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Effective utilization of tracer gas in characterization of underground mine ventilation networks

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A B S T R A C T

Tracer gases are an effective method for assessing mine ventilation systems, especially when other techniques are impractical. Based on previously completed laboratory and field experiments, this paper discusses some common and challenging issues encountered when using tracer gases in underground mines. The discussion includes tracer release methods, sampling and analysis techniques. Additionally, the use of CFD to optimize the design of tracer gas experiments is also presented. Finally, guidelines and recommendations are provided on the use of tracer gases in the characterization of underground mine ventilation networks. This work has informed the practical use of tracer gases in mines, and this body of knowledge is expected to contribute to more efficient and more common use of tracer gases by mine engineers, which will allow for better characterization of mine ventilation system and improved safety. The findings can also be used when using the tracer gas technique in the evaluation of atmospheric environment and air quality investigation in buildings.

1. Introduction

Ventilation is a fundamental to the engineering of underground mines because it has considerable effects on health and safety. Measurements of airflow underground are usually carried out using traditional instrumentation such as vane anemometers, hot-wire anemometers, pitot tubes, and smoke tubes. However, these methods are not practical under certain circumstances in an underground mine. Examples include the measurement of recirculation and leakage, flow in inaccessible zones, and flow with very low velocities. Sometimes traditional instrumentation fails to provide accurate results. For example, in a study that investigated jet fan effectiveness in dead headings, tracer gas results were found to be more accurate than the results of smoke tubes (Timko and Thimons, 1982). Therefore, tracer gas techniques are a valuable tool for accurately measuring airflow in situations where traditional methods cannot be employed and providing information to characterize underground mine ventilation.

The tracer gas technique is a useful and versatile tool for studying mine ventilation systems with a long history of application. The Bureau of Mines (Thimons and Kissell, 1974) conducted a series of tracer gas tests using sulfur hexafluoride SF_6 and proved the usefulness of tracer gas techniques in measuring recirculation, air leakage, airflow in large cross section, low flow velocity, and transit air time. Grenier et al. (1992) used tracer gases to analyze the spread of dust in a fluorspar milling plant. The results indicated that tracer gases behave in the same physical manner as respirable dust and can be used to find patterns in dust movement within a ventilation system. Tracer gas has been accepted by the mining industry as a viable ventilation survey tool. More examples that used tracer

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gas to investigate various ventilation problems can be found in Timko and Thimons' paper (Timko and Thimons, 1982).

Compared to the uses of tracer techniques in underground mine, these techniques are wildly used in the atmosphere studies and environmental monitoring applications (Vanderborght and Kretzschmar, 1984). Pekney et al. (2012) used a perfluorocarbon tracer that was injected together with CO_2 to monitor the leakage of the carbon sequestration technology. Connan et al. (2011) evaluated two computation models for the prediction of atmospheric dispersion by comparing them to a SF_6 tracer study. Belalcazar et al. (2009, 2010) used tracer gas and CFD modeling to study the road traffic emission factors (EFs), and showed that it is possible to estimate the EFs from tracer studies. Jayaraman et al. (2006) used tracer gas in an indoor space experiment for the purpose of evaluating the accuracy of different CFD models. As most of these studies can also be related to the problems in the mine environment, it is evident that the tracer gas technique has great potential in the research of mine safety and health.

An ongoing research project that involves the selection of novel tracer gases for mine ventilation, the development of a methodology to use tracer gases and computational fluid dynamics (CFD) modeling to analyze, predict, and confirm the underground ventilation status together with the location of the damage, and finally validate the developed methodology in the laboratory and in the field are currently being conducted at Virginia Tech. Details of this work have been published in several forums (Jong et al., 2012; Patterson et al., 2010; Xu et al., 2013, 2015).

The focus of this paper is to provide some useful findings for the use of tracer gas based on authors' experience and practice. As this research progressed it was evident that there are few resources in the literature that provide the practical aspects of conducting tracer gas studies in mines. Some essential aspects of the tracer gas technique are discussed as well as new findings and recommendations, and studies in the literature are referenced as well. Using CFD modeling to design tracer gas experiments is also presented in this paper. Some modeling examples are provided to illustrate how CFD can help to determine the optimized tracer release and sampling locations, the release rate and duration, and eventually help to achieve desired results. Tracer gas experiments are time and resource consuming in underground mines, the findings and recommendations provided in this paper can be used by other researchers and industries for the design of tracer gas experiments more efficiently with less trial and error.

