International Journal of Mining Science and Technology 27 (2017) 185–189

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Computational fluid dynamics simulation on the longwall gob breathing

Samuel A. Lolon [a,*], Jürgen F. Brune [a], Gregory E. Bogin Jr. [b], John W. Grubb [a], Saqib A. Saki [a], Aditya Juganda [a]

[a] Department of Mining Engineering, Colorado School of Mines, CO 80401, USA
[b] Department of Mechanical Engineering, Colorado School of Mines, CO 80401, USA

ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form 17 March 2016
Accepted 6 May 2016
Available online 2 February 2017

Keywords:
CFDs
Gob breathing barometric pressure
Explosive gas zone
Longwall mine
Methane explosion

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.

* Corresponding author.
E-mail address: slolon@mines.edu (S.A. Lolon).

http://dx.doi.org/10.1016/j.ijmst.2017.01.025
2095-2686/

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).

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

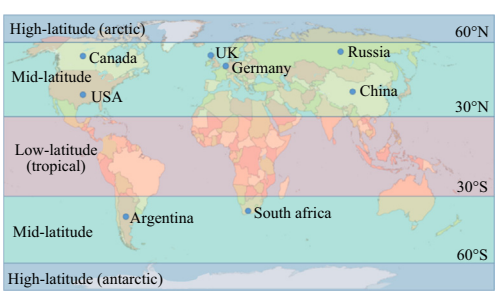

Fig. 1. Köppen classification climate system.

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.

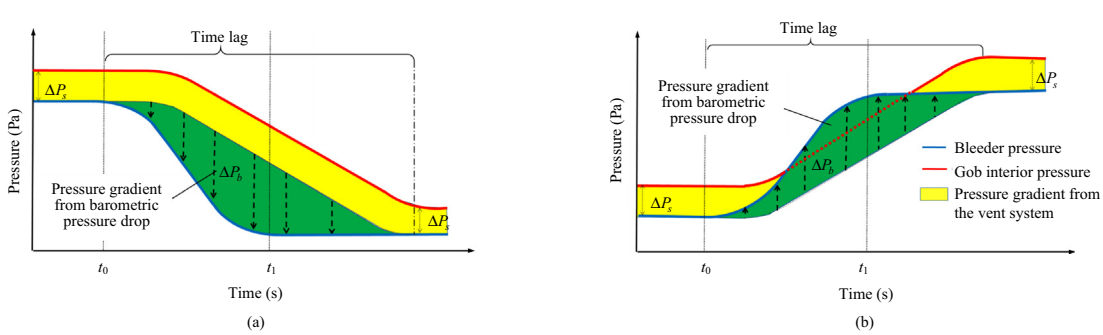

Fig. 2. Pressure conditions for "gob breathing" phenomenon during (a) falling and (b) rising barometric pressures.

4. CFD model description and parameters

In this study, the gob breathing phenomenon is analyzed using a CFD program, Ansys Fluent®. CFD analysis has been successfully used to evaluate ventilation, contaminants, and explosive mixture due to its powerful and versatile capabilities in solving complicated airflow and gas mixing problems. The use of CFD in the mining industry has continued to increase with the high availability but lowered cost of high-powered computing in desktop computers [14].

Figs. 3 and 4 show the three-dimensional bleeder-ventilated panel model and ventilation schematic used in this simulation. The model is 3100 m long, 380 m wide, and 40 m high, which includes the 13 m high rubble zone of the gob. Rectangular entries of 3.3 m by 6 m surround the gob. The gob porosity distribution was computed from a geomechanical model in FLAC^{3D}® which was validated against subsidence data [15]. Permeability was calculated using the Carman-Kozeny equation. The gob in this study has a bathtub-like profile for both porosities which ranges from 10% to 50% and permeability 1.45×10^{-5} to 2.0×10^{-7} m^2. The smallest and highest values of permeability distribution are found to be in the center and around the perimeter of the gob, respectively.

