Designing an experimental apparatus for the testing of novel tracer gases in underground mines

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ABSTRACT: Following a disaster in which ventilation controls have been potentially damaged, the use of multiple tracer gases could allow for rapid assessment of the functionality of ventilation controls. This paper describes the design of an experimental apparatus for the testing of novel tracer gases for mine ventilation surveys. The experimental apparatus will be modeled after a simple mine layout in a tabular deposit. Injection points at the top of the apparatus will allow for the injection and sampling of tracer gases, simulating mine boreholes. Non-adsorbing material will be used to construct the model mine as well as an airtight seal to prevent leakage of tracer gases. Round duct will be used to create the tunnels and will include at least three entries with an exhausting fan. Airflow velocities will be monitored and recorded through sensors placed throughout the experimental apparatus and gas concentrations will be determined from the analysis of samples taken from the apparatus. The model mine will be used to explore the viability of the use of multiple tracer gases for more rapid ventilation surveys by simultaneous injection of the tracer gases into several points that are sampled at a common point, decreasing the time required to perform multiple ventilation surveys. This apparatus will be used in future research including developing methodologies for releasing and sampling tracer gases as well as learning how to quickly model a mine ventilation plan using computational fluid dynamics software.

1 Introduction

Ventilation in underground mines is vital to create a safe working environment. Ventilation helps to dilute dust, improve air quality, reduce exposure to harmful contaminants in the air such as diesel particulate matter (DPM) and arsenic, and to control methane levels for the prevention of mine explosions and ignitions. Tracer gas surveys can be used to ascertain the state of ventilation controls in the event of an explosion or major ground event.

Since the early 1900s, the number of fatalities in mines has been greatly reduced due to the implementation of government regulations and improved technology and control methods. Although there have been improvements, there are still a number of injuries and fatalities related to collapse or fall of roof and ribs, fire, and ignition or explosion of gas or dust. The number of these incidents from 1983 to 2008, for underground coal only, is summarized below in Table 1, and are categorized according to severity of injury; fatalities, number of days lost and number of non-fatal days lost.

Table 1 Summary of Underground Coal Incidents

1983-2008	Fatal	NDL	NFDL	Total
Fall or collapse of roof/ribs	357	3,504	13,085	16,946
Fire	82	2,568	8,129	10,779
Ignition or Explosion of Gas or Dust	82	25	180	287
Total	521	6,097	21,394	28,012

There are several measures that can be taken to control methane levels, including methane drainage, preventing accumulation of combustible or explosive coal dust, eliminating ignition sources, monitoring methane-air mix pressures to ensure they do not reach the detonation pressure level, monitoring sealed areas, and designing and monitoring the ventilation system (Brune *et al*., 2007).

Focusing specifically on ventilation controls, there have been numerous developments and technological advances that have improved ventilation systems. The efficiency of the ventilation system can be measured by using various tools such as vane anemometers, smoke tubes, psychrometers, manometers, and barometers to determine air velocities, temperatures and pressures (Suglo & Frimpong, 2002). Calculating the product of the measured cross sectional area and averaged air velocity is a more traditional and less accurate method of determining air quantity through a section of a mine (Suglo & Frimpong, 2002). A single tracer gas, typically sulfur hexafluoride (SF_6), has been used to evaluate mine ventilation systems since the early 1970's.

In order to further improve and understand ventilation in underground coal mines, research is being conducted to develop better sampling and modeling methods. By building an apparatus modeled after a simple mine layout in a tabular deposit, multiple novel tracer gases can be released simultaneously and sampled using solid phase microextraction (SPME) fibers or syringes at one or more points in the experimental apparatus. Developing a methodology to use multiple tracer gases in tandem with computational fluid dynamics in a ventilation survey is beneficial because it can considerably reduce the time it takes to perform a ventilation survey so that in the event of a mine disaster the status of ventilation controls can be rapidly evaluated.

