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COMPUTATIONAL FLUID DYNAMICS SIMULATIONS AND EXPERIMENTAL VALIDATION OF TRACER GAS DISTRIBUTION IN AN EXPERIMENTAL UNDERGROUND MINE

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ABSTRACT

Following a disaster in a mine, it is important to understand the state of the mine damage immediately with limited information. Computational fluid dynamics can be used to simulate and ascertain information about the state of ventilation controls inside a mine. This paper describes a simulation of tracer gas distribution in an experimental mine with the ventilation controls in various states. Tracer gas measurements were taken in the lab experimental apparatus, and used to validate the numerical model. The distribution of the tracer gas, together with the ventilation status, was analyzed to understand how the damage to the ventilation system related to the distribution of tracer gases. This study will be used in future research in real mine measurements to compare collected and simulated profiles and determine whether damage to the ventilation system has been incurred during an emergency situation, the nature of the damage and the general location of the damage.

Keywords: underground mine ventilation, tracer gas, measurement, CFD, modeling

INTRODUCTION

There is a lack of knowledge about the state of ventilation controls in a mine following the event of a significant incident such as a roof fall, bump, or explosion which requires immediate action. Currently, some information may be gathered safely from the surface, but most information regarding the state of the ventilation controls cannot be known before rescue personnel enter the mine. Having quick access to more information will help decision makers to more effectively manage a mine emergency and increase safety for rescue personnel.

It is essential to model ventilation patterns and the mine environment following an incident in a mine. Tracer gas techniques and numerical simulations using computational fluid dynamics (CFD) can be used to ascertain and simulate information about the state of ventilation controls inside a mine. Tracer gas measurement is an effective method to detect air flow routes and estimate air flow quantity and the rates of dilution and dispersal of contaminants in underground mine ventilation systems [1,2]. Air flow directions and quantities can be estimated by analyzing the tracer gas concentration. Dispersion of tracer gas in underground ventilation system may be very different depending on the location of damage after incident.

The use of tracer gases started in the 1950s in building ventilation systems [3]. Tracer gas techniques have been used in many situations where the standard ventilation survey methods are inadequate [4]. The applications of tracer gases in underground mines include analyzing ventilation patterns, measurement of air leak rates, and evaluating dust control measures [5]. Sulfur hexafluoride (SF6) is widely used as a tracer gas and is ideally suited for use in the underground environment. SF6 is not normally found in the underground environment and it is inert, nonflammable, non-explosive and non-toxic which makes it safe for use in underground mining and other industrial environments. Most importantly, current technology makes it possible to detect very low concentrations of SF6 (in the parts per billion or trillion range) [6, 7].

Computational Fluid Dynamics is a tool which can approximate numerical solutions in cases where experimental solutions are impractical or impossible. With the recent advances in computer technology and the success of CFD, the application of CFD has become increasingly attractive in modeling the ventilation systems in underground mines. It has been used in simulations of explosions [8], methane control [9,10], ventilation system improvement [11,12], gob inertisation methods [13], and spontaneous combustion and mine fires [14,15].

A combination of experimental data and a CFD model of tracer gas dispersion has been used to study airflow and contaminant transport in indoor environments [16-18], pollutant dispersion [19], and other industrial applications. Little research has been done to simulate tracer gas dispersion in underground mines, especially using tracer and CFD simulation to predict the status after emergency in underground mines.

This paper presents both the experimental and numerical results of ventilation status and tracer gas (SF6) dispersion in an experimental laboratory scale mine model with the ventilation controls in various states. Valves are used in the experimental mine model to simulate different ventilation statuses after "incidents" cause changes to the ventilation. Several passive area sources with constant emissions of a tracer gas (SF6) were designed to simulate constant tracer injections in the experiment. The objectives of the experiment were to collect data for evaluating the influence of different locations of damage after incidents and to validate the CFD model. This study indicates that tracer gas concentrations in a mine can be accurately modeled with prior knowledge of the ventilation system. It is the first step toward the research using tracer gas measurements to compare measured and simulated profiles and determine whether damage to the ventilation system has been incurred during an emergency situation, the nature of the damage and the general location of the damage.

