# PRESSURE BALANCING TECHNIQUES TO CONTROL SPONTANEOUS COMBUSTION

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## Abstract

This study presents the results of three laboratory experiments on pressure balancing carried out at the University of Utah's coal mine ventilation model. The model includes simulations of two working areas, one longwall mine gob, and a set of stoppings and seals. It also includes a pressure chamber between the longwall face and the gob. The model is ventilated by one main fan and one bleeder fan. A carbon dioxide injection system, equipped with flow control valves operated by a microprocessor, is used to pressurize the chamber and to maintain the pressure in the chamber slightly higher than that of the gob. During each experiment, fan pressures and stopping resistances were changed, the carbon dioxide injection rate was regulated, and the differential pressures across the stoppings were monitored so that the chamber pressure is always kept slightly higher than that the gob pressure. Result of these experiments are reported in this paper.

## Introduction

Spontaneous combustion (Sponcom) is a safety hazard in underground coal mines. The history of coal mining in the US is replete with mine fires and explosions. Sponcpm accounts for approximately 17% of the total number of fires recorded in the U.S. since 1990. In the U.S., by law, worked out areas in coal mines must be either ventilated by a bleeder system or isolated by explosion proof seals. Experience has shown that seals are not airtight structures and that they allow some leakage of air into or out of the gob. In fact, seals "breathe in and breathe out" with changes in barometric pressure (Francart 1997, and Chalmers 2010). These changes in pressure affect not only the methane emission rate but also the ingress of oxygen to the gob, the lower the pressure behind seals is, the higher the ingress of oxygen. In mines ventilated by a U-tube exhaust system, the gob is often kept under negative pressure. Under these circumstances, an increase in barometric pressure may cause an influx of fresh air into the gob. This quantity may be sufficient to start self-heating of the coal, which can lead to spontaneous combustion.

Depending on the coal characteristics and the ventilation conditions, self-heating of coal can start at temperatures as low as 35 ºC. If the heat is not removed it will increase the coal temperature leading to ignition and fire. The risk of Sponcom fires can be reduced by isolating the mine gob using rated seals, and implementing a suitable ventilation system. However, isolation seals are not airtight structures, thus some leakage of air is expected unless the pressure in the gob is neutralized. The alternative is to use a pressure balancing system. This requires a thorough knowledge of the ventilation system, the seal/stopping construction techniques, the airflow behavior in the gob area, and the gas build-up behind the seal line.

Pressure balancing techniques have been used in many coal mining countries including the U.K., Australia, Poland and India, but not so much in the U.S. coal mines except for a few cases where the longwall panel is ventilated by a bleederless ventilation system. The presently used technique in foreign counties is typically manual and sometimes requires an expert's attention over a long period. The objectives of this study are: (1) to represent a mine gob by a physical model equipped with a microprocessor-based pressure balancing system, (2) to conduct laboratory experiments for different ventilation layouts and mine gob conditions, and (3) to analyze the results and prepare guidelines for the use of pressure balancing systems in coal mines

### *Pressure Balancing Techniques*

Pressure balancing is a term used to describe the reduction of absolute pressure difference across the seals and stoppings of an underground mine. The objective for such a reduction is to decrease or eliminate the ingress of oxygen into the gob and to reduce the risk of initiating a Sponcom fire or explosion. The various pressure balancing techniques used in mines can be grouped into two categories: passive and active (McPherson 1993).

***Passive Pressure Balancing Technique***

Using this technique, the differential pressure across a desired area is achieved by changing the resistances of a few critical stoppings. This is done by rearranging overcasts and regulators to ensure that each stopping or seal around the desired area is exposed to return air pressure. If this is not possible, pressure chambers are constructed by erecting a stopping a short distance (4 to 5 m) outby of an existing seal, and interconnecting them by means of pipes, thus equalizing the pressure across the sealed area. A variation of this technique is called dynamic pressure balancing. Using this technique, pressure balancing is achieved by adjusting the flow rates, first through different airways around the affected area, and then through pressure chambers and flow control pipes. The pipes extend from the main intake or return to the chamber allows the user to establish a continuous circulation of air even through the pressure chamber. The main disadvantage of this method is that it has a limited capacity that is defined by frictional and shock losses of the ventilation circuit of the affected area. This may not be sufficient to neutralize the variations of barometric pressure (Bhowmick et al. 1992).

