CONTROL OF SPONTANEOUS COMBUSTION USING PRESSURE BALANCING TECHNIQUES

by

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ABSTRACT

Coal has an inherent tendency to combust in the presence of oxygen. This phenomena is termed as spontaneous combustion of coal. Pressure balancing is a tool that can be used to solve the problem. Pressure balancing is the technique of equalizing pressure differentials between two areas such as the mine gob and its surroundings so that the flow of air or the ingress of oxygen to the cave area is reduced or eliminated.

Critical factors affecting spontaneous combustion of coal are thoroughly evaluated. These factors include not only the quality of coal but also geological features and mining methods used to extract the coal. The propensity of coal to self-heating can be determined by using a software such as SPONCOM developed for this purpose.

There are two types of pressure balancing namely passive and active. Passive balancing is desirable, as it can be achieved using passive means such as regulators and fans. Dynamic pressure balancing is another type of passive pressure balancing in which chambers are established and pressurized using airflow existing in the mines. If a passive balancing technique is not adequate, then an active pressure balancing could be used. Inert gas is used to pressurize the chamber in an active pressure balancing method.

The University of Utah ventilation laboratory model was upgraded to include an atmospheric monitoring system. The model was used to conduct several experiments to equalize pressure differentials across the simulate gob.

All the vital ventilation control parameters can be observed and recorded using this system. Furthermore, a subroutine was developed to accomplish the pressure balancing system automatically.

Three underground coal mines have been visited as part of this study: one room and pillar and two long wall mines. The objective was to conduct pressure-quantity surveys, and to determine the pressure differentials across the stoppings used to isolate the worked out areas. The results of the surveys conducted in the room and pillar mine are presented and discussed in this study. The study concludes with an inventory of hazards related to spontaneous combustion, control measures, and risk analyses to identify the critical factors.

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CHAPTER 1

INTRODUCTION

Spontaneous combustion is a serious problem in coal mines. This should be studied such that safe working conditions can be provided to miners. This chapter provides a general overview, statement of the problem, a proposed solution, and detailed objectives to be accomplished in this thesis.

1.1 General Overview

Coal is a chief source of energy across the globe. It is used for a variety of purposes ranging from metallurgy to power generation. The quality of coal being used for each purpose is different. Almost all coal produced in the United States is used to generate electricity. Sub-bituminous coal is preferred for power generation which has a carbon content of 35–45 % (U.S. Energy Information Administration 2014). One of the serious problems associated with coal is spontaneous combustion. Spontaneous combustion refers to the tendency of coal to combust in the presence of oxygen and lack of ventilation. It can have safety and economic implications. Moreover, it is a major impediment to production. Coal is mined by two methods, namely opencast and underground. Underground coal mining is practiced through two prominent techniques. Each of them is explained briefly below:

Room and Pillar is used for tabular and lenticular deposits. The concept followed for this method is to sink a shaft or construct a slope or drift, depending on depth of ore, to the elevation of the mining horizon and begin excavating the ore in a room and pillar pattern within the deposit. A multiple entry system, called mains, is first developed, then these are connected to transversal headings, called sub-mains. Continuous miners are utilized for excavating coal. It has a large rotating drum to break the material in front of it. Shuttle cars then load the broken ore onto an onboard conveyor system.

Longwall mining is the most productive technique to mine coal from underground mines. The development of entries is achieved through the conventional room and pillar method using continuous miners. A series of panels branching perpendicular to the mains are driven, leaving a very large solid block of coal, which is also called a panel. In modern longwall operations, face shearers, armored face conveyors, stage loaders and power cables are assembled in the setup room before longwall mining commences. The coal is cut by the back and forth movement of the shearer, which usually excavates all coal within its height capability. A set of shields, advanced sequentially, is used to support the roof as the shearer advances. As the shearer proceeds, a void area or “gob” is formed at the place where coal is excavated by the shearer.

In the United States, mines are governed by Title 30 of Code of Federal Regulation, under which each mine must have an approved ventilation plan. Regulation 30 CFR § 75.371 (cc) of this code, any underground coal mine with a demonstrated history of spontaneous combustion must specify the ventilation system to be used and the actions to be taken to protect mine workers from hazards associated with spontaneous combustion. Moreover, if a bleeder ventilation system is not used, then the method(s) that will be used to control spontaneous combustion and accumulation of methane-air mixtures in the gob must be specified in the ventilation plan.

The two basic ventilation systems used in the Unites States coal mines are the bleeder system and the bleederless system. Each is employed in accordance to their suitability to control methane emissions in the gob. A bleeder ventilation system can further be sub-divided into through flow and wrap around system. A bleederless system is used in mines where spontaneous combustion is a serious threat to the well-being of the mine workers.

Spontaneous combustion of coal is more pronounced in the gob area. As the overlying strata caves in the gob area, the fractured coal can oxidize and start a self heating process, depending upon the air leakage from the mine side. Once the process is started it is difficult to control, owing to the inaccessibility of the area. Moreover, there is always a risk of explosion if the oxygen-methane mixture in the gob is within the explosive range, thus jeopardizing the lives of the mine workers. Evaluation of coal propensities includes studies on constituents of coal and coal-oxygen interaction. This problem is more pronounced with low quality coals. Preventive control measures includes adequate ventilation planning, pressure balancing, and inertization.

Ventilation planning should be formulated with respect to airflow requirements and other major concerns such as spontaneous combustion. The pressure differential across the gob in case of mines liable to spontaneous combustion should be minimal such that airflow towards the gob area can be precluded. Bleederless ventilation with progressive sealing can be used which will be helpful in mitigating the onset of spontaneous combustion in the gob area.

Pressure balancing refers to minimizing pressure differentials between the working face and the gob to inhibit the airflow. Pressure balancing is one of techniques which has been used with a certain degree of success in some of the mines abroad, but not much in the United States.

Inertization refers to injection of inert gas in the gob area to minimize the oxygen content. It is practiced in mines which have problems of spontaneous combustion. Usually nitrogen gas is used in the process, which reduces the oxygen content and render the atmosphere inert.

The parameters affecting the pressure balancing are studied in a laboratory model at the University of Utah (Ventilation laboratory), the results evaluated, and the critical factors determined. The effects of these factors on the control of spontaneous combustion of coal are discussed in this study.

1.2 Statement of Problem

Coal has an inherent tendency to combust in the presence of oxygen. The problem aggravates in confined areas where ventilation provides the required oxygen for the initiation of spontaneous combustion, but not enough to remove the generated heat. Moreover, environmental factors associated with the mining of coal worsen the problem. Once initiated, the self heating process control measures are difficult to implement and sometimes can lead to the loss of a working panel. The gob area in a longwall mine is one of the spots where spontaneous combustion can take place. An early detection of the problem is a very difficult task owing to inaccessibility of the area. Consequences of spontaneous combustion can be manifold including fires and explosions, if the methane concentrations in the gob is within the explosive range. Seals earmarked for separating the working area from the gob are not competent to prevent the leakage and studies have shown that seals "breathe in and breathe out" with changes in barometric pressure (Brady et al. 2008). Barometric pressure variations can cause the inflow of mine air from the face towards the gob. Leakage of fresh air through stoppings is the major cause of an onset of spontaneous combustion in the gob, as it provides sufficient oxygen to oxidize the coal, but at low velocities such that the heat formed is not dissipated.

1.3 Proposed Solution

Inertization and pressure balancing can be viewed as the solutions to the problem. Inertization refers to flooding of the gob area with inert gas such as nitrogen to reduce the oxygen content and render the atmosphere inert. Pressure balancing is used to reduce the pressure differentials across and around the gob area to levels such that the airflow can be precluded. There are two methods which can be employed to achieve pressure balancing: passive and active. Passive pressure balancing aims at using regulators, fans or by establishing a positive pressure chambers which is pressurized with existing airflows; the pressurized chamber does not allow the ingress of air from the mine side towards the gob. An active pressure balancing method uses an external source of gas to pressurize the chamber. The University of Utah ventilation lab model, equipped with a continuous monitoring system and a pressure balancing chamber will be used to monitor and maintain the gob at a pressure equal or slightly lower than the working face. Details of this model, and the results of pressure balancing tests are described in subsequent chapters.

1.4 Thesis Objectives

The objective of this thesis is to obtain a thorough understanding of pressure balancing to control spontaneous combustion in coal mines. The University of Utah coal mine ventilation model is used for this purpose. The model consists of two simulated working faces, crosscuts and a gob area. It is equipped with two fans and a set of regulators to regulate the flow at desired locations. It is also equipped with an atmospheric monitoring and control system operated by a host computer. Although pressure balancing has been employed in several mines abroad, parameters affecting the pressure balancing process have not been thoroughly investigated. In almost all cases, pressure balancing was used as last resort to mitigate the problem of spontaneous combustion. Laboratory models are suitable to investigate and analyze the different parameters governing pressure balancing. Both active and passive pressure balancing methods can be simulated, pressure differentials across and around the gob area can be controlled by changing the regulator resistances and fan duties. Moreover, a pressure chamber and an external gas injection system can be used to investigate the effects of different pressure balancing techniques on pressure distribution in the gob area. In fact, the laboratory model is equipped with a set of flow control devices that can be arranged to simulate different gob ventilation scenarios.

Furthermore, this thesis documents the results of pressure-quantity surveys that were carried out in three underground coal mines: one room and pillar and two longwall mines. Each mine uses a unique way of ventilating the gob area. The collected data are evaluated and the relevant information is used to emulate gob ventilation methods through laboratory experiments. The following is the task breakdown for the thesis:

1. Conduct pressure quantity surveys in two or more underground coal mines.

2. Construct a physical model to simulate a coal mine gob.
3. Equip the model with an automated pressure balancing system.
4. Conduct pressure balancing experiments and evaluate results.
5. Prepare guidelines for safe utilization of pressure balancing techniques.

The University of Utah laboratory ventilation model is constructed of 0.15-m (5.75-in.) diameter pipe and equipped with two fans and an atmospheric monitoring system. The model has two simulated faces, gob area and a bleeder section. Experiments are conducted in the model and results are analyzed. Risk analysis is undertaken so as to implement the process safely. Once all the relevant experiments are conducted and field data analyzed, guidelines are prepared which can be implemented in mines.

CHAPTER 2

LITERATURE REVIEW

Spontaneous combustion of coal has been studied by various researchers across the globe. Experiments and techniques have been designed to predict the propensity of coal towards spontaneous combustion. This not only depends on the coal quality but also on the prevailing environmental conditions of the coal mine. Combining all the aspects to come up on an accurate conclusions to predict spontaneous combustion is difficult. This can be illustrated from the fact that in Jharia (India), the number of thick coal seams with rather poor susceptibility remain infested with fire (Banerjee 2000).

2.1 Spontaneous Combustion of Coal

Spontaneous combustion refers to the tendency of coal to combust in the presence of oxygen and lack of ventilation. Different methodologies employed to determine the spontaneous combustion tendencies of coal include examination of coal constituents and coal-oxygen interaction.

Inherent coal properties are crucial in respect to the heating of coal; factors responsible for heating are discussed below.

1. Inherent moisture— Moisture content of coal plays an important role in propensity of coal towards spontaneous combustion. Heating of coal leads

to the release of moisture, which in turn facilitates opening up the active centers in the coal matrix. High moisture content coal has a higher tendency towards spontaneous combustion.

2. Volatile matter— Volatile matter in coal refers to components of coal, except for moisture, which are liberated at high temperatures in the absence of air. It has been used as a supplementary index to corroborate degree of proneness of coal to spontaneous combustion. High volatile matter coal has higher tendencies towards spontaneous combustion.
3. Oxygen in coal— It has been proved that the liability to spontaneous combustion heating is directly proportional to the dry ash free oxygen percentage of bituminous coals (Smith et al. 1987). Prediction methodologies based on interaction of coal and oxygen are crossing point temperature, and adiabatic and isothermal heating methods. In each of these methods the temperature at which coal begins to self-heat on its own is recorded to come up with the heating propensity of coal.

Several risk ratings were developed to include the effect of environmental setting on propensity of coal to spontaneous combustion. These indices help to provide with definite risk characteristics of coal seams. Most of them encompasses all the factors related to spontaneous combustion potential. Banerjee developed a comprehensive method of risk analysis which included 22 different parameters affecting the spontaneous combustion of coal. A risk rate for each of the parameters was assigned on the basis of an established criteria (Banerjee 2000). The rating assigned to each of them ranges from low to very high. In order to convert these qualitative risk ratings to a quantitative index, values are assigned corresponding to each of the ratings. These value ranges from 0.25 to 1 for low to very high respectively. These values are then added to arrive at the cumulative risk index of the seam towards spontaneous combustion. If the cumulative index adds up to more than 50 % of maximum possible value, coal is deemed to be prone to spontaneous combustion.

One of the more convenient methods to examine the spontaneous combustion tendency of coal, is to use a software developed for the purpose such as SPONCOM. This software was developed by the U.S. Bureau of Mines to predict spontaneous combustion of coal based on self heating temperature (SHT). Self heating temperature (SHT) is the minimum temperature at which coal undergoes sustained exothermic reaction in an adiabatic oven. It is also a measure of coal reactivity to oxygen (Smith 1987). Coal samples ranging in rank from lignite to high volatile-bituminous were taken and their propensity to the spontaneous combustion was determined in an adiabatic oven. The result obtained from these experiments and its correlation with spontaneous combustion history of the coal samples were combined to provide a ranking scheme for establishing coal’s minimum SHT.

Coal samples with minimum SHT of <70˚C were considered to have a high spontaneous combustion potential, those with minimum SHT’s between 70–100˚C to have medium potential, and those with minimum SHT >100˚C to have a low spontaneous combustion potential. A statistical analysis showed that the minimum SHT’s of a bituminous coal strongly depends on dry ash free oxygen content of coal. All the analytical results were incorporated in an expert system called SPOCOM (Smith 1992). Contributing factors towards spontaneous combustion of coal such as geologic, mining conditions and current mining practices were also incorporated in the system. This is an interactive, user friendly, and inexpensive method of seeking expertise.

The program first determines the coal’s spontaneous combustion potential. It can either be high, medium or low, based on coal’s predicted minimum self-heating temperature (SHT) and any effect the mine ambient temperature or previous spontaneous heating occurrence might have on this potential. This value is then further used to evaluate the effect of coal properties, the geologic and mining conditions, and the mining practice on the spontaneous combustion risk of the operation. The program determines the degree of risk for each parameter which can either be low, moderate, high, or very high based on program ranking criteria and self-heating potential of coal.

Most of the input factors are readily definable, such as the moisture content of coal, the depth of cover, the coalbed thickness, or the type of the longwall pillar design. Other factors require the user to rate factors such as the degree of coal friability, geologic factors, and density of coal joints, dikes, and channel deposits. Moreover mining conditions such as degree of floor heave and rib sloughage also need to be entered.

Rating scales for these factors are given in the program, with values from zero to 100, where zero represents the least threat and 100 the greatest threat to spontaneous combustion. As an example, in rating the degree of floor heave, zero represents a low degree, 50 represents a moderate degree, and 100 represents a high degree of risk. The program output gives the spontaneous potential of the coal, its rank, and SHT. Moreover, output also mentions the factors that increase the risk of spontaneous combustion in the underground mining operation. It also includes the degree of risk and details of why these factors increase the risk of spontaneous combustion in the underground mining operation. The program output can be printed to the terminal or to a hard copy printer.

In the determination of spontaneous combustion of coal the values from coal’s proximate analysis and ultimate analysis are used to determine the rank of coal. If the rank of coal is lignite or sub-bituminous, the coal is assigned a high spontaneous combustion potential. If the ranking is bituminous the coal's predicted SHT is determined by:

$$\text{SHT, }^{\circ}\text{C} = 139.7 - [6.6 * \text{Oxygen, \% (DAF)}]$$

The values obtained from the above expression is adjusted for reactivity of coal due to ambient in mine temperature of the coal. A value of 12.8˚C is used as the baseline in-mine temperature:

$$\text{SHT}_{\text{adj}} = [\text{SHT} - (T_{\text{ambient}^{\circ}\text{C}}, -12.8)]$$

Coals with adjusted SHT's < 70˚C are assigned a high spontaneous combustion potential whereas those with adjusted SHT's > 100˚C are assigned a low spontaneous combustion potential.

Factors taken into consideration to arrive at the final rating of coal's spontaneous combustion propensity are as follows:

Geologic properties— It includes seam dimensions in thickness, gradient, and seam anomalies. Concentration of joints, dikes, channel deposits, and clay veins are also taken into consideration. To each of them, factor ranking criteria which categorizes the above in low, medium, and high are assigned based on the entry fed by the user. It is then compared and evaluated against the predefined criteria.

Mining Conditions— The actual mining conditions can be defined by the number of parameters. These parameters are then used in calculation of coal’s spontaneous combustion propensity. The parameters in regard to mining conditions are ambient temperature, coalbed thickness, floor heave, and rib sloughage. The values entered are compared to the predefined values and each of the parameters are categorized in low, medium or high.

Mining Practice— This is the only factor which can be controlled by the operator to an extent. The type of mining (longwall or room and pillar), recovery ratio, gateroad pillar design, the rate of advance or retreat and panel dimensions are all important factors in ranking the risk of spontaneous combustion of coal due to mining practices.

2.2 Mine Ventiation Layouts

The ventilation layout used in underground coal mines can broadly be classified into U system and through-flow system. Both of these systems are explained in this section.

2.2.1 U System of Ventilation in a Longwall Mine

In this system, air travels through the mains, sub-mains, and headgates to ventilate the working faces. Once used, the contaminated air is directed to main returns usually arranged parallel to the main intakes. Stoppings, doors, and regulators are used to separate them from intakes. In each working area, brattice cloths and auxiliary fans are used to direct the air towards the face. In a longwall panel, after ventilating the face, the air splits at the tailgate T- junction. Most of it travels to join the main return while the rest is exhausted through the bleeder ventilation system.

Figure 2.1 shows a schematic of the U-system of ventilation. Air enters the mine through the intake portals. Sets of stoppings separate the intake from the belt entry and belt from the return airway. The schematic below has three working faces, of which two are continuous miner and one is longwall. Faces are ventilated by the intake air, contaminated air is directed towards the main return. Overcasts are used to facilitate crossing of air without mixing. Return air is pulled out through the main exhaust fan.