EXPERIMENTAL MEASUREMENTS

Experimental Apparatus

A simple typical mine layout was designed for experimental purpose. As is shown in Figure 1, it includes one gob panel, one active panel, one stopping, and two regulators. Three possible incidents locations are also designed including explosion damage to the stoppings and causing short circuiting of the airflow between the main entries, a roof fall in the active panel which will block the airflow across the working face, and an explosion in the gob which will block the airflow through the gob. Two boreholes are present: one rescue borehole on the tailgate of the active panel and another borehole in the gob. The normal air flow paths are also shown in Figure 1. The experiment is not set up to include flow through the gob, simply around it.

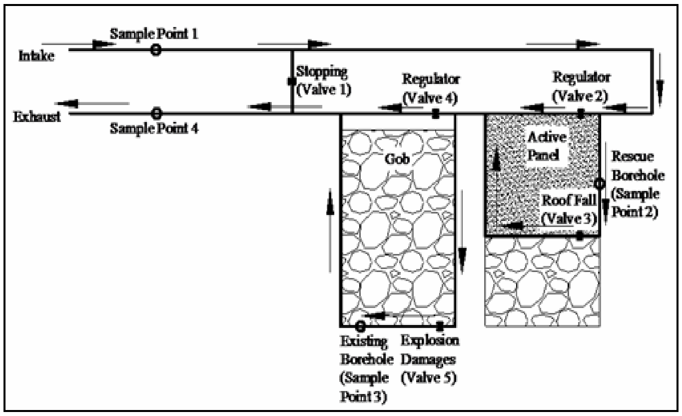


Figure 1. Simple Typical Mine Layout.

The experiments were conducted using the experimental underground mine shown in Figure 2, which is built according to the mine layout shown above. The experimental underground mine is composed of 2 inch (0.0508 m) inside diameter PVC pipes with the maximum dimensions of 261(L)×20 (H)×14(W) inches (6.63×0.51×0.36 meters). The PVC pipes were labeled with numbers for convenient reference. The experimental system has one intake and the exhaust is hooked up to an exhaust fan shown in Figure 3. Five valves (Figure 4) were used to simulate the stopping within the main entry, regulators, and roof fall/explosion damage.

Figure 2. General View of the Experimental System.

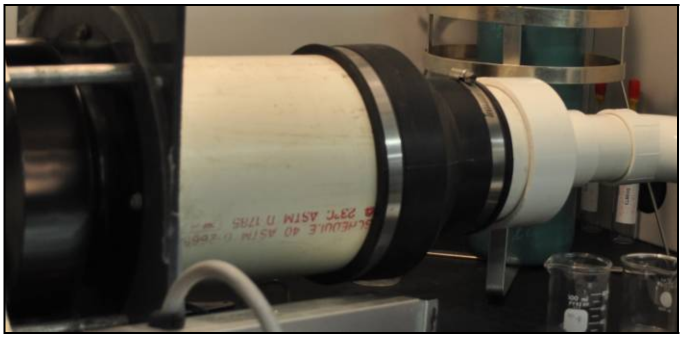


Figure 3. The Exhaust Fan.

Figure 4. Valves Are Used To Simulate Ventilation Controls and Mine Airway Damage.

To continuously measure the velocity in the system, pilot tubes along with differential pressure transducers, connected to a data acquisition computer system were used (Figure 5). The difference between total pressure and static pressure from the pilot tube, which is proportional to the electrical signal, was measured by the differential pressure transducer. The velocity of air is then calculated by software using the follow Equation [20].

$$V = 44.72316 \times \sqrt{\frac{h_{kpa}}{d}}$$

Where

h_{kpa} = [total pressure-static pressure] (kPa)
d = air density (kg/m3)

Figure 5. Pilot Tube and Differential Pressure Transducer.

