USE OF A CO_2 GAS INJECTION SYSTEM IN A LABORATORY MODEL TO STUDY CONTROLLED RECIRCULATION

*V. Gangrade, F. Calizaya, and M.G. Nelson
Department of Mining Engineering
University of Utah
Salt Lake City, UT 84102
United States of America
*(*Corresponding author: gangrade.vasu@utah.edu)*

USE OF A CO_2 GAS INJECTION SYSTEM IN A LABORATORY MODEL TO STUDY CONTROLLED RECIRCULATION

ABSTRACT

Recirculation is the major concern associated with the utilization of booster fans. In controlled recirculation, a portion of the return air is purposely mixed with the intake air and the mixture is directed towards a working district, while the air quantity and gas concentrations in the air are closely monitored and managed. The objectives of this study were to determine the gas concentration in intake and return airways during controlled recirculation, and to determine the recirculation fraction for multiple headings. Experiments were conducted in a laboratory model to determine the effect of controlled recirculation on the quality of air circulated through the working faces. Preliminary results showed that recirculation is beneficial to ventilation planning because it reduces the build-up of air contaminants at the working faces and reduces the overall power consumptions. The experimental results were used to quantify the recirculation fraction and to calibrate ventilation models of the laboratory model. These models are used to simulate the controlled recirculation and to predict the gas concentrations in multiple headings.

KEYWORDS

Ventilation, Booster Fan, Controlled Recirculation, CO_2 Injection

INTRODUCTION

As coal mines get deeper and more extensive, the demands on the mine ventilation systems are substantially increased. Leakage and system resistance both play significant roles in the increased demand on the ventilation system. As mine resistance increases, it is frequently necessary to upgrade the ventilation system to maintain adequate air flow at the development headings. Mostly commonly, ventilation systems are enhanced by upgrading existing surface fans, and developing new ventilation shafts and drifts. These methods are effective means of enhancing a ventilation system but they tend to increase the main fan pressure, the leakage quantity, and the power requirement. Booster fans represent an alternative to installing new high-pressure surface fans or developing new ventilation shafts. However, there are some risks involved with the operation of booster fans, especially, when these are not sited or sized properly. The most significant risk in underground coal mines is the recirculation of air contaminants though the workings.

BOOSTER FANS

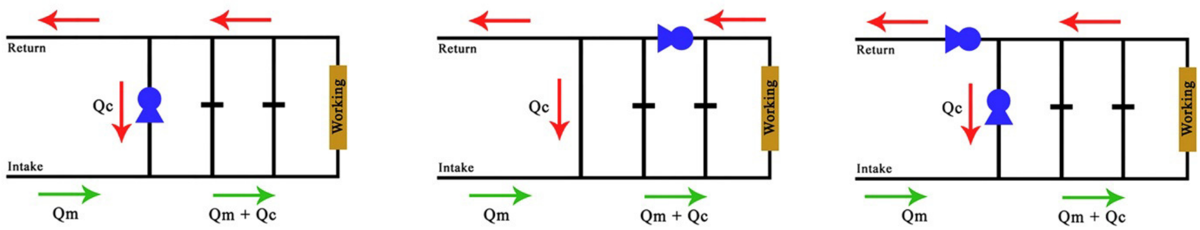
A booster fan is an underground ventilation device installed in the main airstream (intake or return) to increase the quantity of air circulated to one or more working districts (McPherson, 1993). It is installed to operate in series with a main fan and boost the pressure of the ventilation air passing through it. To accomplish this objective, the fan is installed in a permanent stopping and equipped with airlock doors, interlocking devices between main and booster fan controls, and a monitoring system to assess continuously the operating conditions of the fan. Although a booster fan is generally installed in series with a main surface fan, the quantity of air passing through it is usually less than the quantity of air passing through the main fan. A booster fan pressure can be significant, up to several kilopascals, but this pressure is generally less than the operating pressure of a main surface fan (Robinson, 1989).

RECIRCULATION

Recirculation of air contaminants is the main issue associated with the utilization of booster fans. It occurs when the pressure in the return airway is higher than the pressure in the intake airway, causing the return air to leak from the return to the intake. In systems with multiple fans when the booster fans are not sited or sized properly, the possibility of recirculation is quite high. In practice, there are two types of recirculation, (1) controlled recirculation and (2) uncontrolled recirculation.