***Active Pressure Balancing Technique***

Using this method, the differential pressure across an isolation seal or set of seals is equalized by an external pressure source such as a fan, compressed air, or pressurized fluid. This requires the establishment of pressure chambers, the injection of inert gases, and monitoring for pressure differentials and combustion products. It is based on the principle that if there is no pressure difference across the mine gob, then fresh air cannot move into the gob. This strategy eliminates all oxygen from entering the gob, thus reducing the risk of spontaneous combustion. It can be used to equalize large pressure differentials. This method has been used in many coal mining countries including Australia, the United Kingdom, South Africa, Poland, India, and some U.S. coal mines (Bessinger 2005 and Ray 2007).

The pressure balancing system at the Austar coal mine is a good example of the application of this method in controlling spontaneous combustion fires. In this mine, spontaneous combustion was spotted in the gob of a mined out panel. The combustion soon became large enough necessitate the halt of longwall operations and the sealing of the mine. A rehabilitation program was then initiated. This included the implementation of an active pressure balancing system which required the construction of several pressure chambers, the installation of pipelines and flow control valves, and the injection of high pressure nitrogen (LN2). The ultimate objective was to pressurize and maintain the gob at a pressure equal to or slightly higher than that of the atmosphere, regardless of changes in barometric pressure. Austar coal mine was able to maintain the oxygen concentrations in the gob at near zero level and to solve the problem (Brady 2008).

## University of Utah Coal Mine Model

The University of Utah coal mine ventilation model (Figure 1), previously used to simulate a two entry development heading, was modified and upgraded to include two simulated working areas (one continuous miner section and one a longwall section), a mine gob, a pressure balancing chamber, a bleeder section, two fans, and a PC-based monitoring and control system (Jha 2015). The model is constructed of 0.15-m (5.75-in.) diameter pipe and has a main blower fan and a bleeder fan. The pipes are configured in a standard U-shaped ventilation network with one intake and two return airways. Crosscuts are constructed of 0.06-m (2.5-in.) diameter pipes, which act as leakage paths between the intake and the return airways. A container filled with broken rock is used to simulate the mine gob. This section is equipped with a bleeder fan and a set of regulators to simulate different gob ventilation scenarios. The pressure chamber was built by isolating a section of the gob using three fully-closed “stoppings” equipped with flow control pipes and pressure relief valves. An external, automated CO2 injection system is used to pressurize the chamber. A portable compressor is also used to create high pressure differentials between the chamber and the gob.

Both the blower fan and the bleeder fan are centrifugal devices, and each equipped with a variable frequency drive (VFD). This allows the motor to be set at any speed ranging from 3600 rpm (60 Hz) to zero. Fans can be operated individually or in combination as required.

The ventilation monitoring system consists of a host PC and a set of sensors attached to a communication network. It is capable of monitoring the status of up to 29 sensors and controlling the operation of two fans and two gas injection points. The sensors are used to monitor air velocity, fan pressure, pressure differentials across the stoppings, barometric pressure, air temperature, and gas concentration. Figure 2 shows a set of pressure and velocity transducers that are located near the gob area. This figure also shows the gate valves used to isolate the pressure balancing chamber.