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

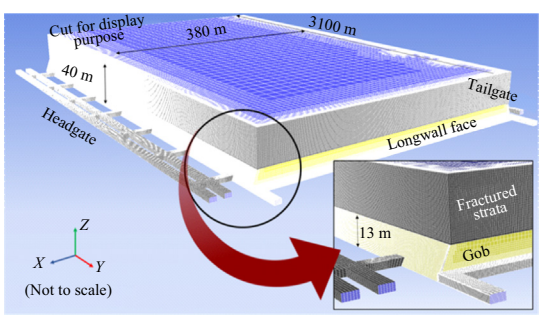

Fig. 3. Three-dimensional CFD model of bleeder-ventilation longwall panel used in this modeling.

Pressure boundary conditions were assigned to all inlets and outlets. The model simulates an exhaust ventilation system with −4980 Pa 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. The ventilation parameters were chosen to represent conditions at a cooperating longwall mine in the western United States. 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 Fig. 5 illustrates the explosibility of the methane-air mixture, created using a color-coded algorithm based on Coward's triangle [1]. 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 by volume. These color codes are used as the reference for Figs. 6–8.

5. Simulation of barometric pressure fluctuations

Fig. 6 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 toward the start-up room. The existence of EGZ in this base case condition agrees with studies that found the possibility that explosive mixture exists in all bleeder-ventilated gobs [1].

Two scenarios of changing barometric pressure are evaluated against the base model. The pressure drops or rises are superimposed on the 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 will increase as the barometer falls.

5.1. Scenario 1: Falling barometric pressure

For this scenario, a barometric drop of nearly 2000 Pa (0.6 in Hg) over a period of 4 days was simulated. This is approximately 17 Pa (0.005 in Hg) per hour. The drop of this magnitude can be caused by local weather systems in US mining districts [7,12].

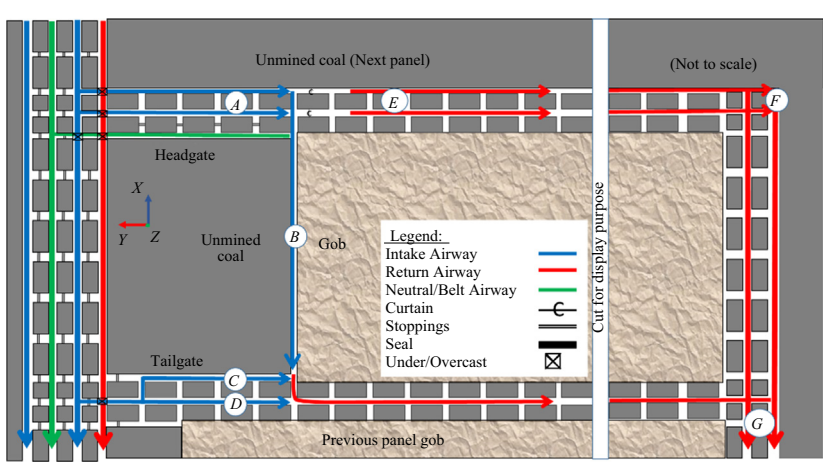

Fig. 4. Typical bleeder panel layout and airflow requirement used in this modeling.

Table 1
Air flow requirement for the base case.

Measurement point	*A*	*B*	*C*	*D*	*E*	*F*	*G*
Flow rate (m^3/s)	44.8	35.4	2.4	2.4	9.4	4.8	49.5

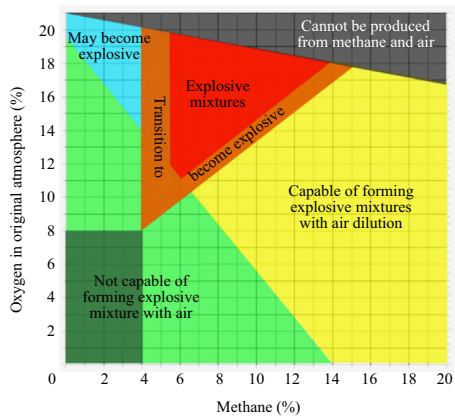

Fig. 5. Explosibility diagram of methane and air mixture [1].