2.2.2 Flow Through System

An alternative to the U-system of ventilation is the flow through ventilation system. In this system intakes and returns are separated geographically. Adjacent airways are either all intake or all return. There are far fewer stopping and air crossing but additional regulation (regulators) is required to control the flow of air through the work area.

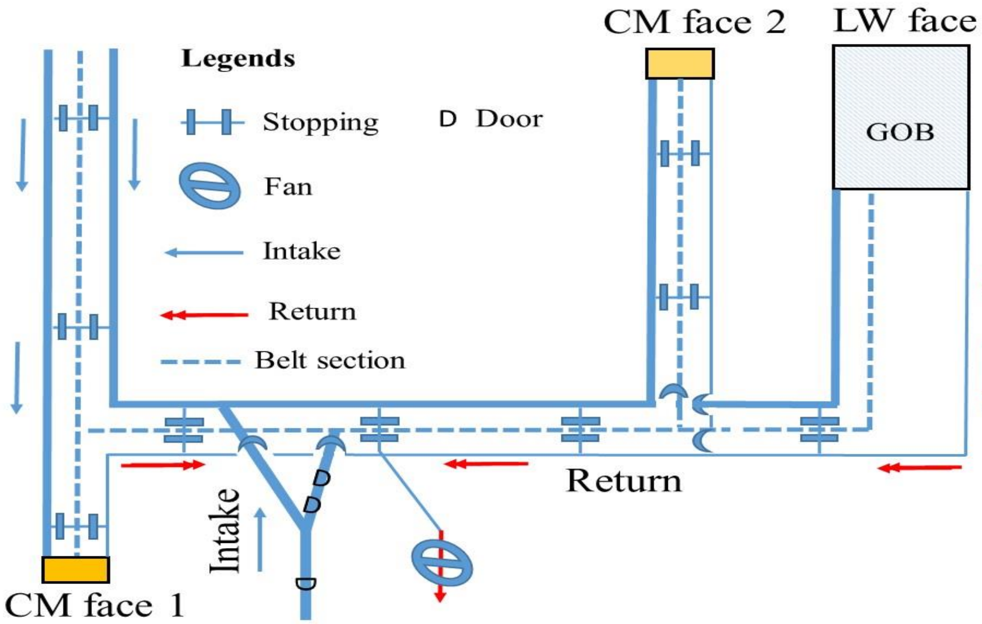

FIGURE 2.1 U- ventilation system in a two-entry panel

Two development headings and one longwall section are shown in the figure. Intake air ventilates each of these faces. After ventilating the sections, air is exhausted through the main return. Overcasts are used to separate intakes and returns and to transfer the contaminated air without mixing. The intake and return airways are separated geographically. Fewer stoppings reduce the leakage to a great extent. Fan pressure generated to fulfill the requirements of the mine are usually lesser as compared to U system of ventilation. Figure 2.2 shows a schematic of the flow through system.

The flow through system can be further divided into two types, flow through main to main, flow through bleeder entries, and punch-out and borehole flow through systems.

1. Flow through main to main— In this system headgate and tailgate entries would be developed from one set of mains and connected to return entries of another set of mains. The main return entries adjacent to panel can be used as setup and recovery rooms or separate rooms can be developed and a barrier installed between them. Separate setup and recovery rooms were developed to provide additional protection for adjacent entries and ventilation controls against stresses created by the gob. Permanent ventilation controls are installed and maintained all across the gob perimeter to control distribution of air.
2. Punch-out and borehole system— This system is designed to course at-least a portion of bleeder airway directly to the surface. There can be one or more openings at key locations to course the air out. A punch-out system is used when reserves can be recovered from an accessible outcrop. Bleeder entries are developed towards the outcrop and punched through to surface.

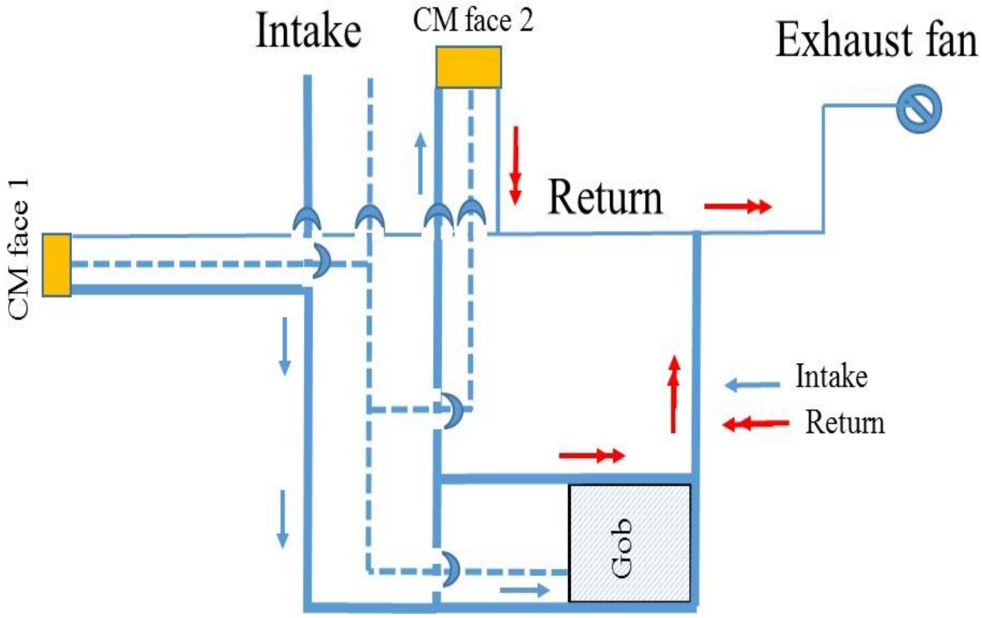

FIGURE 2.2 Flow- through system of ventilation

Boreholes can be used instead of punch-out when the coal bed is shallow but no outcrop is available. The number and location of surface openings depends on size, shape and ventilation requirements of the projected gob. Bleeder fans can be employed such that some of the air-gas mixture can be coursed to the surface. These fans can be initially installed or added to an existing bleeder system to increase the ventilating capacity. The size of the shaft and fan depend on the ventilation requirements of the projected gob.

The location of a bleeder fan can have a major impact on the primary ventilation system. When a high pressure fan is needed, substantial leakage flow can occur near the bleeder fan, ventilation controls should be established such that leakage is minimized. Airflow should be controlled to ensure that adequate pressure differential are maintained in proper direction.

2.3 Longwall Mine Ventilation

Ventilation is essential for an underground mine to maintain a safe and healthy working condition. Statutory regulations are established to ensure that working areas are safe and healthy. These regulations are listed in 30 Code of Federal Regulation (CFR) Part 75. Longwall operations in the U.S. are mostly of the retreat type (Hartman 1997). Longwall face are developed with either two, three, or four entries in each set. A ventilation system in a longwall mine can be divided into bleeder and bleederless systems.

The primary aim of maintaining a bleeder system is to keep the gob clear of gases. A controlled flow across the bleeder entries must be established to weed out the gases. It is usually achieved by placing regulators at strategic locations at both panel ends and by utilizing the permeability of the gob for ventilation (Ramani 1993). A bleeder ventilation system can be separated into two basic designs, the flow through and the wrap around system.

In a bleederless system, the gob area is isolated from the mine workings through stoppings and seals and a flow-through of air is restricted. The primary aim of inhibiting the airflow is to prevent spontaneous combustion. The most common types of bleederless ventilation in U.S. coal mines are the U-tube, back return, and Y type systems. The main advantage of using a modified U-tube or Y system is that the mine gas (methane) is pushed away from the tailgate area. Bleeders are used to ventilate mined-out areas with an intent to sweep methane and other noxious gases (Figure 2.3). Headgates and tailgates are sealed progressively as the longwall face proceeds. Roof fall extends till the edge of these chain pillars. Seals are installed at the crosscut of chain pillars. Seals inhibits the flow of air towards the gob. Figure 2.4 shows a schematic of bleederless system for a longwall panel.

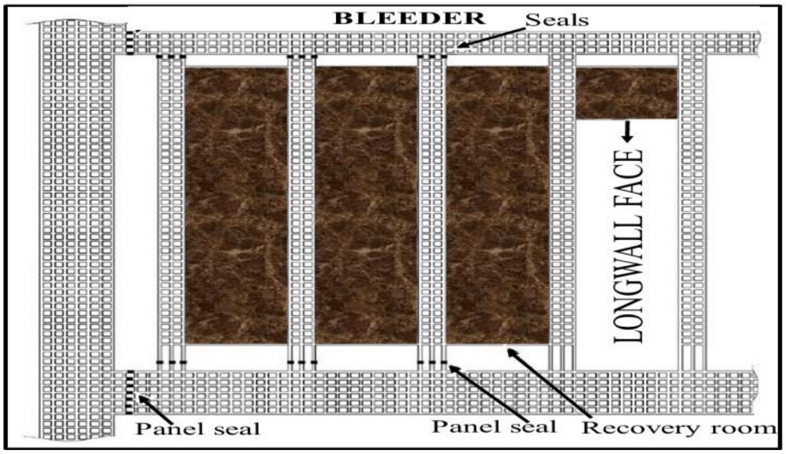

FIGURE 2.3 Bleeder ventilation system

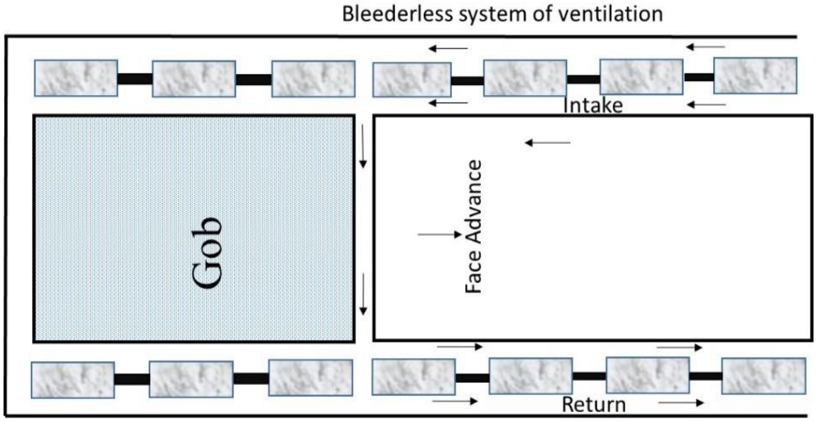

FIGURE 2.4 Bleederless ventilation system

2.4 Methodologies to Control Spontaneous Combustion

Different methodologies can be employed in order to control the problem of spontaneous combustion in underground coal mines. To understand and mitigate the problem of spontaneous combustion seven leading practices have been identified. These are 1) Understanding spontaneous combustion, 2) Detection and monitoring, 3) Pressure differential management, 4) Sealing and inertization, 5) Inhibitors and sealants, 6) Extinguishment planning, 7) Other. (Grubb 2008). Some of the prominent techniques are discussed in detail below.

2.4.1 Progressive Sealing of Gob

Progressive sealing refers to the sealing of the gob area as the longwall face progresses. Seals are constructed at the crosscut of chain pillars in headgate and tailgate sides. It is one of the techniques through which spontaneous combustion can be prevented. The panel ventilation method is either the U or Y system depending on mining and ventilation requirements. Progressive sealing helps in reducing the airflow towards the gob area. For compliance with the requirement to keep the headgate ventilated for the use as next tailgate, the Y system with or without back-return can be utilized on most panels. Inertization can also be practiced with this method. It can either be self or induced inertization. It has been practiced in a number of mines in the U.S., including BHP’s San Juan mine and Arch Coal’s West Elk mine.

The San Juan mine in New Mexico uses inertization along with pressure balancing chambers. Pressure chambers are installed by erecting stopping in parallel crosscuts in bye the longwall face. Both headgate and tailgate sides have these chambers. Nitrogen is introduced in the chamber and gob area. The introduction of nitrogen in the gob prevents the spontaneous combustion problem. It also renders the gob atmosphere inert to explosions. Balance chambers inhibit ingress of oxygen into the gob and the egress of explosive mixtures from the gob. In this mine, chambers are connected to programmable logic controllers (PLC’s) (Bessinger et al. 2005). These PLCs ensure that the chamber are always maintained at higher pressure than the mine and gob side. A tube bundle system is used to monitor the gob atmosphere.

2.4.2 Injection of Inert Gas

Spontaneous combustion is a serious problem in underground coal mines. It is caused by the oxidation of coal in confined areas such as mine gobs with little or no ventilation to dissipate the heat of oxidation. Moreover, the atmosphere behind the gob area may become explosive due to methane emission from broken coal. Presence of oxygen leads to the problem of self heating of coal. This, together with high concentrations of methane can lead to fires and explosions.

Injection of an inert gas into the gob can be a solution to this problem. This process is also termed as inertization. N_2 and CO_2 are used as inert gases in coal mines. The injection of nitrogen decreases the oxygen content in the gob atmosphere. Oxygen is one of the components of the fire triangle. Inertization has been used in many coal mining countries with a reasonable degree of success.

Using an inert gas, control of spontaneous combustion is accomplished by:

1. Reducing the oxygen concentration in the gob atmosphere and around the hot spot. The reduction of oxygen concentration to about 12.5% can reduce the chances of occurrence of spontaneous combustion considerably.
2. Introducing sufficient inert gas into the gob area to dilute the gas composition out of a so called "explosive zone."
3. Cooling the area surrounding the fire, especially when N_2 is used.

Nitrogen is best suited to control spontaneous combustion fires, as it is inert and does not have any major health impact on miners. In case of carbon-dioxide injection, the gas may enter the longwall face through shields and increase its concentration. Carbon dioxide concentration in the general body of air should not exceed 0.5% according to Mine Safety and Health Administration (MSHA) regulation 75.321. It should be noted here that adequate ventilation at the face should be maintained to dilute the air contaminants. One of the advantages for using N_2 is its availability in the general body of air. Nitrogen concentration in air is almost 79%, which can be harnessed by various separation techniques whereas carbon-dioxide has no such facility. Membrane technology is the most widely used technique for harnessing nitrogen from the atmosphere. In general, high purity nitrogen 99% is produced using this technology. Nitrogen can be injected into the fire area in liquid state or in gaseous form through air separation unit/evaporation unit via a pipeline. Liquid nitrogen is beneficial in case of fire as it is cold and dry and imparts a cooling effect into the fire. Moreover, it is much easier to deliver liquid nitrogen on site than other inert gases. It has certain disadvantages such as its availability in unlimited quantities, and the preparatory work required on surface as well as underground.

One of the key concerns with nitrogen injection is its required quantity in the gob which is usually very high owing to leakage through seals. The conditions of seal is crucial in this respect. The attempt to use nitrogen can marginally be successful if seals are not in proper condition. In the United States, few mines practice the injection of nitrogen in gob to mitigate the risk of spontaneous combustion and render the gob atmosphere inert to prevent explosion.

In mines where inertization is applied, the effectiveness of this practice to control spontaneous combustion is reduced to a great extent due to leakage through stoppings and seals. Barometric pressure variations can cause changes in the gob atmosphere. A decrease in the barometric pressure leads to egress of mine gas from gob area and an increase leads to ingress of air into the gob. Leakage of air through the seals can totally be contained if pressure across the seals can be neutralized. The technique used to neutralize the pressure is known as pressure balancing.

2.4.3 Inhibitors and Sealants

Inhibitors are substances that can reduce or stop the rate of oxidation of coal by blocking formation of free radicals and reducing the active center of oxygen attack. They come into play when the spontaneous combustion process has already been started. Inhibitors are particularly desirable when coal is in a crushed state although their applications are particularly difficult in the gob atmosphere. For surface application tar coating, plastic sheeting, and hygroscopic agents such as calcium chloride, sodium chloride and magnesium chloride can be used (Banerjee 1985). Hygroscopic agents are preferred inhibitors.

Sealants are applied to eliminate or restrict the access of oxygen to the coal surface. Sealants have the following six characteristics: 1) compatible to coal, 2) impermeable to air, 3) not thermally degradable to toxic gases, 4) water insoluble, 5) resistant to cracking, and 6) cost effective. Thick coating of asphalt emulsion over the coal surface is used as one of the sealant. Tar and burnt Mobil emulsion in ratio of 1:3 was successfully used over a quarry bench wall in an Indian mine to prevent spontaneous combustion. (Banerjee 1985).

2.5 Pressure Balancing

Pressure balancing is the process of equalizing pressure between two or more target areas. Balancing of pressure across the gob precludes ingress and egress of air from the gob. The pressure balancing process can further be categorized in passive and active.

2.5.1 Passive Pressure Balancing

Passive pressure balancing is the process of equalizing pressure by changing airway resistance by adjusting regulator settings. Pressure balancing can also be achieved by changing existing airflows in a mine by making suitable arrangements. One of the techniques which can be employed in passive pressure balancing is the one that uses existing airflows of main intake or return airways to equalize the pressure across the gob. This can be achieved by raising the ventilation pressure on the return side or decreasing the pressure in the intake side. This usually involves first establishing pressure chambers and then equalizing the pressure difference across the inner seal using passive means, that is, by using pressure control pipes extended from the main intake or return to the chamber depending on the primary ventilation system. Pressure chambers are constructed by erecting a concrete stopping at a distance of 2–3 m from isolation stopping. Passive pressure balancing can also be achieved by changing fan operating conditions.

This technique is practiced in India, Australia, and other countries. In Australia, passive pressure balancing across the sealed gob is achieved using intake and return airflow. Return airways termed as balancing returns are employed to equalize the pressure between a working area and the mine gob. Overcast and regulators are used to direct the air towards the balancing return. Gob side pressure is recorded continuously. Then this is evaluated and when needed, pressure differential are balanced by adjusting pressure control valves or regulator settings. This technique is limited by the pressure available at the intake and return entries.

In the Figure 2.5, U-type of ventilation is used to ventilate the longwall face.