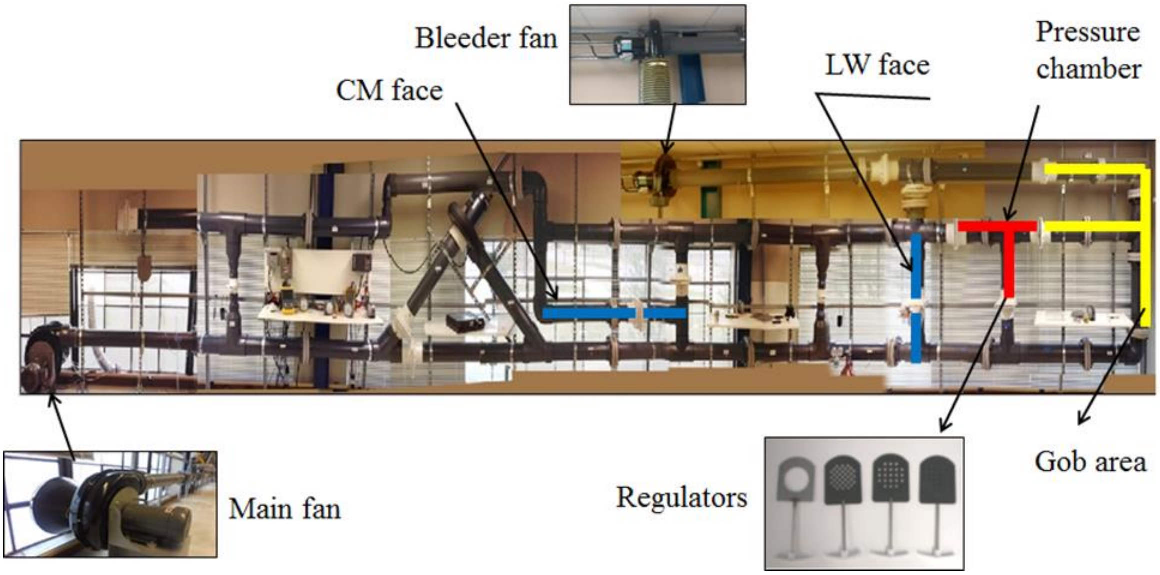


Figure 1: Mine ventilation model showing location of pressure balancing chamber.

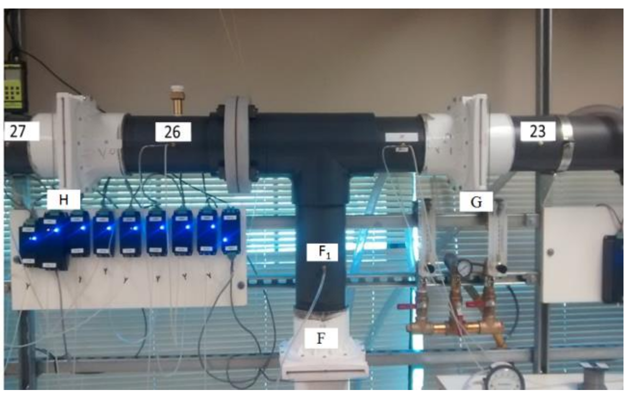


Figure 2: Pressure and velocity transducers installed in the simulated gob area

The monitoring system is operated by a program called VENTLAB, written in National Instruments Lab Windows. Once activated, the program interrogates each system component for control signals. This information is then evaluated and the data gathering process begins. Both fans are controlled by this software and can be set at desired speeds from the keyboard. As soon as the fans are started the transducers begin to transmit data. The data are recorded every second and stored in an Excel file.

## Automatic Pressure Balancing System

To automate the pressure balancing process, the chamber was equipped with a set of pressure transducers, an external pressure source (a $CO_2$ cylinder), and a software-operated, $CO_2$ gas injection system. To activate the system, a sub-routine, APBCON (automatic pressure balancing controller), was written and added to the monitoring software, VENTLAB. Evaluation of pressure differentials and operating a gas injection system are the key functions of this subroutine. If the monitoring system detects a pressure differential greater than 100 Pa across the stopping separating the chamber from the gob, a microprocessor will switch on the flow control valve and pressurize the chamber. When this pressure is equal to or greater than a pre-set upper bound (2900 Pa), the microprocessor will switch off the flow control valve. This will reverse the leakage through the stoppings. Since the chamber is not replenished, the pressure in the chamber will decrease. The process will continue until another pre-set lower bound (100 Pa) is reached. Upon reaching this limit, the program will re-start the gas injection system. This process can be repeated as per the needs of the experiment. The bounds of the program can be changed to simulate different conditions such as the sudden changes in atmospheric pressure. The monitoring system used at the University of Utah lab model is capable of recording and analyzing data collected from a number of transducers simultaneously.

Figure 3 shows the location of active workings (CM face and LW face) and the simulated mine gob. It also shows the locations of the main fans, the gate valves used to simulate stoppings and seals, the pressure chamber and the external pressure source used to pressurize the chamber.