2 Background

The United States Bureau of Mines was founded in 1910 in response to several large-scale mining disasters in an effort to improve the safety of miners (MSHA, 2009). Significant research has been conducted through the Bureau of Mines since its inception. Due to the complexity of mine ventilation systems, it is often difficult to accurately analyze airflow using conventional anemometer and smoke tube techniques, but the use of a tracer gas is an effective means to analyze ventilation controls (Thimons *et al*., 1974). An ideal tracer gas for use in underground mining applications must be chemically and thermally stable, safe, odorless, detectable at low concentrations, and have a low background concentration, and should not be naturally occurring in the environment (Thimons *et al*., 1974). Some other important attributes of the tracer gas are that it is non-corrosive, non-toxic, inexpensive, readily attainable, easily transportable, and non-radioactive (Kennedy *et al*., 1987). During the 1970's the Bureau of Mines determined that sulfur hexafluoride (SF_6) was an ideal gas to use in underground mine ventilation tests (Thimons *et al*., 1974), because it met many of these requirements.

There have been several different tests using sulfur hexafluoride as a tracer gas in both metal/nonmetal and coal mining applications. Early testing of sulfur hexafluoride was completed in a limestone mine in western Pennsylvania (Thimons *et al*., 1974). Further testing expanded to include three different coal mining scenarios: to investigate sealed areas through measurement of air movement and leakage, to measure the effectiveness of a bleeder system, and to evaluate the efficiency of permanent stoppings (Vinson & Kissell, 1986).

In addition to the aforementioned scenarios, it is also important to specifically monitor gob areas to determine methane concentration levels. Gob areas are either sealed off from the main ventilation or ventilated to maintain low levels of methane concentration (Timko *et al*., 1986). Sealing the gob areas helps to prevent, but does not eliminate, the risk of spontaneous combustion that can occur due to the entry of high quantities of oxygen from the main mine air or the loss of explosive gases from the gob area to the main mining areas. Tracer gas testing was conducted in three mines with different gob layouts which included a ventilated gob area in a longwall mine, a small sealed gob area in a room and pillar mine, and a large sealed gob area in a room and pillar mine (Timko *et al*., 1986).

A more recent tracer gas study conducted by the National Institute for Occupational Safety and Health (NIOSH) also evaluated gob areas through the release of sulfur hexafluoride in seven different gob gas ventholes (Mucho *et al*., 2000). Though there were varying results found in each of the three different longwall panels it was determined that the use of tracer gases is a valuable tool for assessing ventilation airflows associated with longwall gobs, bleeders, and gob gas ventholes, as the data obtained from each was used to produce a longwall methane control model (Mucho *et al*., 2000).

Use of multiple tracer gases to evaluate ventilation in mines has been fairly limited. Kennedy *et al.* (1987) explored the use of both Freon-13B1 and Freon-12 as tracer gases in their underground work. They determined that the Freon gases best fit the properties and attributes of an ideal tracer gas to be used in underground mines. They concluded that, overall, the Freon gases perform well as tracer gases but caution that since Freon-12 is used in refrigerants and spray paint background samples must be taken to ensure that the gas is not already present in the mine atmosphere.

Previous scaled mine ventilation testing was conducted by Widodo *et al*. (2008) by injecting methane into straight and curved tubes to measure gas diffusion. They measured the concentration of the methane gas with an infrared adsorption gas detector every 0.1 s. In addition, a hot wire velocimeter was used to measure velocity profiles in the tubes to confirm that turbulent flow was generated.

There are several different methods of releasing and sampling tracer gases. Tracer gases may be sampled using syringes, polyvinylfluoride bags, and vacutainers, as well as SPME fibers. In all cases, a gas chromatograph is used to detect the gases in the sample. Developed in 1990 at the University of Waterloo by Pawliszyn and group, SPME fibers are a unique, solvent-less method of sampling. Due to its simplicity and minimal sample preparation time, SPME fiber technology is suitable for on-site analysis and air monitoring (Chai & Pawliszyn, 1995). SPME fibers have been applied to various industries including foods, polymers and coating, natural products, pharmaceuticals, toxicology, forensics, and environmental aspects such as water, pesticides, soil, and indoor and outdoor air sampling of volatile organic compounds (VOCs) (Koziel & Novak, 2002, Hippelein, 2006).

3 Apparatus

There are several issues to consider when designing an experimental apparatus for mine airflow simulation. These include the topology of the apparatus, creating turbulent flow, measuring the velocity throughout the model mine, and instrumentation of the apparatus.

