DEVELOPMENT OF POTENTIAL REMOTE COAL MINE FIRE RESPONSE MEASURES: USE OF MULTIPLE PASSIVE SOURCE TRACERS AND SIMULATION OF HIGH EXPANSION FOAM FLOW IN SIMULATED GOB MATERIAL

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ACADEMIC ABSTACT

This thesis examines potential improvements to current coal mine fire response measures. In the event of a fire scenario, indirect testing and analysis of the exhausting air is needed to characterize changes in the fire. The application of multiple passive source tracers provides improved detail of complex ventilation interactions over an extended period of time. The first work in this thesis details the testing of the passive release rates for three Perfluorocarbon tracer compounds over a 180-day period. The results of this study demonstrate the ability for the permeation plug release vessel design to release Perfluorocarbon tracers at a steady rate.

Current response methods for a fire in a coal mine gob consist of injection of inert gas and sealing of the mine openings. Injection of high expansion foam into the gob from the surface has potential to improve extinguishment of the fire and reduce the time needed to bring the mine back to an operational state. The applicability of this method requires computational modeling and field testing. The second part of this thesis determines the Darcy and Forchheimer values for high expansion foam flow in simulated gob material with a lab experiment. The experiment was replicated in the CFD software, OpenFOAM, to validate the methods for calculation of the Darcy and Forchheimer values. The results of this study provide a tested methodology for a future full scale modeling of high expansion foam injection in a coal mine gob.

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GENERAL AUDIENCE ABSTRACT

This thesis examines potential improvements to current coal mine fire response measures. In the event of a mine fire, indirect testing of mine air exhaust is needed to track changes in the fire. The use of multiple passive tracer gas testing allows for better detail of air movement over a longer period of time. The first work in this thesis details the testing of the gas release rates for three Perfluorocarbon tracer gases over a 180-day timeframe. The results of this study show the ability for the gas release design to release Perfluorocarbon tracers at a steady rate needed for mine air exhaust testing.

Current methods to extinguish a fire in a coal mine gob involve adding inert gas to the mine and sealing the mine openings. Pumping of high expansion foam into the caved area of the coal mine from the surface has potential to improve extinguishment of the fire and reduce the time needed to bring the mine back to normal conditions. The potential of this method is determined by computer simulations and lab testing. The second part of this thesis determines the characteristics for foam flow in simulated caved material. The lab test was replicated in a computer simulation to prove the methods used to characterize the foam flow were accurate. The results of this study provide a proven method for future full scale computer simulations of foam flow in the caved area of a coal mine.

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INTRODUCTION

While the last major mining disaster in the US due to an explosion was in 2010 at the Upper Big Branch Mine, the potential for severe loss of life and unpredictability of these events proves that research into response of these events is still important today. Since 1976, over 200 miner fatalities have occurred in the United States resulting from underground coal mine explosions (Zipf, Sapko, & Brune, 2007). Methane pockets held within the coal seam can be released during the mining process from the face, floor or roof with no warning. Gob zones in underground coal mines often consist of broken pieces of coal, overburden material and coal from other seams within the caving zone. Presence of these materials results in a high methane concentrations often above the explosive limit of 15%. However, mixing of oxygen rich ventilation air into the gob can create an air mixture that is in the explosive range for methane. Ventilation sweeping across the active face combined with the presence of the longwall equipment creates the potential for danger if numerous safety procedures fail or are neglected.

Non-fatal underground fire incidents also have the potential to have a large impact on the operations of a coal mine. From 1990 to 2007 there were 1,601 reported fires across the entire mining industry (Trevits, Yuan, Smith, & Thimons, 2012). The most impactful of the fire types for mines are fires in the gob, either caused by an ignition or by spontaneous combustion. Of the 1601 fires reported in the NIOSH study, 25 originated from spontaneous combustion. Spontaneous combustion is caused by a self feeding oxidation reaction, where the oxidation of broken coal causes a temperature increase that further increases the rate of oxidation. The reaction progresses until a fire eventually forms, which can also lead to an explosion within the gob if sufficient methane gas and oxygen are present.

The most common method currently employed for extinguishment of a gob fire involve sealing of the mine and injection of inert gases. This method requires a significant cost with injection of the gas and duration of mine closure. Sealing of the mine is not guaranteed to work if unknown air pathways connect the gob area to the surface. One technique to detect and characterize potential connections to the surface is through tracer gas studies. Use of multiple long-term release tracer compounds provide the ability to track any complex interactions between the coal mine and the surface, through release of the tracer underground and sampling at points of interest on the surface. Recent studies into the injection of high expansion foams show it has the potential as an alternative or supplement to injection of inert gases and sealing of the mine. The field of research into improved coal mine fire response and mitigation will continue to expand as new technologies emerge.

Chapter 1: Development, Testing, and Proposed Application of Multiple Passive Source Tracers for Underground Mine Ventilation Systems

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Abstract

The application of passive tracer gas sources in underground mines is particularly useful for long-term tracer studies as well as for studies conducted in permissible areas of underground coal mines. The use of passive Perfluoromethylcyclohexane (PMCH) sources have been previously demonstrated in underground mines, but this new work details the testing of multiple, distinct tracer compounds compatible with passive sources. A description of their potential application in mine ventilation systems is also provided. Three tracer compounds are detailed, which are Perfluoromethylcyclohexane (PMCH), Perfluoroethylcyclohexane (PECH) and Perfluoromethylcyclopentane (PMCP). The release rates of these tracers were examined over a 180-day period at multiple temperatures. The advantages and disadvantages of these sources are presented, along with potential applications in characterizing ventilation circuits, flow through gob and leakage.

1. Introduction

The use of tracer gases for ventilation applications is an established practice with various past research projects conducted using Sulfur Hexafluoride (SF_6). Tracer gas techniques have been applied to assess flow rates, dilutions rates and auxiliary ventilation system efficiencies with quick, reliable and accurate results (Suglo and Frimpong, 2002). Perfluorocarbon tracer (PFT) compounds are a new introduction to ventilation and air modeling applications in terms of ventilation flow characterization (Watson et al., 2007).

PFTs are liquids that are characterized by low background presence in air, low reactivity, high detectability and low toxicity. A design was proposed called a permeation plug release vessel (PPRV) to convert PFTs from a liquid to a gas and then release the gaseous tracer in a controlled manner. The initial concept was originally introduced by Brookhaven National Laboratory and refined later to become the PPRV. The PPRV functions by allowing the volatile PFT liquid to become a vapor in a controlled manner. The vapor diffuses through a permeable silicone stopper at a predictable rate proportional to temperature (Zhang, Ph, & Cloud, 2006).

For use in underground mines, passive release sources need to be durable, be simple to manufacture, have customizable and reliable release rates as well as a long operating life, which are all qualities of the PPRV. The PPRV's design also allows multiple vessels to be bundled together so that a range of release rates greater than the capacity of a single source can be achieved. Additionally, the passive nature of the PPRV allows the deployment of PFTs in multiple locations simultaneously including permissible and human inaccessible areas to characterize complex ventilation interactions. Previous studies have examined release rates as a function of plug thickness and temperature but not for other PFT compounds.

The PPRV used in this study replicates the design applied in Jong et al., 2015. This research studied the PPRV over a 100 day test period using one tracer, Perfluoromethylcyclohexane (PMCH) (Edmund C. Jong et al., 2015). The following project aims to expand on this research and test the effect of temperature on three different PFTs across a longer time frame of 180 days. The primary objective of this experiment is to examine the PPRV's release rates between individual vessels at various temperatures to determine the applicability of the PPRV for long-term ventilation research. A secondary objective of this experiment is to determine the viability of the PPRV for releasing other PFT compounds. For this objective, two additional PFTs, Perfluoromethylcyclopentane (PMCP) and

Perfluoroethylcyclohexane (PECH), will be investigated in conjunction with Perfluoromethylcyclohexane (PMCH).

2. Literature Review

The information in this literature review focuses on the topic of tracers and their use in the mining industry. The review details the background of both gaseous and liquid tracers, the advantages of the tracer types to each other and how the tracers are implemented across different industries. The review also covers the release methods, sampling methods and data analysis for three common types of tracers.

2.1 Tracer Types and Usage

Tracer gases are typically compounds that are non-reactive, stable and posses the ability to be measured at low concentrations. Tracers are either released as a gas or liquid, to track air flows or ground systems. The common compound types of tracers used today are Sulfur Hexafluoride (SF_6), Perfluorocarbon tracers (PFTs) and radioactive tracers (Oyvind & Institutt for energiteknikk, 2007). One of the first recorded testing with tracer gases was conducted by the US Bureau of Mines in 1946. In this scenario, Helium gas was injected in a reservoir to characterize petroleum wells (Frost, 1946).

Sulfur Hexafluoride is a tracer used in short term ventilation surveys and is often referred to as SF_6. The molecular structure of $SF_6$is composed of a single Sulfur atom that is centered between six Fluorine atoms. The symmetry of the six fluorine atoms produces a non-polar gas that is non-reactive to most compounds, excluding solid Lithium. In 1901, $SF_6$was first created by Henri Moissan and Paul Lebeau when Octasulfur reacted with F_2 Fluorine. $SF_6$is often used to characterize gas dispersion in open air environments and infiltration rates into closed structures. The tracer has been used in a variety of applications for underground mines. The US Bureau of Mines applied $SF_6$to determine face ventilation is limestone and coal mines, injected into boreholes to study coal gob and released behind stoppings in order to characterize leakage through the stopping (Timko & Thimons, 1982).

Perfluorocarbon tracers are a group of Perfluorocarbons that are utilized in short term and long term studies on fluid flows. PFTs are available as volatile liquids that turn to vapor at standard conditions in a controlled matter, which allows for PFTs to be used in gaseous and liquid fluid flow applications. PFTs have a low detection level because they do not occur naturally. The molecular structures of PFTs are comprised of carbon chains attached to Fluorine atoms. The structure of the PFTs causes a high electron affinity, which results in low detection limits when using an Electron Capture Detector for sampling analysis (Watson et al., 2007). The US Department of Energy used PFTs along with other tracers to characterize air transport in complex terrains through the ASCOT program (Dickerson, Foster, & Gudiksen, 1984). Liquid application of PFTs are used heavily in the petroleum industry to characterize oil flow and communication between boreholes (Oyvind & Institutt for energiteknikk, 2007; Senum, Fajer, Derose, & Petroleum, 1992).

Radioactive tracers are a group of compounds that consist of at least one radioactive isotope. Radioactive isotopes are elements or compounds with at least one extra neutron. Radioactive tracers are affected by beta, gamma or positron emission decay. Each type of tracer has a different half-life due to this decay. A half-life is used to determine when that isotope was created, with the most well known usage being ^{14}C. Carbon 14 is often used to determine the age of geologic formations due to a long half-life of 5730 years. However, Carbon 14 is naturally occurring so it is not common to use as a tracer. The positron emission which causes the decay in various tracer isotopes makes radioactive tracers useful for medical imaging including SPECT and PET scans (National Institute of Biomedical Imaging and Bioengineering, 2016). Radioactive tracers are implemented in the field of Petroleum Engineering in order to characterize the effectiveness of hydraulic fracturing and other forms of reservoir stimulation (Fisher, Pro Technics, Robinson, & Voneiff, 1995).

2.2 Release Methods

Tracers are released differently depending on the type of tracer and the type of application applied. The two main categories of release types are continuous and pulse injection/release. When releasing sulfur hexafluoride continuously as a gas, a mass controller is utilized. Mass flow controllers use electrical signals to set the release rate of the gas. Temperature and pressure sensors guarantee the flow remains stable regardless of environmental changes (Advanced Energy, 2005). For pulse release of SF_6 the US Bureau of Mines used pressured bottles of known gas volume where the change in bottle weight was used to calculate the amount of tracer released (Timko & Thimons, 1982). Despite the insoluble properties of sulfur hexafluoride, large quantities of SF_6 were dissolved into the ocean using a spray nozzle under high pressure. This study collected water and air samples to characterize ocean gas exchange and fluid flow movement at different depths (A. J. Watson & Ledwell, 2000).

As stated earlier, Perfluorocarbon tracers are suitable for both air and liquid release studies. Under the Urban Dispersion Program by the US Department of Homeland Security, a motor-driven pump system was used to push PFTs onto a screen to facilitate rapid evaporation into the air. That pump system is capable of releasing PFTs in a continuous and pulse style release. In the UDP study, PFTs were released on 6 minute and 30 minute intervals in New York City to simulate airborne chemical movements from a terrorist attack (Allwine & Flaherty, 2007). Brookhaven National Laboratory created a long term release method for release of PFTs into the air, called a Permeation Plug Release Vessel (PPRV). A small capsule, plugged with silicone rubber is used to permeate out a controller flow of tracer over a period of days to months (Zhang et al., 2006). The PPRV design was successfully implemented in a field test to characterize air flows around the longwall of a coal mine (E C Jong, Luxbacher, Karmis, & Westman, 2016). For injection of PFTs as a liquid, the tracers can be continuously mixed with hydraulic fluid, drilling fluid, CO_2 or water. In a study by the Pacific Northwest Laboratory, PFTs were injected with drilling mud to determine chemical contamination of ground core samples (McKinley & Colwell, 1995).

Radioactive tracers, liquid or gas, are suited for biomedical and petrochemical applications. When radioactive tracers are applied as a gas, the tracer is often used for injection into gas wells but has also been utilized for ventilation studies. In one study, Krypton-85 was used to determine the most efficient set up for ventilation of a large livestock building. A pulse of the Krypton tracer was released in the barn and the radioactive decay of the tracer determines the ventilation rate in the livestock barn (Samer et al., 2012). Radioactive tracers have been studied heavily in the petroleum industry with many injection methods developed over the years. In Oklahoma, dry gas pulse injection of three tracers determined the location of a gas breakthrough affecting 25 wells (Welge, 1955). Dry gas continuous injection of Krypton-85 produced transit time data for a reservoir in West Texas, which was used to determine percent gas production from each of the nearby wells (Burwell, 1965). In Alberta Canada, multiple tracers were injected using the Water-alternating-gas method to gather information on a limestone reservoir in the early stages of development (Davis, Blair, & Wagner, 1976).

2.3 Sampling and Data Analysis

When conducting tracer gas studies, large amounts of air or liquid samples are collected. These samples require analyzing through lab equipment and mathematical equations to give practical meaning to the data. When conducting tracer studies using gas tracers released into the air, samples are collected using Vacutainer tubes connected to a syringe to pump in the air-tracer mixture (Timko & Thimons, 1982). A rubber bladder is used on the Vacutainer, which seals the tube when the syringe is removed. In the study previously described by Brookhaven, a Sequential Air Sampler (SAS) was used to pull air through activated charcoal into steel tubes at set increments of time (T. B. Watson et al., 2007). For liquid samples, regular test-tubes with rubber stoppers can be implemented, as maintaining water tightness is easier to achieve than air-tightness.

After collecting samples in a tracer gas study, lab analysis is needed to determine tracer concentrations in those samples. For sulfur hexafluoride studies, a gas chromatograph is needed to analyze the samples. The gas chromatograph takes 0.1 ml samples and determines gas compositions by the time it takes each individual gas species to travel through the heated GC column (McNair & Miller, 1998). The GC data is collected to determine sulfur hexafluoride concentration over time and total tracer recovered, which is used to calculate the volumetric flow rate of the air in the study area by using Equation 1 (Timko & Thimons, 1982).

$$Q_{SF6} = Q_{air} \int c \, dt \qquad (1)$$

Where Q_{SF6} is the total volume of tracer recovered, Q_{air} is the volumetric flow rate of the sampling area and c is the concentration of Sulfur Hexafluoride at that time instance. The total volume of tracer released and total volume of tracer recovered is used to calculated percent tracer flow to that sampling location, which is used to characterize air flow paths in a tracer study. Leakage rates for stopping or any control volumes can be calculated using Equation 2 with data gathered from the GC (Timko & Thimons, 1982).

$$Q = \frac{\ln\left({C_1}/{C_2} \right)}{T_1 - T_2}(-V) \qquad (2)$$

With C representing Sulfur Hexafluoride concentration at time a certain time, T is the time for each of the tracer concentration data points and V is the volume of the area being studied. For tracer studies involving PFTs, similar data calculations are needed but samples are analyzed using a gas chromatograph connected to an Electron Capture Detector (ECD). The ECD works by using a radioactive source that emits electrons through beta decay. The ECD characterizes gas composition by how well that gas sample captures the emitted electrons.

