



Methods to determine the mine gas explosibility – An overview

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ABSTRACT

Mine gas explosions present a serious safety threat in the worldwide mining industry. Since the beginning of mining, many coal miners have been killed due to the explosions. Accordingly, on a regular basis, mine operators should get air samples from the underground atmosphere. At the same time, monitoring and tracking the explosibility of the air sample should be done as a timely matter to avoid any potential explosions. All these works can provide very important information to assist the mine operators to well understand the mine atmospheric status and its trends. In addition, when facing the coal spontaneous combustion, mine fire events, or other chemical reactions related mine accidents, determination of explosibility is a definitely significant work for the safety of miners and mine rescue personnel especially when planning and implementing any mine rescue strategies. For many years, mining engineers and researchers have developed a number of methods for assessing the explosibility of the air–gas–mixture. Their research results provide a baseline for judgments of the mine gas explosibility and in determining the extent of change. In this paper, main popular and typical methods used in mining industry to determine the mine gas explosibility are introduced and reviewed. Case demonstrations for each method are also shown and can be used to instruct readers to understand how to apply them. Finally, a brief discussion about the current methods is presented and some preliminary suggestions are also listed for the further improvements in the future research.

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1. Introduction

Mine gas explosions present a serious safety threat in the worldwide mining industry. They not only cause fatalities, but also bring production losses and huge financial burdens for mining companies. In 2009, a total of 157 gas explosions were responsible for 755 fatalities in Chinese coal mines. This number represented 28.7% of all Chinese coal mine fatalities (Huang, 2010). A total of two explosions in the Pike River Mine disaster that began on November 19th, 2010 in New Zealand killed 29 miners. This mine accident ranks as New Zealand's worst mining disaster since 43 men died at Ralph's Mine in Huntly in 1914 (Wikipedia, 2010). On March 21st, 2011, a serious gas explosion in Pakistan's Sorange mine killed 43 miners (CNN, 2011). In the U.S. coal mining history, gas explosions are also considered as the most dangerous hazard.

The Monongah mine disaster of Monongah, West Virginia, occurred on December 6th, 1907 has been described as “the worst mining disaster in American History”. The lives of 362 workers including children were lost in this underground explosion. According to statistics from the Mine Safety and Health Administration (MSHA), Table 1 shows the historic underground coal mine disasters due to gas explosions from 1970 to 2010 in the United States.

Coal mine explosions initially start with the ignition of the underground combustible gases. According to historical mine disaster statistics, a majority of these explosions have started from or around the sealed areas (Cheng & Luo, 2011). Technically speaking, a sealed atmosphere in a mine-out area of an underground coal mine is simply a volume governed by boundary conditions (Zipf & Mohamed, 2010). Various external or internal factors can affect the compositions in the mine sealed area such as barometric pressure changes, mine seal quality, coal low temperature oxidation, etc. These can induce mass exchanges between the sealed area and the active workings which may create explosive mixture of mine gases, cause intensification of mine fires and create irrespirable atmosphere outby seals. Therefore, under the normal coal mine production situations, the explosibility of the mine

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Table 1
List of coal mine disasters due to gas explosions 1970–2010 in U.S.

No.	Year	Day	Mine name	Location	Type	Deaths
1	2010	4–5	Upper Big Branch Mine	Montcoal, WV	Explosion	29
2	2006	5–20	Darby Mine No.1	Holmes Mill, KY	Explosion	5
3	2006	1–2	Sago Mine	Tallmansville, WV	Explosion	12
4	2001	9–23	No. 5 Mine	Brookwood, AL	Explosion	13
5	1992	12–7	No.3 Mine	Wise, VA	Explosion	8
6	1989	9–13	William Station No. 9 Mine	Sullivan, KY	Explosion	10
7	1983	6–21	McClure No.1 Mine	Dickinson, VA	Explosion	7
8	1982	1–20	No.1 Mine	Floyd, KY	Explosion	7
9	1981	12–8	No.21 Mine	Marion, TN	Explosion	13
10	1981	12–7	No.11 Mine	Knott, KY	Explosion	8
11	1981	4–15	Dutch Creek No. 1	Redstone, CO	Explosion	15
12	1980	11–7	Ferrell No.17	Boone, WV	Explosion	5
13	1976	3–9	Scotia Mine	Oven Fork, KY	Explosion	26
14	1972	12–16	Itmann No. 3 Mine	Wyoming, WV	Explosion	5
15	1970	12–30	No. 15 and 16 Mines	Hyden, KY	Explosion	38

atmosphere, especially for the sealed area, should be monitored and determined in a timely matter. The critical time when the methane or other combustible gases build up to pass the explosive range and may trigger a potential explosion should be carefully watched. The related enforced managements for such circumstances are urgently needed to be performed to avoid any accidents. In additional, when facing a mine accident, determination of explosibility is also a significant work for planning or implementing any mine rescue strategies or accident relief measures. For instance, Francart and Beirer (1997) reported that a real case of the effects by a falling barometer on the mine gas explosibility during performing a mine sealing operation to isolate an accident mine. Mitchell (1996) summarized accident prevention strategies to avoid loss of the properties or lives during a mine fire event. He also suggested that the mine gas explosibility should be watched during the whole fire stage. Hence, in any fire related emergency events, gas samples become critical to those persons who are delegated to fighting the fire. These samples can provide rescue persons with vital information on the status of the atmosphere (Koenning & Bruce, 1987).

