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Computational fluid dynamics simulation on the longwall gob breathing

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ABSTRACT

In longwall mines, atmospheric pressure fluctuations can disturb the pressure balance between the gob and the ventilated working area, resulting in a phenomenon known as "gob breathing". Gob breathing triggers gas flows across the gob and the working areas and may result in a condition where an oxygen deficient mixture or a methane accumulation in the gob flows into the face area. Computational Fluid Dynamics (CFDs) modeling was carried out to analyze this phenomenon and its impact on the development of an explosive mixture in a bleeder-ventilated panel scheme. Simulation results indicate that the outgassing and ingassing across the gob and the formation of Explosive Gas Zones (EGZs) are directly affected by atmospheric pressure changes. In the location where methane zones interface with mine air, EGZ fringes may form along the face and in the bleeder entries. These findings help assess the methane ignition and explosion risks associated with fluctuating atmospheric pressures.

1. Introduction

Methane explosions continue to be a daunting risk for underground coal miners, although the number of related fatalities and injuries in the US coal mining industry has steadily decreased since the establishment of the US Bureau of Mines in 1910. Still, the consequences of a methane explosion are often disastrous, including multiple fatalities and property damage and 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 where explosive methane may accumulate in gob areas and how the flame propagates if ignited [1,2].

Historical mine explosions appear to show a connection between explosions and fluctuating barometric pressure as a result of stormy weather. Several researchers and mining practitioners studied the influence of barometric drops on major coal mine disasters in the United States prior to 1970 [3–5]. 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. They also noted that increased methane content in the mine workings during times of falling pressure. Another study conducted by Fauconnier found similar connections between methane explosions and barometric pressure fluctuations in a majority of gas explosions in South African mines [6]. After 1970, ten out of twelve major mine explosions with five or more fatalities in the US were found to have occurred during the months of November through April, when barometric pressure swings were more abrupt and intense [7].

Despite the fact that fluctuating barometric pressures have been recognized to increase the risk of mine explosions, 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. CFDs modeling can predict the atmospheric conditions in the gob as well as their changes during barometric pressure swings.

2. 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 [8]. Solar radiation causes temperature variations, heating the air and reducing its density. In the absence of heat from the sun, the air cools down, making it denser. Differences in air weight cause pressure changes and air movement. Studies show that fluctuations in atmospheric pressures follow the solar day period [9]. In daily records, the atmospheric pressure exhibits maxima and minima that repeat periodically every 24 and 12 h.

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The 24 h harmonic variation is known as the diurnal, while the 12 h 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 [8]. 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 [6].

The Köppen climate system classifies 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 Fig. 1 [10]. This zone extends from approximately 30–60° of latitude in both northern and southern hemispheres. Countries located in this zone will experience “frontal cyclones” that exist as the result of interaction between warm tropical and cold arctic fronts. These cyclones, which 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 [11]. 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 h period, while severe storms can result in fluctuations of 3400–6800 Pa over the course of 2–10 h [12].

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 [4,7,13].

3. 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, Pa; V is gas volume, m^3; n is number of moles, R is 8.314 J/(K mol); and T is the absolute temperature, K).

$$PV = nRT \tag{1}$$

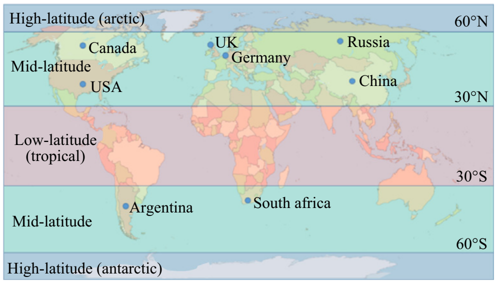


Fig. 1. Köppen classification climate system.

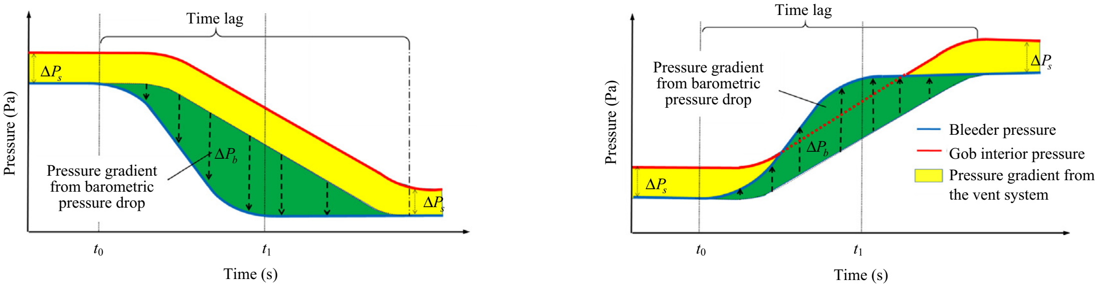
Eq. (1) states that the mole of a gas present in a domain (e.g., gob) is directly proportional to the absolute pressure. As the gob breathes, the changes of gas volume are inversely proportional with the change of barometric pressure. For a bleeder-ventilated, unsealed gob, this volume change allows a certain amount of gases to flow across the boundaries between the gob and the active working areas. Eq. (1) above can be rewritten in terms of the mass flow rate, $\dot{m}$, and pressure change rate, dP/dt, as follows:

$$\dot{m} = dm/dt = V\,dP/RT\,dt \tag{2}$$

When the atmospheric pressure rises or falls, the ambient pressure of the active working areas will change almost instantaneously [13]. 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.

Fig. 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 and 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 Fig. 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 remain constant while the gob pressure continues to adjust 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 Fig. 2. When the barometric pressure drops as shown in Fig. 2a, methane outgassing is driven by the total pressure gradient of $\Delta P_s + \Delta P_b$. In this case, the pressure difference causes the gob to breathe out and release additional methane and air from the gob into the bleeders. In Fig. 2b, the resultant gradient reduces the methane outflow when the barometric pressure rises. During large barometric changes, ΔP_b can exceed ΔP_s, causing bleeder air to push into the gob. 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.



(a)

(b)

Fig. 2. Pressure conditions for “gob breathing” phenomenon during (a) falling and (b) rising barometric pressures.