Fig. 7 shows the EGZ changes during a 24 h 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 Fig. 7, where the start-up room was initially developed. Fig. 7a shows how the fuel-rich zone mixes with air that is already present in the gob, generating a larger EGZ volume. As the pressure continues to drop, the EGZs expand toward both headgate and tailgate sides and leak out into the bleeder entries, as seen in Fig. 7b.

This phenomenon is confirmed by several field investigations that found increased methane on the tailgate entry during barometric pressure drops [13,15]. Fig. 7c and d shows the whole 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.

5.2. 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 h are shown in Fig. 8. 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 Fig. 8b. Around $t = 12–18$ h (as shown in Fig. 8b and c), the outside pressure reduces the methane emission into the gob. There is little change in the size of the fuel-rich body as marked by the yellow zone. As the barometric pressure continues to rise, the gob breathes in more air and pushes the EGZ fringes further toward the gob center, as shown in Fig. 8d.

Over the 24 h 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.

Fig. 9 shows the normalized EGZ volume measured in the gob for both scenarios. The normalized volume is simply calculated by a method of feature scaling as shown in Eq. (3) below:

$$x_i = (x - \min(x))/(\max(x) - \min(x)) \tag{3}$$

where x is the original measured value and x_i is the ith normalized value. Fig. 9 indicates that the fall of barometric pressure steadily increases the EGZ volume, while an increase of barometric pressure initially increases the EGZ volume as the result of further air ingression into the gob and later shrinks the EGZs when barometric pressure is high enough that it slows down the methane inflow.

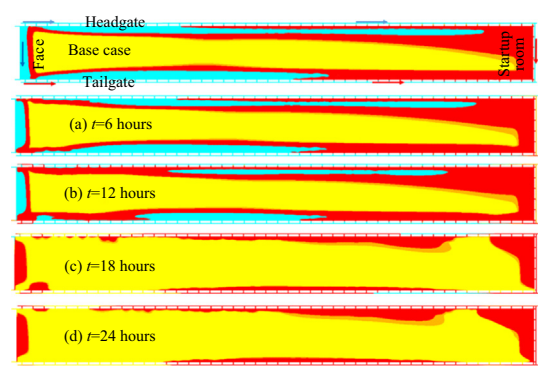

Fig. 7. EGZ transformation during falling barometric pressure.

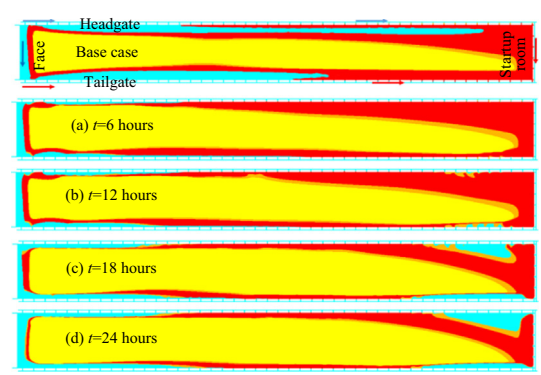

Fig. 8. EGZ transformation during rising barometric pressure.

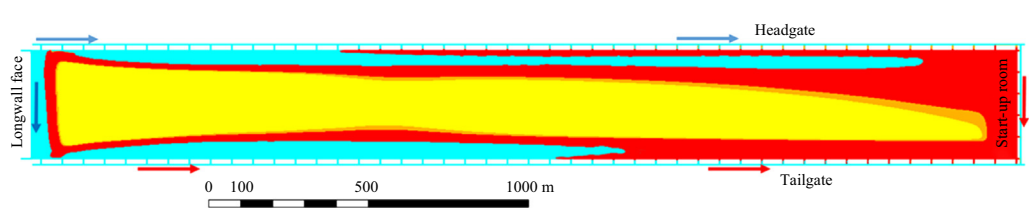

Fig. 6. Initial EGZ formation in the gob as the base case condition.