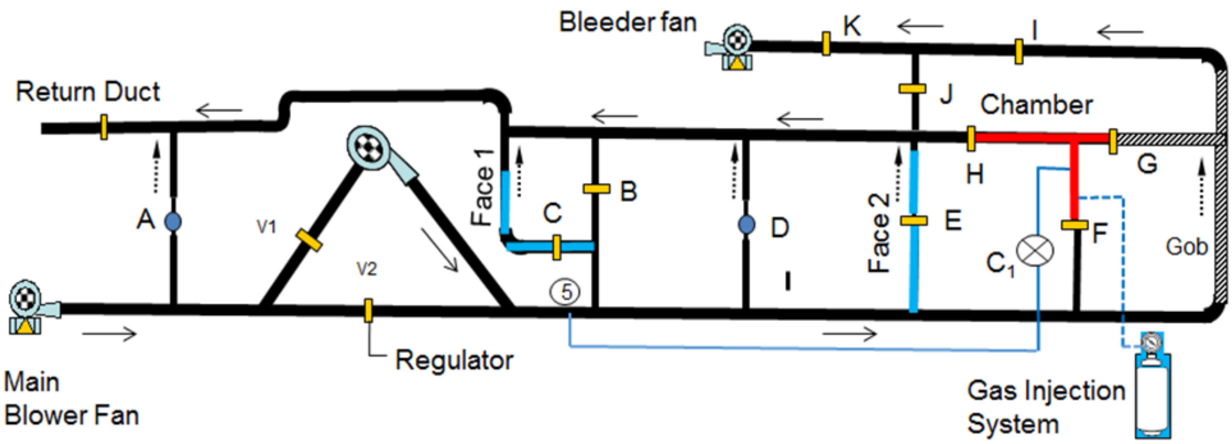


Figure 3: Schematic showing features used in automatic pressure balancing

## Laboratory Experiments

Three laboratory experiments on pressure balancing were carried out at the University of Utah ventilation model: one on passive and two on active pressure balancing techniques. Prior to each experiment, the ventilation model was reconfigured to emulate one of the following gob ventilation systems: (1) Punch-out borehole system, (2) Wrap-around system, and (3) Through-flow bleeder entry system. Figure 4 shows three line diagrams, one for each experiment.

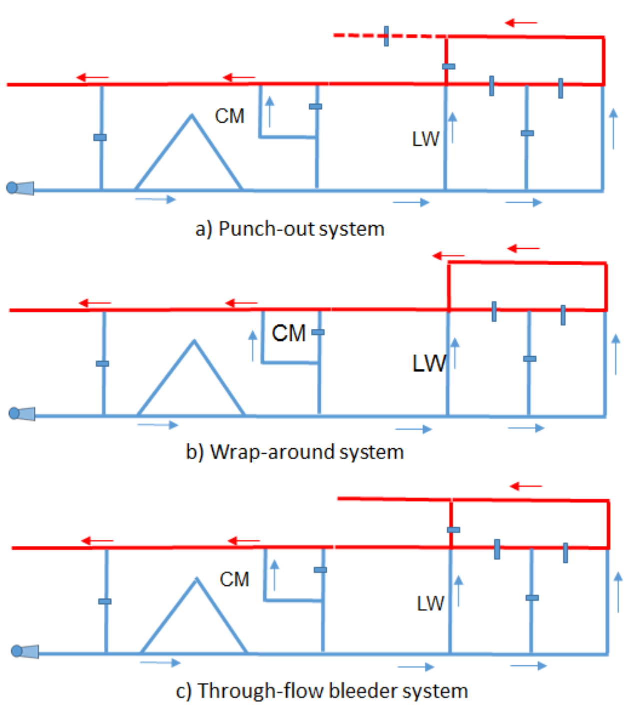


Figure 4: Longwall mine gob ventilation schematics

The initial conditions and the results of these experiments are presented below.

***Case 1. Passive Pressure Balancing***

The aim of this experiment was to test a passive pressure balancing technique in the simulated gob model. The University of Utah model was modified to mimic a Punch-out through flow bleeder system equipped with a pressure chamber and a flow control pipe, connecting the chamber to the intake duct (Figure.4). A 3 mm-diameter silicon pipe, equipped with a pressure gage and a control valve was used to pressurize the chamber. The experiment was conducted under the following conditions:

- Main fan pressure: 1940 Pa, quantity 0.39 $m^3/s$.
- Regulator settings: Regulators I, and J were partially closed, with 5 % of total area open, regulators C and K had 28% of total area.
- Isolation regulators: F and G were fully closed, and H, 0.05% of total area open.

