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Emergency Response Analysis of Fatal Gas Explosions Based on a Case Study

Leilei Li[a]*, Zhifeng Yang[b]

[a]College of Resources & Safety Engineering, China University of Mining & Technology(Beijing), Beijing 100083, China
[b]Hebi Coal Group Mine Rescue Team, Henan Energy & Chemical Industry Group, Hebi 458020, China
lllyjjy@126.com

Focusing on a typical coal mine accident in China, this paper aims to enhance the emergency ability against fatal gas explosions in coal mines. The research data were obtained from the emergency rescue report and an interview with members of the rescue team. The emergency response process of the coal mine was reviewed in details from the angles of emergency organization, decision and disposal. It is concluded that the ventilation recovery and gas discharging must be executed with safety measures, the poor emergency response can be attributed to the customary emergency response mechanism and the lack of emergency knowledge, and the leader of the rescue team must adopt the first and third options to prevent the casualty of the rescuers. The findings of this study offer new insights into the handling of fatal gas explosions in other coal mines.

1. Introduction

Gas explosion poses a serious threat to coal mines all over the world. It is of great importance to reduce the casualty and property loss by emergency response. The emergency rescue must be carried out against the clock and right to the point. Otherwise, the rescuers' own lives will be at stake, not to mention the miners trapped underground. Thus, the effect of emergency response is usually evaluated against the effectiveness of emergency organization, decision and disposal. Quite a few scholars have studied the emergency rescue in gas explosion accidents (Zaidi et al., 2017). Their research angles include the emergency organization mode (Zhang et al., 2012), the emergency response mechanism (Guo et al., 2006), and the emergency decision-making method (Li et al., 2012). Nevertheless, these studies are too theoretical to be applied to actual rescue missions. In view of this, the actual coal mine accidents have been combined into the research on emergency rescue. For example, Feng (2012) conducted a study on case-based reasoning emergency system, aiming to draft a rescue plan promptly. Through the above analysis, this paper probes into the emergency response of a gas explosion accident in Shanmushu Coal Mine, China's Sichuan Province, and discusses the effectiveness of the emergency response against the accident.

2. Case overview and methodology

2.1 Gas explosion accident in Shanmushu Colliery

The gas explosion accident happened in a 620 m-long air roadway with a cross-section area of 8.4 m^2 (Figure 1). At the end of the air roadway, the open-off cut of the working face had already reached 10 m. Two local ventilators were installed to provide fresh air to the working face.

On July 22, 2013, the local power supply network broke down, leading to a black-out in the air roadway. As the ventilators stopped working, the miners in the working area were immediately evacuated to a safe area. Then, the first gas explosion occurred when one of the ventilators resumed operation. Then, the rescue team was ordered to enter the air roadway and explore the disaster situation. Based on the situation, the coal mine mangers and the rescue team leader executed the gas discharging plan. Unfortunately, the second gas explosion happened during gas discharging on July 23, killing seven rescuers before its consequences were eventually contained.

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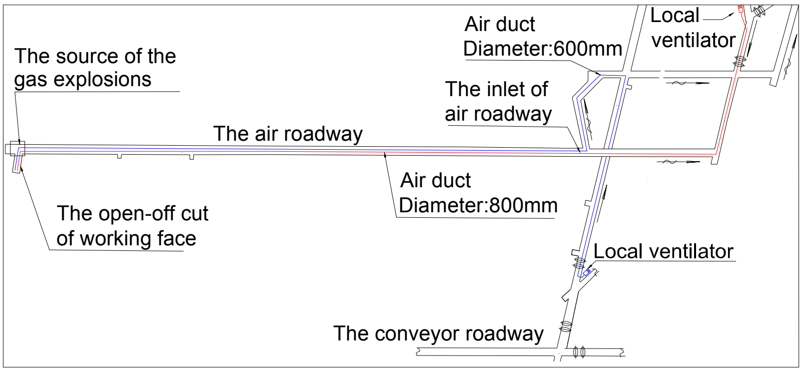

Figure 1: The air roadway struck by the gas explosions

2.2 Research methods

The research data were obtained from two sources: the emergency rescue report released by the National Mine Emergency Rescue Furong Team after an investigation of the coal mine, and an interview by the author with the members of the rescue team. According to previous studies, emergency organization, decision and disposal were selected as the indices of the emergency response effect. The purpose is to find the causes of poor response in the first gas explosion, and identify the proper rescue methods against gas explosion in coal mines.