3.1 Design

The design of the apparatus will be fairly modular. A modular design will allow for the simulation of a greater variety of mine geometries and mine damage scenarios. To create the mine, 2"Ø PVC pipe will be used. It is estimated that each length of pipe will be ≈ 7.6 m (25 ft), using a total of ≈ 90 to 120 m (300 to 400 ft) of pipe.

Although the apparatus will not exactly model a typical underground coal mine due to limited lab space, the topology will be similar in that there will be intake and return entries and various nodes to represent working areas. Figure 1 and Figure 2 outline a sample mine and layout of PVC pipe.

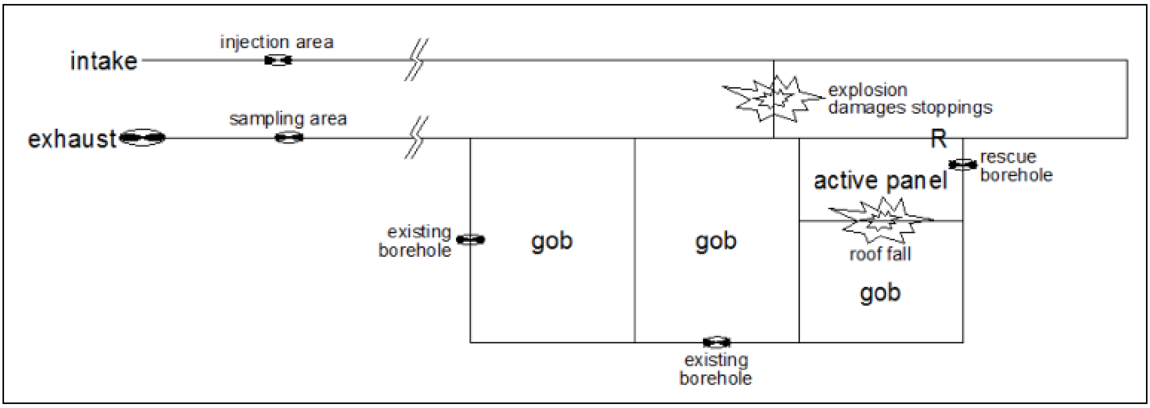

Figure 1 Sample Mine

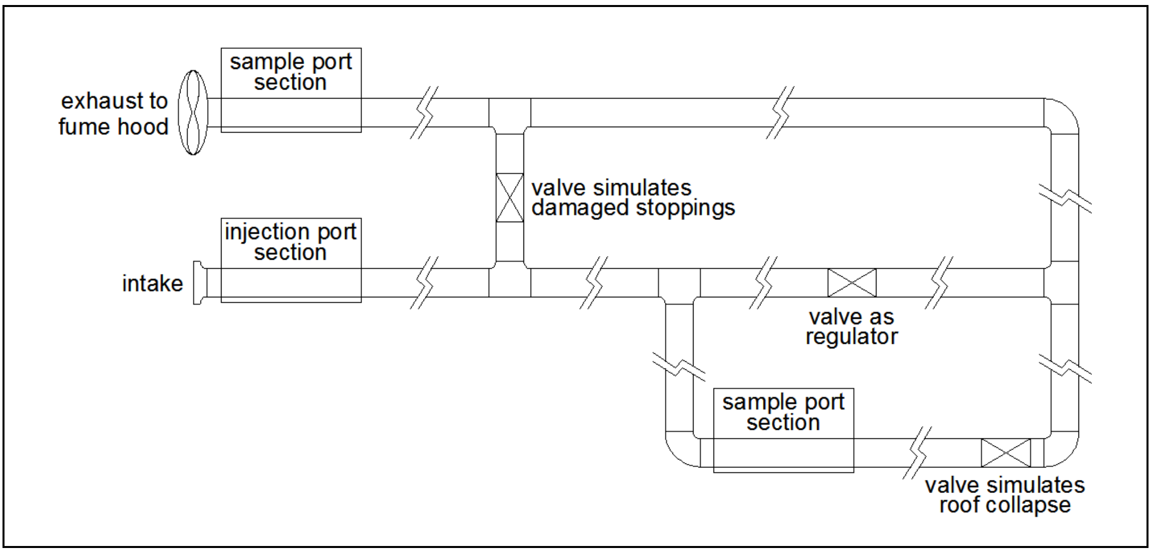

Figure 2 Sample PVC Pipe Layout

The apparatus will be constructed so that different configurations can be created to model changes in ventilation controls and vary the mine layout. Changes in ventilation controls are caused by different events, such as an increase in resistance due to roof falls or a loss of stoppings due to explosions or a planned ventilation change. A modular design will also minimize material expenditures, allowing for the use of minimal instrumentation, and maximizing experimental flexibility.

