of the gob, as there are high, fuel-rich concentrations of methane in the center while the bleeder entries contain less than 2% methane. The EGZ expands towards the start-up room. The existence of EGZ in this base case condition agrees with studies that found the possibility of explosive mixture to exist in all bleeder-ventilated gobs (Brune, 2013; Gilmore et al., 2015).

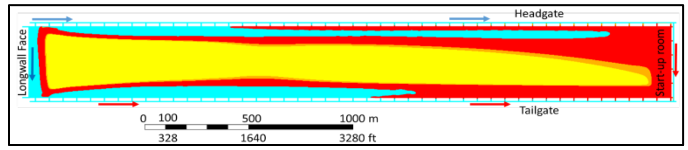

Figure 5. Initial EGZ formation in the gob as the base case condition.

Two scenarios of changing barometric pressure are evaluated against the base model. The pressure drops or rises are superimposed to mine airways, including the bleeder entries. The methane inlet remains at constant pressure. As in reality, methane liberation will be slightly reduced during rising barometric pressure and increases as the barometer falls.

Scenario 1: Falling Barometric Pressure

For this scenario, a barometric drop of nearly 2,000 Pa (0.6 in. Hg) over a period of 4 days was simulated. This is approximately 17 Pa (0.005 in. Hg) per hour. Zipf and Mohamed (2010) and Lolon et al. (2015) showed that drop of this magnitude can be caused by local weather systems in U.S. mining districts.

Figure 6 shows the EGZ changes during a 24-hour period of barometric pressure drop. As the pressure decreases, the methane-rich core area of the gob expands, increasing the EGZ volume near the back area of the gob on the right side of Figure 6, where the start-up room was initially developed. Figure 6a shows how the fuel-rich zone mixes with air that is already present in the gob, generating a larger EGZs volume. As pressure continues to drop, the EGZs expand toward both headgate and tailgate sides, and leak out into the bleeder entries, as seen in Figure 6b. This phenomenon is confirmed by several field investigations that found increased methane on the tailgate entry during barometric pressure drops (Stevenson, 1968; Wasilewski, 2014; Belle, 2014). Figure 6c and 6d shows the entire bleeder entries filled with EGZs. Both figures also show that the EGZ pushes closer to the longwall face, shown on the left side, eliminating the fresh air zone behind the face.

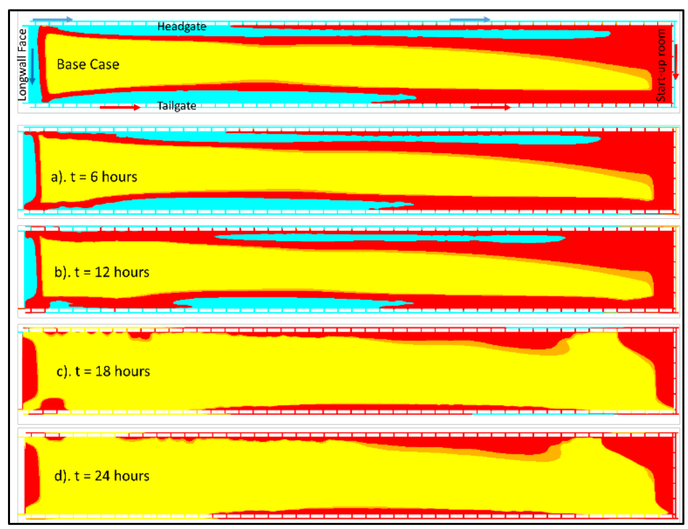

Figure 6. EGZ transformation during the falling barometric pressure.

Scenario 2: Rising Barometric Pressure

In this scenario, the barometric pressure rises at 17 Pa (0.005 in. Hg) per hour. The observations on EGZ conditions for the first 24-hour are shown in Figure 7. The increasing outside pressure induces fresh air ingress from the bleeder entries and the face into the gob. The increased oxygen ingress into the gob results in larger EGZs that build up in the back of the gob as seen in Figure 7b. Around t = 6 to 12 hours, Figures 7a and b, the outside pressure reduces the methane emission into the gob. There is little change on the size of the fuel-rich body as marked in yellow zone. As the barometric pressure continues to rise, the gob "breathes in" more air and pushes the EGZ fringes further towards the gob center, shown in Figures 7c and 7d.