During the experiment the pressure differential between the gob and the chamber was monitored continuously. When this difference was "significant" (> 100 Pa), the pressure in the chamber was balanced by manually opening a flow control valve ($C_1$ in Figure 3). Figure 5, shows the pressure profiles obtained before and after the opening of this valve. A comparison of these profiles (graphs a and b) shows that when the control valve $C_1$ was opened the pressure difference across regulator G, which separates the chamber and gob, dropped from 550 Pa to 105 Pa. Based on these results it is concluded that a pressure chamber equipped with a flow control pipe can be used to balance the pressure across the gob, thus reducing the ingress of oxygen to the simulated gob.

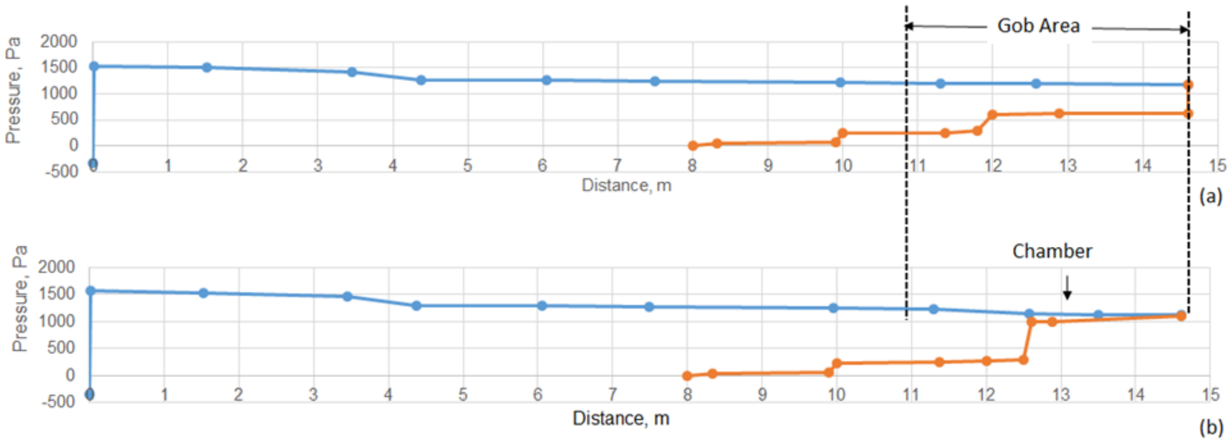


Figure 5 Static pressure profiles with chamber in place; (a) when valves $C_1$ was closed, and (b) after valve $C_1$ was open.

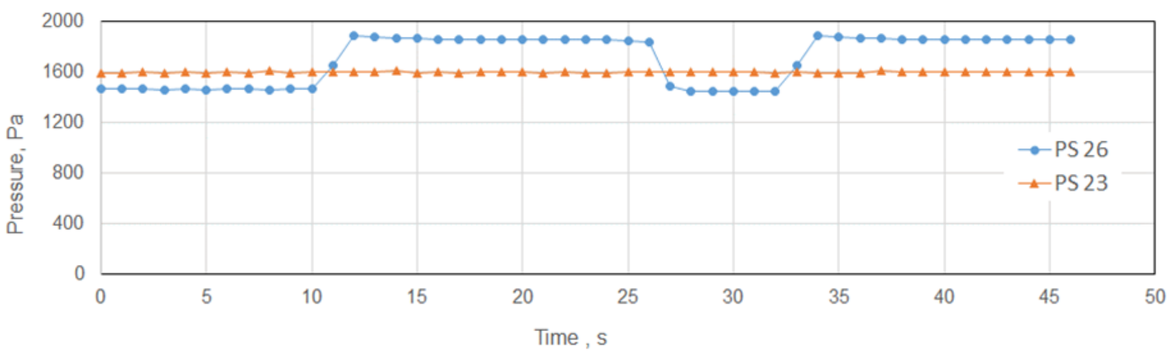


Figure 6. Pressure build-up and decay in the chamber with changes in gas injection rate.

***Case 2. Manually Controlled Active Pressure Balancing***

The objective of this experiment was to test an active pressure balancing technique in a Wrap-around bleeder system. As in the previous case, the chamber was established by using three isolation regulators: F, G, and H. The pressure source was a CO2 cylinder, connected to the chamber by a high pressure hose and a flow control valve. Pressure transducers and CO2 sensors were used to monitor pressure differentials and gas concentrations in the gob. Two pressure transducers, PS 26 (chamber) and PS 23 (gob), were used to monitor pressure differentials across the gob. The initial and final conditions for this experiment are given by:

- Main fan pressure 1790 Pa, quantity 0.40 $m^3/s$.
- Bleeder duct regulator K was fully closed
- Isolation regulators: F and G were fully closed, and H, 0.05% of total area open.
- When adverse conditions were detected, the chamber was pressurized using $CO_2$ gas.