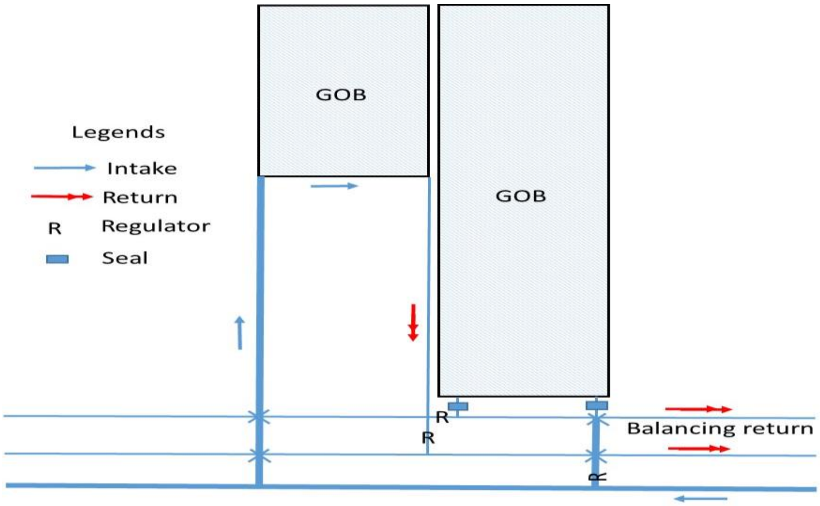

FIGURE 2.5 Schematic showing balancing return

There are two return airways, one of which is called balancing return. Airflow in the balancing return is controlled by means of a regulator located between the section return and main intake. This return is used to balance the pressure across the gob area, while the other return is used to direct air out of the mine. Pressure balancing is achieved by directing the airflow towards the balancing return using a regulator. Overcasts can also be used to direct the air from the main intake to the balancing return. In this manner, pressure balancing can be achieved by using existing airflow. This type of pressure balancing can be used to inhibit the ingress or egress of air from the gob due to changes in barometric pressure. Figure 2.5 shows a mine ventilation schematic in which the pressure in the mine gob is balanced using return air.

Dynamic pressure balancing is a form of passive pressure balancing. It has been used in Indian mines since 1960s (Ray et al. 2004). It is one of the most effective methods to neutralize the pressure differential across the isolation stoppings and to control spontaneous combustion. Chambers are established by erecting a stopping parallel to a seal. The chambers are connected through pipes that are used to equalize the pressure differentials between intakes and returns. Existing airflow in the mine are used to pressurize chambers.

The following procedure can be used to prevent spontaneous combustion using dynamic pressure balancing:

1. Monitor pressure drop across the isolation stopping around the clock to determine the range of pressure variations.
2. Adjust the air flow rate through the relevant circuit of the mine, such that pressure differential across the inner stopping or seal is reduced to the minimum possible value.
3. Neutralize the remnant pressure across the stopping by adjusting the air flow rate directed to the chamber through the pressure control pipes.

Dynamic pressure balancing can be applied not only to a panel but to a complete section of a mine, where mined out panels are sealed off or only localized areas are ventilated. Figure 2.6 shows a mine schematic and the general layout of a pressure chamber that can be used to equalize the pressure across the isolation seal.

The main disadvantage of this method is that the amount of pressure difference that can be neutralized by changing the airflow through ventilation circuit is dependent on the ventilation layout, airway resistances, and the location of the affected zone. In case the pressure required to balance the remnant pressure between the mine and gob area is not available, active balancing needs to be implementes.

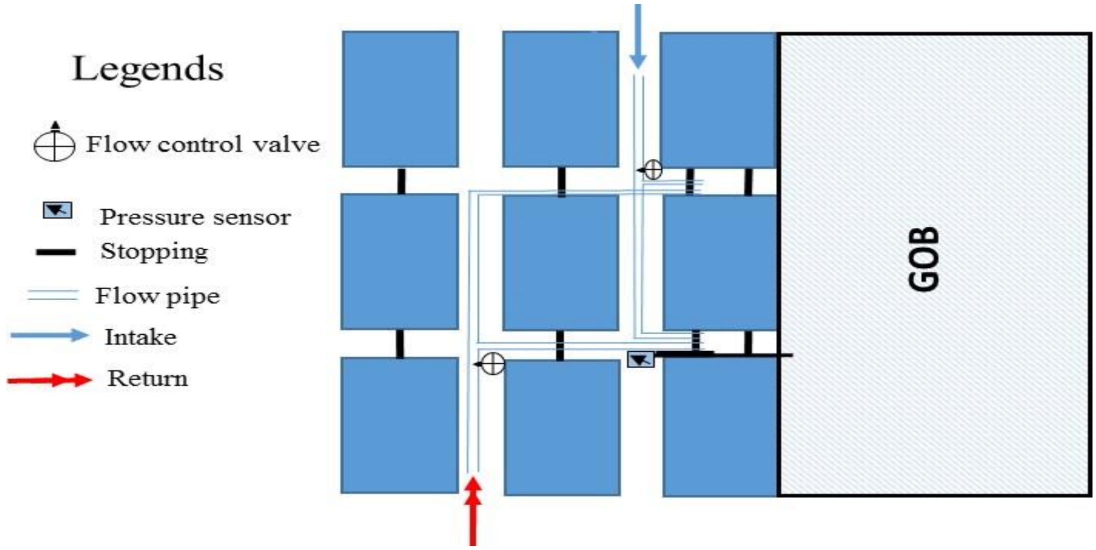

FIGURE 2.6 Simple layout of dynamic pressure balancing

2.5.2 Active Pressure Balancing

Active pressure balancing is the process of equalizing the pressure across the isolation seals using pressure chambers and an external pressure source. It is based on the principle that if there is no pressure difference across the mine and gob interface, then fresh air cannot move into the mine gob or vice versa. This strategy eliminates all oxygen from entering the gob, thus eliminating the risk of spontaneous combustion. To accomplish this, an external pressure source, maintained at a pressure slightly higher than that caused by barometric pressure variation, is required. This pressure source can be pressurized nitrogen, CO_2 or compressed air. Pressure chambers are installed by erecting stopping parallel to seals. Then these chambers are pressurized using an inert gas in a controlled manner. Often, nitrogen is used in coal mines. This can be produced as liquid nitrogen on the surface and transported and delivered in a gaseous state to pressure. This technique was successfully implemented in Austar coal mine in Australia, (Brady et al. 2008).

Nitrogen is an inert gas and does not pose any significant health and safety concerns to the miners when delivered into a confined area in a controlled manner. This technique was introduced at Austar mine, to effectively manage atmosphere in an area affected by spontaneous combustion fire (Brady et al. 2008). The aim of installing and pressurizing such chambers was to eliminate air leakage from mine workings into the gob, thus reducing the ingress of oxygen to the gob. Pressure chambers, when installed out-bye the sealed area, can be used to control spontaneous combustion fires effectively.

An automatic pressure balancing system is a form of an active pressure balancing in which the pressure balancing process is automated using microprocessors. The pressure chamber is established by erecting a second stopping (stopping 2) some distance away from the isolation stopping (stopping 1). Pipes extending across these stoppings are used to monitor pressure differentials and to inject nitrogen into the chamber. A manometer is used to measure the pressure differential across the isolation stopping (stopping 1). When this differential pressure is negative, pressurized nitrogen is injected into the chamber. The process will stop only when the pressure in the chamber is slightly higher than the pressure in the gob.

A central nitrogen line, extended along the intake airway is used to inject nitrogen in the pressure chamber and the gob when negative pressure differential is recorded. The whole process can be automated using microprocessors to monitor pressure differentials and to activate the appropriate control valve when a pressure imbalance signal is received, that is, when the pressure in the chamber falls below the pressure in the gob. Figure 2.7 shows a schematic of an automatic pressure balancing system in a mine cross-cut.

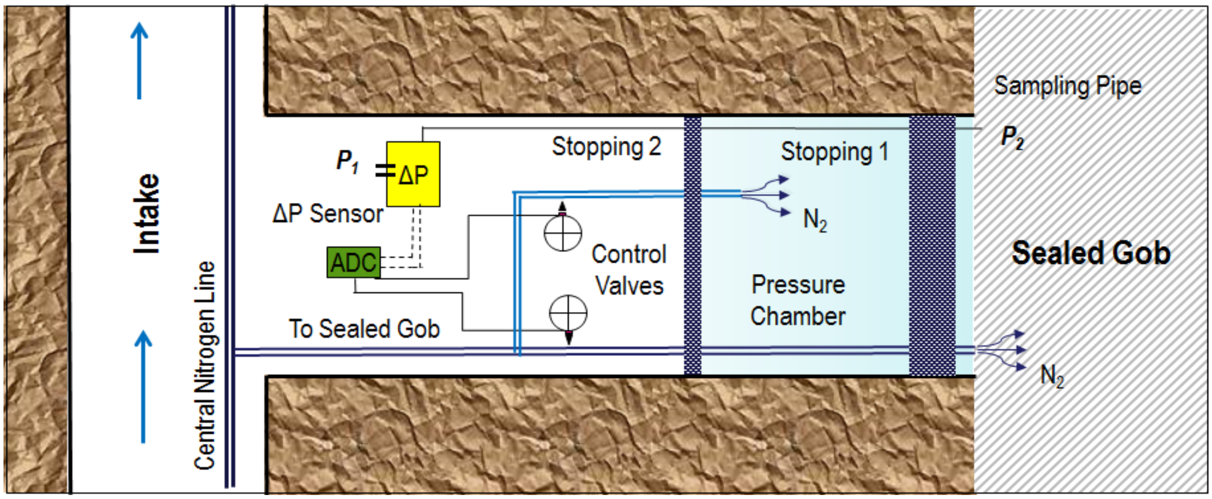

FIGURE 2.7 Positive pressure chamber used for active pressure balancing

CHAPTER 3

UNIVERSITY OF UTAH LABORATORY MODEL

Investigating real world problems is difficult in mines because production and safety must not be adversely affected during scientific experimentation. It is also difficult to change variables for an experiment in a mine. These impediments can easily be overcome by using a scaled model. The University of Utah has a coal mine ventilation model built to carry on scientific experimentation and represents a 1:25 scale of a coal mine entry.

3.1 Model Description

The model consists of 0.15-m diameter ductwork configured in a common U-shaped ventilation system. There are two crosscuts between intake and return. These crosscuts are partially open to emulate the leakage existing in mines. The model consists of two fans in total: one blower and one exhaust. Fans can be fired individually or in combination as per the needs of the experiment. Crosscuts are constructed of 0.06-m (2.5-in) diameter pipes, and act as leakage paths between the intake and the return airways. Two airways, designated as a continuous miner and longwall face, are used to simulate two active workings.

All the fans are of centrifugal type, and are equipped with variable frequency drive (VFDs). This allows the motor to be set at any frequency ranging from 0 to 60 Hz.

Gate valves or regulators are used at desired locations to control the flow of air.

There are nine sets of perforated gate-valves each, having holes of different diameters. The regulator opening ranges from 0.05% to 50% of the cross-sectional area. High resistance regulators are used at the simulated pressure chamber to simulate leakage, whereas other regulators are used at different locations to control the airflow. Figure 3.1 shows the University of Utah laboratory model and Figure 3.2 shows a schematic of the laboratory model.

FIGURE 3.1 University of Utah laboratory model.

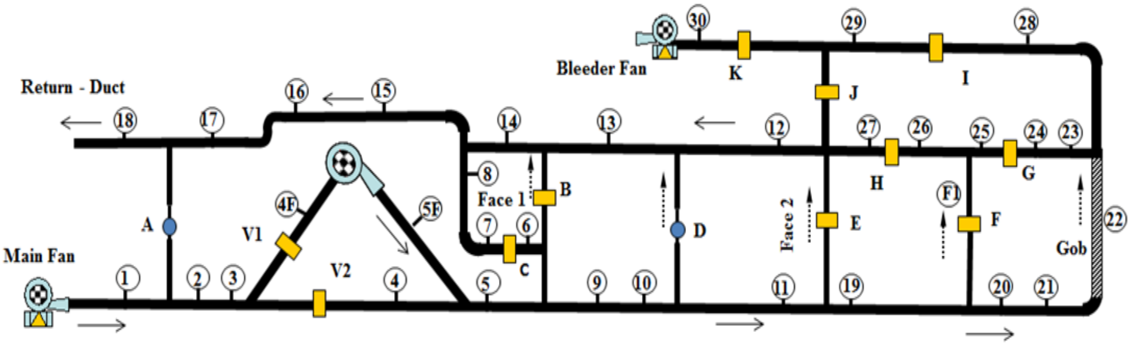

FIGURE 3.2 Schematic of the laboratory model

There are two faces, Face 1 represents the continuous miner face, and Face 2 is the longwall face. The gob area is shown towards the end. The gate valve slots are shown as yellow boxes. Regulators of different openings can be inserted in these slots according to the needs of the experiment. Crosscuts A and D are used to simulate the leakage path.

The model is used to conduct several pressure balancing experiments. Perforated gate valves with different openings were used as regulators to control the flow of air and achieve the desired quantities at the simulated working faces. A container filled with broken rock is used to simulate the mine gob.

3.2 Continuous Monitoring System

The University of Utah laboratory model is equipped with a microprocessor based atmospheric monitoring and control system. The monitoring system consists of a host PC attached to a communication network and a set of air velocity and pressure transducers, and a CO_2 gas injection system. The parameters recorded by these transducers are transmitted to the computer.

Each transducer is equipped with its own microprocessor controlled by the host PC. Typical functions performed by the microprocessor include scaling, averaging, filtering, and verification of signals throughout the system. All communication in the system uses RS 485 standard interface hardware. Each module draws a small amount of power (~ 30 mA) from 12-V DC bus for its internal digital and analog circuitry. Each module has a unique address and responds to control and query commands sent across the network. Figure 3.3 shows transducers mounted at the simulated gob area.

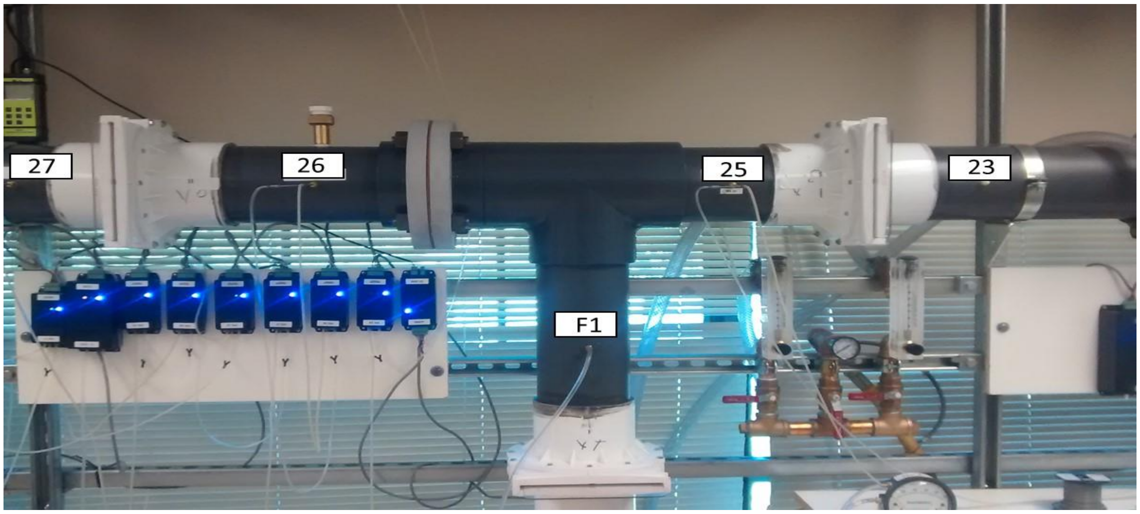

FIGURE 3.3 Transducers installed at the model.

The hardware is monitored, and the results reported at a rate that allows the simulator operator to view changes in ventilation dynamics in real time. All data acquisition and control commands occur within a 1, 3, 5, 10 or 30 second period. This cyclic period was chosen so as to have enough flexibility to record data. Each instrument or control node has its own microprocessor to perform communications and localized data processing. Only the results after processing are transferred between portions of the system, not the raw data itself. Additionally, since each instrument node is intelligent by design, there is sufficient processing power to perform self calibration and auto zeroing of analog inputs. Eliminating and compensating for instrument drift and recalibration allows for greater service life of each system component. There is still the need to do periodic instrument checking. Periodic maintenance of filters and disposables is required (Fredsti 2012). In order to use the monitoring system, all the modules are fired. After which the ventilation system software is started. All the fans are controlled using the software and can be set at desired speed from the computer. As soon as the fans are started the pressure transducers begin to transmit data. The data transmitted consists of static, velocity, and total head. CO_2 transducers also transmits the concentration of gas in parts per million (ppm). A gas injection system can be initiated in case of active and automatic pressure balancing. The rate of injection of the gas can be set from the computer. Once the injection rate is set the injection continues at the specified rate. Data transmitted from all the modules can be seen in real time at the user interface. Since the readings are displayed in real time, changes in system settings can be made from the keyboard instantaneously.

Additionally a subroutine was created to achieve automatic pressure balancing. This subroutine can be activated whenever required. It contains a set of commands written as code to achieve automatic pressure balancing under different set of conditions.

The following is a summary of the components currently used with this system:

1. Pressure transducers used to monitor the static, velocity, and total pressure across the system. In total 25 pressure transducers are installed.
2. CO_2 gas injection and sampling system used to control the flow of carbon dioxide and to determine its concentration at three strategic locations.
3. Fan control devices used to change the fan speed for different experimental conditions.

This system was used to continuously monitor and record data for a set of laboratory tests. The data were recorded every second and stored in an excel file. The data in this file were then processed to analyze and evaluate the effect of variations of fan pressure and regulator resistances on airflow distribution across the gob.

Graphical user interface shows position of pressure transducers, anemometers, and regulators. Figure 3.4 (a) shows the gob section of the atmospheric and control system.