In controlled recirculation, a portion of the return air is purposely mixed with the intake air and the mixture is directed to a working district while the quantity of air is closely monitored and managed. Controlled recirculation can increase the capacity of the ventilation system by increasing the quantity and air velocity near the production areas (Dhar, 1987). Uncontrolled recirculation occurs when the air is passed from the return airway to the intake airway through doors and stoppings in an uncontrolled manner. Since the recirculating air is not expected then there is the potential for the buildup of air contaminants including mine gases, dust and heat in the section of the mine where recirculation is occurring.

Depending upon the position of the booster fan in relation to the workings, there are three types of controlled recirculation: (1) cross-cut recirculation, (2) in-line recirculation and (3) combined recirculation. Figure 1 illustrates the three types of recirculation. The simplest configuration is cross-cut recirculation (Figure 1a). This system maintains the intakes and returns free for travel and unobstructed by airlock doors. In the in-line system of Figure 1b, the booster fan is located in the return airway inby the recirculation cross-cut. In this position, the fan is sized to purposely recirculate a fraction of the return air. When an in-line fan is used in combination with a cross-cut fan (Figure 1c), the recirculation is known as combined recirculation. It is used to ventilate remote workings from the surface connections. The system gives greater degree of flexibility (McPherson, 1993).



(a) Cross-cut recirculation (b) In-line recirculation (c) Combined recirculation

Figure 1 – Types of controlled recirculation

In each case, the through-flow ventilation in the mains is shown as Q_m with Q_c representing the flow quantity passing from return to intake, to give an enhanced airflow of Q_m+Q_c in the workings. The ratio $F = Qc/(Qm + Qc)$ is known as the recirculation fraction. The fan that creates the recirculation develops a pressure of P_r. Part of to overcome friction this pressure is used to recirculate the air, and the difference (P_{o1}, P_{o2} and P_{o3}) to overcome the frictional losses around the recirculation path.

Controlled recirculation is used in deep mines to increase the face air velocity, to control the concentration of air contaminants and to reduce ventilation costs (Calizaya, 2009). Although this technology is prohibited in U.S. underground coal mines, it is used in metal and non-metal mines.

UNIVERSITY OF UTAH
COAL MINE VENTILATION MODEL

Active coal mine ventilation systems are complex and dynamic and for these reasons, accurate and detailed field experiments are difficult to conduct. In addition, because booster fans are not used in U.S. coal mines, field experiments to study the characteristics of recirculation in an active coal mining environment are not possible. A scaled ventilation model of a coal mine including a booster fan system was developed so that flow recirculation experiments could be conducted in an environment where conditions could be controlled and variables could be systematically modified.

Model Parameters

A laboratory mine ventilation model was constructed of 6-inch-diameter pipe, as shown in Figure 2. A schematic of the model is shown in Figure 3. The pipes are configured in a standard U-shaped ventilation network with one intake and one return joined by three crosscuts, referred to as A, C, and D. The crosscuts are constructed of 2.5-inch-diameter pipe and act as leakage paths between the intake and the return. The magnitude of the leakage flow through these crosscuts is controlled by means of perforated valves of variable open areas. The percentage of the open area of the valves can be related to the quality (or leakage) of stopping construction in an actual ventilation system.

An additional crosscut joins the intake and the return airways. It is identified as development heading (cross-cut B) in Figure 3, to represent an active mining section; it is constructed of 6-inch-diameter pipe. The other section is the face, which is the free split in the ventilation system, is completely open so the quantity of air that passes the face is dictated by the system pressures and is not limited by a regulator. To control the flow across the development heading and prevent the majority of air from short circuiting the system, the crosscut representing the development heading is equipped with a gate valve modified to reduce its cross sectional area by 50%.

A pressurized CO_2 cylinder is used to simulate the gas emissions during the mining process. The gas can be injected at different stations in the laboratory model. It can also be injected at multiple stations simultaneously.

Finally, the laboratory model is equipped with two centrifugal fans: one main fan installed as a blower at the system intake, and a booster fan located in a bypass duct between crosscut A and the development heading shown in Figure 2. Both fans, equipped with variable frequency drives, are capable of operating between 0 and 60 Hz. Several experiments were conducted by varying the physical conditions and the fan speeds. The results of a sample experiment are presented below.