The experiment was started by operating the main fan at its full speed (60 Hz) and monitoring the gage pressures along the ductwork and pressure differentials around the simulated gob. When the pressure differential between the gob and the chamber was greater than 100 Pa, then the gas injection system was opened manually, held for few seconds, and then shut off. This caused the chamber to be pressurized and a new steady-state level was reached. When the gas injection system was shut off, the chamber pressure returned to its initial level due to reverse leakage from the chamber to the gob. This process was repeated to observe the pressure variations in the chamber.

When the experiment was initiated, the differential pressure across the gate valves separating the chamber from the gob was -150 Pa. This was created by the back pressure caused by closing the regulator K in a wrap-around ventilation system. Under this condition, the chamber was held under negative pressure. This pressure difference is sufficient to cause the ingress of gob gas into the face. To mitigate the problem, carbon dioxide was injected into the chamber at the rate of 10 lpm.

This inflow of gas pressurized the chamber to a maximum of 1,860 Pa, and reversed the pressure difference across the stopping (regulator G) from –150 Pa to 450 Pa, causing the pressurized gas to migrate from the chamber into the gob. This flow reversal could be sustained as long as the gas injection rate was kept constant. When the gas injection was stopped, the pressure in the chamber returned to its initial level. Figure 6 shows the pressure differences between the chamber and the gob for the two conditions: without and with gas injection into the chamber. Based on these results it was concluded that the pressure chamber can be used to stop the gas flow from the gob into the face.

**Case 3. Automatic Pressure Balancing**

The objective of this experiment was to test an automatic pressure balancing system that was added to the University of Utah ventilation model. The model was set up to simulate a through-flow bleeder ventilation system. In this case, when adverse conditions were detected, the CO2 injection system was operated automatically. The initial and final conditions for this experiment are given by:

- Main fan pressure: 1,670 Pa, quantity: 0.48 $m^3/s$.
- Regulator settings: regulators E, I, had 50% of its total area open, C had 28 % of its area open, K and J were fully open.
- Isolation regulators: F and G fully closed, and H had 0.001% of total area open.
- Final condition was established by switching on and off the CO2 gas injection system automatically.

Once the initial condition was established and the chamber pressure recorded (1,300 Pa), the automatic flow control sub-routine, APBCON, was activated while the monitoring system was operating. The sub-routine evaluated the pressure differentials against the pre-set values and operated the flow control valve to balance the pressure across the isolation stoppings. The evaluation was made every second. For an injection rate of 10 lpm at 34,500 Pa, the maximum pressure in the chamber (4,700 Pa) was achieved within 5 s. The program then stopped the injection process and allowed the chamber to be depressurized by leakage through the isolation stopping. The elapsed time before the minimum allowable pressure (1,800 Pa) was reached was 95 s. Figure 7 shows the pressure variations in the chamber and gob areas when the gas flow control valve was activated by the monitoring system. Once the injection system was started, the pressure build-up in the chamber was quite rapid. When a preset pressure differential of 3,400 Pa was reached, then the injection system was stopped automatically. Because of the reverse leakage, this differential pressure decayed over time to a point when the lower bound (100 Pa) was reached. This process of starting and stopping the gas injection system can be repeated as long as significant pressure differentials are detected. Three such cycles were observed in this experiment.

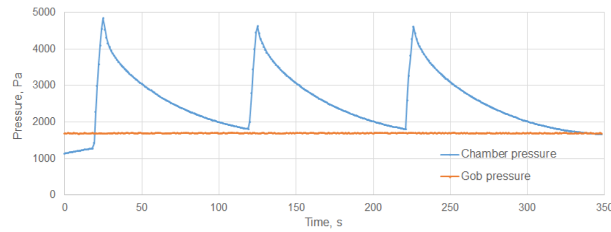


Figure 7. Pressure profiles generated by the automatic CO2 gas injection system

Figure 8 shows pressure profiles for the ventilation model when the pressure balancing sub-routine was activated. Figure 8(a) shows the pressure profiles before the CO2 injection system was activated, and Figure 8(b) shows the profiles when the gas pressure in the chamber was about 2000 Pa. Based on these graphs it can be concluded that the automatic gas injection system implemented at the University of Utah lab can detect adverse conditions in the gob area and pressurize the chamber so that leakage through the isolation stopping is always from the chamber to the gob.