Fundamental researches about the gas-mixture explosibility have been done by many researchers. Kondo, Takizawa, Takahashi, and Tokuhashi (2006) developed an extension Le Chatelier's equation to calibrate the flammable limits for fuel mixtures with considering carbon dioxide dilution effects. Kondo, Takizawa, Takahashi, Tokuhashi, and Sekiya (2008) also modified the Le Chatelier's equation to calibrate the flammable limits for fuel mixtures when nitrogen is used as the only inert gas. The influences by the ambient pressure on the flammable limits of organic gases are investigated (Arnaldos, Casal, & Planas-Cuchi, 2001; Carona et al., 1999; Goethals et al., 1999; Piqueras, García-Serna, & Cocero, 2011; Vanderstraeten et al., 1997), and a series of fitting equations are proposed to identify their relationships. Temperature, as another important environmental parameter, has also a great effect on the flammable limits (Britton, 2002; Catoire & Naudet, 2005; Dwyer, Hansel, & Pilips, 2003; Rowley, Rowley, & Wilding, 2010; Zhou, Wang, Li, Li, & Hu, 2008). Moreover, applying these guidelines to determine the mine gas explosibility are also done by researchers. Zigmund and Janovsky (2007) developed the graphical computer software named "Vybuchovy trojuhelnik" for assessment of explosibility of fuel–air mixture. Jacobs and Porter (1998) proposed their algorithms to generate a control chart depicting the changes in percent of combustibles and the lower and upper explosive limits of the current atmosphere. The gas explosion handbook also gave a brief introduction to gas explosion safety.

Based on current knowledge of the subjects and experiences, it can apply them to practical problems in the industry (Bjerketvedt, Bakke, & Wingerden, 1997).

Due to the Sago mine disaster of 2006, the U.S. Mining industry becomes more aware of the atmospheric composition with sealed atmospheres (Zipf & Mohamed, 2010). Preparations should be made for just such an occurrence. Hence, this paper summaries and reviews the current popular methods to determine the mine gas-mixture explosibility and help mine operators to more understand what type of gas-mixture is likely explosive and guide them to improve the underground mine atmosphere managements.

2. Methods for determining explosibility for mine atmosphere

In a sealed mine area, the following categories of gases make up the sealed mine atmosphere. They are: (1) gases emitted from the original coal seams, such as CH₄, CO₂, H₂, etc. Methane is the No. 1 combustible gas in the underground atmosphere and is also the most dangerous hazard in underground mining existing sedimentary minerals such as coal, trona, potash, limestone, oil shale and salt. Methane has an explosive range between 5% and 15% and the concentration of 9.5% is the most dangerous scenario due to complete combustion of the air–methane mixture. Other underground gases are mainly by-products of the coal formation process; (2) products of chemical reactions in underground mine including low temperature coal oxidation, combustion or gas explosions. Most of them are alkane (C_nH_{2n+2}), alkene (C_nH_{2n}) or alkyne (C_nH_{2n-2}) series of hydrocarbon gases. (3) atmospheric gases, which refer to the gases can be found in an ambient air sample. Almost 99% of them are consisted of nitrogen and oxygen; the remains are very small quantity of argon and carbon dioxide; and (4) other inert gas, N₂ or CO₂, injected into the sealed volume in order to extinguish the mine fire events or minimize the risk of potential explosions. Generally, the so-called mine gas actually is the mixture of the above gases. The following sections are going to discuss the methods to determine the mine gas explosibility.

2.1. Tertiary diagram

In order to represent the different combinations of three gas compositions, the tertiary diagram has been developed in assisting a graphical demonstration. Dwyer et al. (2003) introduced the diagram to determine the explosibility of the fuel–air–inert mixtures. Fig. 1 a) shows a tertiary diagram with a mixture of hydrogen, oxygen and nitrogen. The top vertex of the diagram represents 100% hydrogen and the base of the triangle represents 0% hydrogen, so as oxygen and nitrogen. Therefore, the diagram can be used to represent any ratio of hydrogen, oxygen and nitrogen at ambient conditions. Using line A as an example, it represents 30% hydrogen. It is the same thing for Line B (30% oxygen) or Line C (30% nitrogen). Accordingly, the example Point D on the line A is consisted of 30% hydrogen, 27% oxygen and 43% nitrogen, and Point E can be considered as the pure air (0% hydrogen, 21% oxygen and 79% nitrogen).

Fig. 1b) provides the full tertiary diagram for a mixture of hydrogen, oxygen and nitrogen including the flammability envelope for ambient conditions. If the gas sample is inside the envelope, which means it is explosibility. The explosions may take place once a flame is provided. Line F is drawn from air (Point E in Fig. 1a) to 100% hydrogen and thus any mixture of hydrogen and air alone must lie on line F. Two points of intersections which are formed by the line F and the flammability envelope is actually the lower flammable limit (LFL) and upper flammable limit (UFL) for hydrogen in air, respectively (Dwyer et al., 2003).

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