Other design characteristics include a roughened pipe interior to appropriately model the interior of a mine tunnel and help create turbulent flow. Five or six sampling and injection ports along with a Pitot tube to measure air velocity will be placed throughout the apparatus. An example of the instrumentation is shown in Figure 3.

3.2 Turbulent Flow

Given that the model mine must fit in limited laboratory space and have adequate cross sectional area for instrumentation, designing for the development of turbulent flow is challenging. In order to ensure accuracy of the tracer gas results, it is essential that turbulent flow exists in portions of the model that correspond with primary mine ventilation conduits, both to create a realistic model and encourage tracer gas dispersion. The standard definition of turbulent flow is that turbulent flow exists when the Reynolds number is greater than 4000. The Reynolds number can be calculated using Equation (1) below.

$$\mathrm{Re} = \frac{\rho VL}{\mu} = \frac{VL}{\nu} = \frac{QL}{VA} \qquad (1)$$

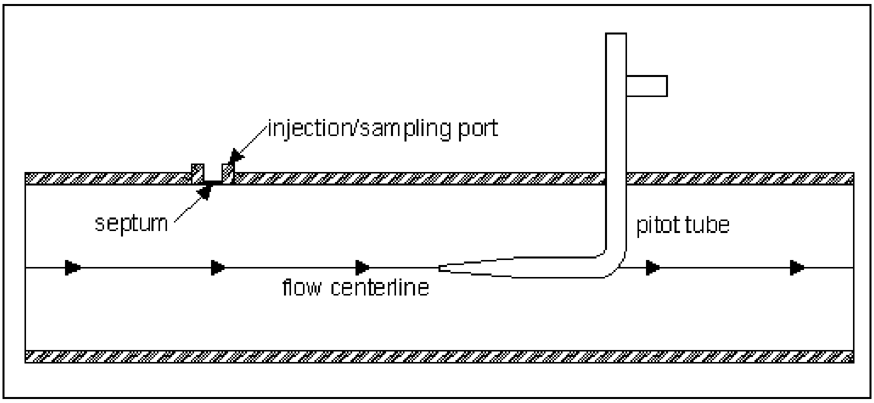

Figure 3 Cross section of sampling area with Pitot tube

where: ρ = density of the fluid (kg/m^3),
V = fluid velocity (m/s),
L = length (m),
μ = dynamic viscosity (kg m/s),
ν = kinematic viscosity (m^2/s),
Q = volumetric flow rate (m^3/s), and
A = pipe cross-sectional area (m^2).

It was found that turbulent flow initially develops in the entrance region which has an entrance length that is a function of the diameter of the pipe (Lien *et al*., 2004). Equation (2) (Young *et al*., 2007) is valid only for turbulent flow and can be used to calculate the entrance length needed to develop fully turbulent flow.

$$L_{entrance} = 4.4 \cdot \mathrm{Re}^{1/6} \cdot D \tag{2}$$

where: $L_{entrance}$ = entrance length (m),
Re = Reynolds number, and
D = diameter of pipe (m).

It will take ≈ 7.6 m (25 ft), of pipe to initially develop fully turbulent flow; however, after each bend or valve, there may be minimal loss of turbulent flow and fully developed turbulent flow will resume in a few feet. Since the apparatus will have 180° turns due to limited space, turbulent flow will have to be redeveloped multiple times. The critical velocity or minimum velocity to ensure turbulent flow is calculated using equation (3) below (Hartman *et al*., 1997). Using this equation it was determined that the minimum velocity to ensure turbulent flow must be at least 1.2 m/s (240 fpm).

$$V_c = \frac{\mathrm{Re}\mu}{\rho D} \approx \frac{0.06}{D}\ (m/s) \tag{3}$$

where: V_c = critical velocity (m/s),
Re = Reynolds number for turbulent flow (4000), and
D = diameter (m).