For analysis of radioactive tracer samples, a slightly different approach is utilized. Determination of tracer concentration depends on counting particle emissions due to radioactive decay. These counting techniques differ when using tracers at various concentrations. Counting techniques include scintillation, proportional counters and Geiger counters (Oyvind & Institutt for energiteknikk, 2007). For scintillation counting, the tracer is mixed with a compound that emits light when on the presence of radioactive decay. The lights flashes are counted in lieu of decay counts to determine concentration of the tracer (National Diagnostics Laboratory, 2004). Proportional counters utilize multiple detectors to measure the incident radiation in addition to detection of the radiation decay counts. This method creates the capability of differing between types of radiation decay from the tracers (Theodorsson, 1992).

3. Experimental Design

As previously discussed, three PFTs, PMCH, PMCP and PECH, were chosen for testing. The two previously untested tracers, PECH and PMCP, were selected for their ability to be simultaneously detected with PMCH using available laboratory equipment. These specific tracers have yet to be studied for application in underground mines.

The PPRV that will be employed consists of a 6.35 cm (2.50 in.) long aluminum cylinder with an inside diameter of 0.711 cm (0.280 in.). The cylinder has one permanently closed end and one open end. Each vessel was filled with 0.6ml of the desired volatile liquid tracer. The PPRV was then capped using a 1 cm long silicone plug pressed into the open end using a thin layer of silicone grease. Once sealed, the PFT will permeate the silicone plug, with its steadily released at a rate proportional to the ambient temperature (Jong et al., 2015). An example of the PPRVs used in this experiment is shown in Figure 1.

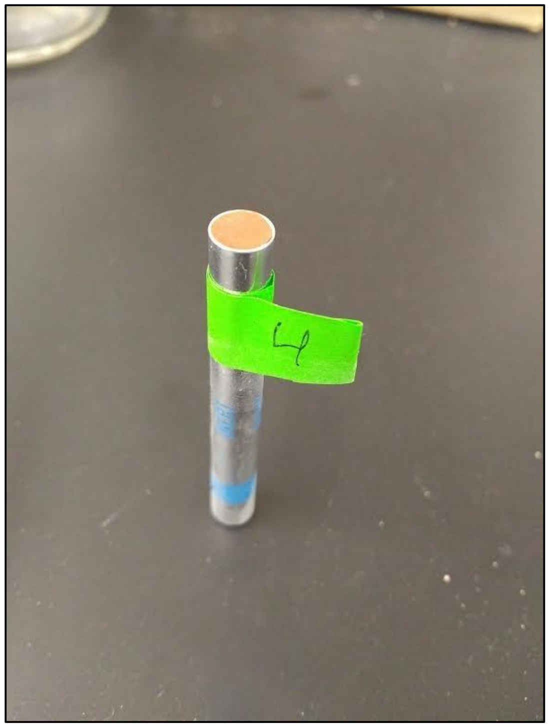

Figure 1: Example of PPRV Design and Labeling

The release rates of the three tracer gases PECH, PMCH and PMCP were measured at the temperatures 10℃, 21℃ and 50 ℃. The temperature extremes 10℃ and 50℃ were chosen because they were the lowest and highest controlled temperatures, respectively, achievable with the available equipment that represented realistic mine temperatures. The 21℃ middle temperature was chosen to provide a central point for the temperature range. A laboratory refrigerator and hot water bath were used to create the 10℃ and 50℃ conditions, respectively.

For each of the temperature conditions, a beaker filled with sand was used to contain the PPRVs. The sand helped to regulate the temperatures to which the PPRVs were exposed, preventing sudden temperature fluctuations. The PPRVs were inserted into the sand as far as possible while keeping the surface of the plug out of the sand. Nine PPRVs were placed into each of the beakers, producing 27 PPRVs in total, with three of each PFT compound per beaker.

The PPRV release rates were recorded as weight changes over time using an analytical scale accurate to 0.1mg. During each data recording session, the PPRVs were chosen at random from each of the temperature conditions to prevent any sampling bias.

For the first 60 days of the study, the PPRVs were measured on a bi-weekly basis to monitor the sources' equilibrium period. During equilibrium, the PPRVs' release rates are either inconsistent or not significant and thus do not require detailed monitoring. After this time, the PPRVs were then weighed once a week until the 180-day measurement period elapsed. Only data points after the PPRVs reached an equilibrium period were used for final analysis.

4. Results

The release rates of the PPRVs were determined by performing a regression on the change in weight over time of the PPRVs. The corresponding R^2 value for each PPRV weight slope provides an indication of the precision of the individual source release rate, while the release rates of the individual PPRVs can be compared to determine the precision between vessels of the same compound and temperature. The graphs of the PPRVs change in weight over time, are shown in Figures 2, 3 and 4. In the three figures displaying total weight released, each PFT compound had three PPRVs for each temperature. An example of the naming convention used in these figures is as follows: PMCH 1-3 represent the three PMCH PPRVs at 50℃, PMCH 4-6 represent the PMCH PPRVs at 21℃ and PMCH 7-9 represent the PMCH PPRVs at 10℃.

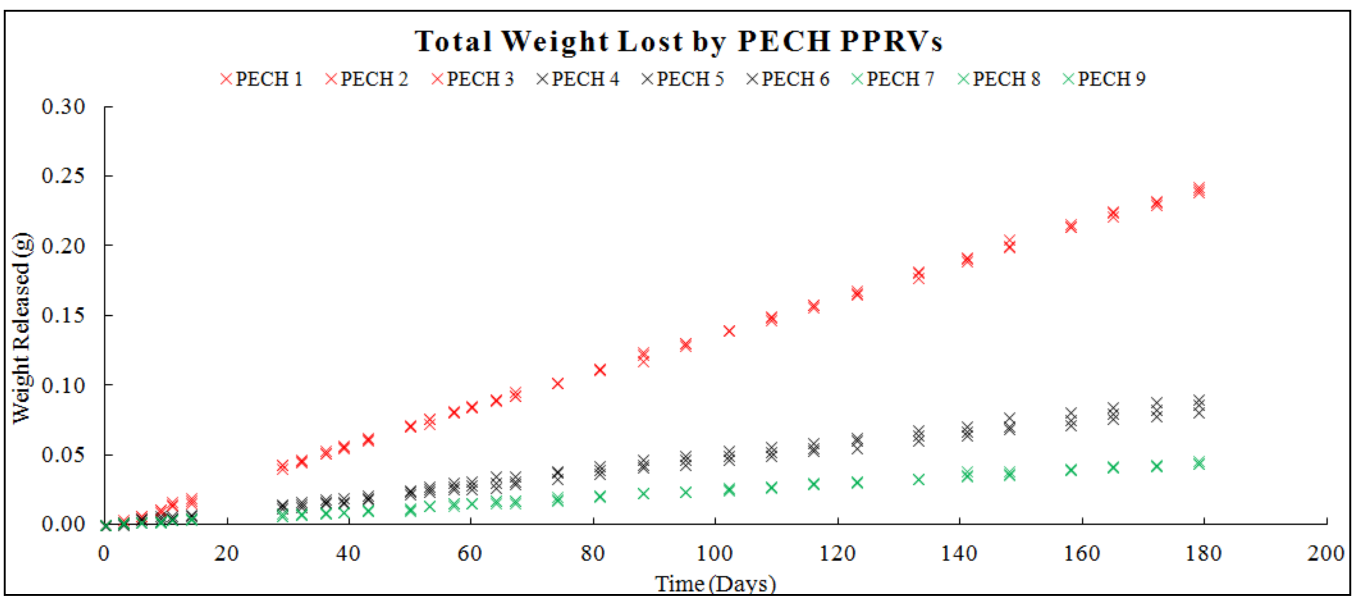

Figure 2: Total Weight Release of PECH PPRVs across Three Temperatures

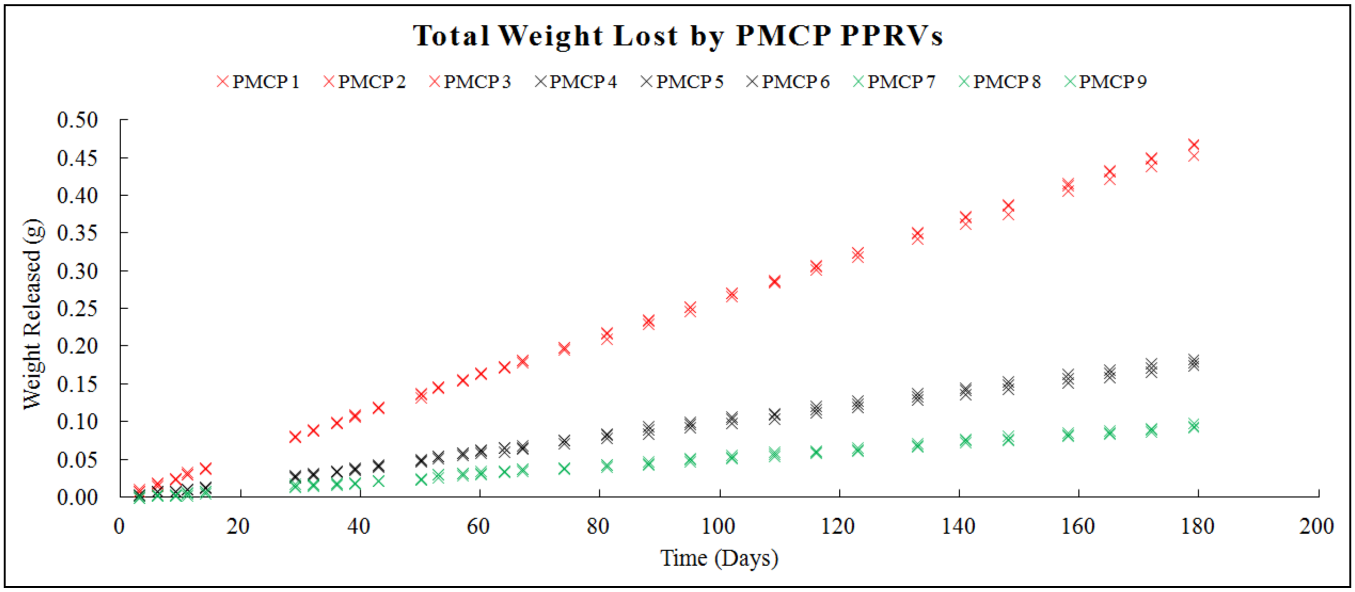

Figure 3: Total Weight Release of PMCP PPRVs across Three Temperatures

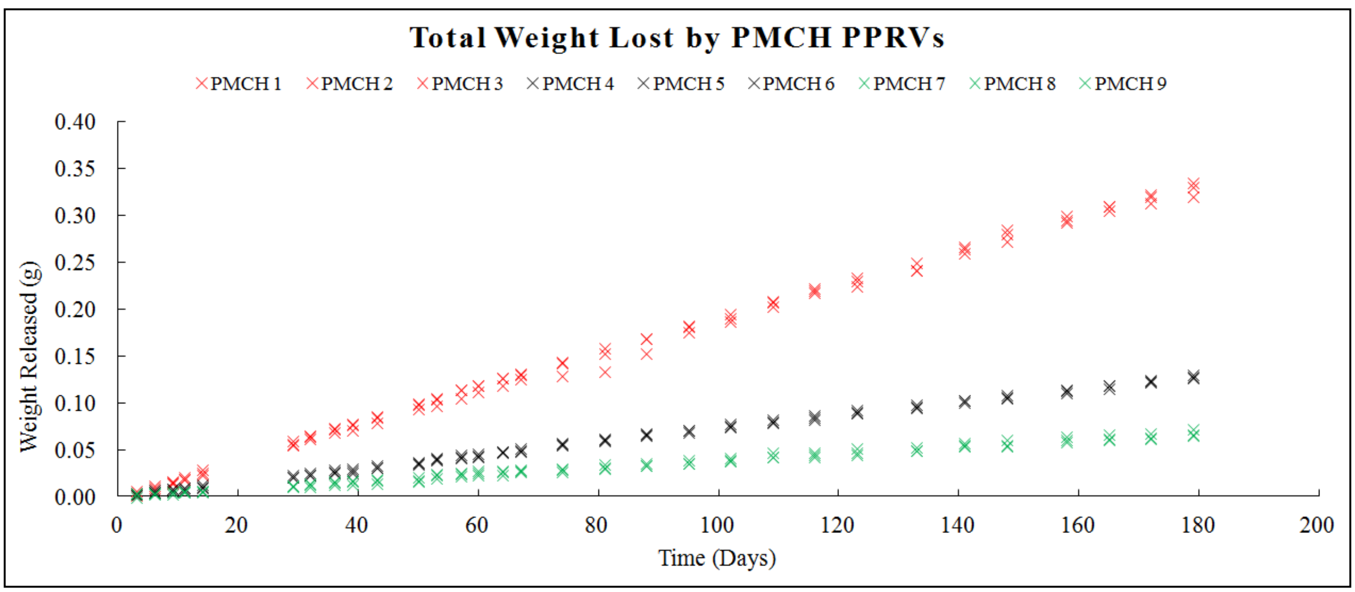

Figure 4: Total Weight Release of PMCH PPRVs across Three Temperatures

The statistical analysis of the release rates between PPRVs of the same PFT compound and temperature is in Table 1. This analysis shows that the PPRV compound groupings within each temperature groups were very precise with a maximum relative standard deviation of 3.7%. As stated earlier, the data from the statistical analysis did not include points during the equilibrium period of the PPRVs, which encompassed 14 days at the beginning this study. However, these points were included in the Figures 2, 3 and 4 to represent all of the data collected during this study. The R^2 values for each of the PPRVs are located in Table 2, which represent the strength of the data's linear correlation for each individual source. The magnitude of the R^2 values indicates that the sources exhibited excellent release rate stability over time. This aspect is apparent especially considering that the lowest R^2 value was 0.994, which still indicates a strong linear correlation.

Table 1: Statistical Analysis of Release Rate Between Individual PPRVs by PFT and Temperature

	PECH			PMCP			PMCH		
Temperature (°C)	10	21	50	10	21	50	10	21	50
Mean (mg/day)	0.25	0.49	1.33	0.53	1.01	2.55	0.37	0.71	1.84
Std Dev (mg/day)	0.004	0.018	0.014	0.013	0.024	0.039	0.013	0.003	0.010
RSD (%)	1.4	3.7	1.1	2.4	2.4	1.5	3.6	0.5	0.5

Table 2: Individual PPRV $\boldsymbol{R^2}$ *Value for the Slope of Weight Change*

	PECH			PMCP			PMCH		
Temperature (°C)	10	21	50	10	21	50	10	21	50
Vessel 1	0.994	0.999	1.000	0.999	0.999	1.000	0.996	0.999	0.999
Vessel 2	0.996	0.999	0.999	0.998	1.000	1.000	0.997	0.999	1.000
Vessel 3	0.997	0.999	1.000	0.998	1.000	1.000	0.997	0.999	0.997

Figure 5 displays the average release rate plotted against temperature and grouped by PFT compound. Although trend lines for each tracer compounds are included in Figure 5, insufficient data was collected to establish a statistically verified equation for determining release the rate from temperature. These trend lines can serve as a reference for future studies implementing these tracer compounds and PPRV design. The R^2 value was above 0.992 for each of the tracers, which strongly indicates that the data closely follows the linear release rate trednline.