## Conclusions and Discussions

The University of Utah coal mine ventilation model has been modified and upgraded to include two simulated working areas (continuous miner and longwall sections), a mine gob, a pressure balancing chamber, a bleeder section, two fans, and a PC-based monitoring and control system. This model was used to conduct three experiments, one with passive pressure balancing and two with active pressure balancing.

Passive pressure balancing was achieved by opening a flow control valve of a 3-mm diameter silicon pipe extended between a high pressure inlet duct and the chamber. Active pressure balancing was achieved by injecting CO2 to the pressure chamber, first manually, and then automatically. For the latter, an automatic CO2 injection system was activated so that the chamber pressure was always kept slightly higher than the gob pressure.

Prior to each experiment, the laboratory model has been reconfigured to emulate one of the following gob ventilation systems (1) Punch-out borehole system, (2) Wrap-around system, and (3) Through-flow bleeder entry system. This was accomplished by changing the position of a set of regulators and by switching on/off the main fan or the bleeder fan. In every experiment the flow quantities directed to the active workings were kept practically constant.

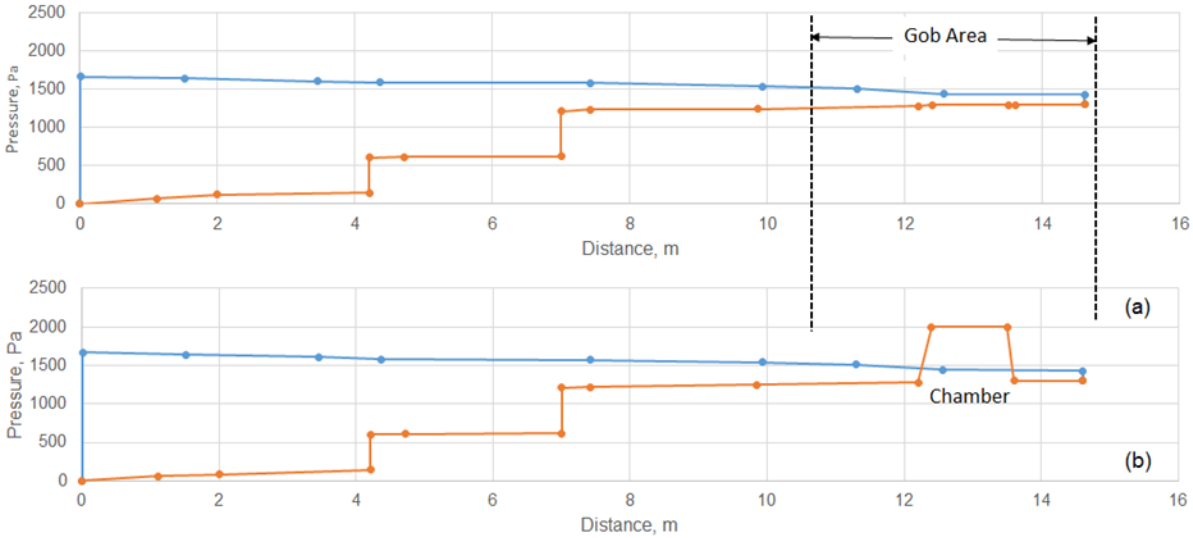

Figure 8. Pressure profiles when chamber was pressurized automatically.

This study has shown that pressure balancing, operated by passive or active means, can be used to neutralize the flow of air through the gob, regardless the type ventilation system used. However, from an economic point of view, the through-flow system is the most efficient, because for the same flow distribution through the workings it requires less air power and produces lower pressure differentials than the other systems.

Pressure balancing is an effective technique that can be used to prevent the onset of spontaneous combustion in coal mines if implemented in a timely manner. If the pressure differential across the mine gob is neutralized, then air will not circulate through it, and the self-heating of coal will be eliminated. In practice, this can be accomplished by operating a pressure balancing system in the gob area.

## Disclosure

This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff.

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