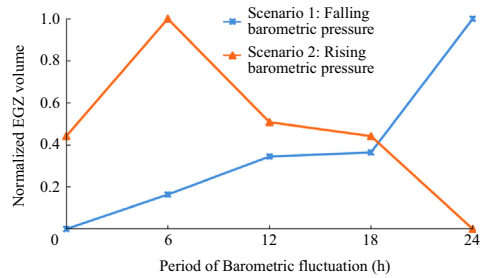

Fig. 9. Normalized EGZ volume in the gob during barometric pressure fluctuations.

6. Conclusions

A review of historical mine explosions in the United States, South Africa, and Australia shows that barometric pressure fluctuations have a significant impact on the likelihood of an explosion. This study examines how barometric pressure changes affect the size and location of 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 toward 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 keeps the active workings and bleeder entries pressurized, eliminating the outgassing of methane from the gob. EGZs still exist immediately next to the bleeder entries and present a fire and explosion hazard to mine foremen examining the bleeder system.

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

Acknowledgments

The authors gratefully acknowledge the financial support of the National Institute for Occupational Safety and Health – United States (No. 211-2014-60050).

References

[1] Gilmore RC, Marts JA, Brune JF, Bogin Jr GE, Grubb JW, Saki SA. CFD modeling explosion hazards-bleeder vs. progressively sealed gobs. In: Proceedings of the 10th international mine ventilation congress, Sun City. p. 1–6.
[2] Fig MK, Bogin Jr GE, Brune JF, Grubb JW. Experimental and numerical investigation of methane ignition and flame propagation in cylindrical tubes ranging from 5 to 71 cm-Part I: Effects of scaling from laboratory to large-scale field studies. J Loss Prev Process Ind 2016;41:241–51.
[3] McIntosh CB. Atmospheric conditions and explosions in coal mines. Geogr Rev 1957;47(2):155–74.
[4] Boyer RF. Coal mine disasters: frequency by month. Science 1964;144 (3625):1447–9.
[5] Kissell FN, Nagel AE, Zabetakis MG. Coal mine explosions: seasonal trends. Science 1973;179(4076):891–2.
[6] Fauconnier CJ. Fluctuations in barometric pressure as a contributory factor to gas explosions in South African mines. J South Afr Inst Min Metall 1992;92 (5):131–47.
[7] Lolon SA, Gilmore RC, Brune JF, Bogin Jr GE, Grubb JW, Zipf Jr RK, et al. Effect of decreasing barometric pressure on explosive gas zones in bleeder ventilated longwall gobs. In: Proceedings of the 15th North American mine ventilation symposium, Blacksburg. p. 1–7.
[8] Lindzen RS, Chapman S. Atmospheric tides. Space science reviews. Dordrecht-Holland: D Reidel Publishing; 1969.
[9] Harris MF. Pressure-change theory and the daily barometric wave. J Meteor 1954;12:394–404.
[10] Köppen W, Wegener A. The climates of the geological past. English translation of 'Die Klimate der Geologischen Vorzeit', Berlin, Stuttgart: Borntraeger Science Publishers; 1924.
[11] Pidwirny M. The mid-latitude cyclone-fundamentals of physical geography. 2nd ed. Online eBook; 2006.
[12] Zipf Jr RK, Mohamed KM. Composition change model for sealed atmosphere in coal mines. In: Proceedings of the 13th U.S./North American mine ventilation symposium, Sudbury, Ontario; 2010. p. 493–500.
[13] Wasilewski S. Influence of barometric pressure changes on ventilation conditions in deep mines. In: Archives of mining sciences, Warsaw; 2014. p. 621–39.
[14] Wallace K, Prosser B, Stinnette JD. The practice of mine ventilation engineering. Int J Min Sci Technol 2015;25(2):165–9.
[15] Belle B. Evaluation of barometric pressure (BP) and cage effect on longwall tailgate gas levels. In: Proceedings of the 10th international mine ventilation congress, Sun City; 2014. p. 501–11.