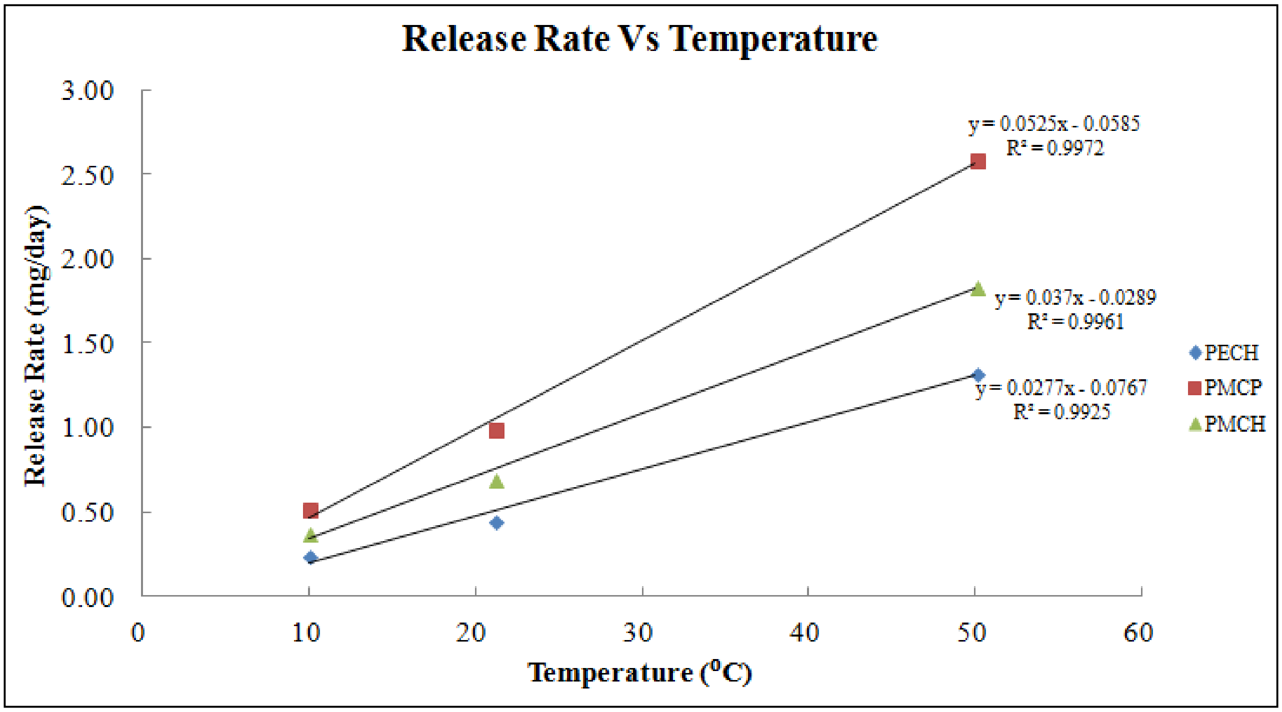

Figure 5: Temperature vs Release Rate of Tracers PECH, PMCP and PMCH contained in PPRVs

5. Discussion

The design of the PPRV allows for long-term and varied use in mining applications. The availability of multiple, compatible PFTs also permit the simultaneous deployment of multiple tracers in different locations. This ability increases the number and complexity of studies that can be performed, such as the modeling of complicated transport systems and air infiltrations (Batterman, Jia, Hatzivasilis, and Godwin, 2006). Examples of an in mine PPRV test and some potential applications are provided in the following section.

In order for a tracer gas to be feasible for in mine use, sufficient tracer has to be released in relation to the airflow quantity to maintain a detectable limit for the gas chromatography machine. A study was conducted in an underground longwall mine where PMCH was released with the PPRV design near the longwall face to test if a PFT could be released at a detectable limit within a mining environment (Jong, et al., 2016). One hundred PPRVs were utilized to reach a concentration of 3 to 21 ppt at the sampling point, which were sufficient to be detectable by the GC. The study showed that PFTs and the PPRV are suitable in a large-scale mining environment for ventilation purposes.

Flow through the gob is difficult to model because of its complex shape combined with its limited access to the interior. Several studies have applied tracer gases for this purpose. For example, the National Institute of Occupational Health and Safety used the tracer SF_6 to model how geologic factors and mining factors influenced gas flow in a long wall gob by releasing the tracer gas at seven different gob locations. This study detailed high communication between vent holes within the gob and limited communication between the vent holes and the underground ventilation system for this mine (Diamond et al., 2002). The data from this study was then used to model the strata surrounding the gob, showing the permeability between the gob gas vent holes and that the production vent holes had a greater influence on the shut-in pressure than the bleeder system (Mucho,-2000). If PFTs were used for this study, different gob vent holes could use different tracers to show not only the level of communication between holes but also discern flow paths between release and sampling locations. The long-term stability of the PFTs would also allow for the modeling of gob-hole interaction changes over time.

Another useful application of tracer gases in coal mining is the characterization of leakage through stoppings from abandoned sections. Numerous studies, such as research by the Bureau of Mines, have used SF_6 to find the leakage through permanent and temporary stoppings. PPRVs could be used in a similar manner to study leakage but could have the added advantages of long-term passive deployment as well as the option of applying multiple PFT compounds in both fresh air and permissible areas.

SF_6 has also been used to track air flows through a sealed abandoned mine section. For example, a study conducted by the Central Mines Rescue Stations measured flow velocity and direction through gob and sealed fire fields to assess the risk of spontaneous heating of coal (Buchwald and Jaskólski, 2004). The PPRV could also be in this instance to track flow through the abandoned sections with the added advantage of being utilized passively over a longer period. The ability to monitor flow through sealed sections can be used as an early indication of developing characteristics that may cause gas accumulations behind the seal. Increased leakage through nearby cracks in the strata or increased pressure behind the seal can also be monitored.

6. Summary

The study presented in this paper exampled 27 PPRVs filled with three different tracer compounds, PMCH, PECH and PMCP over a 180 day period. Statistical analyses showed low relative standard deviation values, <5%, within PPRVs filled with the same compound and subjected to the same temperature. The low relative standard deviations show that the PPRVs were very precise and did not exhibit any defects from the manufacturing process.

The R^2 values calculated for each PPRV were all over 0.99, which represent a very high linear correlation for each individual source. As such, the PPRV group as a whole exhibited a steady release rate within each temperature condition over the 180-day test period. Based on this result, the PPRV design has shown its viability for both long duration investigations as well as its ability to accept multiple PFT compounds.

7. References

Advanced Energy. (2005). Fundamentals of Mass Flow Control.

Ahmad, I., Sahay, N., Varma, N. K., & Sinha, A. (2009). Application of High Expansion Nitrogen Foam to Control Mine Fire. *Mine Fires in Indian Coal Industry*.

Allwine, K. J., & Flaherty, J. E. (2007). *Urban Dispersion Program Overview and MID05 Field Study Summary*.

ANSUL. (2013). Class A, B and LNG Fures High Expansion Foam. Retrieved from http://www.ansul.com/en/us/pages/ProductDetail.aspx?productdetail=Class+A%2C+B%2C+%26+LNG+Fires+High-Expansion+Foam

Batterman, S., Jia, C., Hatzivasilis, G., & Godwin, C. (2006). Simultaneous measurement of ventilation using tracer gas techniques and VOC concentrations in homes , garages and vehicles. *Journal of Environmental Monitoring*, *8*(Advance Web Article), 249–256. https://doi.org/10.1039/b514899e

Buchwald, P., & Jaskólski, Z. (2004). Application of the SF 6 Tracer Gas in Identifying Mine Air Flows through Abandoned Workings Sealed from the Ventilation System. *International Mining Forum*, *5*, 169–178.

Burwell, F. (1965). Multiple Tracers Establish Waterflood Flow Behavior. *Oil and Gas*.

Coombs, J. (n.d.). Modelling of Porous Media in OpenFOAM. *The University of Adelaide*.

Davis, J. A., Blair, R. K., & Wagner, O. R. (1976). Moni toring and Control Program for Miscible a

Large Scale. In *Society of Petroleum Engineers of AIME*. New Orleans.

Daza, M. B., Luxbacher, K., & Lattimer, B. (2018). RHEOLOGY OF HIGH EXPANSION FOAM, 1–7.

Diamond, W. P., Schatzel, S. J., Garcia, F., Lascola, J. C., Mccall, F. E., Jeran, P. W., & Niosh, H. (2002). Characterization of Gas Flow in Longwall Gobs : Pittsburgh Coalbed , PA. In *North American Mine Ventilation Symposium* (p. 12).

Dickerson, M. H., Foster, K. T., & Gudiksen, P. H. (1984). Experimental and Model Transport and Diffusion Studies in Complex Terrain with Emphasis on Tracer Studies. *Boundry-Layer Meteorology, 30*, 333–350.

Dong, S., Lu, X., Wang, D., Wang, H., Zheng, K., Shi, Q., & Chen, M. (2017). Experimental investigation of the fire-fighting characteristics of aqueous foam in underground goaf. *Process Safety and Environmental Protection, 106*, 239–245. https://doi.org/10.1016/j.psep.2016.12.009

Fisher, K., Pro Technics, Robinson, B. M., & Voneiff, G. W. (1995). A Comprehensive Study of the Analysis and Economic Benefits of Radioactive Trace Engineered Stimulaiton Procedures. In *SPE annual Technical Conference* (pp. 957–964). Dallas, TX: Society of Petroleum Engineers.

Frost, E. . (1946). Helium tracer studies in Elk Hills, California. *Report of Investigations (US Bureau of Mines)*.

Gardiner, B. S., Dlugogorski, B. Z., & Jameson, G. J. (1998). Rheology of fire-fighting foams. *Fire Safety Journal*, *31*(1), 61–75.

Gieras, M., Klemens, R., Rarata, G., & Wolański, P. (2004). Determination of explosion parameters of methane-air mixtures in the chamber of 40 dm 3 at normal and elevated temperature. *Internation Symposium on Hazards, Prevention and Mitigation of Industiral Explosions, 5*, 10–14.

Gilmore, R. (2007). Computational Fluid Dynamics Modeling of Underground Coal Longwall Gob Ventilaiton Systems Using a Devleoped Meshing Approach.

Greenshields, C. J. (2016). OpenFOAM User Guide, (June). Retrieved from http://foam.sourceforge.net/docs/Guides-a4/OpenFOAMUserGuide-A4.pdf

Grubb, J. (2008). *Preventative Measures for Spontaneuous Combustion in Underground Coal Mines*.

Colorado School of Mines.

Huw, P., Sezer, U., & Kelello, C. (2009). Prevention and Control of Spontaneous Combustion; Best Practice Guidelines for Surface Coal Mines in South Africa. Retrieved from http://www.coaltech.co.za/chamber databases/coaltech/Com_DocMan.nsf/0/AAB37D3149EC72FE42257839002F59BB/$File/Spontaneous Combustion Guidelines - Feb 2011.pdf

Jong, E. C., Luxbacher, K. D., Karmis, M. E., & Westman, E. C. (2016). Field test of a perfluoromethylcyclohexane (PMCH) permeation plug release vessel (PPRV) in an underground longwall mine. *Mining Technology*, *125*(2), 65–71. https://doi.org/10.1179/1743286315Y.0000000012

Jong, E. C., Peng, Y., Bradley, W. T., Luxbacher, K. D., Agioutantis, Z., & Mcnair, H. M. (2015). Development of a perfluoromethylcyclohexane (PMCH) permeation plug release vessel (PPRV) for tracer gas studies in underground mines. *Process Safety and Environmental Protection*, *95*, 136–145. https://doi.org/10.1016/j.psep.2015.02.012

Kai, C., & Zhenlu, S. (2012). Prevention and Control of Coalfield Fire Technology. *Internation Journal of Mining Science and Technology*, *22*(5), 657–663.

Karacan, C. Ö. (2008). Modeling and prediction of ventilation methane emissions of U.S. longwall mines using supervised artificial neural networks. *International Journal of Coal Geology*, *73*(3–4), 371–387. https://doi.org/10.1016/j.coal.2007.09.003

Karacan, C. Ö., Esterhuizen, G. S., Schatzel, S. J., & Diamond, W. P. (2007). Numerical Analysis of the Impact of Longwall Panel Width on Methane Emissions and Performance of Gob Gas Ventholes. *International Journal of Coal Geology*, *71*(2–3), 225–245. https://doi.org/10.1016/j.coal.2006.08.003

McKinley, J. F., & Colwell, F. S. (1995). Application of erfluorocarbon tracers to microbial sampling in subsurface enviroments using mud-rotary and air-rotary drilling techniques. *Journal of Microbiological Methods*, *26*, 1–9.

McNair, H. M., & Miller, J. M. (1998). *Basic Gas Chromatography*. Wiley.

Moore, T. D. J., Deul, M., & Kissell, F. N. (1976). Longwall Gob Degasification With Surface Ventilation Boreholes Above the Lower Kittanning Coalbed, RI 8195.

MSHA, D. of L. (n.d.). Actions for excessive methane 30 CFR 75.323.

MSHA, D. of L. (1996). Methane Detectors 30 CFR 75.342.

Mucho, T. P., Diamond, W. P., & Garcia, F. (2000). Implications of Recent NIOSH Tracer Gas Studies on Bleeder and Gob Gas Ventilation Design. In *SME Conference* (p. 16).

Muljadi, B. P., Blunt, M. J., Raeini, A. Q., & Bijeljic, B. (2016). The impact of porous media heterogeneity on non-Darcy flow behaviour from pore-scale simulation. *Advances in Water Resources*, *95*, 329–340. https://doi.org/10.1016/j.advwatres.2015.05.019

National Diagnostics Laboratory. (2004). Principals and Applications of Liquid Scintillation Counting.

National Fire Protection Agency. (2005). NFPA 11 Standard for Low- , Medium- , and High-Expansion Foam.

National Institute of Biomedical Imaging and Bioengineering. (2016). Nuclear Medicine. Retrieved from https://www.nibib.nih.gov/science-education/science-topics/nuclear-medicine

Oyvind, D., & Institutt for energiteknikk. (2007). *AN EXPERIMENTAL STUDY OF TRACERS FOR LABELING OF INJECTION GAS IN OIL*. University of Bergen.

Pappas, D., & Mark, C. (1993). *Behavior of Simulated Longwall Gob Material*.

Phelps, T. (2013). Monitoring Subsurface Fluid Flow using Perfluorocarbon Tracers. Oak Ridge National Laboratory.

Samer, M., Berg, W., Fiedler, M., Ammon, C., Sanftleben, P., & Brunsch, R. (2012). *A comparative study among H20 balance, heat balance, CO2 balance and tracer gas technique for airflow rates measurement in naturally ventilated dairy barns*.

Senum, G. I., Fajer, R., Derose, W. E., & Petroleum, B. (1992). Petroleum Reservoir Characterization by Perfluorocarbon Tracers.

Sheinson, R. S., Williams, B. A., Green, C., Fleming, J. W., Anleitner, R., Ayers, S., … Barylski, D.

(n.d.). THE FUTURE OF AQUEOUS FILM FORMING FOAM (AFFF): PERFORMANCE PARAMETERS AND REQUIREMENTS Ronald S. Sheinson, Bradley A. Williams, Christian Green, James W. Fleming, Robert Anleitner.

Singh, M. M., & Kendorski, F. S. (1981). Strata Disturbance Prediction For Mining Beneath Surface Water And Waste Impoundments. In *1st Annual Conference on Ground Control in Mining*.

Smith, A. C., Mucho, T. P., Trevits, M. A., & Cummins, M. (2005). THE USE OF NITROGEN-ENHANCED FOAM AT THE PINNACLE MINE FIRE.

Smith, A. C., Trevits, M. A., Mucho, T. P., Ozmet, A., Walsh, J. B., Smith, A. C., & Trevits, M. A. (2010). Evaluation of Gas-Enhanced Foam for Suppressing Coal Mine Fires. *2010 SME Annual Meeting and Exhibit*, 17.

Sohr, H. (2001). The Navier-Stokes equations. https://doi.org/10.1007/978-3-0348-0551-3

Suglo, R. S., & Frimpong, S. (2002). Accuracy of Tracer Surveys in Auxiliary Ventilation Systems in Coal Mines. *North American Mine Ventilation Symposium*, 169.

Theodorsson, P. (1992). Quantifying Background Components of Low-Level Gas Proportional Counters. *RadioCarbon*, *34*(3), 420–427.

Timko, R. J., & Derick, R. L. (1988). Analysis of a Fire in a Colorado Coal Mine. *Proc 4th Int'l Mine Ventilation Congress*.

Timko, R. J., & Thimons, E. D. (1982). Sulfur hexafluoride as a mine ventilation research tool-Recent field applications. *US Bureau of Mines*, *8735*, 15. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Sulfur+Hexafluoride+as+a+Mine+Ventilation+Research+Tool-+Recent+Field+Applications#0

Trevits, M. A., Yuan, L., Smith, A. C., & Thimons, E. D. (2012). NIOSH MINE FIRE RESEARCH IN THE UNITED STATES.

University of Surrey. (n.d.). Positron Emission Tomography. Retrieved March 21, 2018, from http://personal.ph.surrey.ac.uk/~phs1ns/PhD/research_tops/pet.html

Watson, A. J., & Ledwell, J. R. (2000). Oceanographic Tracer Release Experiments Using Sulphur

Hexafiuoride. *Journal of Geophysical Research*, *105*, 14,325-14,337.

Watson, T. B., Wilke, R., Dietz, R. N., Heiser, J., & Kalb, P. (2007). The Atmospheric Background of Perfluorocarbon Compounds Used as Tracers. *Environmental Science and Technology*, *41*(20), 6909–6913.

Web Elements. (n.d.). Sulfur: Sulfur Hexafluoride. Retrieved March 20, 2018, from https://www.webelements.com/compounds/sulfur/sulphur_hexafluoride.html

Welge, H. (1955). Super Fleuths Trace Flow of Injected Gas. *Oil and Gas*, 77–79.