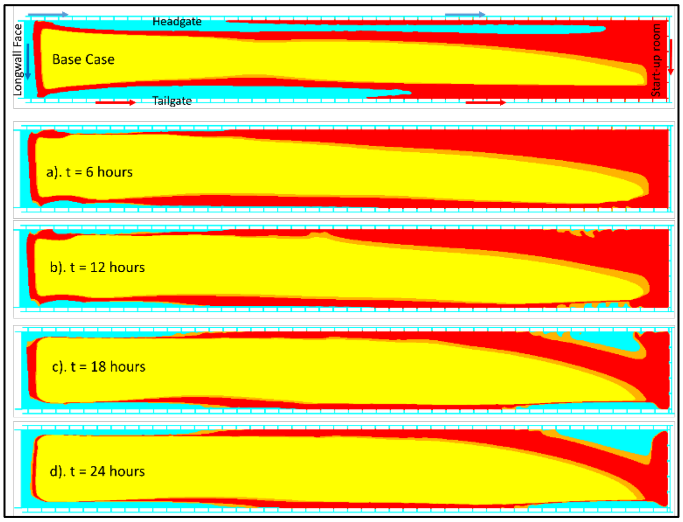

Figure 7. EGZ transformation during the rising barometric pressure.

Over the 24-hour period, EGZ fringes exist around the entire perimeter of the methane-rich core zone. The ingressing face and bleeder air keeps the active mine entries below 2% methane, but the EGZ fringes remain directly adjacent to these entries that must be inspected by mine examiners.

Figure 8 shows the normalized EGZ volume measured in the gob for both scenarios. The fall of barometric pressure steadily increases the EGZ volume, while an increase of barometric pressure initially increases the EGZ volume but later shrinks the EGZs due to reduced methane inflow.

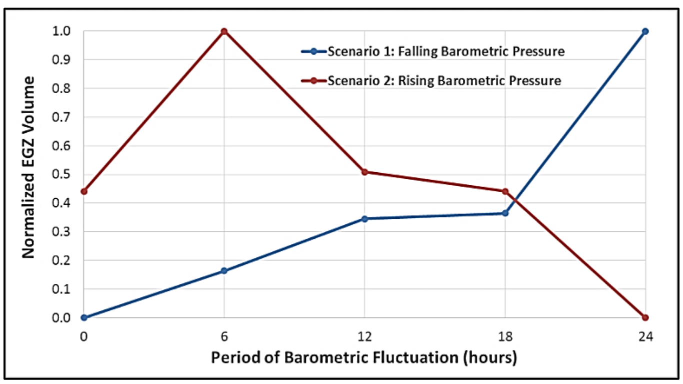

Figure 8. Normalized EGZ volume in the gob during barometric pressure fluctuations.

CONCLUSIONS

A review of historical mine explosions in the United States, South Africa and Australia shows that barometric pressure fluctuations have a significant impact. This study examines how barometric pressure changes affect the size and location of Explosive Gas Zones (EGZs) in bleeder ventilated longwall gobs. Both rises and drops in pressure scenarios are modeled to observe “breathing” effects of the gob.

During falling barometric pressures, EGZs expand and start to leak into the inby bleeder and tailgate entries before expanding outby towards the active face. Observations by several researchers confirm this phenomenon.

Rising barometric pressure induces bleeder and face air ingression into the gob, initially increasing EGZ volume. As the outside pressure continues to rise, the methane emission into the gob eases off, reducing the fuel for the EGZs. Modeling also confirms that a rise of barometric pressure maintains the active workings and bleeder entries pressurized; eliminating the outgassing of methane from the gob. EGZs still exist immediately next to bleeder entries and present a fire and explosion hazard to mine foremen examining the bleeder system.

The findings of this study help in the assessment of the explosion risk and potential locations for the EGZ monitoring in the event of barometric pressure fluctuations.

ACKNOWLEDGEMENT

This research was funded by the National Institute for Occupational Safety and Health (NIOSH) under contract number 211-2014-60050. This support by NIOSH is gratefully acknowledged.

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