3. Results

3.1 The emergency organization

Targeted at coal mine accidents, the emergency organization commonly involves the rescue headquarters, the rescue team, the medical team and the logistics support group. Among them, the rescue headquarters and the rescue team are the dominant forces of the organization. In the event of emergencies, the emergency organization makes emergency decisions, and fulfils five main functions: decision making, information management, consultation, supervision and resource support (Gui, 2007). Hence, a good emergency organization is the key to accident handling. Since no one was killed in the first gas explosion, coal mine managers did not recognize the seriousness of the situation, and only set up a basic emergency organization (Figure 2), which is unable to fully evaluate the risk of the accident. Because of the casualties in the second gas explosion, the basic emergency organization was replaced by a robust rescue organization (Figure 3). The new mechanism lays the basis for scientific decision-making. As can be seen from Figures 2 and 3, the robust emergency organization can realize all the five main functions mentioned above, while the basic one creates a security loophole due to the lack of functions.

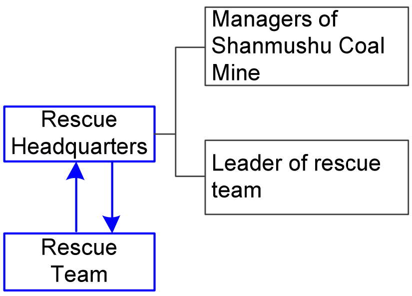

Figure 2: The basic emergency organization system

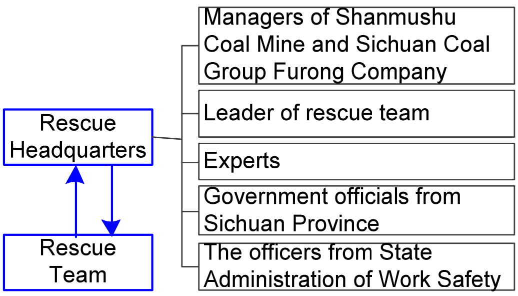

Figure 3: The robust emergency organization system

3.2 The emergency decision

Emergency decisions must be made based on the disaster situation reported by the rescue team. Table 1 lists some of the locations explored by the rescue team in the air roadway of Shanmushu Coal Mine.
In light of the disaster situation reported by the rescue team (Table 2), the basic emergency organization decided to discharge the mixed gas from the disaster area as specified in the gas discharging plan. Since the

explosion range of natural gas is 5.3 %~15.6 % (Gamezo et al., 2012), the mixed gas may explode if there is any spark in the air roadway. Unware of the danger, the rescue headquarters ordered the rescue team to discharge the mixed gas without any precautions against gas explosion.

Table 1: Some of the locations explored by the rescue team

Location	Description
Ⅰ	The location that is 2 meters away from the inlet of the air roadway
Ⅱ	The location that is 180 meters away from the inlet of the air roadway
Ⅲ	The location that is 300 meters away from the inlet of the air roadway
Ⅳ	The location that is 480 meters away from the inlet of the air roadway
Ⅴ	The end of the air roadway

Figure 4 shows the process of emergency decision-making by the basic emergency organization. It is clear that the decision is purely cognitive and in lack of clear understanding of the actual situation. The order to discharge the mixed gas was still received by the rescue team, despite that volume fraction of CH_4, CO, CO_2 and O_2 were 5.8 %, 280 ppm, 0.8 %, 18.8 %, respectively and the temperature (T) was 32 ℃ at 540 m away from the inlet of the air roadway. Maybe the rescue team was accustomed to the situation to some extent.