Zhang, H., Ph, D., & Cloud, A. (2006). The Permeability Characteristics of Silicone Rubber. In *Global Advances in Materials and Process Engineering*. Dallas, TX: Society for the Advancement of Material and Process Engineering.

Zipf, R., Sapko, M., & Brune, J. (2007). Explosion Pressure Design Criteria for New Seals in U . S . Coal Mines. *Information Circular 9500*.

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Chapter 2: Determining Darcy and Forchheimer Coefficients for High Expansion Foam Flow in Simulated Gob Material through a Pressure Drop Experiment and Comparing Results to OpenFOAM Models

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Abstract

Research on foam generators for fire extinguishment started at the US Bureau of Mines in the 1960s. That research included studies of high expansion foam flow over a fire source via travel in entries or crosscuts. High expansion foam has the potential to be injected into coal mine gob to extinguish a gob fire. Direct injection could served as a more targeted and direct method for gob fire extinguishment, compared to sealing of the mine and inert gas injection. In order to determine the feasibility of this method, lab scale testing and simulation through CFD software is needed. For fluid flow in porous media to be simulated in OpenFOAM, Darcy and Forchheimer coefficients that are based on the types of fluid and porous media being tested are required. Darcy and Forchheimer coefficients are obtained experimentally by a pressure drop test. This test measures foam flow rates and pressures for steady state flow through a porous zone consisting of gravel, which represents coal gob material. The determined coefficients are implemented in OpenFOAM to test the applicability of the OpenFOAM software by comparing the model results to the lab scale test results. This paper presents the methods used in the pressure drop experiment, the resulting Darcy and Forchheimer values and the replication of the experiment in OpenFOAM to test the applicability of the software.

1. Introduction

Use of high expansion foam as an indirect firefighting method has been previously tested in many industries and has been implemented in the coal mining industry multiple times since at least the 1980s (Timko & Derick, 1988) along with recent foam technology advances involving nitrogen enhanced foam (Ahmad, Sahay, Varma, & Sinha, 2009; Smith, Mucho, Trevits, & Cummins, 2005). The majority of firefighting foam use in coal mines involves utilizing a large blower fan connected to a foam generator in order to produce high expansion foam within the mine entry. The foam creates a plug in the entry that travels towards the location of the fire and is capable of blocking airflow. Fire fighting foams control a fire by separating the oxygen source from the fire by plugging the entry, by cooling the fire through physical contact of the foam, or by separating the fire from the fuel source with formation of a fluid layer at the bottom of the foam plug. Recent research has involved injecting fire fighting foams through boreholes into entries to control ventilation, to apply foam closer to the fire and to avoid mine rescue teams operating underground (Smith et al., 2010).

Firefighting foam has the potential to be injected through boreholes into an underground coal mine gob in order to suppress a fire in the gob. Current methods to extinguish a coal mine gob fire require sealing of the mine and injection of inert gases, as these fires are difficult to access. This technique has been proven successful, but inert gas injection is costly and the process results temporary to permanent mine closure (Huw, Sezer, & Kelello, 2009). Initial case studies of foam injection into gob have been performed, where the injection of three phase foam into a burning open pit gob achieved extinguishment of the coal in a period of nine months (Kai & Zhenlu, 2012). Lab tests and computational fluid dynamics modeling are proposed methods to characterize foam flow in gob material and to determine potential applications.

One of the challenges with characterizing flow in caved material is calculating the permeability and porosity of that material. For an underground coal mine gob, the permeability changes with location to the longwall face and depth within the gob. Due to the hazard of working near a caved area and low accessibility to the area, indirect measurement techniques are used to estimate the gob parameters. Lab experiments can be conducted in order to simulate the gob material and estimate the porous resistance values needed for computational modeling. The objective of this research is to perform a lab experiment on high expansion foam flow through simulated gob material to calculate values for porous resistance and to import those values into the computational modeling software to validate the modeling software for simulating foam flow in porous media.

2. Literature Review

This literature review covers topics relevant to the high expansion foam modeling for use in a coal mine gob and starts with the background on longwall mining, gob development and effects on the ventilation system. The relevant characteristics of the gob material for flow through porous media are also discussed. The literature review then covers types of high expansion foam, methods for producing the foam and the non-Newtonian properties of the foam. This section concludes with information on the OpenFOAM software and the solvers which will be used in this research project.

2.1 Longwall Mining

The two main methods for mining coal underground are longwall mining and “room and pillar” mining. Longwall mining allows for a higher percentage of the coal in place comparatively to be extracted but is not always applicable due to geological requirements and effects from subsidence. Figure 6 displays multiple views of a typical longwall configuration. The longwall shearer shown in section C of Figure 1 takes continuous cuts out of coal as it moves across the seam, which gets carried out by a conveyor system that runs along the panel width. The shearer and conveyor system are protected by a row of shields that support the weight of the caved roof that becomes the gob. As the shearer takes cuts of coal, the conveyor and shield system moves forward, causing the overburden to cave down behind it. As the longwall setup moves further forward, the gob becomes more compacted due to the vertical stresses from the increased weight of the caved material no longer supported by shields or pillars.

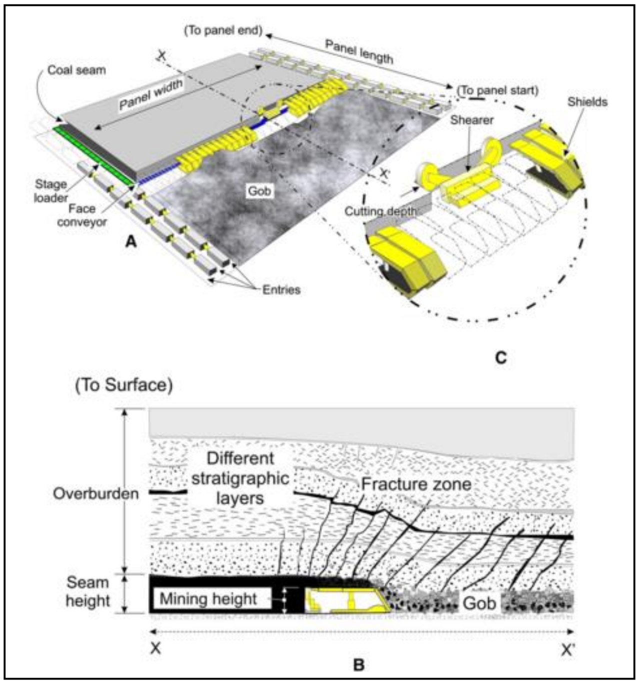

Figure 6: A. Panel diagram with a three-entry gate road system, B. Cross-section along view of panel setup, C. Close up view of longwall shearer and shields (C. Özgen Karacan, 2008)

The gob material contains liberated coal and shale that release large quantities of methane. Bleeder systems are used to sweep fresh air across the longwall face for workers operating the shearer and carry gob methane into the return airways. Methane has an explosive limit of roughly 5% to 15% depending on the composition of other gases (Gieras, Klemens, Rarata, & Wolański, 2004). Along the longwall face methane concentrations are kept below 1% to maintain a factor of safety for preventing an ignition at the face. Methane detectors are set to sound an alarm at a methane concentration greater than 1% and deactivate electric equipment when the concentration reaches 2% (MSHA, 1996). Work is not permitted while the methane concentration is above 1% and miners are withdrawn if the concentration rises to 1.5%. The methane concentration is only allowed to reach 2% in bleeders or return air sections (MSHA, n.d.).

A ventilation diagram for a full bleeder longwall setup is shown in Figure 7. The neutral airways in the diagram are for the conveyor belts that transport coal from the longwall face towards the surface. A full bleeder setup is an effective ventilation setup for a gassy coal mine not prone to spontaneous combustion. A spontaneous combustion prone mine would use a semi or bleederless ventilation configuration to prevent oxygen from infiltrating the permeable zone of the gob close to the longwall face. In a bleederless plan, the return areas beyond the active longwall face are blocked off and become unventilated areas. Both ventilation schemes may implement gob ventilation boreholes to exhaust off the methane buildup within the gob.

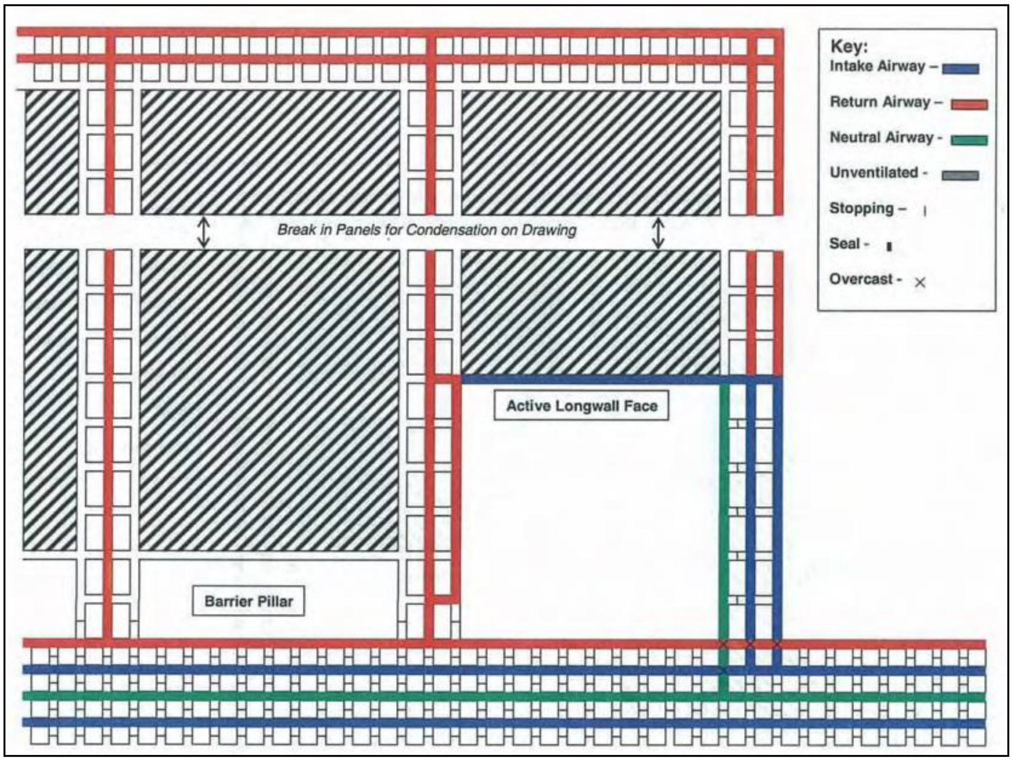

Figure7: Ventilation Scheme for Longwall Coal Mine (Grubb, 2008)

Gob ventilation boreholes (GVBs) are effective in gassy mines where the methane released can be captured and sold in the natural gas market. Methane from gob ventilation boreholes can also be released directly into the atmosphere or stored onsite if needed. The air pressure between the coal mine and the surface can be enough to force drainage of methane into the GVBs. The boreholes are drilled before mining of the section to limit the methane released during liberation of the coal, which prevents "gasing off" of the mining section. The boreholes are often built with a surrounding casing until 200ft above the actively mined seam, to capture methane released during the caving of the seams other than the active mining seam (C. Ö. Karacan, Esterhuizen, Schatzel, & Diamond, 2007). An example of the effectiveness of GVBS was shown when uncapping of a surface gob gas ventilation borehole in the Lower Kittaning Coalbed was able to reduce the methane concentration in the return air by up to 75% (Moore, Deul, & Kissell, 1976).

2.2 Gob Characteristics

Depending on geologic location, distance to roof control and depth, gob will have varying properties for size distribution, permeability and porosity. The changes in porosity and permeability are from increasing compression due to the gob being further from roof support. Figure 8 shows how caving affects the rock column and the different zones of influence that are produced. Within the fractured zone, below the aquiclude zone and above the gob material, an area of high permeability can be present from the caved material supporting an unbroken rock seam. Estimated permeability values for the gob material from various studies range from a maximum of 1.01×10^{10} mD to a minimum of 1.00×10^{6} mD (Gilmore, 2007). Porosity values calculated from laboratory tests were found to range from 0.802 to 0.078 mD for intact shale and from 0.790 to 0.152mD for intact sandstone, based on the severity of strata compression (Pappas & Mark, 1993).

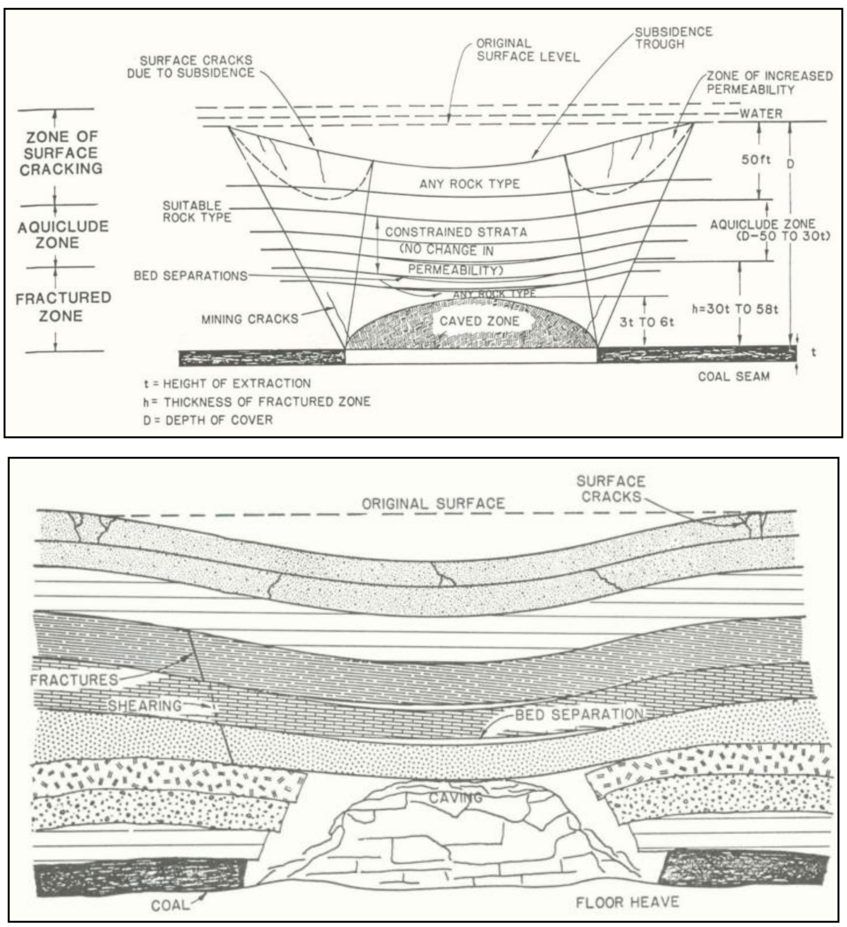

Figure 8: Strata Response to Caving of Coal Seam (Singh & Kendorski, 1981)

The porosity and permeability characteristics of the gob have an effect on the penetration of the ventilation air which dictates the methane levels near the longwall active face. Determining how changing ventilation patterns affect the location of the explosive range of methane is crucial for safety at the longwall face. Mesh models of a longwall sections have previously been produced to estimate oxygen and methane levels within the gob (Gilmore, 2007). The red areas of the models represented an area where the methane content in within the explosive limit and the yellow areas represented an area where the methane content would be considered explosive if diluted with additional air. With this ventilation plan, the areas of most concern would be the corners of the headgate and tailgate of the longwall.

Another form of characterizing a porous media like a coal mine gob is through the Darcy and Forchheimer Law. The Darcy and Forchheimer coefficients are used to describe the resistance of porous media to pressure driven flow. The Darcy value describes low flows where the inertial effects can be ignored. The Forchheimer value is used described non-linear pressure based flow due to a higher Reynolds number (Coombs, 2017). The Darcy and Forchheimer law is presented in Equation 3:

$$\frac{\partial p}{\partial x} = \frac{\mu}{\kappa} V - \frac{\rho}{\kappa_1} V^2 \qquad (3)$$

Where p is pressure, μ is viscosity, κ is the intrinsic permeability (1/m), $\kappa_1$is the inertial permeability (1/m^2), ρ is density (kg/m^3) and V is the flux (m/s). The equation can be rewritten where the Darcy and Forchheimer coefficients are as follows, as shown in Equation 4:

$$D = \frac{1}{\kappa} \quad F = \frac{1}{\kappa_1} \qquad (4)$$

Due to the complexity of mathematically solving for the Darcy and Forchheimer coefficients, the values used are calculated experimentally through a pressure drop experiment (Coombs, n.d.). Intrinsic permeability is used for when there is only Darcy flow but inertial permeability is needed when the flow velocity is high enough for inertial effects to become relevant.