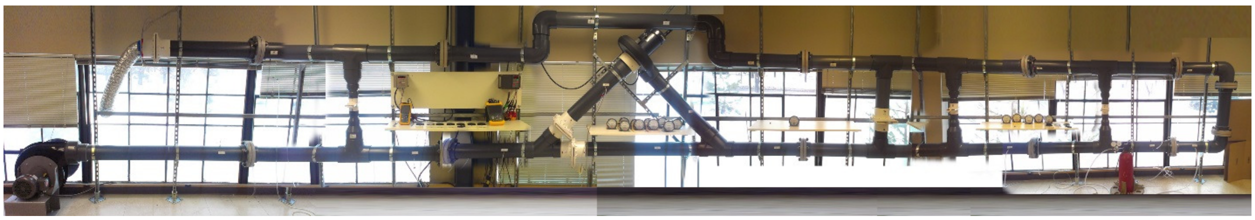


Figure 2 – Picture of the laboratory model

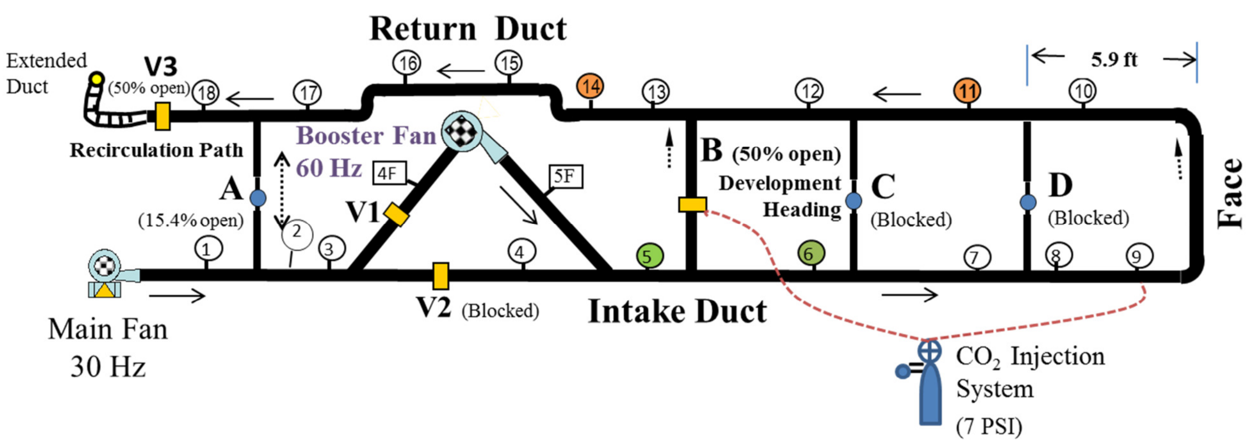


Figure 3 – Schematic of the laboratory model

Experimental Test

The objective of this test was to demonstrate the general behavior of controlled flow recirculation and to observe the variations of gas concentrations with the changes of fan pressure. The experimental conditions of the model are described as follows.

Experimental Conditions

- Regulator plate #4 (15.4% open) was installed in cross-cut A to induce flow recirculation, and the regulators in bypass duct V2 and cross-cut V3 were fully blocked. The simulated face was fully open.
- The main fan was set to operate at low speed (30 Hz) and the booster fan at high speed (60 Hz).

- The CO_2 gas was injected at stations B and 9. To avoid freezing of the injection pipe, the gas flow regulator was set to operate at 7 psig.
- The CO_2 gas concentrations were monitored at stations 5 and 6 (intake side) and at stations 11 and 14 (return side).
- Pitot tubes and a TSI digital manometer were used to measure the static and velocity heads, and two ALTAIR-5 multi-gas detectors to measure the CO_2 concentrations.

Calculations and Results

Pressure-Quantity Survey

Pressure and quantity surveys were conducted for two conditions: (1) using the main fan only and (2) using the main and booster fans. The velocity heads, H_v, were measured at different stations in the ductwork. These were used to determine the airflow rates, Q. Table 1 shows a summary of average airflow quantities for the two fan conditions. These were used to calculate the leakage quantity from intake to return for the single fan system, and the recirculation rate from return to intake for the two fan system. Figure 4 shows changes in airflow rates over time during the experiment. For the two fan condition, a recirculation fraction of 19% was estimated. The recirculation fraction, RF, is defined as the ratio of the quantity of air circulated through cross-cut A to the quantity of air directed to the working areas. The calculations for pressure-quantity survey were done for two different conditions. In case of only main fan running the air leaks from the cross-cut A and in case of both main and booster fan running the air is recirculated through cross-cut A. In both cases, the intake air divided into the development heading and working face on the basis of equivalent resistance.