A rotameter was used to measure the flow rate of tracer gas (SF6) into the apparatus. Air samples were taken using glass syringe and Gas Chromatograph (GC) with electron capture detector (ECD) was used to analyze air samples and measure SF6 concentration.

Experimental Procedure

Although the five valves' states can be changed to simulate different situations and ventilation statuses, only two experiments were performed in this work. Case #1, defined as having only valve 1 closed, simulates normal ventilation status with the air flow paths shown in Figure 1. Case #2, with all the valves open, simulates the situation in which an explosion has damaged stoppings in the main entries. Air flow becomes short circuited due to the damage so that relatively little air reaches the panels, most intake air flows directly from the intake entry, through the crosscuts where stoppings were damaged, and is exhausted directly. The air flow paths in case #2 were shown in Figure 6.

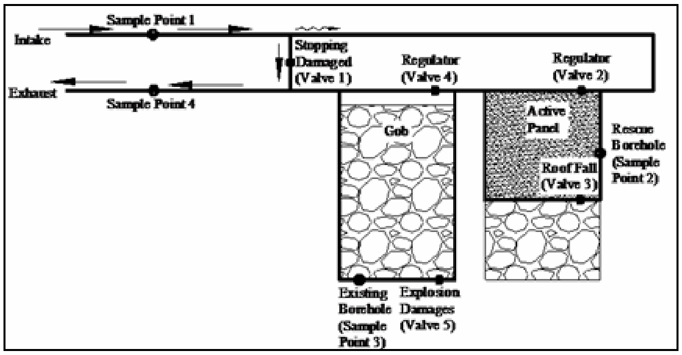


Figure 6. Flow Path of Case 2 after the Stopping Was Damaged by Explosion.

Before releasing SF6, the exhaust fan was turned on allowed to run until the flow reached a steady-state, marked by the air velocities no longer changing. The tracer gas was released just inside the inlet at a constant rate of 1 liter per minute. Air samples were taken after ten minutes had elapsed while tracer gas was released to ensure a stable airflow and tracer gas distribution. Air samples were drawn through septa at four different sample points which are shown in Figure 1 and for each location three measurements were repeated.

CFD MODELING

Geometry and Mesh

Auto CAD 2007 was used for three-dimensional modeling and the commercial software Ansys ICEM CFD, which is recognized as the fastest hexahedral mesh generation tool, was used to generate the mesh. An unstructured, hexahedral mesh was generated to represent the size and geometry of the lab experimental mine model. The "O" grid is used on the pipe cross section with fine mesh near the pipe wall and coarse mesh in the center. Figure 7 shows part of the mesh and Figure 8 shows the O grid mesh on the pipe cross section.

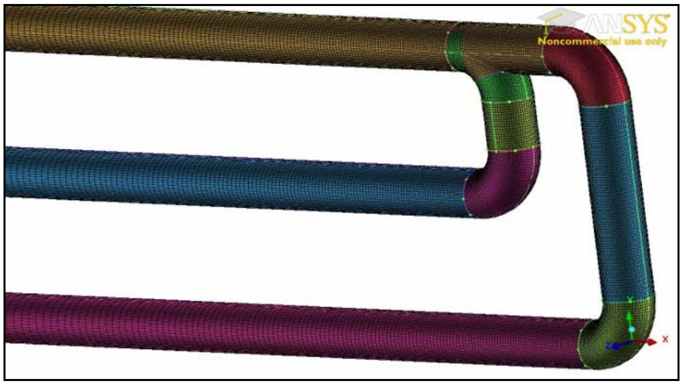


Figure 7. Part of the 3D Model and Meshing.