2.3 Fire-fighting Foams

Fire-fighting foams have been used in many industries, from fuel fires to airplane hangars, due to the ability for the foams to extinguish fires through multiple types of interactions. Foams can cool the fire, separate the flames from the fuel, separate the flames from oxygen and suppress vapors released from the fuel. One of the most widely tested and implemented fire fighting foams is aqueous film forming foam (AFFF). AFFF forms a film over the fuel source after the foam has dissipated, making it highly effective for fire extinction (Sheinson et al., n.d.). AFFF is either applied as a 1%, 3% or 6% concentrate, with the remaining mixture being water. For modeling of high expansion foam, the rheological parameters are needed to describe the non-Newtonian fluid properties. The non-Newtonian transport is modeled through the power law equation that requires n and k coefficients. Fire fighting foam has a n value of 0.29, k_1 value of 2.63 and k_2 value of 2.29 (Gardiner, Dlugogorski, & Jameson, 1998). Experimental tests have also been used for AFFF that will provide validation for any models produced with similar n, k_1 and k_2 values.

High expansion foams are implemented in fire-fighting applications due to its ability to travel relatively far distances and fill large volumes. High expansion foams are typically formed from a 2% concentrate and can be produced at expansion ratios from 200 to over 1000. Common uses for high expansion foams include filling hangars, warehouses, cargo ships and mine entries (ANSUL, 2013). When modeling foam rheology based on the power law equation, high expansion foam has n values of 0.4044 to 0.4091 and a k value of 2.356 to 2.549 (Daza, Luxbacher, & Lattimer, 2018).

In an experiment conducted by NIOSH, nitrogen enhanced foam was tested for remote fire fighting capabilities in a coal mine through boreholes and underground deployment. Figure 9 shows the mine diagram for the test injection experiment. Common obstacles found in a coal mine were created to test foam movement in the presence of normal mine conditions. When the foam reached the simulated gob pile in this experiment, the foam was able to penetrate the material and cool the rock mass, indicated by temperature sensors. In the same experiment, crib blocks were able to cause foam build up allows the foam be used an underground ventilation tool to redirect air flows (Smith et al., 2010).

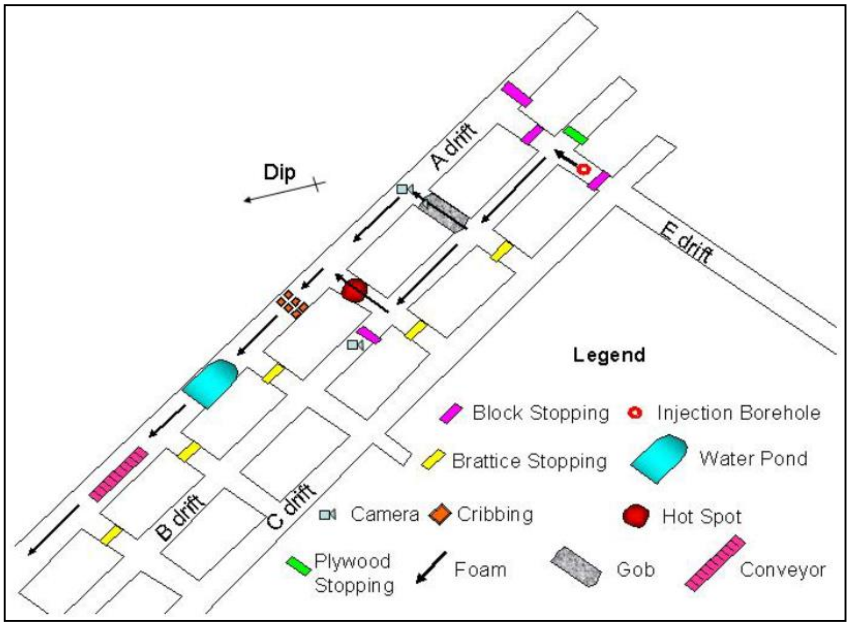

Figure 9: Borehole Injection Experiment Mine Diagram (Smith et al., 2010)

A laboratory experiment was also performed on AFFF foam to test flow through gob and the cooling effectiveness of the foam. Foam was injected into simulated gob material from below, unlike GVB injection which would release foam from above. The gob material was simulated as a mixture of stone and coal that was heated by heating coils in the center. The foam was shown to effectively penetrate the porous gob media and cool the rock mass around the heating coils (Dong et al., 2017). The foam in the test was able to penetrate the gob and isolate gas bubbles from the heat source.

2.4 OpenFOAM

The software used for this project is OpenFOAM which is an open source computational fluid dynamics program. OpenFOAM is formally known as a C++ library that uses solvers and utilities. The various solvers allow for the ability to model specific problems such as non-Newtonian flow, multiphase flow, compressible flow, transient models, etc. The OpenFOAM software contains tools for pre-processing, geometry meshing and post-processing. Post-processing and model computation are done through the ParaView program that is included with the OpenFOAM software package (Greenshields, 2016).

The OpenFOAM solvers applied are related to fluid flow and thus solve variations of the Navier-Stokes equations to compute the models. The Navier-Stokes equations are partial differential equations that describe fluid flow based on the conservation of mass within a control volume. For a compressible fluid the three equations would be the continuity equation, the momentum equation and the energy equation (Sohr, 2001). The equations are calculated for set discretized volumes that are determined by the geometry mesh. With a finer mesh the delta x, y, and z are smaller, which allows for improved detail and accuracy in the model. That increased detail comes at the cost of a longer computational time and can be limited by the capabilities of the computer and software used.

3. Experimental Design

To calculate the Darcy and Forchheimer coefficients for foam flow through a porous media, a pressure drop test is required. The experimental apparatus for a pressure drop test contains two main components: A foam generator, based on NFPA 11 Standards, capable of producing foam at various flow rates, and a Programmable Logic Controller with pressure transducers to measure the drop in pressure along the length of the porous section of the PVC pipe (National Fire Protection Agency, 2005). As seen in Figure 10, the foam generator consists of a pump connected to a spray nozzle that emits the foam solution across a #60 mesh screen. When air from the blower fan passes through the screen covered in foam solution, foam bubbles are produced. The expansion ratio of the foam is determined by the flow rate of the air and the flow rate of the foam solution. The blower fan used in the test is connected to a variable frequency drive in order to produce foam at various flow rates and expansion ratios.

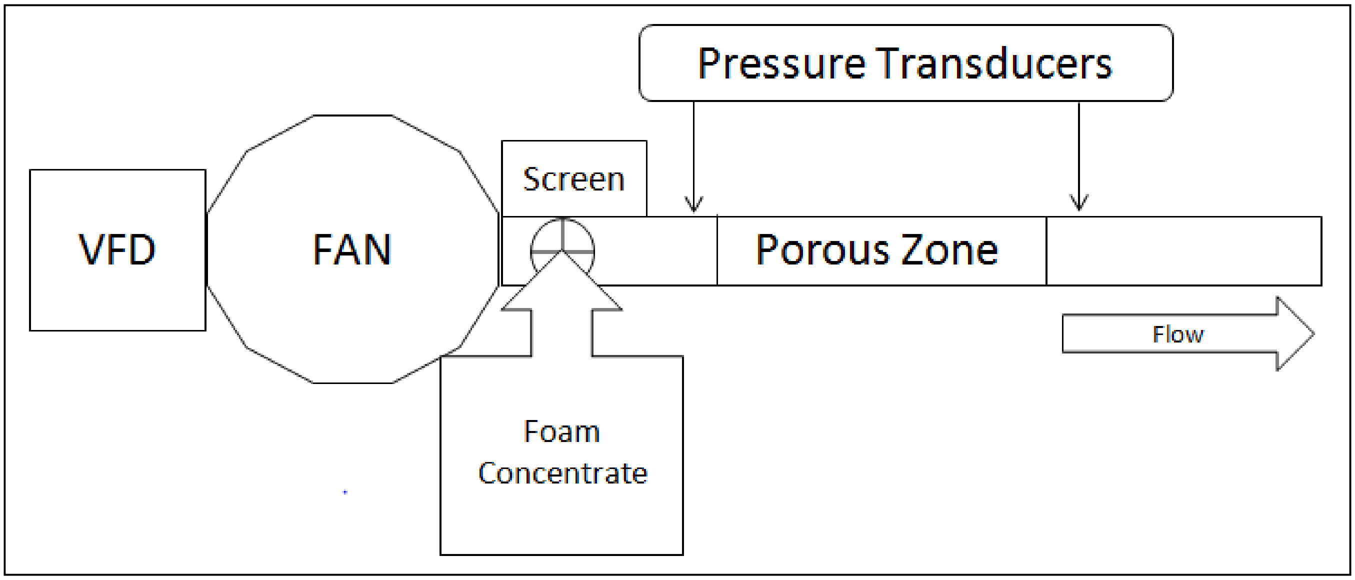

Figure 10: Pressure Drop Test Set Up

The pipe in this experiment is a 4-inch diameter PVC pipe that is 6 feet in length after the foam generator screen. The pipe contains a porous section that is 15 inches in length and filled with river rocks that are an average diameter of 2 inches. The porous section is positioned 4 feet from the spray nozzle to allow for the foam flow to develop. The pressure transducers are located on either side of the porous section and measure a pressure drop up to 1.5 psi. The foam concentrate used is Chemguard 2% Xtra High-X. When the foam exits the PVC pipe, it drops into a 500 gallon catchment tank.

4. Data Analysis

The pressure drop test uses fan speeds of 61.5, 58.5 and 55.8 Hz to obtain the resulting pressure drops and outlet velocities. The pressure drop across the porous section is plotted against outlet velocity in order for a second degree polynomial trend line to be calculated. The trend line is calculated using the least squares method, which minimizes the sum of the square of the residuals. As seen in Equation 5, the trend line represents the pressure drop ΔP as a function of velocity v, with the coefficients α and β.

$$\Delta P = \alpha v^2 + \beta v \qquad (5)$$

The α and β values in Equation 5, which are determined by the trend line, are then used to calculate the Darcy and Forchheimer coefficients using Equations 6 and 7:

$$D = \frac{\beta}{\mu \Delta x} \qquad (6)$$

$$F = \frac{2\alpha}{\rho \Delta x} \qquad (7)$$

Where μ is the dynamic viscosity of the foam, Δx is the length of the porous section and ρ is density of the foam. When calculating the Darcy value, the dynamic viscosity μ is different for each of the three fan speed scenarios, which results in three separate Darcy coefficients. To calculate the dynamic viscosity for each scenario the wall shear rate and power law model are used as described by Equations 8 and 9:

$$\gamma_w = \frac{32Q}{\pi D^3} \qquad (8)$$

$$\mu = k\gamma_w^{n-1} \qquad (9)$$

Where Q is the flow in meters cubed per second and based on the outlet flow of the pressure drop test. D is the diameter of the PVC pipe used in the pressure drop test. The values k and n are the consistency and power law indexes, respectively. The values for k and n were taken from a study where a pipe viscometer was used to determine the rheology of high expansion foam; the consistency index has a value of 2.3562 and the power law index has a value of 0.4044 (Daza et al., 2018). These values correspond to foam with an expansion ratio between 250 and 600.

5. OpenFOAM Software

5.1 Model Solvers

OpenFOAM is a free open source computational fluid dynamic software that contains a large library of solvers. The program runs in the Linux environment and uses the C++ coding language to call directories, run commands, start solvers and operate post processors. These solvers compute variations of the Navier-Stokes equations in order to determine flow of fluids. Variations of the solvers are used to solve for the addition of temperature, multiple fluids, non-Newtonian fluids, compressible fluids, particle tracking and combustion (Greenshields, 2016). The two solvers used for the research presented in this paper are the InterFoam and PorousSimpleFoam solvers.

The InterFoam solver computes multiphase flow for incompressible, isothermal fluids. The solver works by utilizing a volume of fluid phase-capturing interface approach (Greenshields, 2016). The InterFoam solver produces transient models which compute the model changes over a set duration of time. Transient models allow for the capturing of the foam flow development but have a longer computational time compared to steady-state models. The multiphase aspect of the solver is used to detail the interaction between the foam as a single fluid with the surrounding air. The InterFoam model is utilized to characterize the foam front before and after it travels through the porous section of the PVC pipe.

The PorousSimpleFoam solver produces single-phase steady-state models of the foam flow. Due to the steady-state aspect of this model, the entire PVC pipe is filled with foam, allowing for the single-phase assumption to be applied. Unlike the transient model that solves fluid flow based on time steps, the steady-state solution is derived by running iterations of the model until the difference between iterations drops below a preset threshold. This method determines the stable solution based on initial conditions preset in the model. Due to the fewer complexities in this modeling method, model results from this solver take a fraction of the time compared to the InterFoam solver. The models from both solvers are used to compare the steady-state foam flow average velocities between OpenFOAM to the pressure drop test, as well as comparing the foam flow velocities of the models to each other.

5.2 Model Setup

OpenFOAM models are initialized using the *blockMesh* command, which calls up the *blockMesh* directory containing model parameters. The *blockMesh* in OpenFOAM details the extents of the model, the naming of the boundary conditions and the size of the model mesh. The extents of the *blockMesh* models were 72 inches in length by 7 inches in height by 7 inches in width. The mesh was split into 700 cells in the x direction, 40 cells in the y direction and 40 cells in the z direction. This produces a cell size of 4.45cm by 2.61cm by 2.61cm. The *blockMesh* is utilized along with an AutoCAD model using the *snappyHexMesh* command in order to produce the final OpenFOAM model, which consists of the AutoCAD model shape containing the *blockMesh* cells. The borders of the mesh were refined in the *snappyHexMesh* directory as shown in Figure 11. The cell refinement allows for an improved shaped of the pipe and provides greater accuracy when simulating the foam interaction with the pipe walls.

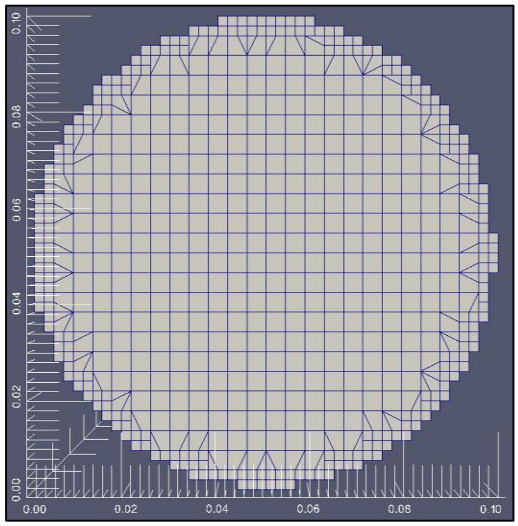

Figure 11: SnappyHexMesh Pipe Cross Section

5.3 Model Properties and Assumptions

High expansion foam in the OpenFOAM software was modeled as a single fluid with uniform properties, ignoring the bubble structure of the foam. The foam was modeled as a shear thinning fluid that follows the Power Law equation as detailed in Equation 5. The simulated foam had a density of 4.079 kg/m^3 cubed, which was based on an assumed expansion ratio of 350. The expansion ratios of the foam used in the pressure drop test were between 325 and 375. The foam was assumed to be incompressible at this pressure range and exhibit laminar flow. The incompressibility and laminar assumptions allow for use of OpenFOAM solvers that include implementation of porous media zones.

As stated earlier in the paper, the porous zones in the OpenFOAM software are characterized by the Darcy and Forchheimer coefficients. The Darcy and Forchheimer values represent the porous resistance of the simulated gob material to the flow of the foam. The Forchheimer value was needed in addition to the Darcy value, because the inertial effects of the foam flow cannot be ignored with the pressures and velocities present in the lab test. When using porous resistance to describe the simulated gob, the porosity value was not needed. Both of the OpenFOAM solvers treat the porous resistance values as uniform throughout the porous zone. In a discrete porous model where each individual gob piece in included, the porous resistance would vary depending on proximity to the individual gob fragments.

6. Results and Discussion

6.1 Pressure Drop Experiment Results

The Darcy and Forchheimer coefficients are determined by conducting a pressure drop experiment, which collects foam velocity and pressure drop data across the porous zone for three different fan frequencies. The pressure drop data is plotted against the foam flow velocity data in order to create a second degree polynomial trend line using the least squares method. The pressure drop, velocity, point of divergence and trend line results are shown in Figure 12.