Main fan only

- Main fan running at 30 Hz
- $Q_{intake} = Q_{face} + Q_{heading}$
  $0.029 = 0.017 + Q_{heading}$
  $Q_{heading} = 0.012$ m^3/sec
- Leakage = $Q_{exhaust} - Q_{intake}$
  Leakage = 0.043 – 0.029 = 0.014 m^3/sec

Main fan and Booster fan running

- Main fan running at 30 Hz and booster fan running at 60 Hz
- $Q_{intake} = Q_{face} + Q_{heading}$
  $0.089 = 0.048 + Q_{heading}$
  $Q_{heading} = 0.041$ m^3/sec
- $Q_{recirculation} = Q_{intake} - Q_{exhaust}$
  $Q_{recirculation}$ = 0.089 – 0. 072 = 0.017 m^3/sec
- Recirculation fraction (McPherson, 1993)

$$RF = \frac{(Qi - Qe)}{Qi} \qquad \text{(Equation 1)}$$

⇨ (0.089 – 0.072) / 0.089 = 0.19
Where, Qi= Quantity in intake and
Qe= Quantity in exhaust

The recirculation fraction can be calculated using the quantities of air measured in the intake and the return. The results from the calculations are summarized in Table 1 below.

Table 1 – Quantity of air and recirculation

Fan condition	Station	Quantity m^3/sec	Remarks
Main fan only	2 (intake)	0.029	**Leakage Q_L = 0.014 m^3/sec**
	8 (face)	0.017	
	B (development heading)	0.012	
	18 (exhaust)	0.043	
Main and booster fan	2 (intake)	0.089	**Recirculation = 0.017 m^3/sec**
	8 (face)	0.048	
	B (development heading)	0.041	
	18 (exhaust)	0.072	**RF = 0.19**

Figure 4 below shows the quantity of air measured at the 2 stations in intake and 2 stations in return airway. It can be seen that air flow rate is almost doubled when booster fan is running.