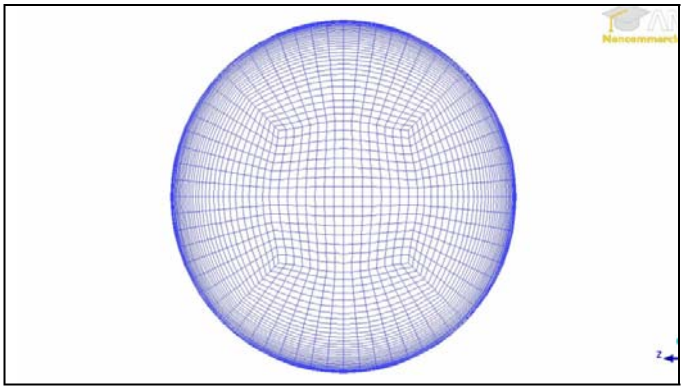


Figure 8. The "O" Grid Applied to Pipe Cross Section

The Turbulent Airflow Model

A proper turbulence model needs to be selected to simulate the pipe airflow and tracer gas dispersion. A steady state solution for the Reynolds averaged Navier-Stokes equations with the standard k-? turbulence model were employed to predict the incompressible turbulent airflow and user-defined scalar transport without chemical reaction and heat transfer was performed to predict tracer gas dispersion. The model was selected because it achieves reasonable accuracy over a wide range of turbulent flows in industrial flow simulations.

The inlet and the outlet of the model were specified as velocity inlet and pressure outlet, respectively. 403.38 Pa gauge pressure was applied to the outlet according to the experimental measurement. 18.0 ft/s (5.5 m/s) and 22.0 ft/s (7.0m/s) were applied to the inlet for Case #1 and Case #2, respectively. All of the other surfaces are treated as stationary walls with no slip. Both air and wall temperatures are assumed constant.

The numerical simulations in this study were conducted using the commercial CFD package, ANSYS FLUENT 12.1, to simulate the airflow and tracer gas dispersion for the same scenarios used during the laboratory tests. A first order upwind scheme was used for variables including pressure, momentum, turbulent kinetic energy and turbulent dissipation rate. Discretized airflow equations were solved with the SIMPLE algorithm in the CFD program to couple the pressure, velocity, momentum and continuity equations.

RESULTS AND ANALYSES

Air velocities were measured at four sample points and were used to calibrate the CFD model. Table 1 shows the measured and simulated velocities. Generally the computed airflow velocity agreed qualitatively with the experimental data. However, obvious errors exist in quantitative comparison. For example, in Case #2, simulated velocities at Point 2 and Point 3 are less than the measured data at the respective points. As we know in this case, the airflow was short-circuited, so the velocities at Point 2 and Point 3 should be small. We can conclude that it is very possible the measured velocity is not accurate. The difference between measured and simulated data may be mainly caused by three factors: the precision and error of the differential pressure transducer, the leakage of the experimental model, and the boundary conditions of the computer model. Since the study is the first step of the project, the data are accepted for now before further improvements are made.

Table 1. Measured and Simulated Velocity at Four Sample Points.

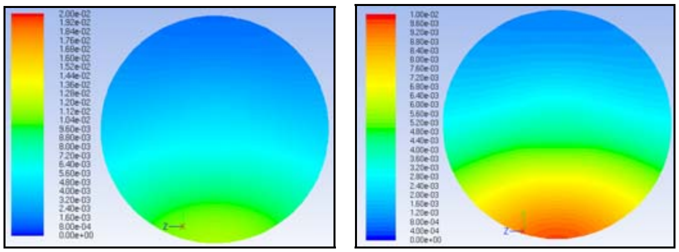
		Point 1	Point 2	Point 3	Point 4
Case 1	Measured	6.9 m/s	3.8 m/s	3.7 m/s	7.0 m/s
	Simulated	6.8 m/s	3.6 m/s	3.5 m/s	7.0 m/s
Case 2	Measured	8.2 m/s	2.0 m/s	1.9 m/s	8.5 m/s
	Simulated	8.3 m/s	0.4 m/s	1.5 m/s	8.8 m/s

SF6 was only used in Case #2. Air samples were taken three times at each sampling location and the average concentrations were calculated to compare with the simulated result. During the experiment, SF6 was released at a constant rate of 1 L/min through a ¼-inch inside diameter tube and placed 10cm inside the air inlet. In the computational model, SF6 was released from a point source (¼-inch cube) at the same location as the experiment, with a mass flow rate of 401 kg/m3*s which is equal to the 1L/min SF6 flow rate. For Case #1 the measured SF6 concentration is not available, but computer simulation was conducted.