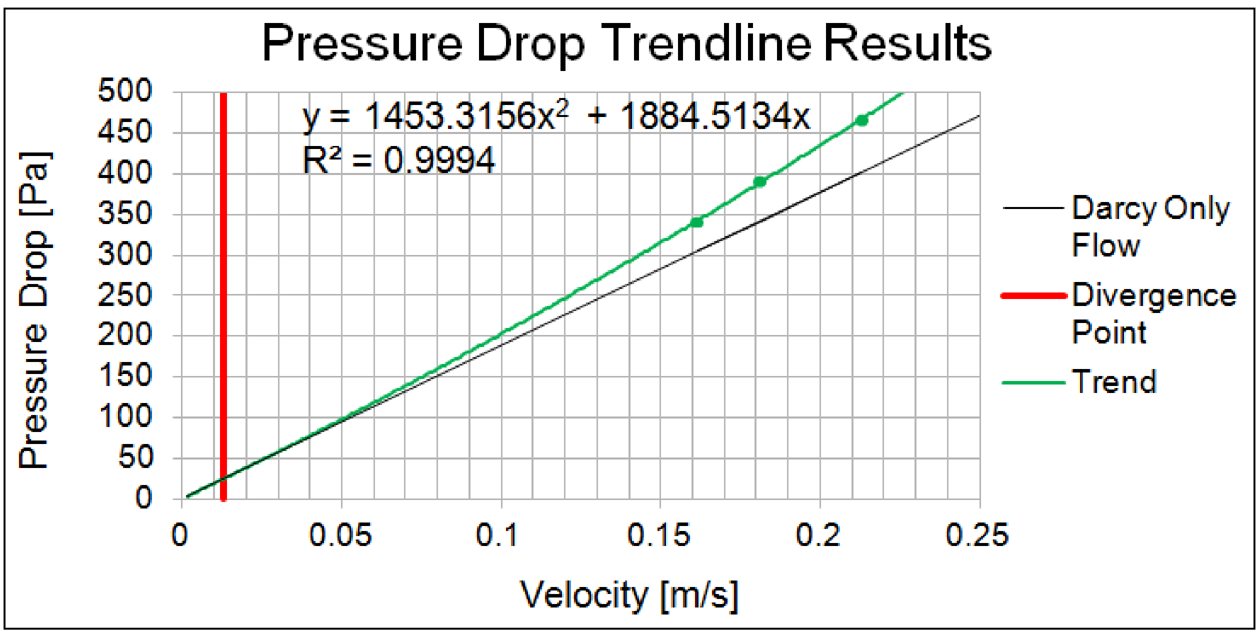

Figure 12: Pressure Drop Trend Line Results

In Figure 15, Darcy flow alone is shown as a comparison to the combine Darcy and Forchheimer trend line acquired from the pressure drop test. The comparison of the two data sets shows that the foam flow is affected by inertial effects and the Forchheimer value is needed for computational modeling. The divergence point is calculated by determining the velocity that results in a dimensionless apparent permeability of 0.99. The dimensionless apparent permeability is defined as the permeability divided by the Darcy permeability (Muljadi, Blunt, Raeini, & Bijeljic, 2016).

As described in the data analysis portion of the paper, the x and x^2 coefficients of the trend line are used to calculate the Darcy and Forchheimer values by applying Equations 6 and 7. Because the viscosity of the high expansion foam changes for each fan frequency, the Darcy value also changes for each of the three fan speeds. Table 3 displays the calculated Darcy and Forchheimer values for each of the pressure drop data points.

Table 3: Darcy and Forchheimer Results for Pressure Drop Experiment

Fan Frequency (Hz)	V (m/s)	ΔP (Pa)	Darcy (1/m2)	Forchheimer (1/m)
61.5	0.2131	467	229740	1870
58.5	0.1812	391	175400	1870
55.8	0.1615	341	142540	1870

6.2 OpenFOAM Model Results

The Darcy and Forchheimer values were imported into the OpenFOAM software directories, along with the density and non-Newtonian properties in order to replicate the pressure drop experiment. CFD models were created for each of the three fan frequencies and replicated for both computational solvers. The average foam flow velocities in the six models were calculated and compared to the velocity data from the pressure drop experiment to validate the pressure drop experiment as well as the OpenFOAM software. Pressure and velocity cross sections from the OpenFOAM models can be found in the Appendices.

The figures in the appendices show slices along the pipe for velocity and pressure. Pressure is measured in pascals for the InterFoam models, and for the PorousSimpleFoam models pressure is described as pressure over density. A slice was also taken perpendicular to the pipe to represent the flow profile of the foam and was used to determine foam flow velocity for the table of results. Table 4 details the average velocity values from the OpenFOAM models and the pressure drop experiment. The velocity data was then used to compare the OpenFOAM models to the experimental data by finding the percent difference of the two corresponding models to each lab test. The results of the validation test are located in Table 5.

Table 4: Velocity (m/s) in Porous Section of Lab Experiment and Models

Fan Frequency (Hz)	Lab Test	InterFoam Model	PorousSimpleFoam Model
61.5	0.2131	0.2056	0.2050
58.5	0.1812	0.1734	0.1727
55.8	0.1615	0.1515	0.1504

Table 5: Percent Difference between Models and Respective Lab Tests (%)

Fan Frequency (Hz)	InterFoam Model	PorousSimpleFoam Model
61.5	-3.519	-3.801
58.5	-4.305	-4.691
55.8	-6.192	-6.873

The percent difference in velocity between the OpenFOAM models and pressure drop test results ranged between -3.5 to -7%, while the percent difference between the InterFoam and the PorousSimpleFoam models ranged between 0.29 to 0.73%. The percent difference between models utilized the average of the two models as the comparison value for the percentage. The error between the experimental data and model data was well within the expected range for this experiment.

6.3 Error and Limitations

The main source of error in this experiment is attributed to data collection during the pressure drop experiment. The error produced from data collection is not obvious in the R squared value, but does result in an error with the Darcy and Forchheimer values. The model foam expansion ratio of 350 is also a source of error, because the actual expansion ratio based on the mixing ratios is between 325 and 375. The density of the foam is determined by the expansion ratio which affects the calculation of the porous resistance values and the physics of the foam movement within the OpenFOAM models.

The results of the pressure drop test and the implementation of porous resistance in OpenFOAM are affected by limitations when applying these results for use of high expansion foam flow in coal mine gob modeling. The calculated Darcy and Forchheimer values from the pressure drop experiment only apply to scenarios with a foam expansion ratio of 350, a gob material consisting of 2-inch river rocks and a pressure range lower that 467 Pa. To create OpenFOAM models of an actual coal mine gob scenario pressure drop experiments would need to be conducted on compressed gob and overburden material at pressure ranges found in a foam firefighting scenarios. The OpenFOAM solvers used in this experiment also do not take temperature into account when solving foam flow. To model a fire scenario, either new solvers will need to be implemented that include the temperature variable in the base code or future studies will be needed to determine the effects of fire presence on foam flow in a gob environment.

7. Summary

This paper conducted a pressure drop experiment on high expansion foam in the lab in order to calculate the porous resistance of simulated gob material, which is represented by the Darcy and Forchheimer values. The calculated porous resistance values were imported into OpenFOAM using the InterFoam and PorousSimpleFoam solvers, in order to validate the pressure drop experiment for determining porous resistance and to validate the use of OpenFOAM for use in simulating high expansion foam flow in a coal mine gob. Validation was determined by comparing the foam flow rate in the pressure drop tests to the flow rate in the OpenFOAM models.

The OpenFOAM model foam flow rates had an error range of -3.5 to -7% compared to the pressure drop experiment data. The difference between the InterFoam models and the PorousSimpleFoam models was in a range of 0.29 to 0.73%. The model error values validate that both the InterFoam solver and the PorousSimpleFoam solver are feasible for simulation of high expansion foam flow in gob material. The error results also validate the implementation of a pressure drop experiment in calculating the porous resistance of gob material. The results of this study only apply to the foam expansion ratio, fan pressure range and porous media material used. The validation of the pressure drop test and OpenFOAM software permits creation of full scale longwall models that can determine the applicability of injection of high expansion foam into the coal mine gob.

8. References

Advanced Energy. (2005). Fundamentals of Mass Flow Control.

Ahmad, I., Sahay, N., Varma, N. K., & Sinha, A. (2009). Application of High Expansion Nitrogen Foam to Control Mine Fire. *Mine Fires in Indian Coal Industry*.

Allwine, K. J., & Flaherty, J. E. (2007). *Urban Dispersion Program Overview and MID05 Field Study Summary*.

ANSUL. (2013). Class A, B and LNG Fures High Expansion Foam. Retrieved from http://www.ansul.com/en/us/pages/ProductDetail.aspx?productdetail=Class+A%2C+B%2C+%26+

LNG+Fires+High-Expansion+Foam

Batterman, S., Jia, C., Hatzivasilis, G., & Godwin, C. (2006). Simultaneous measurement of ventilation using tracer gas techniques and VOC concentrations in homes , garages and vehicles. *Journal of Environmental Monitoring*, *8*(Advance Web Article), 249–256. https://doi.org/10.1039/b514899e

Buchwald, P., & Jaskólski, Z. (2004). Application of the SF 6 Tracer Gas in Identifying Mine Air Flows through Abandoned Workings Sealed from the Ventilation System. *International Mining Forum*, *5*, 169–178.

Burwell, F. (1965). Multiple Tracers Establish Waterflood Flow Behavior. *Oil and Gas*.

Coombs, J. (n.d.). Modelling of Porous Media in OpenFOAM. *The University of Adelaide*.

Davis, J. A., Blair, R. K., & Wagner, O. R. (1976). Moni toring and Control Program for Miscible a Large Scale. In *Society of Petroleum Engineers of AIME*. New Orleans.

Daza, M. B., Luxbacher, K., & Lattimer, B. (2018). RHEOLOGY OF HIGH EXPANSION FOAM, 1–7.

Diamond, W. P., Schatzel, S. J., Garcia, F., Lascola, J. C., Mccall, F. E., Jeran, P. W., & Niosh, H. (2002). Characterization of Gas Flow in Longwall Gobs : Pittsburgh Coalbed , PA. In *North American Mine Ventilation Symposium* (p. 12).

Dickerson, M. H., Foster, K. T., & Gudiksen, P. H. (1984). Experimental and Model Transport and Diffusion Studies in Complex Terrain with Emphasis on Tracer Studies. *Boundry-Layer Meteorology*, *30*, 333–350.

Dong, S., Lu, X., Wang, D., Wang, H., Zheng, K., Shi, Q., & Chen, M. (2017). Experimental investigation of the fire-fighting characteristics of aqueous foam in underground goaf. *Process Safety and Environmental Protection*, *106*, 239–245. https://doi.org/10.1016/j.psep.2016.12.009

Fisher, K., Pro Technics, Robinson, B. M., & Voneiff, G. W. (1995). A Comprehensive Study of the Analysis and Economic Benefits of Radioactive Trace Engineered Stimulaiton Procedures. In *SPE annual Technical Conference* (pp. 957–964). Dallas, TX: Society of Petroleum Engineers.

Frost, E. . (1946). Helium tracer studies in Elk Hills, California. *Report of Investigations (US Bureau of Mines)*.

Gardiner, B. S., Dlugogorski, B. Z., & Jameson, G. J. (1998). Rheology of fire-fighting foams. *Fire Safety Journal*, *31*(1), 61–75.

Gieras, M., Klemens, R., Rarata, G., & Wolański, P. (2004). Determination of explosion parameters of methane-air mixtures in the chamber of 40 dm 3 at normal and elevated temperature. *Internation*

Symposium on Hazards, Prevention and Mitigation of Industiral Explosions, *5*, 10–14.

Gilmore, R. (2007). Computational Fluid Dynamics Modeling of Underground Coal Longwall Gob Ventilaiton Systems Using a Devleoped Meshing Approach.

Greenshields, C. J. (2016). OpenFOAM User Guide, (June). Retrieved from http://foam.sourceforge.net/docs/Guides-a4/OpenFOAMUserGuide-A4.pdf

Grubb, J. (2008). *Preventative Measures for Spontaneuous Combustion in Underground Coal Mines*. Colorado School of Mines.

Huw, P., Sezer, U., & Kelello, C. (2009). Prevention and Control of Spontaneous Combustion; Best Practice Guidelines for Surface Coal Mines in South Africa. Retrieved from http://www.coaltech.co.za/chamber databases/coaltech/Com_DocMan.nsf/0/AAB37D3149EC72FE42257839002F59BB/$File/Spontaneous Combustion Guidelines - Feb 2011.pdf

Jong, E. C., Luxbacher, K. D., Karmis, M. E., & Westman, E. C. (2016). Field test of a perfluoromethylcyclohexane (PMCH) permeation plug release vessel (PPRV) in an underground longwall mine. *Mining Technology*, *125*(2), 65–71. https://doi.org/10.1179/1743286315Y.0000000012

Jong, E. C., Peng, Y., Bradley, W. T., Luxbacher, K. D., Agioutantis, Z., & Mcnair, H. M. (2015). Development of a perfluoromethylcyclohexane (PMCH) permeation plug release vessel (PPRV) for tracer gas studies in underground mines. *Process Safety and Environmental Protection*, *95*, 136–145. https://doi.org/10.1016/j.psep.2015.02.012

Jong, E. C., Peng, Y., Bradley, W. T., Luxbacher, K. D., Agioutantis, Z., & McNair, H. M. (2015). Development of a perfluoromethylcyclohexane (PMCH) permeation plug release vessel (PPRV) for tracer gas studies in underground mines. *Process Safety and Environmental Protection*, *95*, 136–145. https://doi.org/10.1016/j.psep.2015.02.012

Kai, C., & Zhenlu, S. (2012). Prevention and Control of Coalfield Fire Technology. *Internation Journal of Mining Science and Technology*, *22*(5), 657–663.

Karacan, C. Ö. (2008). Modeling and prediction of ventilation methane emissions of U.S. longwall mines using supervised artificial neural networks. *International Journal of Coal Geology*, *73*(3–4), 371–387. https://doi.org/10.1016/j.coal.2007.09.003

Karacan, C. Ö., Esterhuizen, G. S., Schatzel, S. J., & Diamond, W. P. (2007). Numerical Analysis of the

Impact of Longwall Panel Width on Methane Emissions and Performance of Gob Gas Ventholes. *International Journal of Coal Geology*, *71*(2–3), 225–245. https://doi.org/10.1016/j.coal.2006.08.003

McKinley, J. F., & Colwell, F. S. (1995). Application of erfluorocarbon tracers to microbial sampling in subsurface enviroments using mud-rotary and air-rotary drilling techniques. *Journal of Microbiological Methods*, *26*, 1–9.

McNair, H. M., & Miller, J. M. (1998). *Basic Gas Chromatography*. Wiley.

Moore, T. D. J., Deul, M., & Kissell, F. N. (1976). Longwall Gob Degasification With Surface Ventilation Boreholes Above the Lower Kittanning Coalbed, RI 8195.

MSHA, D. of L. (n.d.). Actions for excessive methane 30 CFR 75.323.

MSHA, D. of L. (1996). Methane Detectors 30 CFR 75.342.

Mucho, T. P., Diamond, W. P., & Garcia, F. (2000). Implications of Recent NIOSH Tracer Gas Studies on Bleeder and Gob Gas Ventilation Design. In *SME Conference* (p. 16).

Muljadi, B. P., Blunt, M. J., Raeini, A. Q., & Bijeljic, B. (2016). The impact of porous media heterogeneity on non-Darcy flow behaviour from pore-scale simulation. *Advances in Water Resources*, *95*, 329–340. https://doi.org/10.1016/j.advwatres.2015.05.019

National Diagnostics Laboratory. (2004). Principals and Applications of Liquid Scintillation Counting.

National Fire Protection Agency. (2005). NFPA 11 Standard for Low- , Medium- , and High-Expansion Foam.

National Institute of Biomedical Imaging and Bioengineering. (2016). Nuclear Medicine. Retrieved from https://www.nibib.nih.gov/science-education/science-topics/nuclear-medicine

Oyvind, D., & Institutt for energiteknikk. (2007). *AN EXPERIMENTAL STUDY OF TRACERS FOR LABELING OF INJECTION GAS IN OIL*. University of Bergen.

Pappas, D., & Mark, C. (1993). *Behavior of Simulated Longwall Gob Material*.

Phelps, T. (2013). Monitoring Subsurface Fluid Flow using Perfluorocarbon Tracers. Oak Ridge National Laboratory.

Samer, M., Berg, W., Fiedler, M., Ammon, C., Sanftleben, P., & Brunsch, R. (2012). *A comparative study among H20 balance, heat balance, CO2 balance and tracer gas technique for airflow rates measurement in naturally ventilated dairy barns*.

Senum, G. I., Fajer, R., Derose, W. E., & Petroleum, B. (1992). Petroleum Reservoir Characterization by Perfluorocarbon Tracers.