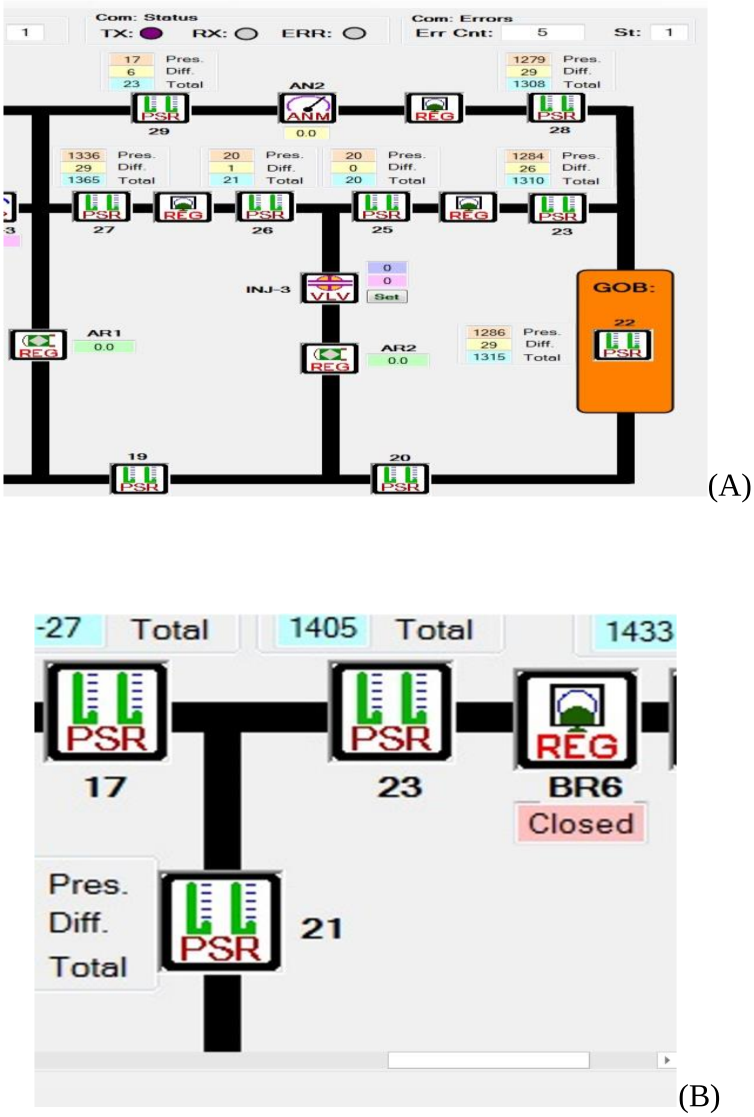

FIGURE 3.4 Gob section of University of Utah atmospheric monitoring system

Figure 3.4 (b) depicts the position of key components of the model. The readings obtained from the system are displayed next to these symbols. Station numbers are indicated against each of these transducers. Pressure transducers measure static, velocity, and total head whereas hot wire anemometers measure velocity of air in the system. Real time display of system characteristics helps the user to observe the model and change settings.

3.3 Model Similitude

Similitude is a concept used in the testing of engineering models. Real life problems are often investigated using a prototype or a lab model. A model is said to have similitude with the real world application if the two share geometric, kinematic, and dynamic similarity. Each of these concepts are explained below.

Geometric similarity means the model is the same shape as the real world application and is usually accomplished by simply scaling down in size. The physical quantities involved in geometric similarity are length, area, and volume.

Kinematic similarity means the fluid flow characteristics are scaled (streamlines are similar). When fluid motions are kinematically similar, the patterns formed by streamlines are geometrically similar at corresponding times.

Dynamic similarity means the ratios of all forces acting on corresponding fluid particles and boundary surfaces in the two systems are constant. In this context, the Reynolds number is of particular relevance. The Reynolds number can be defined as the ratio of inertial forces to viscous forces. The formula is given in Equation 3.1.

$$N_R = \frac{\rho D V}{\mu} = \frac{D V}{\upsilon} \tag{3.1}$$

Where,

N_R = Reynolds number (dimensionless)

D= diameter of conduit (m)

V=relative velocity of fluid (m/s)

μ = dynamic viscosity (Pa s)

υ = Kinematic viscosity (m^2/s)

It is often impossible to achieve absolute similitude during a model test. In these cases, some aspects of similitude may be neglected, focusing on only the more important parameters. In fluid dynamics, the most common dimensionless parameter used to analyze similitude is the Reynolds Number (Murphy 1950).

If the Reynolds number is satisfied, the geometric and kinematic criteria are also satisfied (Murphy 1950). The lab model was constructed using circular ducts, whereas coal mine airways are noncircular. The hydraulic diameter, Dh, is a common term used to calculate the Reynolds number for noncircular ducts (Murphy 1950). The formula for this is in Equation 3.2.

$$Dh = 4A / O \tag{3.2}$$

Where,

Dh = hydraulic diameter (m)

A = cross sectional area (m^2)

O = inside perimeter (m)

From ventilation surveys conducted in two underground coal mines in the east coast, it was found that main intake and return airways have on the average the following dimensions: 4.57 m wide and 3.04 m high. Similar cross sections were reported in a National Institute of Occupational Health and Safety (NIOSH) study on bleeder performance in southern Pennsylvania (Schatzel et al. 2011). For this cross-section, hydraulic diameter is 3.65 m. Table 3.1 shows model similitude parameters

TABLE 3.1 Model similitude parameters

Parameters	**Coal Mine**	**Model**
Air Density (kg/m^3)	1.12 kg/m^3	1.00 kg/m^3
Air velocity(m/s)	1.87 m/s	16.5 m/s
Airway diameter(m)	3.65 m	0.147 m
Reynolds number	3.79 x 10^5	3.85 x 10^5

Reynolds numbers of the mine and laboratory model is calculated using Equation 3.1 and 3.2. The calculated Reynolds numbers at the mine and model are closely corelated. The flow is turbulent in both cases (NRE > 4000).

3.4 Sample Experiment

A sample experiment was conducted to observe the pressure profile of the model. The profile gives an idea of the system characteristics.

Initial Conditions:

- Main fan pressure: 1935 Pa.
- Flow rate 0.46 m^3/s.
- Regulator settings: Regulators A, and D, with 5% total open area, represent high quality stoppings with almost zero leakage flow, regulators C and E (at 28% and 100% open area respectively) represent working faces, and other regulators (F and G at 8%, H at 28%, J at 8%, and K, closed). Airways used to simulate leakage have less diameter as compared to those used for rest of the model.

Pressure across the model is measured using pressure transducers. These transducers record pressure every second and transmit data to the computer. All the data recorded by these transducers can be stored in a Microsoft Excel file. These are then used to plot the pressure profile of the model shown in Figure 3.5. Flow at the continuous miner and longwall face were 0.11 m^3/s (240 cfm) and 0.24 m^3/s (520 cfm) respectively. Pressure drop towards the gob area is 100 Pa.

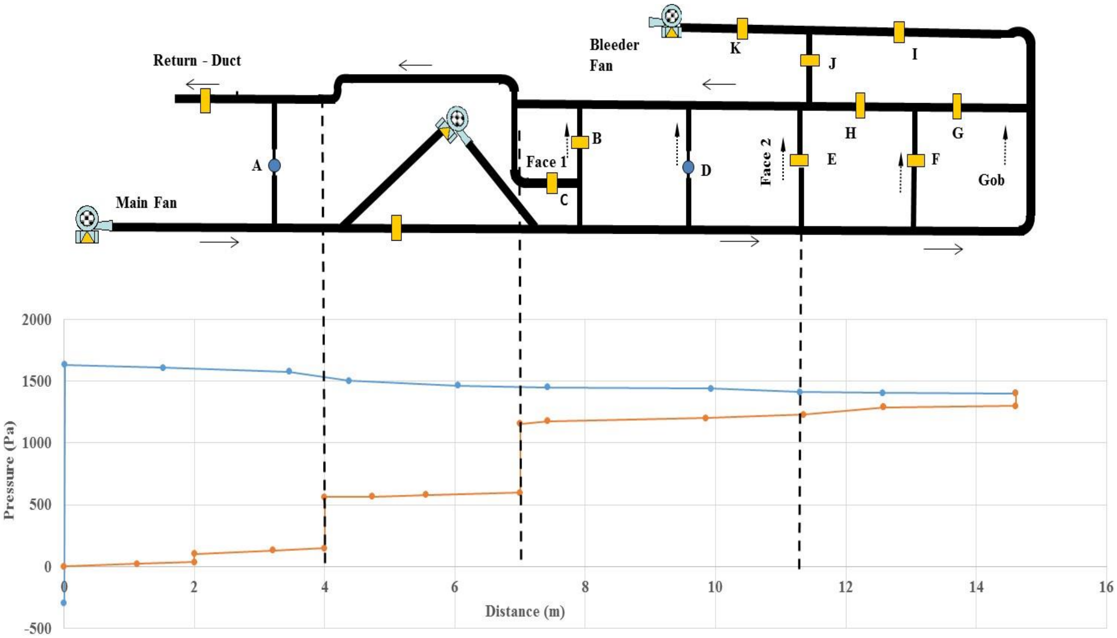

FIGURE 3.5 Pressure profile for the experiment

CHAPTER 4

PASSIVE PRESSURE BALANCING

Experiments on passive pressure balancing were conducted at the University of Utah ventilation model. Passive pressure balancing was achieved by using fans, regulators, and stoppings within the ventilation model.

Ventilation systems used in underground mines vary from mine to mine based on local flow requirements. In order to observe the effect of these systems on spontaneous combustion, four experimental tests were conducted at the University of Utah lab model. The model has enough flexibility so that these ventilation scenarios can be emulated by changing fan settings, regulator resistances, and by blocking the outlet ducts of the model. Once a ventilation scenario was established and the fan(s) started, the initial conditions were recorded using a continuous monitoring system. If the pressure differentials were deemed to be large enough as to initiate a spontaneous combustion problem, passive pressure balancing was implemented. Figure 4.1 shows a schematic of the University of Utah laboratory model.

Dynamic pressure balancing requires the establishment of a pressure chamber. Once built, the chamber is pressurized by connecting the chamber to a higher pressure point of the model. This was made by using 3 mm diameter silicon tubing equipped with a control valve. When this valve was open, the pressure inside the chamber increased gradually.

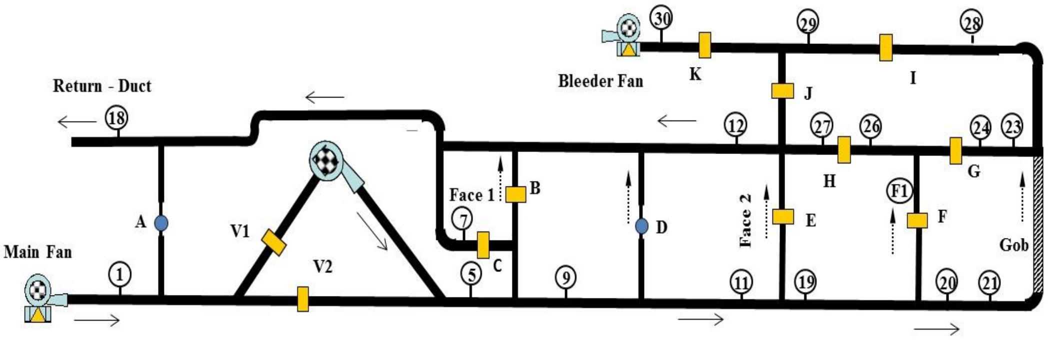

FIGURE 4.1 Schematic of University of Utah laboratory model.

Gate valves of different open areas were used to simulate leakage paths and installing pressure chamber. The model also shows the locations of various flow control devices required for each ventilation scenario. In this section, four ventilation scenarios were emulated by changing these control devices. In all the cases, regulators A, B, D and V1 were closed, while regulator E was kept open. Measuring stations that are crucial for each test are depicted in Figure 4.1. Figure 4.2 shows four line diagrams for four gob ventilation scenarios presented in this section. The four ventilation scenarios are: (a) wrap around system, (b) punch-out system, (c) push-pull system, and (d) flow through system.

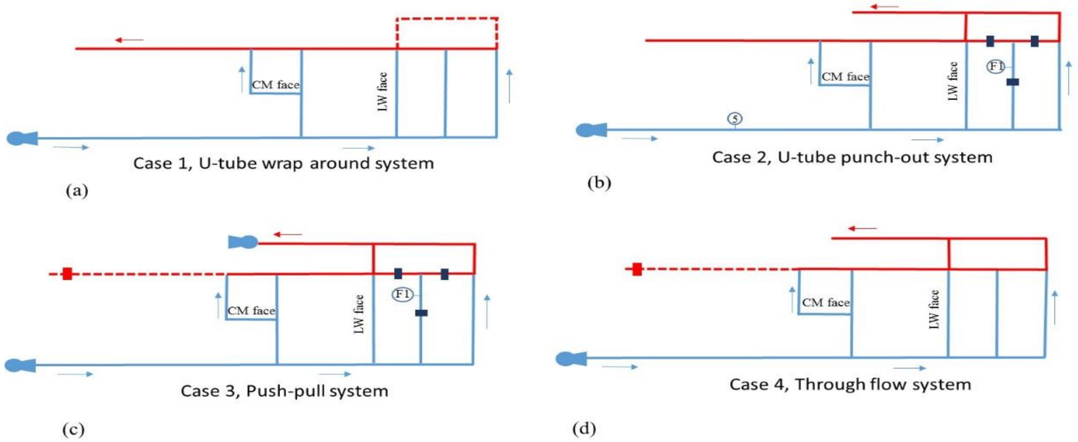

FIGURE 4.2 Line diagram showing different ventilation scenarios.

The blue lines depict the intake paths and the red lines the return airways. The main pathway used for ventilation is shown in bold. The dashed lines depict airways that are partially blocked such that a minimal flow rate is exhausted through it. Direction of flow of air is indicated using arrows.

4.1 Laboratory Experiments

Pressure balancing experiments were carried out at the University of Utah lab model. Four cases are described and their results discussed in 4.1.1.

4.1.1 Case 1: U-Tube Wrap around System

This case shows a modified U-tube wrap around a longwall ventilation system in which faces are ventilated using intake air and exhausted through return airways (Figure 4.2 a). The objective of this test was to minimize the pressure differential across the gob by changing the airway resistance in the model.

For the initial condition, the regulator in one of the airways (regulator K in Figure 4.1) was partially blocked so that only 28% of its total area was open. This allowed a fraction of the gas generated in the gob to be vented to the surface. For the final condition, this regulator was fully closed and regulator J was partially open. In each case, a blower fan was the only source of pressure for the system. The initial and final conditions and the results of each test are presented below. Initial and final conditions are given by:

- Main fan pressure: 1947 Pa.
- Quantity delivered: 0.45 m^3/s.
- Regulator settings: Regulators (C at 28% open area, F at 50%, G at

8%, H at 28%, J at 8%, and K at 28%) represent leakage paths.

- For the final condition, regulator K is fully closed while J was 28% open.

Air pressure–quantity measurements were taken using a barometer, manometers, pitot tubes, and a thermometer. Pressure differential were measured using manometers. The results of these measurements were used to determine the fan duty and plot pressure gradients. In this case, the blower fan supplied 0.45 m^3/s of air at 1947 Pa of static pressure. Out of which, 0.10 m^3/s was available at continuous miner and 0.30 m^3/s was directed towards longwall face. In Figure 4.3, the blue line indicates pressure profile in the intake airway and the red line indicates the pressure profile in the return side. Under these conditions, the differential pressure across the gob area was about 100 Pa.

A final condition was setup to observe the variation by changing one of the regulators openings in the model. The pressure differentials across the gob were controlled using stoppings and regulators were placed between the cross-cuts and the simulated mine gob. The new system imitates a longwall section in which the regulator in the bleeder entry (regulator K in Figure 4.1) is almost fully closed, and the regulator in the inbye cross-cut (J) is partially open. This arrangement was used to minimize the pressure differential across the gob. Figures 4.3 (a) and (b) show the static pressure profile for initial conditions and final conditions respectively. The pressure generated by the main fan was 2040 Pa, slightly higher than that recorded in the previous case. This pressure decreased as the air moved towards the longwall face. The pressure differential across the gob were practically nil, indicating that the gob air was stagnant. This can be observed by comparing the pressure profiles at the simulated mine gob by dashed vertical lines in Figures 4.3 (a) and (b).

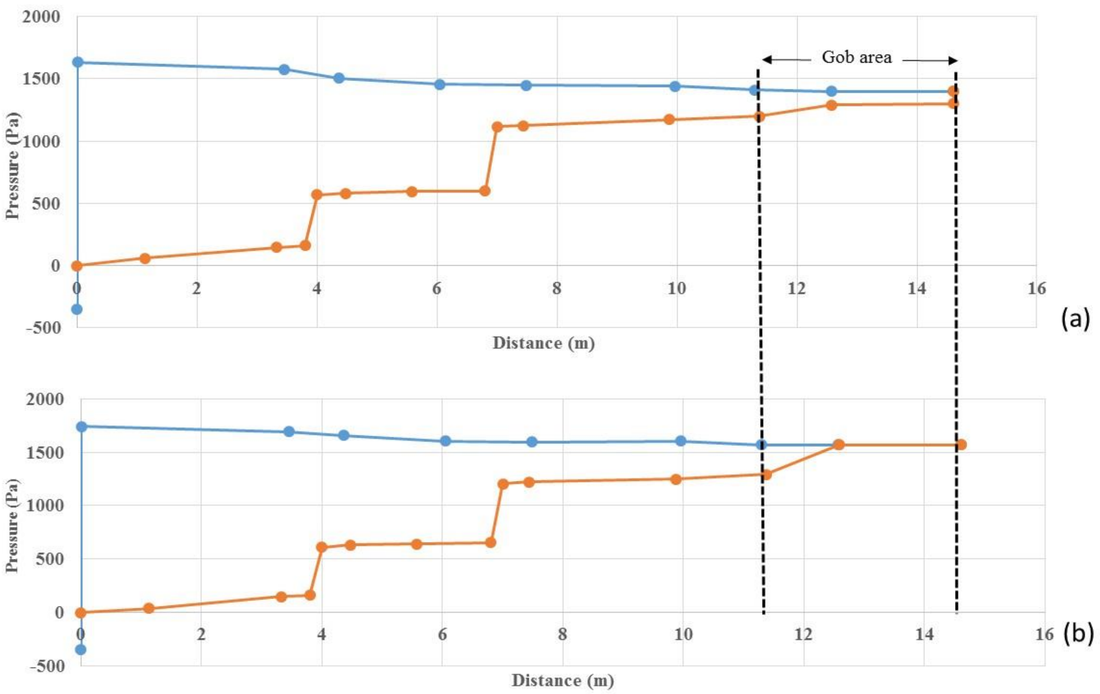

FIGURE 4.3 Static pressure profiles for wrap around system (a) initial condition and (b) final condition.