2. Tracer gas techniques

2.1. *Choices of tracers*

Sulfur hexafluoride (SF_6) is a widely accepted standard tracer gas that has been used in mine ventilation studies. It was first used in the building ventilation system sixty years ago (Dick, 1950) and has been widely used for ventilation analysis both in buildings and underground mines (Kennedy et al., 1987). SF_6 is non-toxic (Lester and Greenberg, 1950), and the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limit (PEL) and the American Conference of Governmental Industrial Hygienists's (ACGIH) Threshold Limit Value (TLV) for SF_6 is 1000 ppm (OSHA, 1993). The amount of SF_6 released to a mine is generally much less than either the PEL or TLV limit. SF_6 can be detected accurately using gas chromatography (GC) in concentrations as low as parts per trillion. It is also odorless, colorless, chemically and thermally stable, and not found in the natural environment. It is not measurably adsorbed on sandstone and coal. These are all desirable properties as a tracer gas (Thimons and Kissell, 1974). There are a wide range of applications of SF_6 in underground mines, including the study of ventilation recirculation, fan effectiveness, and flow rates estimation (Thimons et al., 1974; Thimons and Kissell, 1974), the measurement of air leakage and dust control effectiveness (Timko and Thimons, 1982), the measurement of turbulent diffusion (Arpa et al., 2008), the study of methane control (Mucho et al., 2000), and the application of SF_6 to characterize underground mine ventilation systems after emergency (Xu et al., 2013, 2015). Some alternative gases have also been used as mine ventilation tracers, such as nitrous oxide and helium. However, because they are not easily detected, large amounts need to be released thus causing transportation problems and difficulty in achieving stable flows (Kennedy et al., 1987).

It has long been realized that multiple tracer gases can add flexibility to ventilation surveys in many ways. Multiple gases not only allow the release of different tracers at different points without increasing the number of collected gas samples, but also provide more information because the source of each tracer in one sample can be identified and air flows in different zones can be investigated simultaneously with multiple tracers. Once a tracer is released to the mine, it may take days to weeks for the tracer background to be reduced to a level that will not affect the next test. However, if multiple tracers are available, a different tracer can be used to conduct another test right after the previous test. Although the advantages are apparent, the use of the multiple tracer technique is still not common in underground mines. One key requirement for identifying other tracer gases is that the gas should be measurable by the same method being used for SF_6, which is the most commonly used tracer gas. SF_6 is commonly analyzed by GC, so it would be better if the other tracers were able to be analyzed by the same GC method. Using the same GC method, the additional tracers should have similar sensitivity to SF_6 as well as be able to be separated from SF_6. Kennedy et al. (1987) investigated six Freons that are promising candidate tracer gases. They found that only Freon-13B1 ($CBrF_3$) and Freon-12 (CF_2Cl_2) were within two orders of magnitude of the sensitivity of SF_6 when analyzed using a GC with an electron capture detector. The other four Freon gases were several orders of magnitude less sensitive. $CBrF_3$ and CF_2Cl_2 were tested in the field and it was concluded that they perform well as mine ventilation tracer gases and are comparable to SF_6. Batterman et al. (2006) used hexafluorobenzene (HFB) and octafluorotoluene (OFT) for indoor ventilation tracers. However, those two tracers were not simultaneously analyzed with SF_6. Have used propane (C_3H_8) as a tracer gas to evaluate the ventilation system of a full face tunnel boring machine, but pointed out that it cannot be used in coal mines (Stokes and Stewart, 1985). Patterson, (2011) researched the selection of novel tracer gases that can be used in mines together with SF_6. Freon 14 (CF_4), C_3F_8, and PMCH (C_7F_{14}) were tested on different columns using various GC methods. CF_4 and C_3F_8 were found to have much less sensitivity than SF_6 on the tested columns, with similar retention times to SF_6. PMCH was reported to be an appropriate tracer if used together with SF_6. A GC protocol was developed that can be used to analyze SF_6 and PMCH concurrently on an HP-AL/S capillary column. One drawback of the protocol is the long 18 min