Sheinson, R. S., Williams, B. A., Green, C., Fleming, J. W., Anleitner, R., Ayers, S., … Barylski, D. (n.d.). THE FUTURE OF AQUEOUS FILM FORMING FOAM (AFFF): PERFORMANCE PARAMETERS AND REQUIREMENTS Ronald S. Sheinson, Bradley A. Williams, Christian Green, James W. Fleming, Robert Anleitner.

Singh, M. M., & Kendorski, F. S. (1981). Strata Disturbance Prediction For Mining Beneath Surface Water And Waste Impoundments. In *1st Annual Conference on Ground Control in Mining*.

Smith, A. C., Mucho, T. P., Trevits, M. A., & Cummins, M. (2005). THE USE OF NITROGEN-ENHANCED FOAM AT THE PINNACLE MINE FIRE.

Smith, A. C., Trevits, M. A., Mucho, T. P., Ozmet, A., Walsh, J. B., Smith, A. C., & Trevits, M. A. (2010). Evaluation of Gas-Enhanced Foam for Suppressing Coal Mine Fires. *2010 SME Annual Meeting and Exhibit*, 17.

Sohr, H. (2001). The Navier-Stokes equations. https://doi.org/10.1007/978-3-0348-0551-3

Suglo, R. S., & Frimpong, S. (2002). Accuracy of Tracer Surveys in Auxiliary Ventilation Systems in Coal Mines. *North American Mine Ventilation Symposium*, 169.

Theodorsson, P. (1992). Quantifying Background Components of Low-Level Gas Proportional Counters. *RadioCarbon*, *34*(3), 420–427.

Timko, R. J., & Derick, R. L. (1988). Analysis of a Fire in a Colorado Coal Mine. *Proc 4th Int'l Mine Ventilation Congress*.

Timko, R. J., & Thimons, E. D. (1982). Sulfur hexafluoride as a mine ventilation research tool-Recent field applications. *US Bureau of Mines*, *8735*, 15. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Sulfur+Hexafluoride+as+a+Mine+Ventilation+Research+Tool-+Recent+Field+Applications#0

Trevits, M. A., Yuan, L., Smith, A. C., & Thimons, E. D. (2012). NIOSH MINE FIRE RESEARCH IN THE UNITED STATES.

University of Surrey. (n.d.). Positron Emission Tomography. Retrieved March 21, 2018, from http://personal.ph.surrey.ac.uk/~phs1ns/PhD/research_tops/pet.html

Watson, A. J., & Ledwell, J. R. (2000). Oceanographic Tracer Release Experiments Using Sulphur Hexafiuoride. *Journal of Geophysical Research*, *105*, 14,325-14,337.

Watson, T. B., Wilke, R., Dietz, R. N., Heiser, J., & Kalb, P. (2007). The Atmospheric Background of

Perfluorocarbon Compounds Used as Tracers. *Environmental Science and Technology*, *41*(20), 6909–6913.

Web Elements. (n.d.). Sulfur: Sulfur Hexafluoride. Retrieved March 20, 2018, from https://www.webelements.com/compounds/sulfur/sulphur_hexafluoride.html

Welge, H. (1955). Super Fleuths Trace Flow of Injected Gas. *Oil and Gas*, 77–79.

Zhang, H., Ph, D., & Cloud, A. (2006). The Permeability Characteristics of Silicone Rubber. In *Global Advances in Materials and Process Engineering*. Dallas, TX: Society for the Advancement of Material and Process Engineering.

Zipf, R., Sapko, M., & Brune, J. (2007). Explosion Pressure Design Criteria for New Seals in U . S . Coal Mines. *Information Circular 9500*.

9. Acknowledgements

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Conclusions

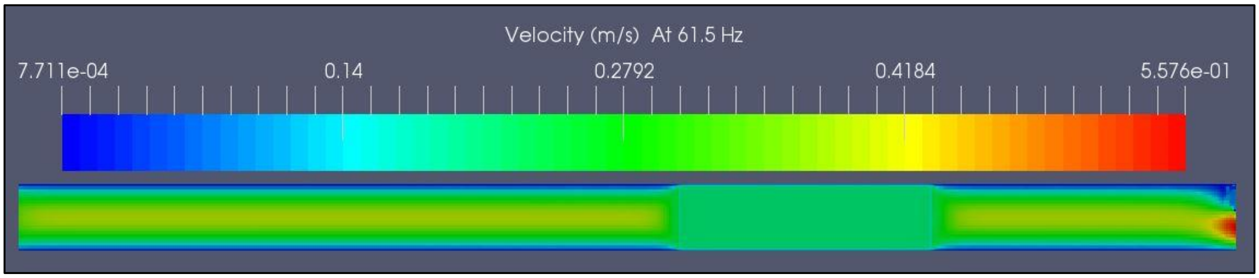
The purpose of this thesis was to further develop fire response measures for underground coal mines. The two studies in this thesis included work on tracer gases and high expansion foam. Tracer gases are used to indirectly track changes in the fire and mine ventilation. High expansion foam has the potential to extinguish a coal mine gob fire from the surface through borehole injection.

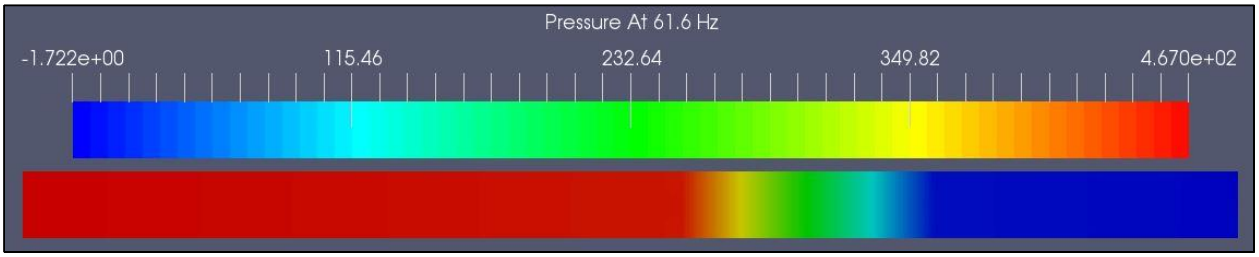
In the first work of this thesis, release rates of the Perfluorocarbon tracers, PMCH, PECH and PMCP were measured over a 180 day period for the PPRV design. The release rates of the three tracers were determined to have relative standard deviations under 5% for PPRVs of like tracer and temperature. The R^2 values calculated for each PPRV were all over 0.99, which represent a very high linear correlation for each individual source. The PPRV design has exhibited potential for both long duration and complex ventilation characterization with multiple tracer compounds.

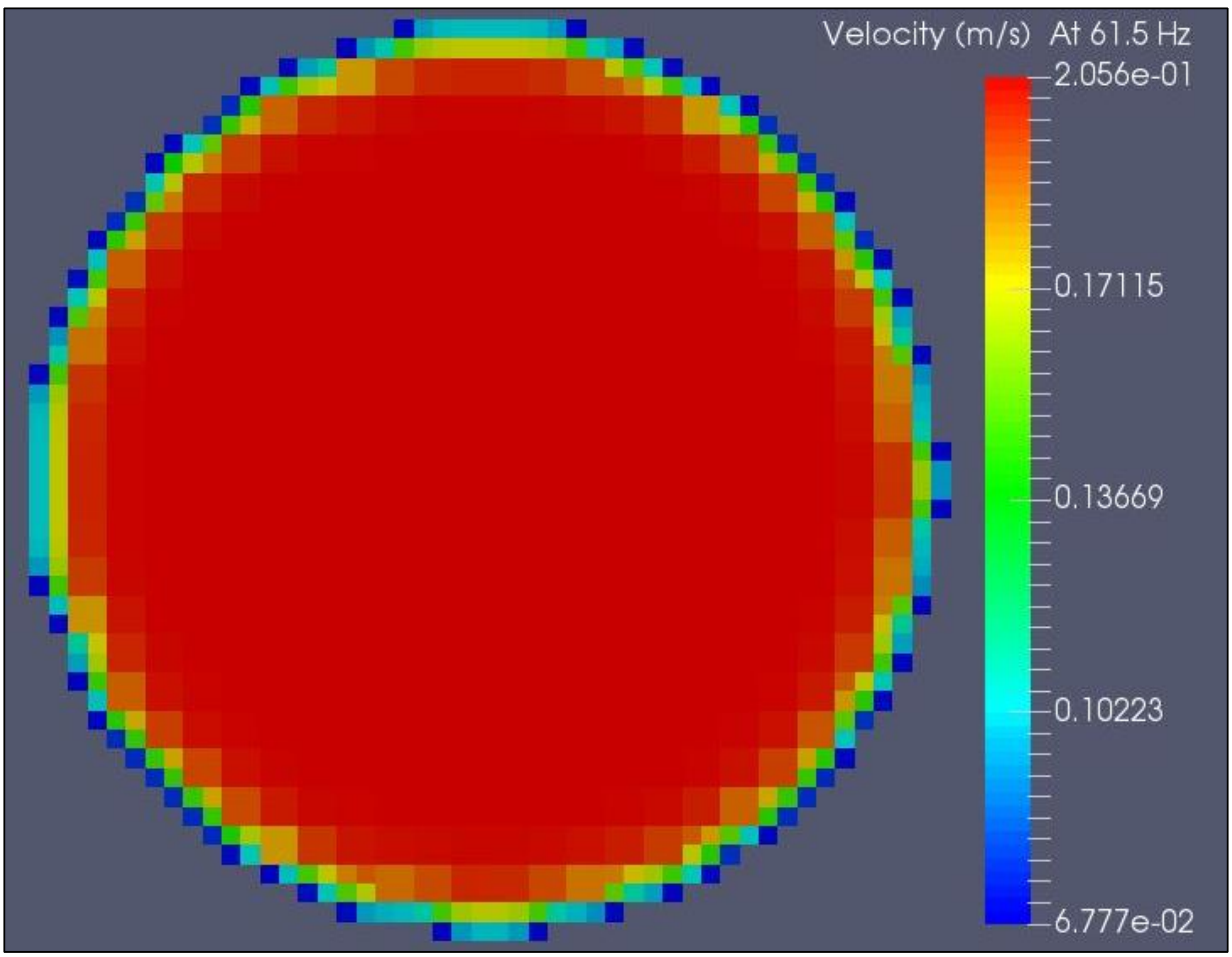
The second study in this thesis tested a method for determining the Darcy and Forchheimer values for high expansion foam flow in simulated gob material. The laboratory experiment was replicated in the CFD software, OpenFOAM, to validate the use of the lab test and the OpenFOAM software for foam flow in gob material. The OpenFOAM model had an error range of -3.5 to -7% compared to the lad tests when comparing foam flow rate. The flow rate difference between the two types of solvers used in OpenFOAM models varied from 0.29 to 0.73%. The model error values validate that both of the OpenFOAM solvers are capable of simulating high expansion foam flow in gob material and the pressure drop experiment is suitable for calculating the porous resistance of gob material.

The validation of the pressure drop test and OpenFOAM software provides a proven method for development of an entire gob model, which assesses the applicability of using high expansion foam injection to extinguish a gob fire. Validation of the PPRV design for multiple tracer compounds in the first work of this thesis allows for the tracking of mine ventilation air during the entirety of a fire event with the capability of tracking interactions between different mine openings and shafts. These two works provide potential improved measures to indirectly monitor and extinguish mine fires, which provides safe alternatives for mine rescue and response teams.

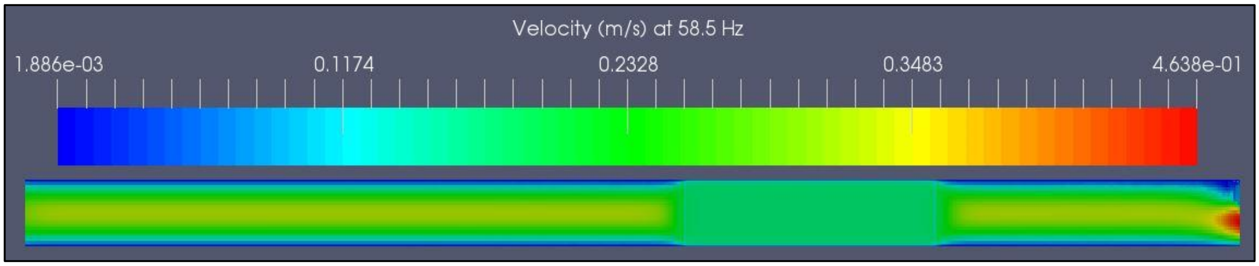
Appendix A: InterFoam Model Results at 61.5 Hz