4.1.2 Case 2. Punch-Out System and Pressure Chamber

The aim of this experiment was to test a passive pressure balancing system in the simulated gob model. The University of Utah ventilation model was modified to include a pressure chamber and a flow control pipe, connecting the chamber to the main intake. In this case, most of the air is exhausted through the main return, while some portion of airflow is routed out through the bleeder airway. The chamber was built by isolating a section of the gob using three fully closed stoppings, F, G and H. Tubing were connected so that the existing airflow in the intake and return can be used to raise the pressure in the chamber. The connection was established from station 5 to F1, shown in case (b) of Figure 4.2. Two 3-mm diameter silicon tubes were used to connect the chamber to the intake and return airways. These tubes were equipped with pressure gages and flow control valves. A test was conducted under the following conditions:

- Main fan pressure: 1940 Pa.
- Regulator settings: I, and J were partially closed, with 5 % of total area open, regulators C and K had 28% of total area.

During the experiment the pressure differential between the chamber and the gob was monitored continuously. When this difference was notably significant, the pressure in the chamber was balanced by manually opening the flow control valves C1, depending upon the relative pressure in the chamber, shown in Figure 4.4. Figure 4.5, shows the pressure profile obtained before and after the opening of control valve C1, which was used to balance the pressure in the chamber.

A comparison of the pressure profiles shown in Figure 4.5 (a) and 4.5 (b) shows that when the control valve C1 was opened the pressure difference across regulator G, which separates the intake and gob, dropped from 550 Pa to 105 Pa. Numbers indicated on pressure profile represents measuring stations. Based on these results, it was concluded that a pressure chamber equipped with flow control pipes can be used to balance the pressure.

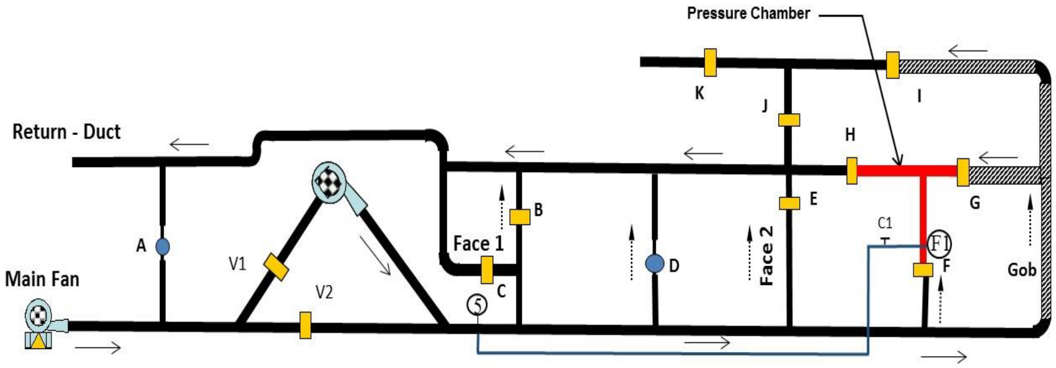

FIGURE 4.4. Schematic of the model for passive pressure balancing system

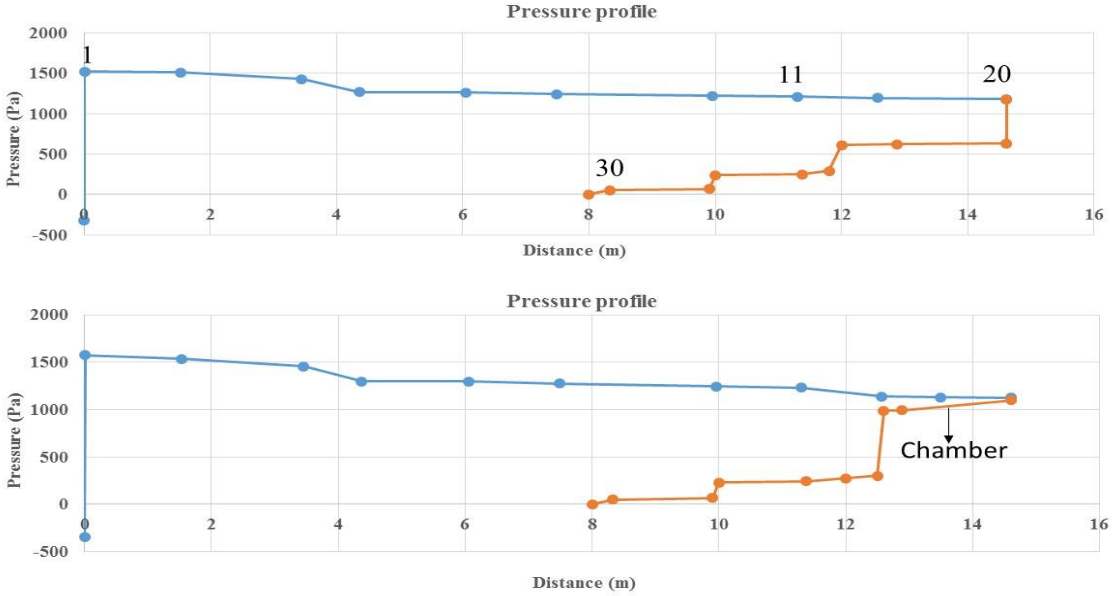

FIGURE 4.5 Static pressure profiles with pressure chamber in place; (a) when valves C1 was closed, and (b) after control valve C1 was open.

4.1.3 Case 3. Push-Pull System

This experiment was conducted to simulate a push-pull ventilation system. Two fans, a blower, and an exhauster were used, only bleeder airway was used for exhausting return airway as shown in case (c) of Figure 4.2. Initial conditions were by:

- Main fan pressure: 1030 Pa, Exhaust fan pressure: -1100 Pa.
- Quantity delivered: 0.48 m^3/s.
- Regulator resistance: Regulators C, G, I, had 50% of total area open, H and G were 28% open, while F was 8% open, and regulators E, J, and K were fully open.

Once the initial conditions were established, both fans were started. Airflow across the simulated continuous miner and longwall faces were 0.11 m^3/s (230 cfm) and 0.32 m^3/s (630 cfm), respectively. These values were similar to the U system of ventilation. Flow requirements were kept practically constant such that a fair comparison can be made between different ventilation systems.

It can be observed that pressure increases after the longwall face. This change is attributed to the fact that flow towards the gob area is very low, most of the velocity pressure is thus converted into static pressure in the gob area. The pressure differential recorded in this area was 292 Pa. Passive pressure balancing is not an option because the pressure available in intake duct (upstream the workings) is not sufficient to reduce the differential pressure in the gob. A pressure chamber was established using two fully closed regulators at F and H, while regulator G was 0.05% open. CO_2 was used to pressurize the chamber and the pressure differential was reduced to 70 Pa. Figure 4.6 (a) shows the static pressure profile for this scenario.

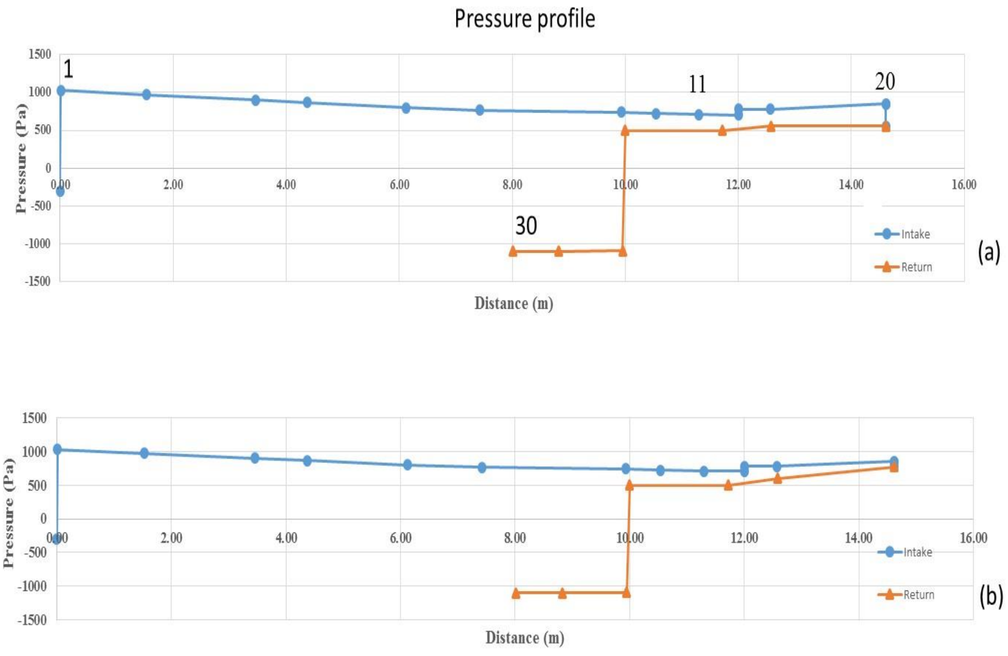

FIGURE 4.6 Pressure profile for the experiment, (a) initial condition with no chamber (b) final condition with chamber pressurized using CO_2

4.1.4 Case 4. Flow Through System

This experiment is related to the flow through ventilation system. In this system, intake and return airways are geographically separated. This scenario is depicted by Case (d) of Figure 4.2. It was simulated in the lab by using the bleeder return duct unobstructed except for the exhaust fan which was switched off. Initial conditions for this experiment are given below:

- Main fan pressure: 1605 Pa,
- Quantity delivered: 0.51 m^3/s.
- Regulator settings: regulators I: 50% of their area open, H and G, 28% open, F, 8% open, regulators C, J, and K were open.

The flow rates at the simulated continuous miner and longwall faces were 0.11 m^3/s (220 cfm), and 0.31 m^3/s (620 cfm), respectively. The pressure differentials across the gob area were substantially low as compared to other ventilation scenarios. On the average the pressure drop was 17 Pa. Air ventilates the working sections, after which it is exhausted through the bleeder duct. However, geographically, the exhaust is closer to the longwall face. So, the pressure required to overcome the frictional losses are much less compared to what was observed in U-system of ventilation. Moreover, the airflow towards the gob area is minimal such that pressure variation observed was almost nil. Pressure chambers or any other means of pressure balancing techniques are not required. However, to counteract possible barometric pressure variations, a pressure chamber can be installed between the intake and the gob. After which either passive or active pressure balancing can be used to pressurize these chambers and negate the effect of changes in barometric pressure. Figure 4.7 shows the pressure profile of this experiment.

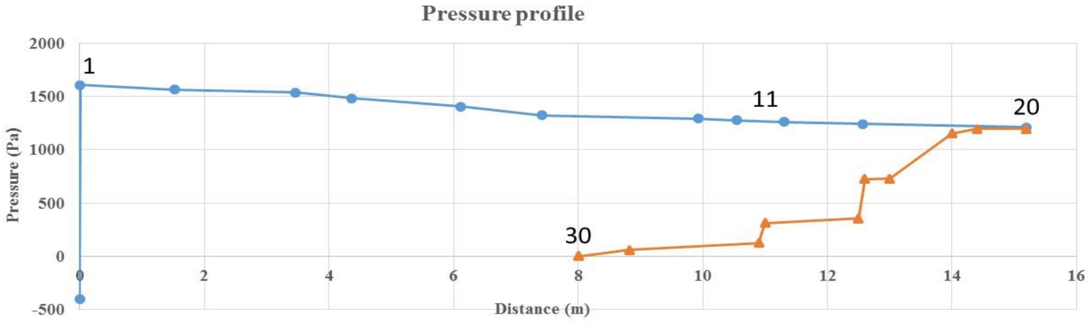

FIGURE 4.7 Static pressure profile for a through-flow ventilation system

A detailed theory and explanation on using active pressure balancing to mitigate effects of barometric pressure variation on the gob area is presented in Chapter 5.

4.2 Summary and Conclusions

Passive pressure balancing techniques were tested at the University of Utah laboratory model. Four cases were investigated. In each case, the objective was to neutralize the pressure differentials across the simulated gob. This was achieved in three cases. The fourth, did not require any pressure balancing. In each case, a test was started by recording the initial conditions, activating the fans, and measuring pressure differentials to establish critical locations. After which pressure balancing was implemented, and the final condition evaluated. A comparison between initial and final conditions was conducted to determine the efficacy of pressure balancing in reducing pressure differentials, thus reducing the ingress of oxygen to the simulated gob. In order to achieve pressure balancing regulator resistances can be changed at critical locations. This action was taken in Case 1. Another effective and efficient technique to balance pressure is by using pressure chambers. Once the chamber is established, it can be pressurized using existing high pressure airflows in a mine. This approach was used for Case 2. Case 3 emulates a push-pull ventilation system where pressure balancing was achieved by adjusting the position of two regulators. In Case 4, a through flow system was established and pressure differentials across the gob monitored. An evaluation of the collected data showed that pressure differentials across the gob area were much smaller than the other systems, and pressure balancing was not required.

Different ventilation systems are used in underground coal mines. The most common ones are U tube with wrap around, U tube with punch-out, push-pull, and through-flow systems. All these systems were simulated in the lab. In every case, the airflow requirements at the simulated workings were kept practically constant so that the results could be comparted and the layouts where pressure balancing can make difference can be determined. This study has shown that the flow through system is the most effective one for reducing or eliminating pressure differentials in gob areas. “Push-pull” and “U-tube” with punch-out bleeder systems are also effective but not as much as the flow through system. Table. 4.1 shows the four ventilation scenarios that were emulated in the laboratory model. In summary, of the different ventilation systems used in underground coal mines, the flow through system, with or without bleeder fan is the best one to mitigate spontaneous combustion fires.

TABLE 4.1 Ventilations scenarios simulated in lab model.

Case	Primary ventilation system	Gob ventilation scenario	Pressure balancing device
1	U-tube blower system (main fan only)	U- tube, Wrap-around system	Changing, regulator setting.
2	Blower system (Main fan only)	U-tube, punch-out system	Dynamic pressure Balancing
3	Push-pull (Main + Exhaust fan)	Flow through system	Dynamic pressure balancing
4	Blower system (Main fan)	Through flow system	---

CHAPTER 5

ACTIVE PRESSURE BALANCING

5.1 Introduction

Active pressure balancing requires the construction of pressure chamber(s) and an external pressure source. In the lab model, a pressure chamber was established by enclosing a portion of the simulated mine gob using gate valves of different resistances. Gate valves of variable open areas were used to emulate the leakage existing in real mines.CO_2 and compressed air were used as external pressure sources to pressurize the chamber. Crucial parameters such as pressure in the chamber, gob area, and flow rates at the faces were recorded continuously. Two sets of active pressure balancing experiments were conducted in the lab model: manual and automatic. In every case, a pressure chamber was first established, next the fans were activated, and pressure differentials at critical points monitored and evaluated, and the chamber was pressurized, when required.

5.2 Pressure Chamber

A pressure chamber is used to balance pressure between mine and gob. A portion of the University of Utah lab model was modified to establish the chamber. Gate valves were used to enclose a portion of the gob such that a chamber can be established. The gate valves used to isolate the chamber had variable open areas to emulate leakage through stoppings and seals in underground mines. This chamber physically separates the simulated longwall face from the gob.

5.3 Monitoring System

The University of Utah model was recently upgraded to include a continuous monitoring system. The objective of such a system was to record ventilation parameters continuously. These data can then be analyzed and used to balance the pressure in the simulated gob. Pressure transducers, hot wire anemometers, atmospheric pressure sensors and CO_2 concentration monitors were installed to accomplish this objective. Pressure transducers records the static, velocity and total pressures, an atmospheric sensor measures barometric pressure and air temperature, and a hot wire anemometer measures the air velocity. The CO_2 injection system consists of flow control valves, rotameters, and CO_2 sampling monitors. The data obtained from these transducers are continuously relayed to the host computer.

5.4 Effect of Barometric Pressure on Gob Ventilation

Changes in barometric pressure have a deep effect on ingress and egress of air from the gob area. An increase in the barometric pressure results in the ingress of air to the gob, while the lowering of the barometric pressure leads to the migration of gob gases to the mine working. This phenomenon occurs because the gob is often isolated by means of stoppings and seals, hence subject to small variation of pressure, while the working areas such as the longwall face is affected with changes in barometric pressure. In one of the experiments conducted at the lab model, a drop of 235 Pa of barometric pressure was observed in 5 hour. Figure 5.1 shows the barometric pressure profile for the lab model.