Table 2 shows the measured and simulated SF6 concentrations for Case #2, also shows the simulated SF6 concentration for Case #1. There are differences between measured and simulated SF6 concentration. The measured results are generally larger than the simulated results. This is probably due to absorption of SF6 to the PVC pipes, although the parameters and boundary conditions used to simulate SF6 also need calibration. Figure 9 shows the SF6 distribution at a cross-section of Sample Point 1 in Case #1 and Case #2. From the contours one can see the CFD model can compute the diffusion of tracer gas and visualize the distribution. Because in Case #1 the velocity at the inlet is less than that of Case #2 (5.5 m/s and 7.0 m/s respectively), SF6 was diffused less in Case #1 than in Case #2 and has a different distribution over the cross-section.

Table 2. SF6 measured and simulated concentration.

		Point 1	**Point 2**	**Point 3**	**Point 4**
Case 2	Test 1	3.00mg/L	7.41mg/L	6.81mg/L	9.61mg/L
	Test 2	3.67mg/L	3.00mg/L	4.80mg/L	6.31mg/L
	Test 3	6.33mg/L	6.65mg/L	6.65mg/L	6.96mg/L
	Average	4.67mg/L	5.69mg/L	6.09mg/L	7.40mg/L
	Simulated	3.60mg/L	4.00mg/L	4.00mg/L	4.00mg/L
Case 1	Simulated	4.60mg/L	5.10mg/L	5.10mg/L	5.10mg/L



Case #1 Case #2

Figure 9. SF6 Distribution Contours in the CFD Model in Cross-Section at Sample Point 1.

CONCLUSIONS AND FUTURE WORK

This study investigated airflow and SF6 transport in an experimental coal mine through both experimental measurements and numerical simulation with CFD under two different cases (airflow patterns). An experimental coal mine, based upon a simple typical mine layout, was built using PVC pipes. Pitot tubes, differential pressure transducers, a computerized data acquisition system, and a gas chromatograph were used to measure the air velocity and tracer gas distributions throughout the simulated mines. The numerical simulations used CFD with the standard k-? turbulence model and user-defined scalars to simulate airflow and tracer gas (SF6) distribution.

Measured data were used to calibrate the CFD model and the simulated results were compared with the measured results. The velocities and the SF6 diffusion results were acceptable while there are differences between the computed and measured results. Errors exist in both the physical experiment and the CFD model and further experimental improvement and validation of CFD model are needed.

The present study is the first step toward research intending to use tracer gas measurements to compare measured and simulated profiles and determine whether damage to the ventilation system has been incurred during an emergency situation as well as the nature and the general location of the damage. Results showed that the methods used are feasible although improvements are needed. Further work will include: (1) Experimental measurement validation and design improvement including calibrating the velocity measurement results, controlling and analyzing the errors from the differential pressure transducers, and improving the location of velocity measurement. (2) The PVC pipes may also need to be replaced with a material that is less prone to SF6 adsorption. (3) Further calibrating the CFD model, especially the boundary conditions, diffusivity of SF6, mass flow rate of SF6. Also, it may be helpful to using the second order upwind scheme to achieve more accurate results. (4) Studying more cases under different airflow patterns to find the optimum location to release the tracer gas and techniques to release tracer gas which include the tracer dilution method, the constant injection method, or other methods will be constructive. (5) Finally, future experiments will use multiple tracer gases and comparing the efficiency over the use of single tracer gas.

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