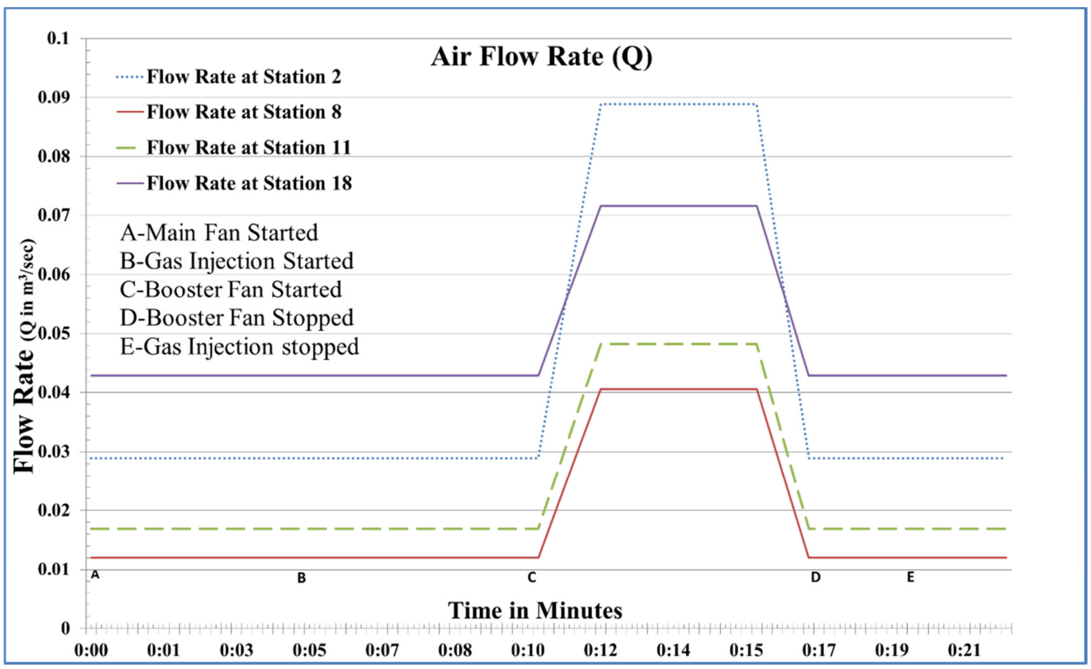


Figure 4 – Graph representing air flow rate in the model

Carbon Dioxide Concentrations

Carbon dioxide gas was injected at station 8 (face) and station B (development heading) as shown in Figure 3. The flow rate was controlled by a regulator which for this experiment was set at 7 psig. At this pressure, the injection rate was fairly constant for about 20 minutes. The gas concentrations were monitored continuously at Stations 5 and 6 in the intake airway and at stations 11 and 14 in the return ducts. Figure 6 shows the CO_2 gas concentrations monitored at these stations. Point A to B shows the background concentration of CO_2 in air measured for 5 minutes, which was almost zero. In this condition only the main fan was running. As soon as the CO_2 gas was injected, there was a sudden increase in gas concentration in the return air (point B to C). This reached a maximum of 0.30 % in 1 minute and remained fairly constant thereafter. No change in gas concentration was detected in the intake air at stations 5 and 6, because there was no recirculation. As soon as the booster fan was started (point C) there was a sudden decrease in CO_2 concentrations in the return airway. The concentration fell down from 0.30 % to 0.13 % at station 14 and from 0.26 % to 0.12 % at station 11. The booster fan recirculated 19 % of the return air, increasing the CO_2 concentration to 0.05 % in intake air, which is almost negligible. When the booster fan was stopped after 16 minutes (point D) the CO_2 concentration in the return air went back to 0.30 %. Gas injection was stopped after about 18 minutes (point E), which caused a decrease in the gas flow rates in the intake and return airways.

The gas concentration was calculated using the following relationship:

$$Concentration = \frac{q\ (gas\ emission) \times 100}{Q\ (air\ flow\ rate)} \qquad \text{(Equation 2)}$$

The CO_2 concentrations were measured at two stations in the intake and two stations in the return. The concentration was not measured directly in cross-cut B, in order to allow proper mixing of CO_2 in air. Rather, it was calculated using the gas concentrations and flow rates measured at other stations (using equations 1 and 2).

Main fan only

- $C_{return} = 0.3\%$; $Q_{return} = 0.029\ m^3/sec$
- $q_{return} = (0.3/100) \times 0.029\ m^3/sec = 8.7 \times 10^{-5}\ m^3/sec$
- $C_{face} = 0.26\%$; $Q_{face} = 0.017\ m^3/sec$
- $q_{face} = (0.26/100) \times 0.017\ m^3/sec = 4.42 \times 10^{-5}\ m^3/sec$
- $q_{heading} = 8.7 \times 10^{-5} - 4.42 \times 10^{-5} = 4.28 \times 10^{-5}\ m^3/sec$
- $C_{heading} = q_{heading} / Q_{heading} = [(4.28 \times 10^{-5})/0.012] \times 100 = 0.35\ \%$

Main fan and Booster fan

- $C_{return} = 0.13\%$; $Q_{return} = 0.089\ m^3/sec$
- $q_{return} = (0.13/100) \times 0.089\ m^3/sec = 1.157 \text{ x } 10^{-4}\ m^3/sec$
- $C_{face} = 0.11\%$; $Q_{face} = 0.048\ m^3/sec$
- $q_{face} = (0.11/100) \times 0.048\ m^3/sec = 0.528 \text{ x } 10^{-4}\ m^3/sec$
- $q_{heading} = 1.157 \times 10^{-4} - 0.0528 \times 10^{-4} = 0.629 \times 10^{-4}\ m^3/sec$
- $C_{heading} = q_{heading} / Q_{heading} = [(6.29 \times 10^{-5})/0.041] \text{ x } 100 = 0.15\ \%$

Figure 5 represents the concentrations of carbon dioxide at different stations. It can be seen that the concentration of gas in return airway decreases considerably when both main and booster fans are running.