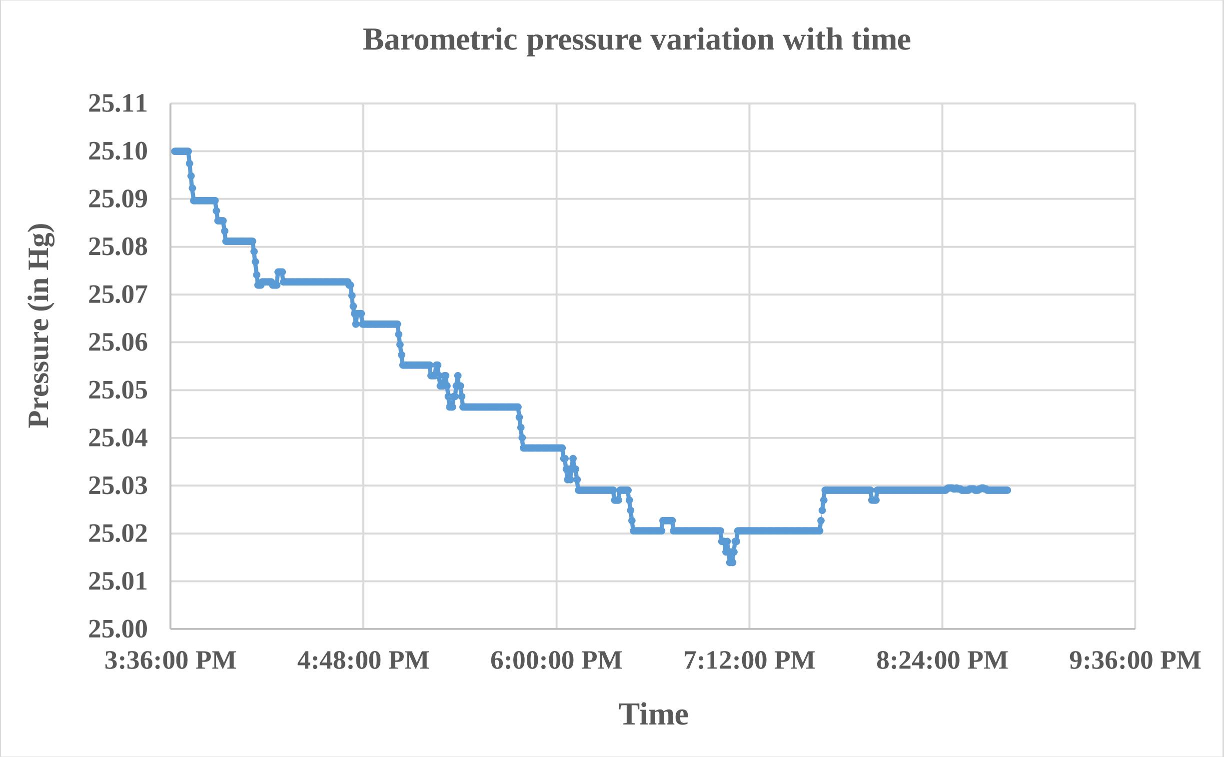

FIGURE 5.1 Barometric pressure variation with time

5.5 Pressure Balancing Experiments

This section includes two sets of active pressure balancing experiments: (a) using manually controlled CO_2 injection valves, and (b) automatic pressure balancing. In every experiment, system characteristics were recorded first using the continuous monitoring system, then the data were evaluated and the gas injection system activated to achieve pressure balancing. Pressure transducers located at three stations in the model (23, 26, and 27 in Figure 3.3) were used for recording gage pressures at the gob, chamber and mining areas, respectively. These pressures were then evaluated using a subroutine to ensure that the pressure in the chamber was always equal or greater than the mining and gob areas.

5.6 Active Pressure Balancing – Manually Controlled Method

Depending on the quality of the gate valves used to establish the pressure chamber, two cases of active pressure balancing experiments were set up: (1) using gate valves of the same resistance, and (2) using gate valves of variable resistance. In the former, the open areas of the three gate valves were kept constant. In the latter, the open area of at least one valve was increased to simulate a low resistance stopping. In both cases pressure balancing was achieved by using an external pressure source. CO_2 and compressed air were used to pressurize the chamber. An expert judgement is required to start the injection system when the simulated mining area or the gob pressure poses an imminent danger of either a spontaneous combustion event or methane gas inundation. These hazards can be precluded by raising the pressure in the chamber above the two affected areas.

5.6.1 Case 1: Active Pressure Balancing: Constant Gate Valve Resistance

For this experiment, three gate valves were used to establish the pressure chamber. Of these, two were fully closed (F and G) and the third (H) had 0.05% of its total area open. The chamber volume was 0.03 m^3 (1.2 ft^3). The pressure source was represented by a CO_2 cylinder, connected to the chamber by a high pressure hose and a flow control valve. Pressure transducers and CO_2 sensors were used to monitor pressure differentials and gas concentrations in the gob. Two pressure transducers (PS 26 and PS 23 in Figure 3.3) were used to monitor pressure differential across and around the gob. The initial and final conditions for this experiment are given by:

- Main fan duty: Pressure 1790 Pa, quantity 0.41 m^3/sec.
- Regulator settings: Regulators A, B, D, F, G, and K were fully closed;

H, 0.05% open.

- When adverse conditions were detected, the chamber was pressurized using CO_2 gas.

Specifically, 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 (stage 1). The gas injection system was then opened to reach a pre established flow rate, held for few seconds, and then shut off (stage 2). This caused the chamber to be pressurized and a new steady state level 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. The initial conditions and the results achieved are presented below.

When the experiment was initiated (stage 1), 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 Figure 4.1 and using a wrap around ventilation system. Under this condition, the chamber was held under negative pressure. The flow observed at the continuous miner and longwall faces were 0.11 m^3/s and 0.29 m^3/s, respectively. This pressure difference is sufficient to cause the ingress of gob gas into the face. To mitigate the problem, CO_2 was injected into the chamber at the rate of 10 lpm (stage 2). Figure 5.2 shows the pressure profile for the experiment.

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 part of the pressurized gas to migrate from the chamber into the gob. This flow reversal can be sustained as long as the gas injection rate is kept constant. When the gas injection

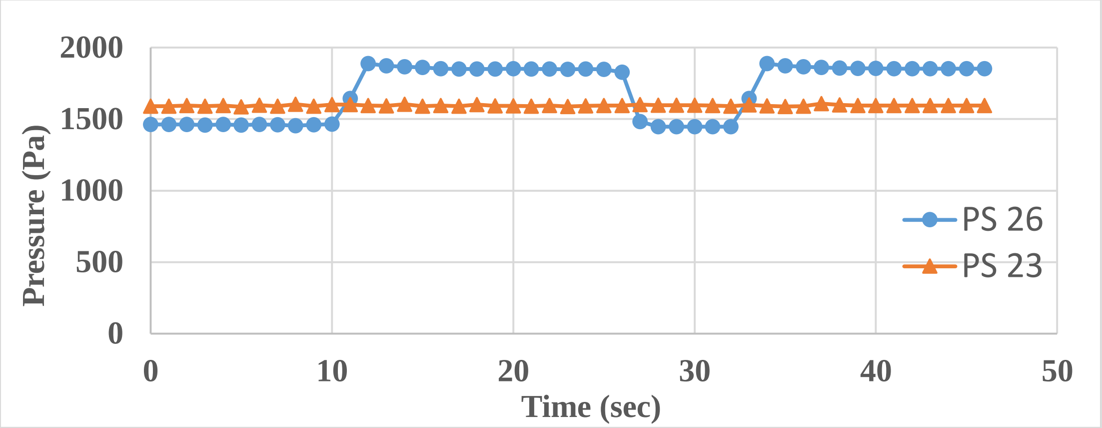

FIGURE 5.2. Pressure build-up and decay in the chamber with changes in gas injection rate.

was stopped, the pressure in the chamber returned to its initial level. Figure 5.2 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.

5.6.2 Case 2: Active Pressure Balancing: Variable Gate Valve Resistance

Pressure chambers are built to achieve pressure balancing in certain areas of a mine. In this context, the conditions under which stoppings are kept during mining are crucial to the effectiveness of the chamber. Damaged stoppings will cause an increased leakage, resulting in a rapid decay of pressure. An experiment was conducted to simulate the build up and decay of pressure in the chamber with changes in regulator resistances.

The initial and final conditions for this experiment are given by:

- Main fan duty: Pressure 1880 Pa.
- Quantity delivered: 0.46 m^3/s.

- Regulator settings: Regulators A, B, D, F, G, and K were fully closed, H, 0.05% open.
- Final condition established by increasing the area of regulator H from 0.05 to 0.1% open.

As in the previous case, the pressure chamber was established using three gate valves: two fully closed (valves F and G in Figure 3.3), and one (H) in which the open area was changed for the two conditions. For the first condition, the valve H had 0.05% of its total area open. When the air pressure in the chamber was less than the gob pressure, the gas injection system was initiated manually. Compressed air was used as a source of injection which was injected at the rate of 10 scfm. The chamber was pressurized to almost 3500 Pa. The time elapsed before the chamber achieved a steady state was about 7 seconds. Once the steady state condition was achieved, the flow control valve was shut off. The partially open gate valve induced leakage and depressurized air in the chamber. The elapsed time before the chamber reached its initial pressure (without injection) was 4 seconds. The air pressure in the chamber was monitored continuously using a micromanometer. The results are shown in Figure 5.3 (condition 1).

The experiment was repeated for a second condition, in which the area of gate valve H was increase to 0.1% open. As in the previous case, the chamber was pressurized to about 2700 Pa. Once the steady state condition was attained the control valve was shut off. Again, the partially open gate valve induced leakage and depressurized the chamber. Figure 5.3 (condition 2) also shows the profile obtained for this experiment. In both cases, the air pressure in the gob area was kept constant.

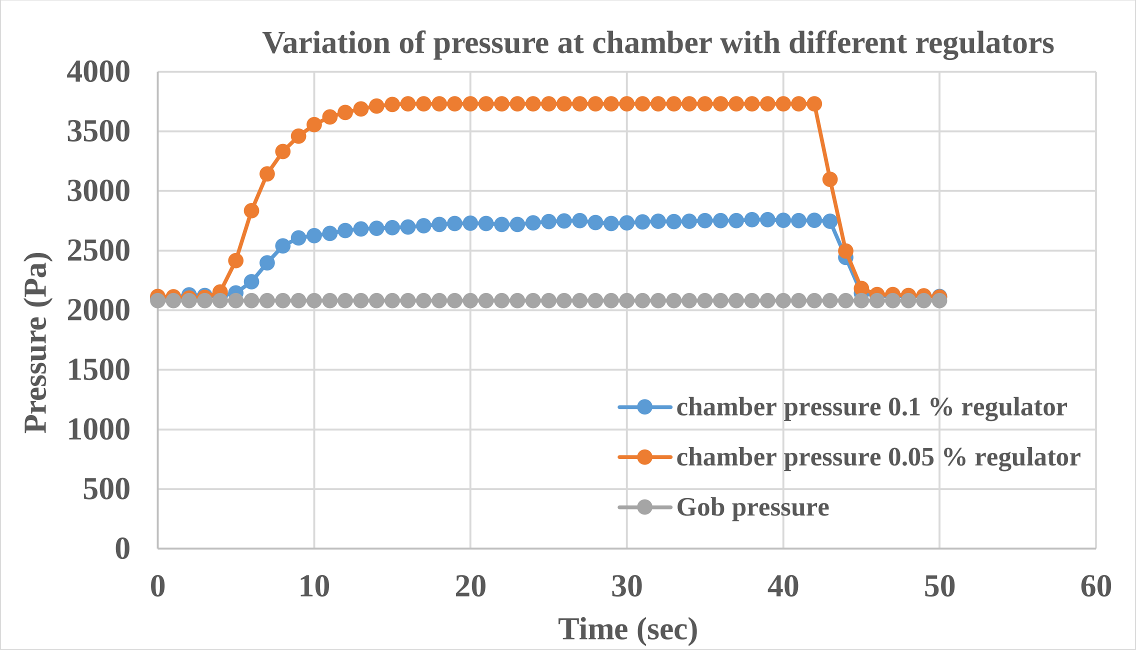

FIGURE 5.3. Pressure profiles for two gate valve conditions.

5.7 Automatic Pressure Balancing Method

This method, in addition to an external pressure source, requires an atmospheric monitoring and controlled system. 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. In this context, the sampling rate is crucial. Sampling rate refers to the interval at which data is collected from the system. Usually, this is collected at one second interval, however, it can be changed for different conditions. An experiment is stated by setting up the initial conditions and switching on the monitoring system. This action allows the system to interface with all the transducers and collect data. The fan duties can be adjusted via the monitoring system. Once an experiment is completed, the collected information can be recorded in ASCI format and opened as an Excel file. This enables the operator to analyze the data easily. To automate the pressure balancing process, a subroutine, APBCON (Automatic pressure balancing controller), was written and added to the monitoring software. Once the program is initiated, it evaluates the collected data, compares the pressure differential between the chamber and the gob, and between the chamber and the longwall face. If the chamber pressure is less than the pressure of either side, gob, or longwall face, the program will open the flow control valve and initiate the gas injection process. The gas injection will continue until a predefined maximum pressure in the chamber (upper bound) is reached. For pressure balancing, this pressure should be slightly greater than the pressure of either side, gob or longwall face. Once the preset minimum pressure in the chamber is achieved, the program will shut off the flow controlled valve automatically.

The automatic pressure balancing is an additional feature in the atmospheric monitoring system, which can be initiated when required. It can be used to ensure that the pressure in the chamber is always greater than the pressure of either side, gob, or longwall face. Figure 5.4 shows the flow chart of a subroutine which was developed to automate the pressure balancing system at the University of Utah lab model.

The following logic is used by the subroutine: if the monitoring system detects a “significantly negative” pressure differential across any stopping separating the chamber from the gob or work area, the program will switch on the gas flow control valve, pressurize the chamber, and evaluate the pressure differentials continuously. When the chamber pressure is equal to or greater than a preset value (2000 Pa), the control valve will be switched off. This will reverse the leakage flow direction and decrease the chamber pressure. The process will continue until another preset value (lower bound) is reached, which in this case is set at 100 Pa. Upon reaching the lower bound, the program will again

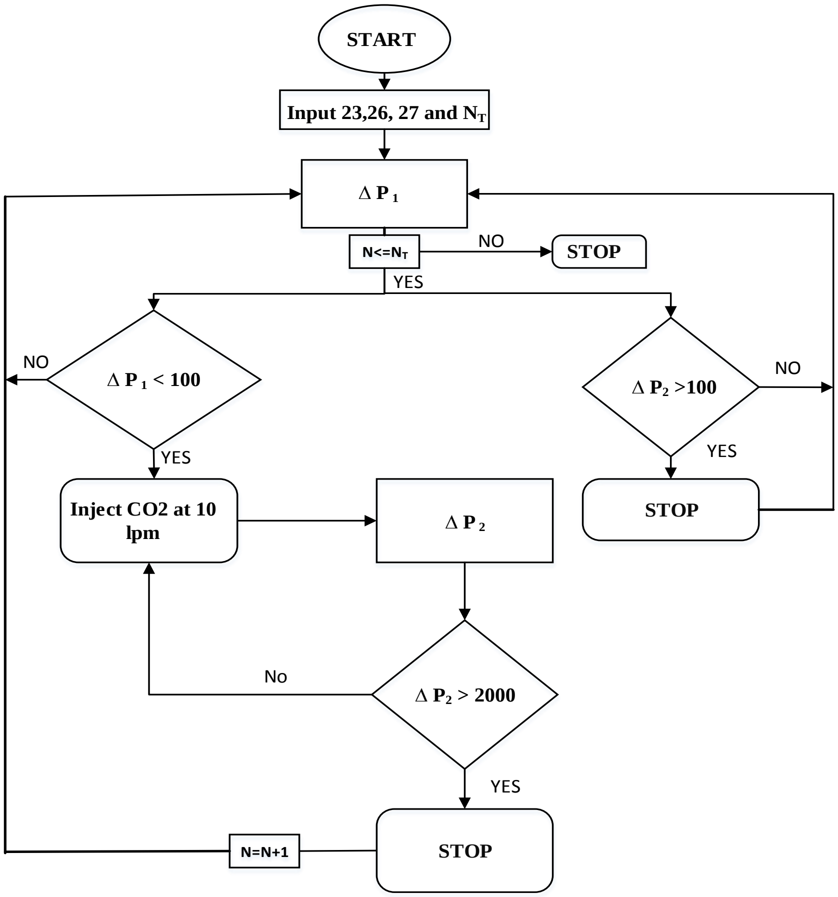

FIGURE 5.4. Flow chart for automatic pressure balancing

start the gas injection process. 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 variations in atmospheric pressure. Figure 5.4 shows a flow chart describing the control process. Based on Figure 5.4, automatic pressure balancing is performed by comparing two pressure differentials: $\Delta P_1 = \Delta P_{26-23}$ or ΔP_{26-27}, $\Delta P_2 = \Delta P_{26-23}$ and ΔP_{26-27}. The subscripts refer to pressure differential between two corresponding stations. N_T is the required number of iterations set by the user for one experiment. In the field this can vary from days to months depending on the local conditions.

Several experiments were conducted to test the above mentioned subroutine. The initial conditions and the results of one of these experiments is described below.

5.7.1 Case 3: Automatic Pressure Balancing: Constant Gob Pressure

The objective of this experiment was to test the flow control subroutine described previously. The initial and final conditions for this experiment are given by:

- Main fan pressure: 1900 Pa, quantity delivered: 0.48 m^3/s.
- Regulator settings: A, B, V1, D, G, F were fully closed, regulators E, I, had 50% of its total area open, while H had 0.001% open, C had 28% of its area open, K and J were fully open.
- Final condition was set by switching on the flow control valve of the gas injection system automatically as per the flow chart shown in Figure 5.4.

Once the initial condition was established, the main fan was switched on and the relevant data recorded by the continuous monitoring system. The flow requirements at continuous miner and longwall faces were set to be 0.13 m^3/s and 0.32 m^3/s, respectively. The ratio of these quantities is close to what has been observed in underground coal mines. Automatic pressure balancing is achieved by enabling the flow control subroutine while the monitoring system is operating. The subroutine compares the pressure differential against the preset values and operates the flow control valve to balance the pressure across the chamber stoppings. This comparison is made every second. For an injection rate of 10 lpm, the maximum pressure in the chamber is usually achieved within 5 seconds. The program stops the injection process as soon as the maximum preset pressure in the chamber

(2000 Pa) is reached. Then, this is allowed to decay due to leakage through the stoppings. The elapsed time before the minimum allowable pressure is reached was 95 s. Figure 5.5 shows a pressure profile for the ventilation model when the pressure balancing routine was activated. Based on this graph, to reverse through the isolation stoppings, the chamber pressure was increased from about 500 Pa to 2200 Pa.