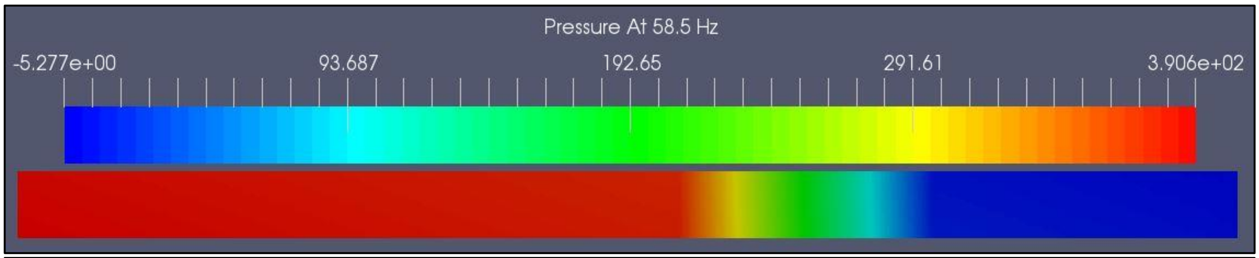


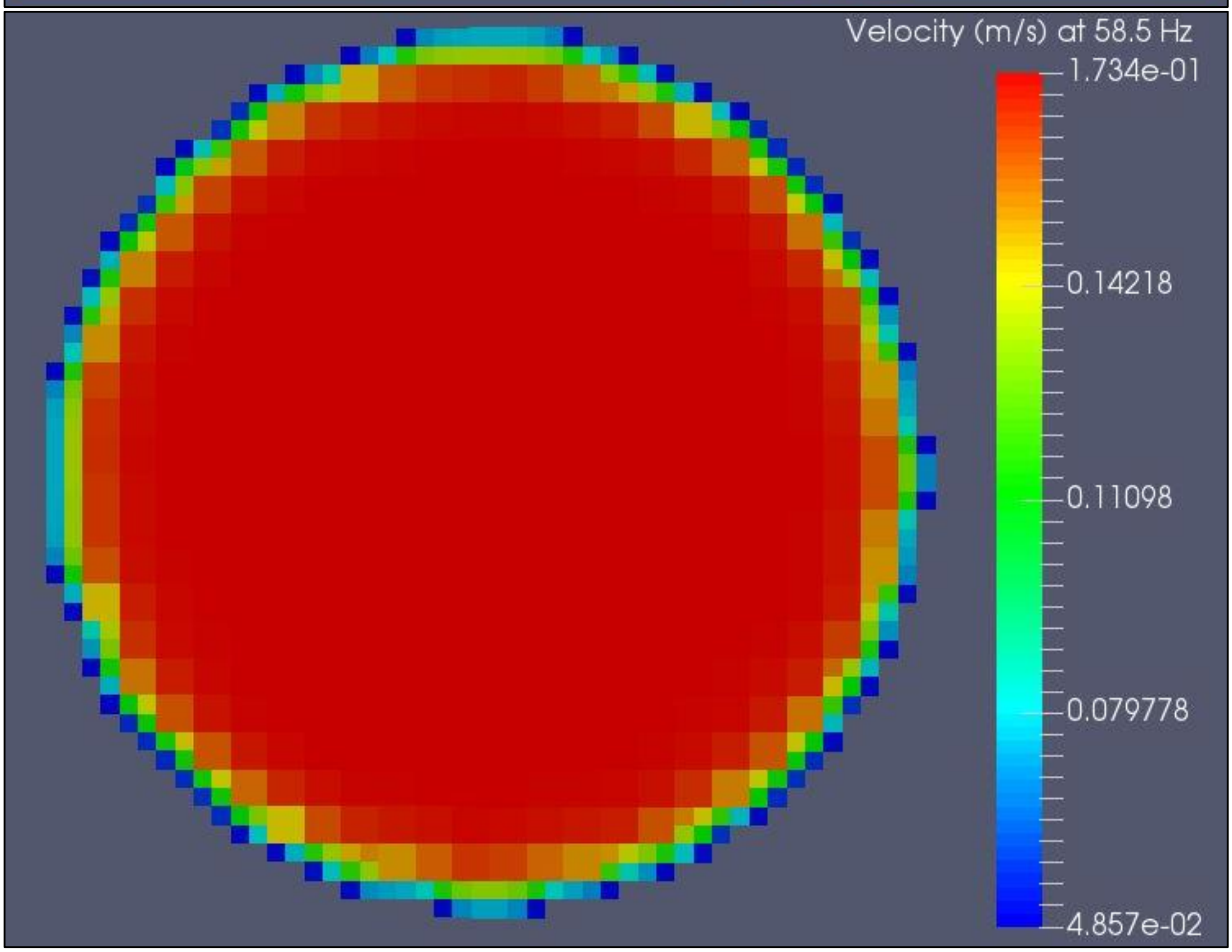




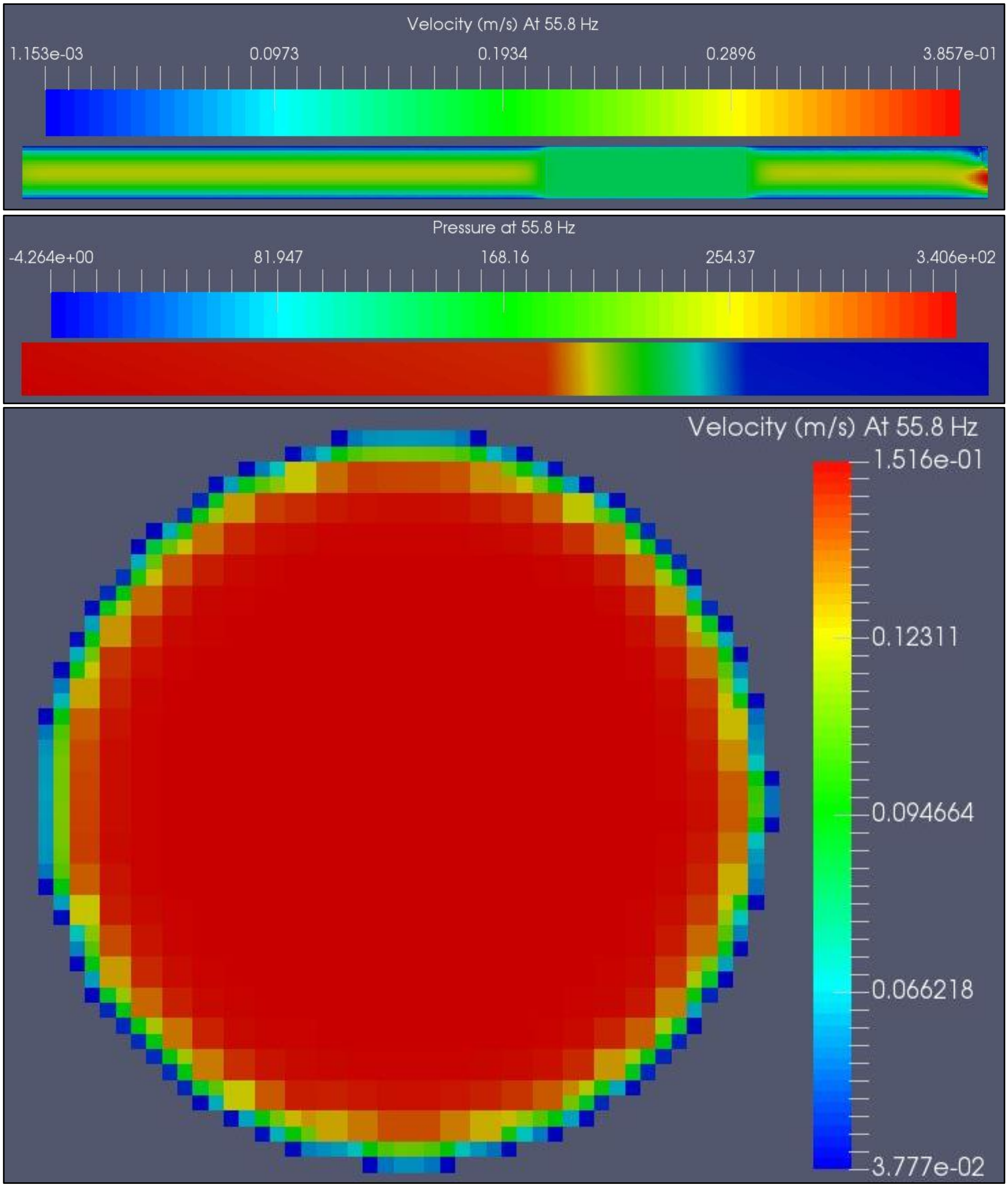
Appendix B: InterFoam Model Results at 58.5 Hz



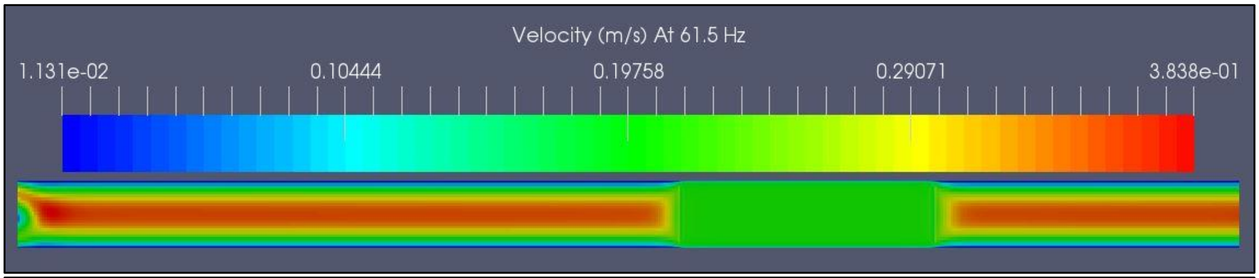


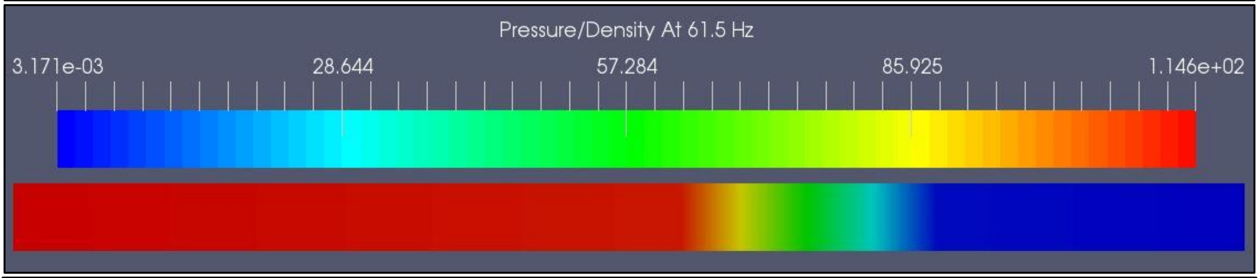


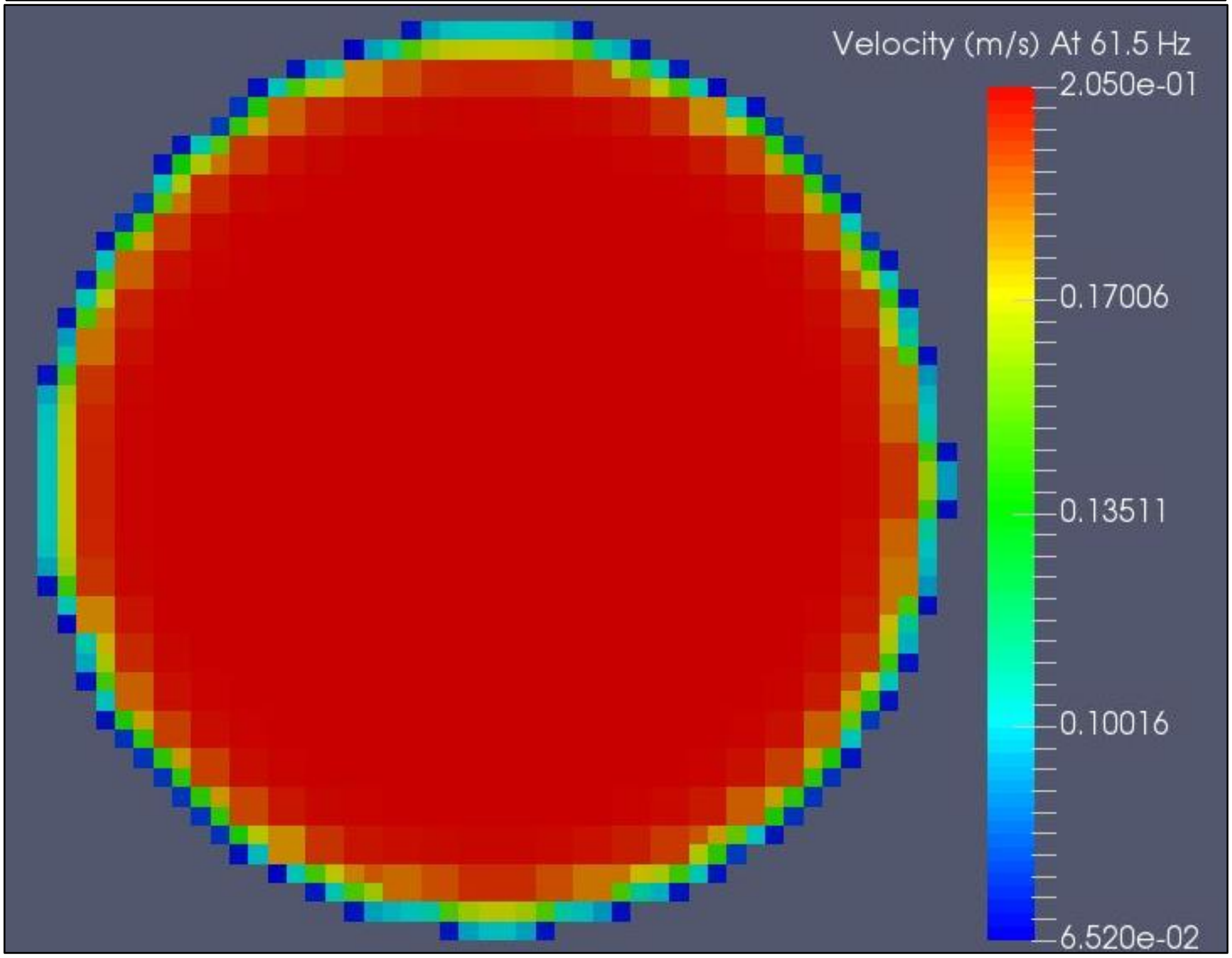
Appendix C: InterFoam Model Results at 55.8 Hz



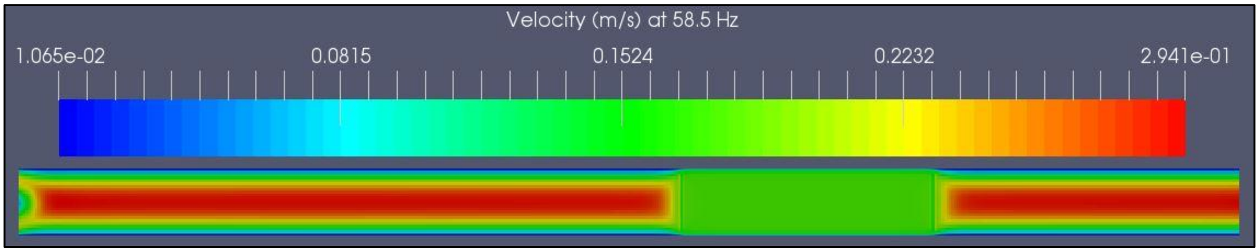
Appendix D: PorousSimpleFoam Model Results at 61.5 Hz

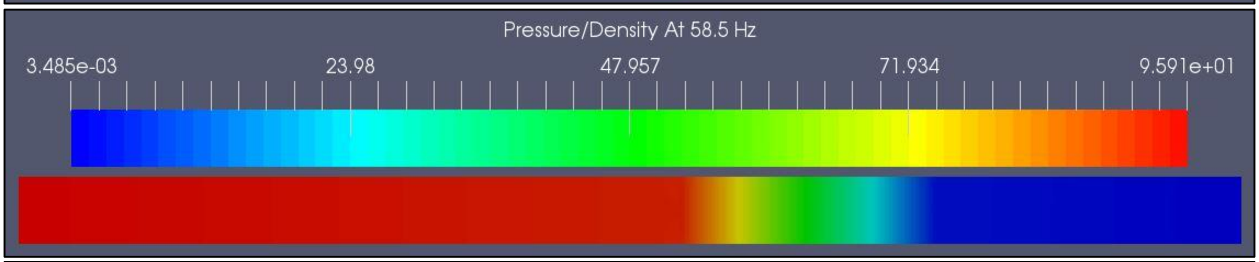


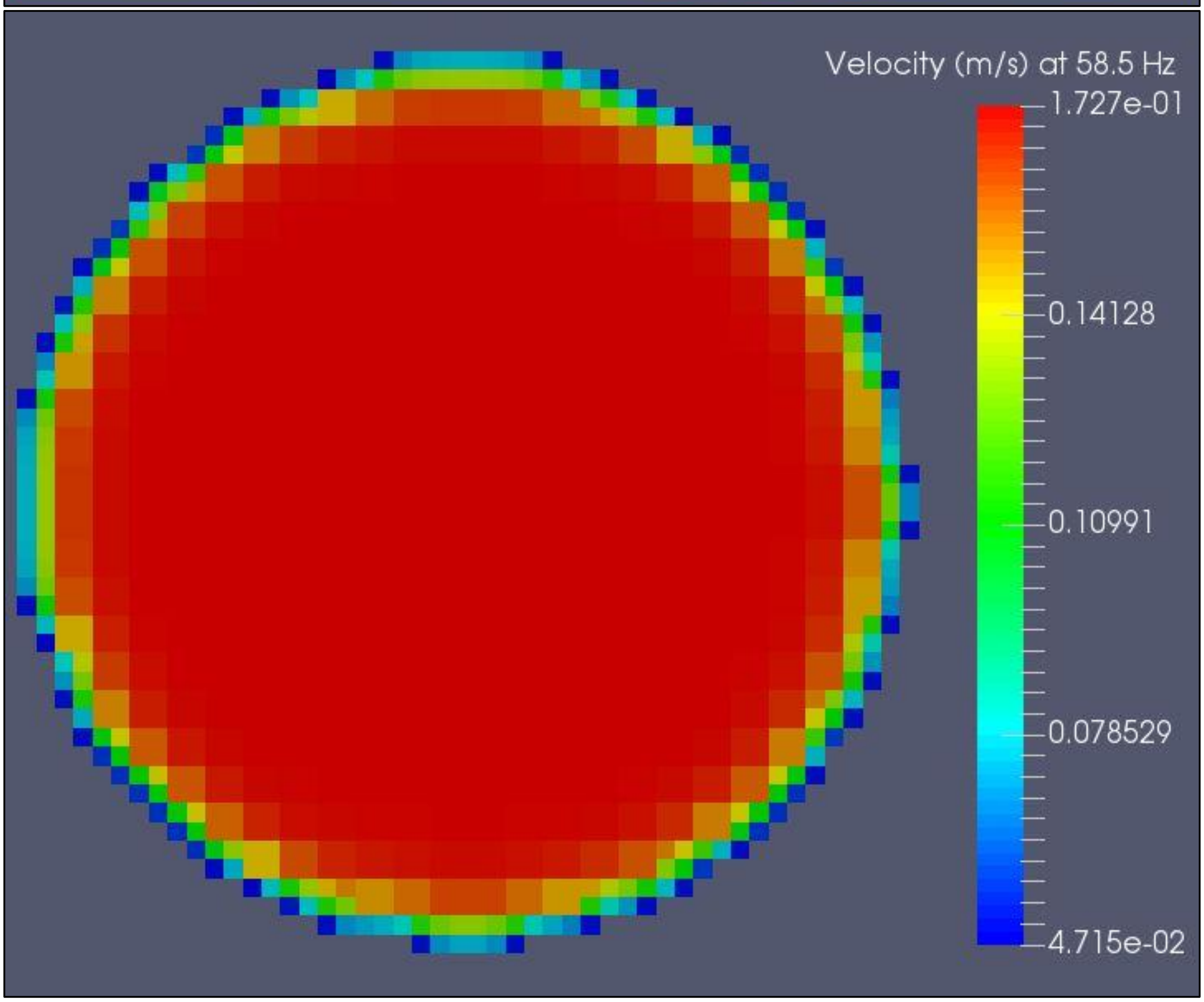




Appendix E: PorousSimpleFoam Model Results at 58.5 Hz







Appendix F: PorousSimpleFoam Model Results at 55.8 Hz