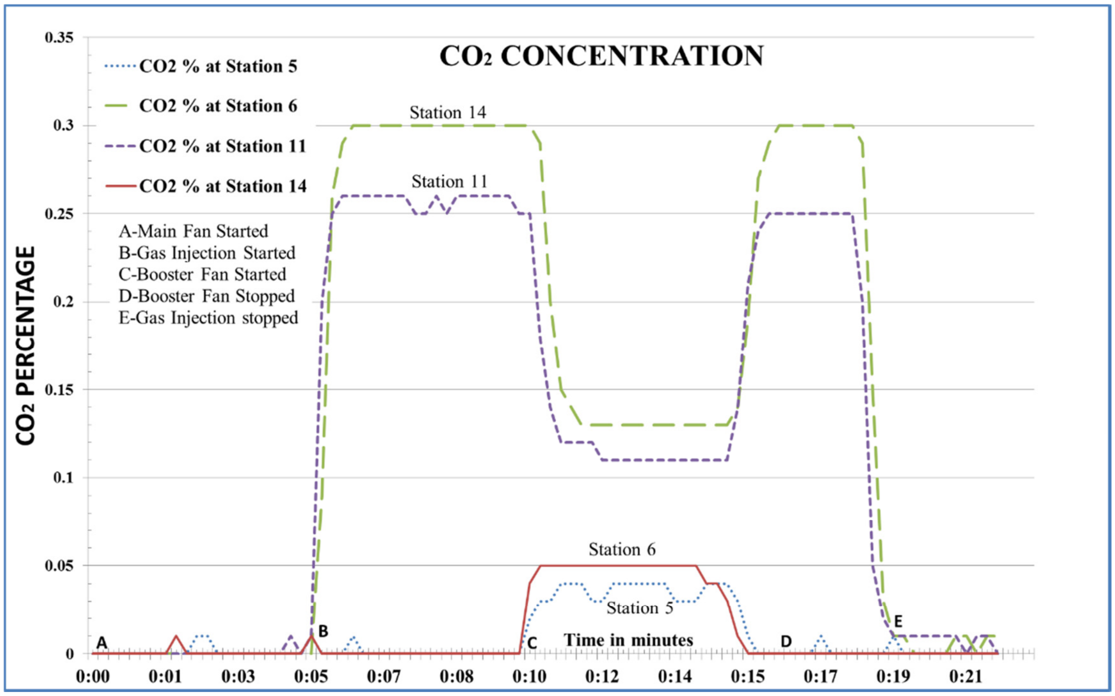


Figure 5 – Graph representing concentration of carbon dioxide at different stations

Discussion

Two sets of measurements were taken during the experiment, pressure-quantity surveys and CO_2 concentrations. The results of these measurements are shown in Figures 4 and 5. This experiment showed that the operation of the booster fan increased the capacity of the whole ventilation system. Figure 4 shows that when both fans are running, the airflow rates in each branch have increased substantially (> 50 %). In this configuration, 19% of the return air is recirculated. This recirculation further increases the quantity of air in the model. To study the air flow distribution through a network with multiple headings, the development section is represented by a cross-cut of equivalent resistance. Figure 6 shows an expanded version of this section.