Figure 5.6 shows the pressure variations in the chamber and gob areas when the gas flow control valve was activated by the monitoring system. Once started the injection system and the pressure build-up in the chamber is quite rapid. This depends on the quality of the isolation stoppings. When a preset pressure differential of 2000 Pa was reached, then the injection system was stopped automatically. Then, 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 differential are detected. Since there is still some gas available in tubes after the gas injection is turned off, the chamber is pressurized till 2900 Pa The number of trials in this experiment was set to three.

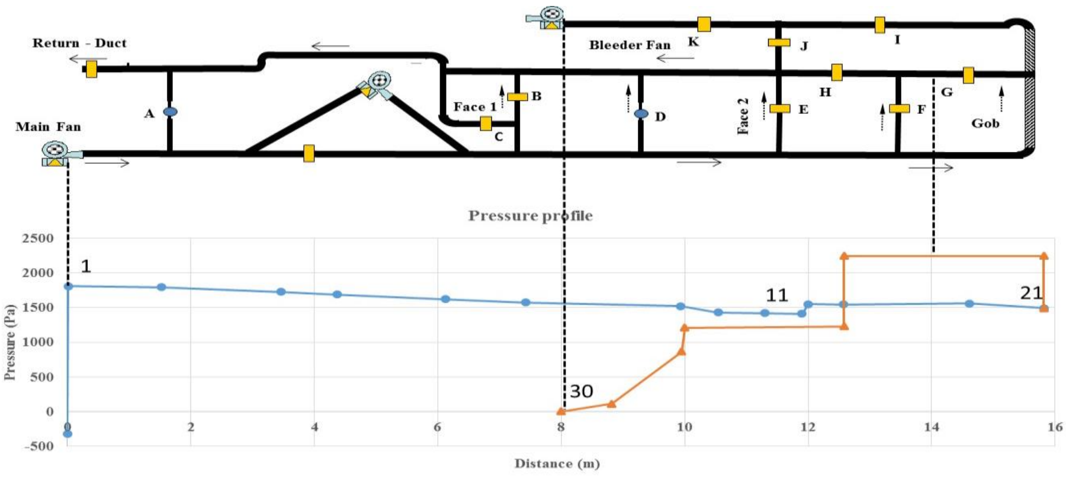

FIGURE 5.5 Pressure profile with automatic pressure balancing

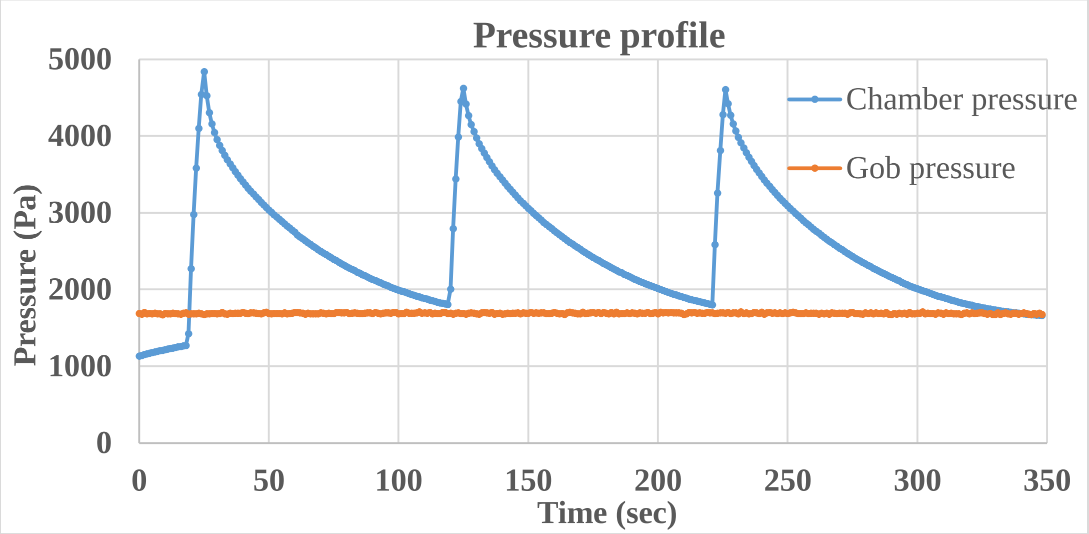

FIGURE 5.6 Pressure profiles generated by the automatic CO_2 gas injection system

In a mine, as the longwall face progresses, the gob is subject to caving and subsidence. Depending on local conditions, the fractured zone can propagate all the way to the surface. Under such conditions, the gob pressure is practically equal to the atmospheric pressure. However, the overburden strata just above the working area are still free of cracks, therefore not affected by the changes in atmospheric pressure. In this case, a differential pressure is created between the mine and gob areas. This difference may be sufficient to induce transient flows in the ventilation system. In order to reduce this difference, pressure chambers can be established and connected to the surface through boreholes. Under these conditions, the chamber would be at a pressure almost equal to atmospheric pressure, thus neutralizing the pressure differential across the isolation stoppings. Figure 5.7 illustrates a case in which a pressure chamber is used to manage transient flows in the gob area. This is a simple application of a pressure balancing technique to mitigate mine hazards created by changes in atmospheric pressure.

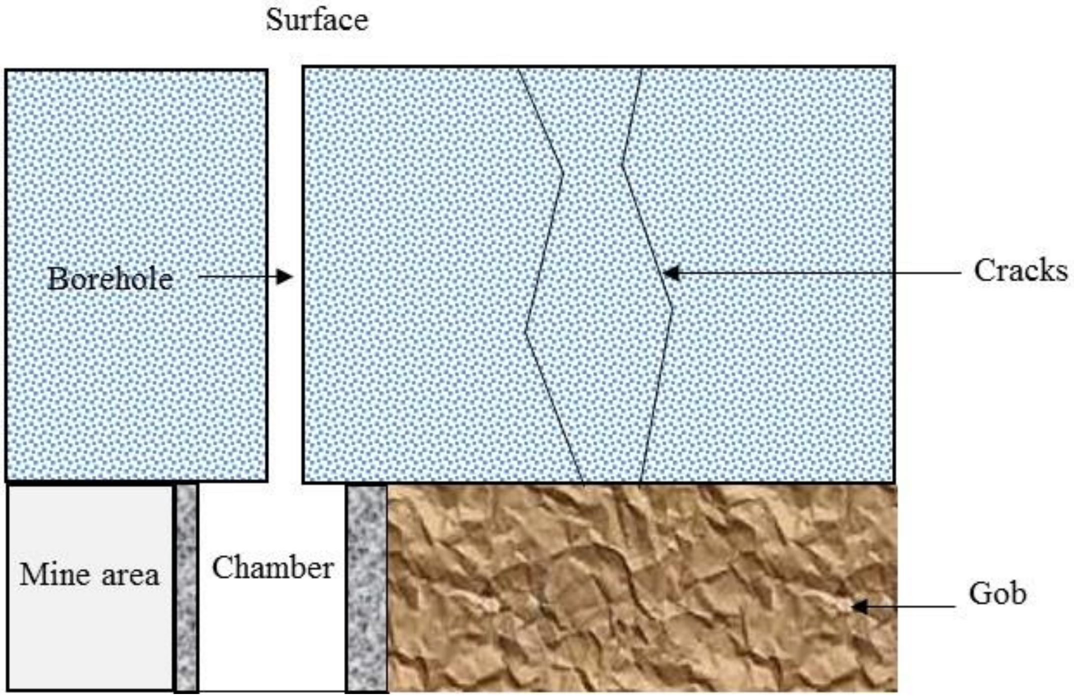

FIGURE 5.7 Schematic showing pressure balancing

5.8 Summary and Conclusions

Active pressure balancing is a viable technique to control spontaneous combustion in coal mines. It is desirable when passive balancing cannot be used to accomplish this objective. It requires a pressure chamber(s) and an external pressure source which could be operated manually or automatically. Two experiments were conducted to observe the efficacy of this technique in equalizing pressure differential in a simulated mine gob. In both cases, carbon dioxide was used as the pressure source which was injected manually. In the first case, the pressure chamber was established by using three seals, represented by high resistance gate valves. When the chamber was pressurized using CO_2, the chamber pressure declined mainly due to leakage to the external environment. In the second case, two seals of the chamber were replaced by stoppings of lesser resistances. The use of these stoppings increased the leakage from the chamber to the simulated gob, thus accelerating the pressure decay rate in the chamber.

Automatic pressure balancing is another type of active pressure balancing in which the external pressure source is operated automatically. A subroutine to automate the process was developed and incorporated to the laboratory model's continuous monitoring system. A third experiment was conducted to illustrate the application of this subroutine to equalize the pressure differential in the simulated gob. The results of this experiment showed the pressure differential in the gob, direction, and quantity of leakage flow rates, can be controlled using the monitoring system automatically.

CHAPTER 6

FIELD VISIT TO A COAL MINE

6.1 Introduction

Mine visits are essential to gain a thorough understanding of complex ventilation systems. The main objectives of these visits are to collect data and conceptualize the process of pressure balancing. In this context, pressure quantity surveys of mines helps in evaluating and analyzing critical ventilation parameters. In this chapter, one such visit to a coal mine is described in detail. For confidentiality purposes the mine will be referenced as Mine A.

6.2 Description of Mine A

Mine A is located in the southern Illinois region in the midwest United States. Coal is mined out using a room and pillar mining method. The mine follows a fish-tail ventilation system; where the intake air splits into two directions at the section mouth. This ventilation system allows the mine to have a large number of entries in a panel, which increases the life of the panel. Mine A has 21 entry panels; 3 intake airways (primary escape way), 3 neutral airways comprising of belt, travel way (secondary escape way and storage entry), seven return entries on the left side and eight return entries on the right-side of the panel. The average time to mine out a panel is 1.5 years. Another important aspect of ventilation system is antitropal ventilation; meaning that the belt and air in the belt entry moves in opposite directions.

Dimension of the pillars measured in the panels are 18 x 18 m (60 x 60 ft) center to center, while the mains have 25 x 25 m (80 x 80 ft) pillars. The entries are 5.4 m (18 ft) wide and 2.2 m (7.4 ft**)** high. The overburden is planer, and, for the most part, an even 76 m (250 ft) deep.

6.3 Ventilation Survey and Results

The purpose of the visit was to conduct pressure quantity surveys, to inspect seals and stoppings used to isolate mined out areas, and to use this information to develop conceptual pressure balancing designs. The mine uses an exhaust system equipped with twin fans in parallel arrangement. Of these, only one is used at a given time. The capacity of this fan is 380 m^3/s of air at 1.75 kPa of total pressure. Figure 6.1 shows a ventilation schematic of this mine. This figure also shows the locations of three active workings, and a summary of the surveyed data. A brief evaluation of the surveyed data shows that of the total quantity, about 64.3 m^3/s was available to ventilate the surveyed area (B). The total flow rate measured in the return airways was 65.1 m^3/s. The highest pressure differential recorded across the intake-belt stopping was 3.75 Pa (0.015 in w.g), while at the intake- return stopping was 36.75 Pa (0.147 in w.g). Table 6.1 shows a summary of results of the survey.

Figure 6.1 also shows the schematic of the mine plan with the ventilation system and working area. The seals installed at the gob area were inspected to evaluate the feasibility of constructing pressure chambers to implement an active pressure balancing system to counteract the negative effects of changes in barometric pressure in the mined out area.

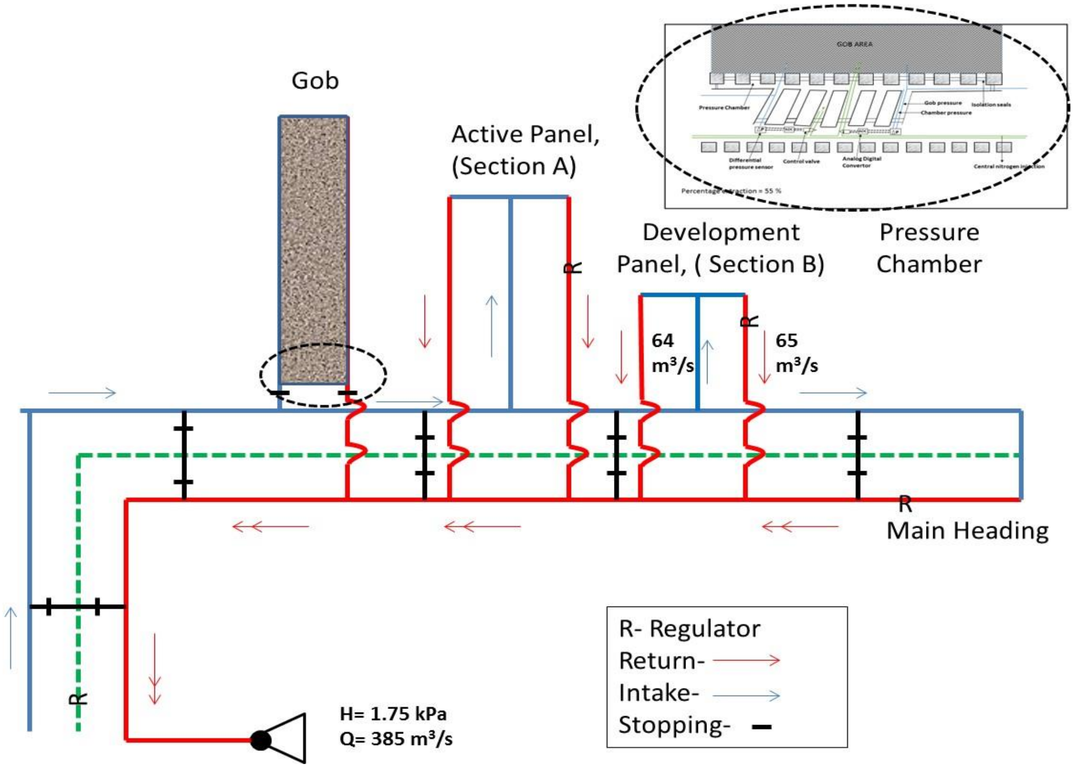

FIGURE 6.1 Mine A ventilation schematic showing P-Q survey results.

TABLE 6.1 Ventilation Survey data for Mine “A”.

Station No.	Quantity Measurements			Quantity	Types of airways	Pressure drop
	Area m^2	Velocity m/s	Quantity m^3/s			
1	17.4	0.52	9.0	64.3	Intake airways	3.75 (across intake and belt)
2	11.7	2.1	24.6			
3	14.8	1.82	26.9			
4	11.9	0.31	3.7			
1	13.3	2.26	30.1	65.1	Return Airways	36.75 (across intake and return)
2	14.2	2.24	31.8			

The seals were constructed and maintained as per MSHA guidelines and rated to withstand pressures greater than 827 kPa. The seals are built to isolate the working sections from worked out panels. However, as discussed in previous chapters, these seals are not completely airtight, and some leakage, ingress and egress of air, into or from the gob area is expected, especially when such an area is fractured and subject to changes in barometric pressure. In shallow mines, with fractured overburden, changes in barometric pressure pose a significant risk to spontaneous combustion and methane gas inundation. Pressure balancing can be used to control this situation effectively. The intake shown in Section B (in blue) was surveyed, there are, in fact four intakes depicted by one bold blue line. The readings mentioned in Table 6.1 for intakes corresponds to these four intakes. There were two returns which is shown by the red line (Section B) in Figure 6.1. The readings for intake and return were close to each other, demonstrating accurate measurement.

6.4 Conceptual Pressure Balancing Design

Pressure balancing is the process of equalizing pressure differentials between two areas separated by stoppings or seals. In a coal mine where the coal is susceptible to spontaneous combustion, this is accomplished by establishing a pressure chamber between a mining area (face) and caved area (gob), monitoring pressure differentials, and injecting an inert gas such as nitrogen to the chamber in a controlled manner. In an attempt to produce a conceptual pressure balancing system for Mine A, a plan was put together and a proposed operating procedure outlined. The plan includes the construction of a pressure chamber, the procurement of an external pressure source and an upgrade of an existing atmospheric monitoring system. The chamber consists of seals and stoppings equipped with gas sampling ports and flow control valves. Seals that are already in place are used to isolate the worked out area. Stoppings to be built in nearby cross-cuts are added to isolate the chamber from active workings. Liquid nitrogen, stored on surface and piped to the gob area is used as an external pressure source. Pressure transducers capable of measuring pressure differentials across the stoppings and seals are added to the existing mine monitoring. Once this system is in place, it can be operated manually and the gob can always be kept at a pressure lower than the active mining area. The operating procedure to be used can be summarized by the following steps:

- Monitor pressure differentials across the isolation seals and stoppings. This can be accomplished by the atmospheric monitoring system.
- Evaluate the pressure differentials. The objective of this evaluation is to ensure that the chamber pressure is always higher than the gob pressure.
- Activate the gas injection system. If the condition stated in step 2 is not fulfilled then the chamber should be pressurized by opening the flow control valves. Nitrogen can be injected to pressure the chamber in a controlled manner.

Figure 6.2 shows a schematic of a proposed pressure balancing chamber for Mine A. This is a conceptual design of a pressure chamber that can be used to neutralize the pressure difference across the isolation seals and the chamber so that the leakage of air to the sealed area (gob) is excluded. The mine gob is isolated by means of high pressure (120-psi) seals. A set of low pressure (60-psi) stoppings is used to separate the chamber from the intake airways. The chamber is equipped with two pipes connecting the chamber with the intake and return airways, respectively. The pressure in the chamber is monitored by a manometer. The pressure difference across the low pressure seals is balanced by adjusting the flow rates through the pipes. A second pipe is used to draw air samples from the gob area and to monitor the pressure difference between the chamber and the gob (gage 2). Figure 6.2 shows a schematic for conceptual pressure balancing.

6.5 Summary of the Findings

A pressure quantity survey was conducted, and relevant ventilation parameters were recorded and evaluated. Seals in the worked out areas were inspected. A conceptual pressure balancing system suitable for a room and pillar coal mine was devised by adding all the necessary facilities to the current mine infrastructure. It is expected that this design can be used to mitigate potential hazards associated with spontaneous combustion in this mine.