3.3 Velocity Measurements

Velocity measurements will be taken at each of the sampling and injection points in order to perform an accurate mass balance. Klopfenstein (1998) describes the basics of Pitot tubes, measuring air velocity and quantity, as well as common Pitot tube sensing tip designs. To balance cost and accuracy, a tapered Pitot static tube will be used. The inner and outer channels of this tube will allow for both dynamic and static pressures to be measured. The Pitot static tube will also eliminate the need to consider boundary layer issues on the tube wall as well as reduce holes, fittings, and tubing throughout the ductwork. Equation (4) (Klopfenstein, 1998) is used to calculate the velocity at each point.

$$V = 44.72136 K_{pitot} \cdot \Gamma_{pitot} \cdot \sqrt{\frac{h_{kPa}}{d}} \tag{4}$$

where: V = air velocity (m/s),
K_{pitot} = Pitot tube constant,
Γ_{pitot} = gas compression constant,
h_{kPa} = [total pressure-static pressure] (kPa), and
d = air density (kg/m^3).

Two additional parameters, air temperature and barometric pressure, must be measured in order to calculate the density of air, Equation (5), influencing the velocity equation (Klopfenstein, 1998).

$$d = 3.4834 \cdot \frac{G}{Z} \cdot \frac{P_B}{T_K} \tag{5}$$

where: d = air density (kg/m^3),
G = ideal specific gravity [molecular wt of gas (kg mol/kg)/molecular wt of air (kg mol/kg)],
Z = compressibility factor of gas,
P_B = barometric pressure (kPa), and
T_K = absolute temperature (Kelvin).

When solely measuring the density of air, a simplified calculation may be used. The relative humidity inside the apparatus should also be measured as it affects the density. Klopfenstein (1998) provides the correction factor that can be applied to the density to account for the relative humidity.

$$CF_d = 1 - \left[\frac{0.3783 \cdot \frac{RH}{100} \cdot P_s}{P_B} \right] \tag{6}$$

$$Ps = 1.7526 \times 10^8 \cdot e^{(-5315.56/T_k)} \tag{7}$$

where: CF_d = density correction factor,
RH = relative humidity (%), and
P_s = partial pressure of water vapor at T_k (kPa),

The corrected density (d_{cor}) to be used in the velocity equation is given by equation (8) (Klopfenstein, 1998).

$$d_{cor} = d \cdot CF_d \tag{8}$$

The corrected density measurements will allow accurate velocity calculations to ensure turbulent flow throughout the apparatus.

3.3.1 *Instrumentation*

As previously mentioned, Pitot-static tubes will be used for velocity measurement. Very low-pressure differential pressure transducers will be used to measure the dynamic pressure from the Pitot tubes. The density of air needs to be known in order to quantify the flow rate using a Pitot-static tube. The density of air is calculated using the air pressure and air temperature, which will be recorded with a digital thermometer and digital barometer, respectively. The outputs from the differential pressure transducers, thermometer, and barometer will be fed into a data acquisition system (DAQ) and recorded by a PC. Computation of air velocities and quantities will be carried out by the PC.

4 Sampling

Sampling will be conducted through use of SPME fibers and vacutainers. Vacutainers will be evacuated prior to use and SPME fibers will be inserted into the gas chromatograph to be conditioned at 150°C (300°F) prior to use to ensure they are free of other analytes. For analysis, air samples will be injected into an electron capture (ECD) gas chromatograph (GC). Results of the two sampling methods will be analysed and compared.

5 Conclusion

Overall, this apparatus will allow for the refinement of release and sampling methods for the application of multiple tracer gases in the lab, which can then be tested in the field. In addition, novel tracer gases can be tested in the model to identify gases that can be used in tandem with sulfur hexafluoride to conduct quicker ventilation surveys in the event of a mine disaster. Flexibility in the layout of the apparatus will allow for various mining scenarios. Standard tracer gas profiles will be generated to compare with CFD generated tracer gas profiles after ventilation changes. Ventilation changes will initially be made in a known area, but will later be made by a third party to ensure a "blind" experiment. Methodologies developed in the lab for rapid collection of tracer gas profiles will be verified in the field and recommendations made for transfer to emergency underground mining situations.

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