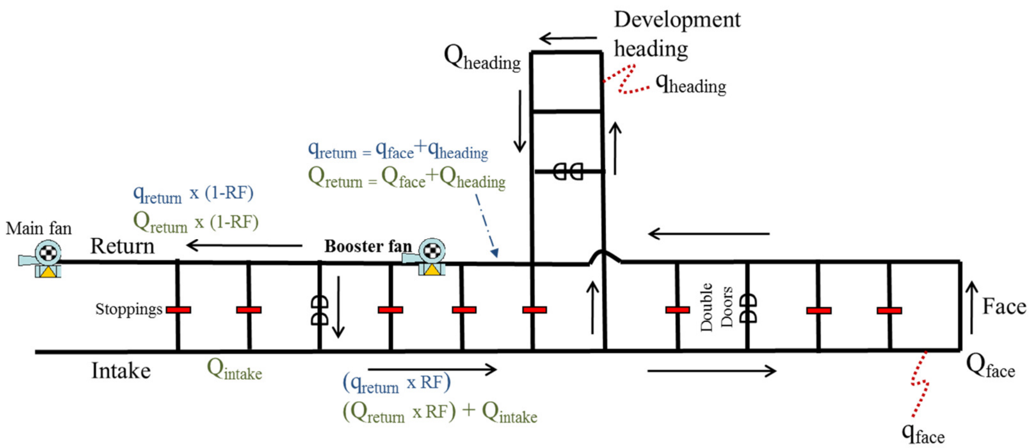


Figure 6 – Schematic showing relation between mine and laboratory model

The CO_2 gas was injected in the intake branch near the simulated face and the readings for CO_2 concentration are taken down stream, allowing enough time for proper mixing of CO_2 in the return air (Figure 3). The percentage of CO_2 in this heading was calculated as the ratio of total gas flow rate to the total quantity of air circulated through the face (Equation 2). The CO_2 concentration was also measured in the intake airway, and found to be almost negligible because of the increased air flow rate (Figure 5). This indicates that even on recirculating the maximum quantity of return air the gas concentration level in fresh air does not increases significantly, contrary to the popular belief, there indicates that there is no gas buildup in the intake airway. Although, there is some increase in gas concentration in the intake air, this can be managed by changing the recirculation fraction, so that the concentration can be kept below the threshold limit. In this experiment, for the same CO_2 injection rate and increased air flow rate, controlled recirculation reduced the gas concentration at the face and development heading by about 50 %.

When properly sited, booster fans will always increase the total quantity of air in the system and reduce the leakage quantity. For an in-line controlled recirculation system where the gas emission rate remains fairly constant and the quantity of air to the face increases, the overall gas contaminant concentration of the ventilating air will always decrease.

CONCLUSIONS

The use of booster fans to assist in the ventilation of either individual panels or the entire mine is not common in coal mines. This is because the installation of additional shafts or larger surface fans is often preferable to the operational problems and costs associated with installation of underground booster fans. Furthermore, current regulations in U.S. prohibit the use of booster fans in underground coal mines. However, significant increases in volumetric requirements at higher production rates, increases in block geometry and depth of workings, and the development of new mines in under environmentally sensitive areas, booster fans become a more attractive and economically viable solution.

The potential for recirculation is a risk that can be managed. As the laboratory model data demonstrate, the size of the booster fan relative to that of the main fan is an important consideration. If the booster fan operates at a pressure as large as or larger than the main fan pressure, there is significant potential for recirculation. In addition, the location of a booster fan in a ventilation system has a significant impact on recirculation. The closer the booster fan is to the development sections, the greater the likelihood of recirculation regardless of the booster fan pressure. To limit the potential for system recirculation, the location of a booster fan in a ventilation system should be thoroughly evaluated. The fan should be located so that pressures in the intake airways are higher than pressures in the return airways and the formation of neutral points should be avoided. It is important to note that, as the mine develops further from a booster fan, the section resistance increases and the potential for recirculation decreases. Recirculation can be controlled by adequately sizing and positioning the fan. Recently developed technology, such as wireless communication, automatic monitoring systems, and improved power system control, can contribute to the correct and safe operation of booster fans.

Under current U.S. regulations, which prohibit the use of booster fans in underground coal mines, it is difficult to conduct meaningful, in-mine research on booster fans systems. Computer simulations, laboratory studies, and comparison to systems used in non-coal mines are the only available tools for research. Research in, and the experiences and regulations of other countries provide important comparisons for the potential use of booster fans in U.S. For example, the use of booster fans can facilitate continued operation of a mine that is being considered for closure because of high ventilation costs. When a booster fan is properly installed, with correctly-designed bulkheads, a good monitoring system, and optimized sizing and position, it can function just as well and just as safely, as any other system in the mine.

REFERENCES

Calizaya, F. (2009). *Guidelines for installing and operating booster fans in underground mines.* Proceedings of the Ninth International Mine Ventilation Congress. New Delhi, India: Oxford and IBH.

Dhar, N., McPherson, M.J., and Mousset-Jones, P. (1987). *The effects of controlled recirculation on mine climate.* Proceedings of 5th Annual Workshop Generic Mineral Technology Center Mine systems Design and Ground Control. Tuscaloosa, Alabama.

Robinson, R., (1989). *The use of booster fans and recirculation systems for environmental control in British coal mines.* Proceedings of the 4th US Mine Ventilation Symposium. Littleton, Colorado: SME.

McPherson, M. (1993). *Subsurface Ventilation Engineering (Online Edition, 2013)* *http://www.mvsengineering.com/filelibrary/file_25.pdf*. Mine Ventilation Services.