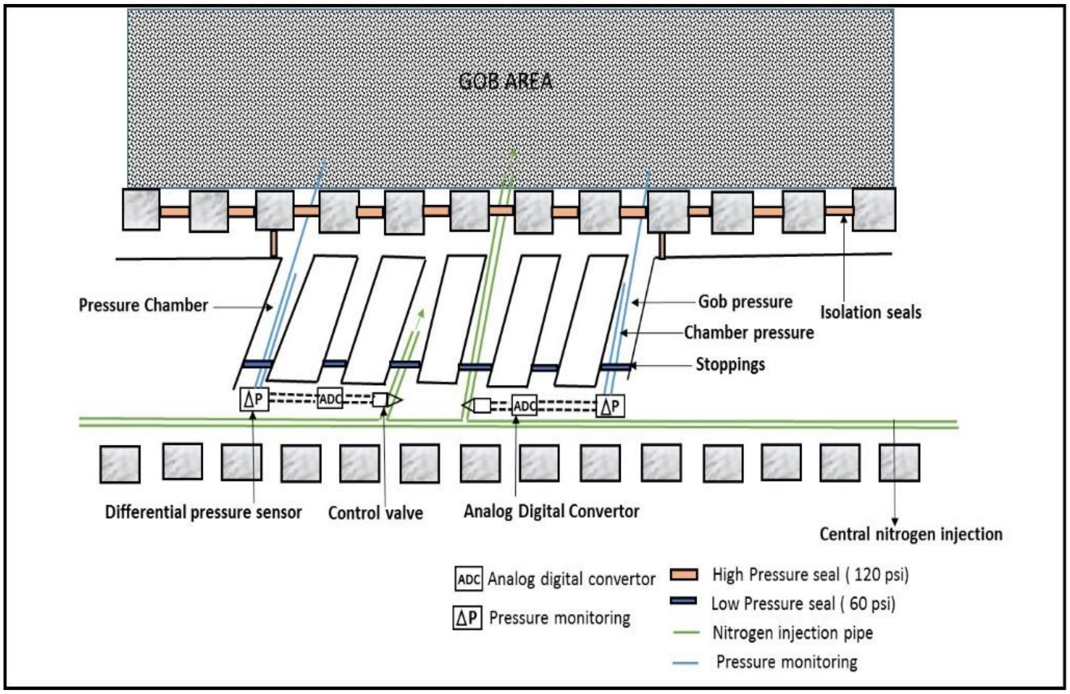

FIGURE 6.2 Conceptual pressure balancing design.

CHAPTER 7

RISK ASSESSMENT FOR SPONTANEOUS COMBUSTION IN MINES

Spontaneous combustion is a serious hazard in coal mines. Risk assessment of the process assists management in evaluating potential hazards and developing strategies to control the problem. In this chapter, a risk tool called “bow-tie” analysis is used to evaluate risk associated with spontaneous combustion in a coal mine. Mitigating measures corresponding to these risks are also suggested. Mine A is used as the sample mine for this analysis.

7.1 Bow-Tie Analysis

Bow- tie analysis is a powerful tool for risk assessment and control. It combines causes and consequence analyses into one diagram. The diagram when plotted resembles a bow-tie. In the process the hazards and consequences are linked through a series of event lines. Following are salient features of bow-tie analysis:

- Visual, simple, and effective tool which combines cause and consequence analyses in one diagram.
- Potential threats and consequences for a top event and

corresponding preventive and recovery controls are illustrated, which are often linked to a safety management system. It is easy to understand and comprehend at upper management and administration level.

- Helps to better prepare and equip mines to deal with the potential hazards.

7.2 Risk Analysis Using Bow-Tie

Interaction of coal and oxygen is an exothermic process, and the accumulation of this heat can lead to mine fires and explosions of catastrophic consequences. This has both safety and economic implications and should be addressed and managed properly. This analysis is done for a sample sub-bituminous coal mine. Spontaneous combustion is a serious threat in mines with these types of coal, especially when they are not ventilated properly. Bow-tie analysis can be used to understand the complexities of the problem in a better way.

Important features included in a bow- tie analysis are threat, preventive measures, top event, recovery measures, and consequences. Threats are conditions that can eventually lead to the happening of an unfavorable event termed as top event, which for this analysis corresponds to initiation of spontaneous combustion. All the “threats” are evaluated and necessary preventive measures are put together. These preventive measures are barriers which prevent the threat to release the unwanted energy. Each preventive barrier is arranged in sequence of implementation. Having recovery measures in place, should the hazard occur, is an integral part of bow-tie analysis. It helps to have a detailed plan of mine preparedness for a case of emergency. Control measures are required to subside the effects of the top event. These measures are also placed in sequence of their implementation. All the control measures can be listed and analyzed and the responsibilities for putting each one of them in place assigned.

The potential causes or threats which can lead to the hazard of spontaneous combustion are multifold and include geologic disturbances, coal quality, mining method, production rate, environmental conditions, and method of ventilation. Corresponding to each threat, preventive control measures are placed. Since some of them are related to inherent coal seam characteristics and the mining method used, such as geologic features, and how caved areas are ventilated, special emphasis should be placed on studying these characteristics and documenting them in the mine maps. This is crucial, as failure to do so can enhance the rate of spontaneous combustion, which once started, is difficult to control due to limited and costly control measures.

Threat factors associated with the mining method should be carefully evaluated and taken into consideration when planning for the control of spontaneous combustion. Ventilation is one of the crucial parameters in mines as the coal-oxygen interaction is the main catalyst of spontaneous combustion. It should be planned in a manner such that spontaneous heating can be prevented. This can be achieved by lowering the pressure differential across pillars and stoppings, inhibiting the flow of air to gob areas, and increasing air velocity at certain places to dissipate heat. Coal needs a certain amount of time before spontaneous heating can set off and initiate the fire. This also depends on the mining method and rate of extraction. High production rates such as those achieved with longwall mining method, will definitely assist any control plan developed to mitigate the spontaneous combustion problem. The level of humidity is another factor which can enhance or reduce the rate of combustion and should be addressed properly by keeping in mind all the available options. Escalating factors, which are conditions that lead to increased risk by reducing the effectiveness of barriers, should also be taken into account. Controlling these escalating factors should be considered in the analysis so that control barriers work effectively.

When all the control measures have been established and understood, the recovery measures can be addressed. The consequences of spontaneous combustion can vary in degree from the loss of panel and mining equipment to mine closure. The control measures that should be put in place vary from isolation of mined out areas, installation of rescue chambers, to training of mine personnel on fire control and orderly evaluation. In case of pillar fire, task training should include the use of fire extinguishers, safety lines, and mine evacuation. Mine workers should be trained in using Self-contained self-rescue (SCSR) apparatus and in following escape way routes and refuge chambers, which are vital against carbon monoxide poisoning. In gassy mines, the risk of explosion is always present, especially in the gob areas where methane concentrations are high, sometimes within the explosive range, which can be ignited by the spontaneous combustion process.

Once spontaneous combustion is started it is difficult to control. Bow-tie analysis can help us to appropriately visualize the process and have control measures in place. Furthermore, it leads to the creation of preventive measures and controls not currently in place. Once the senior management is familiar with all these preventive controls and recovery measures, then informed decisions can be made. For effective risk management these controls should be communicated to the mine workers, such that an adequate response to an unwanted event is taken in a timely manner. Moreover, proper training should be provided to all workers so that their preparedness can help in mitigating potential losses caused by this hazard. Proper training of personnel is crucial not only to achieve production targets but will also to reduce injuries and fatalities. All the controls and recovery measures from this analysis can be linked to the planning and management system so that all decisions are taken considering the tolerable risks and resources available. When all the considerations of the analysis are met, it is expected that the mine will achieve its production targets without any disruptions. In case of an adverse event, mine workers will be prepared to assist the management to control and mitigate the hazards and risks associated with spontaneous combustion of coal.

Figure 7.1 shows a bow-tie analysis for Mine A. Potential threats and contributing factors are outlined. These are propensity of coal to spontaneous combustion, geologic disturbances, type of ventilation system, humidity, mining method, and rate of extraction. For each of these threats, preventive measures are devised and illustrated. A detailed study of the properties of coal and geologic features will assist management to assess the risks associated with spontaneous combustion. Moreover, the ventilation method to be adopted should be based on the characteristic of coals. If the coal is susceptible to spontaneous combustion, pressure differentials across the mined-out areas should be minimized. A bleederless ventilation system can be used to this purpose. The use of other ventilation control devices, such as booster fan and pressure chambers should also be considered. Furthermore, to reduce possibility of spontaneous combustion planning should be such that highest possible production rate can be ensured. In such a case, the coal extraction time is faster than the incubation period or the time elapsed before the spontaneous combustion is initiated. If the coal is extracted before the incubation period and mined-out area is sealed, then the hazard of spontaneous combustion will be prevented.

The success of any spontaneous combustion control method depends on the availability of an environmental monitoring system. In coal mines, monitoring systems are used to collect reliable information on several factors including gas concentrations and pressure differentials in real time. This information is crucial to prevent the onset of unwanted events. Control measures to mitigate the severity of problem should always be in place. In case of fires, these measures include water/mist sprays, Gels, Halons, lifelines and rescue chambers. Furthermore, mines should also be prepared to mitigate advanced stages of fire by isolating and injecting inert gas to the affected area.

This analysis will help in having a better understanding towards spontaneous combustion process. Ventilation system to be implemented in the mines can be decided based on outcome of this analysis.

7.3 Result and Discussions

Bow-tie analysis of spontaneous combustion can assist management in evaluating all the possible factors contributing to potential hazard. This can be achieved by reviewing literature on the matter, and relating it to the actual mine being evaluated. Crucial aspects that can contribute towards spontaneous combustion problem for Mine “A” are the ventilation method and the coal production rate. Pressure differential across the gob area should be controlled. Pressure balancing can be a viable and effective technique as explained in previous chapters. The rate of production is usually low in room and pillar mines. This may pose a threat since small fires cannot be controlled by burying them. The worked out area should be sealed in a timely manner such that oxygen-coal interaction time can be reduced to a minimum. All the senior personnel working in the mines should be involved in developing and implementing the plan, such that all the relevant points can be covered. Preventive control and recovery measures should also be devised. By doing so, mine workers can understand the nuisance of the problem, and contribute in solving potential hazards in a timely manner. Figure 7.1 also summarizes the potential hazards, preventive measures, mitigating techniques and the consequences if these are not implemented.

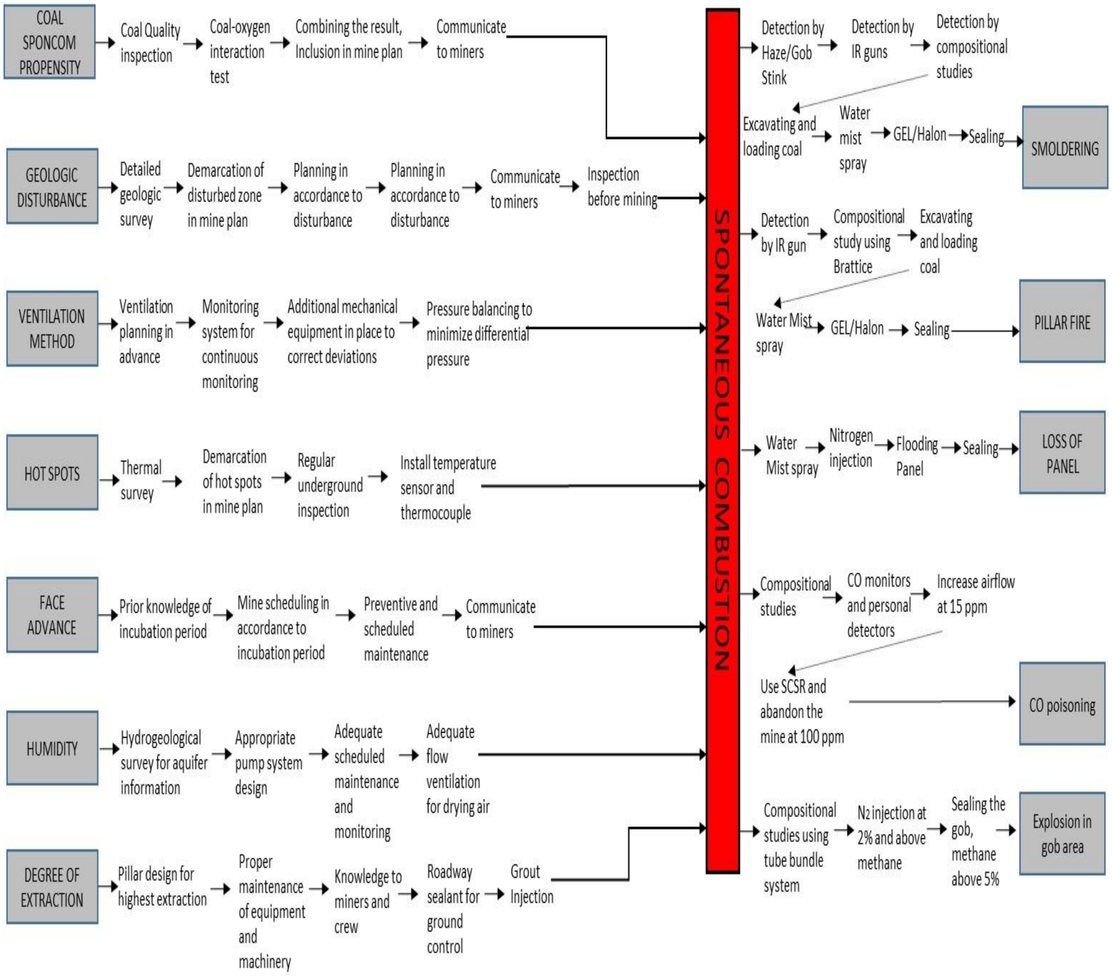

FIGURE 7.1 Bow-tie analysis of spontaneous combustion.

CHAPTER 8

CONCLUSIONS AND DISCUSSIONS

8.1 Conclusions

Coal has an inherent tendency to self heating and combusting with the presence of oxygen. This process is known as spontaneous combustion. Once the ignition process has started, it is very difficult to control. In the past, countries such as India, China, and the United States have had severe fires due to spontaneous combustion of coal. These have had drastic negative social and economic implications. In two cases, one in India and another one in United States., the entire town had to be evacuated and relocated. Thirty years after the fire was initiated, the Centralia's fire is currently still burning to this present day.

Pressure balancing is an effective technique which can be used to prevent the onset of spontaneous combustion if implemented in a timely manner. It is a well known fact that air naturally moves only when there is a pressure differential between two points. If there is no pressure differential across the mine gob, the air will not circulate through the worked out areas, thus the oxidation of coal will be eliminated. In practice, this can be accomplished by implementing and operating a pressure balancing system in the gob area. Pressure balancing techniques are categorized as either passive or active. Passive pressure balancing is achieved by changing the duties of a set of ventilation control devices such as stoppings, regulators, and fans. Active pressure balancing is achieved with external sources of pressure. Pressure chambers are established and balancing is accomplished by using existing higher pressure airways or from injection of inert gas from external sources. When existing mine air and pressures are used to pressurize chambers there has to be a location where pressures are greater than the pressure found near the gob. Active pressure balancing requires a pressure chamber and an external pressure source. Pressurized inert gases such as nitrogen are used for pressurizing chambers.

Depending on the gas content in the coal seam, different ventilation methods can be used to ventilate the active workings and mined out areas of a coal mine. The most commonly used ventilation systems are U-tube, and flow-through with a bleeder fans. In order to observe the effect of the ventilation system on pressure differentials across the gob area, experiments were conducted using the University of Utah laboratory model. The model is dynamic and versatile so that by changing the position of a regulator or changing fan settings, different ventilation system can be emulated. In every experiment the flow quantities directed to the active workings (faces) were kept practically constant. This was done so that a fair comparison between systems could be made. While making minor changes to the systems and maintaining nearly constant required face demands, the most suitable system that minimizes the differential pressures across the gob can be identified. In this study, the flow through system was identified as the most suitable one for implementing a pressure balancing system, either passive or active.

The University of Utah laboratory model has been upgraded to include an atmospheric monitoring and control system. This system is capable of recording most of the ventilation parameters including pressure differentials, air velocities, barometric pressures, air temperatures, humidity, and CO_2 concentrations. The system is equipped with an electronic remote CO_2 injection system capable of switching on/off a flow control valve automatically such that the chamber pressure is always kept slightly higher than that the gob pressure. Currently, the control process is achieved automatically.

Bow-tie risk analysis of spontaneous combustion for a coal mine has been outlined and the critical factors were also identified. This type of analysis can assist management in evaluating all the possible factors such that preventive and mitigating measures can be implemented.

8.2 Discussions

Pressure balancing techniques have been used only in a few U.S. coal mines, but extensively in many other coal mining countries including Australia, Poland and India. One reason for this is that U.S coal mines utilize different ventilation patterns than those followed in other countries; another reason is the mine depth. Except for a few mines, in the U.S., coal mines are typically located at depths less than 300 m, where it is economic to sink a new shaft for ventilation.

The pressure balancing system can be used effectively in the U.S. coal mines. However, a thorough evaluation of propensity of coal mines to spontaneous combustion should be required. Tools such as SPONCOM 2.0, developed by NIOSH can be used for this purpose. Once it has been established that a coal seam is liable to spontaneous combustion, a decision should be made on the appropriate ventilation system. A flow through ventilation system has been found to be more efficient at balancing pressures than other comparable systems. The optimal ventilation system should reduce the pressure differentials between intakes and returns so the potential for spontaneous combustion can be mitigated effectively.

Mines should always be prepared to deal with spontaneous combustion fires. This requires a thorough understanding of the problem and planning for the multiple scenarios. A conceptual design of a pressure balancing system should be evaluated at this stage. The design will differ from one mine to another due to specific environments and needs. Once the requirements of the system are identified, the method of pressure balancing can be decided. The efficiency of the system depends on the way pressure chambers are designed. Seals and stoppings should be maintained and monitored regularly. Pressure chambers should remain pressurized for long periods of time.

This study has shown that pressure balancing could be an effective method of controlling spontaneous combustion for many U.S. coal mines. When implemented, especially in sub bituminous coal mines, many adverse events resulting from the hazards of spontaneous combustion could be reduced substantially.

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