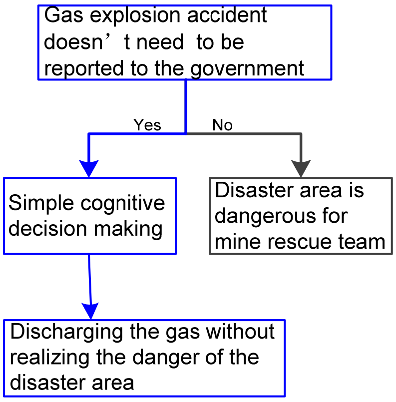

Figure 4: The basic emergency decision making

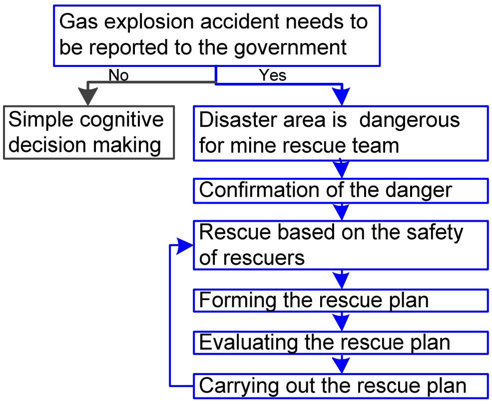

Figure 5: The robust emergency decision making

The robust emergency organization took over the command over the emergency response and dealt with the second gas explosion. Based on the situation reported by the rescue team (Table 2), the experts drew two main conclusions. First, the trapped rescuers were basically dead because 4 hours had elapsed since the explosion, longer than the longest working hours of the positive pressure respirators carried by the rescuers;

Second, there was a chance of another gas explosion in the disaster area. Then, the robust emergency organization decided to make the disaster area inert with nitrogen gas. This measure supressed combustion reaction and ensured the safety of the rescue. In addition, the rescue headquarters ordered to save the trapped rescuers after confirming the safety of the disaster area: the injected volume of nitrogen was enough to substantially reduce the volume fraction of methane and oxygen. As shown in Figure 5, the robust emergency decision-making process involves scientific analysis of the disaster situation and the adoption of forceful and targeted measures.

Table 2: The disaster situation reported by the rescue team

Location	The first gas explosion					`Location	The second gas explosion				
	CH_4 (%)	O_2 (%)	CO (ppm)	CO_2 (%)	T (□)		CH_4 (%)	O_2 (%)	CO (ppm)	CO_2 (%)	T (□)
□	0.5	20.1	0	0.1	23	□	0.2	20.1	15	0.1	25
□	5.5	19.8	2000	1.2	25	□	2.8	18	160	0.8	27
□	11	19.8	700	1.2	32	□	5.8	15	3200	1.3	60

Of course, the second gas explosion might not happen if the rescue headquarters had made a scientific decision based on the disaster situation. The change trend of gas in the disaster area (Figure 6) provides an important reference to the understanding of the disaster situation. In Figure 6, the thick dash line is the lower limit of oxygen (12%). The methane will not explode if the oxygen volume fraction is below the lower limit. The fine dash line is the lower explosion limit of methane (5%) in the case of a light fire. If its volume fraction is below this limit, the methane will not explode when it is mixed with oxygen (Gamezo et al., 2012; Yu, 2005). According to Figure 6(a), the mixed gas might explode if there was any fire from II to V, indicating that it was dangerous to enter the disaster area. However, second gas explosion could be prevented if the rescue headquarters and the rescue team had taken some safety measures. From Figure 6(b), it can be seen that the mixed gas could explode near IV. Through comparison, it is learned that oxygen volume fraction declined after the second gas explosion, but the residual oxygen could still sustain an explosion if methane volume fraction fell in the explosive range. In view of the situation, the rescue headquarters and the rescue team eliminated the explosion risk and successfully handled the second gas explosion. The results demonstrate the importance of gas volume variation in emergency decision-making.

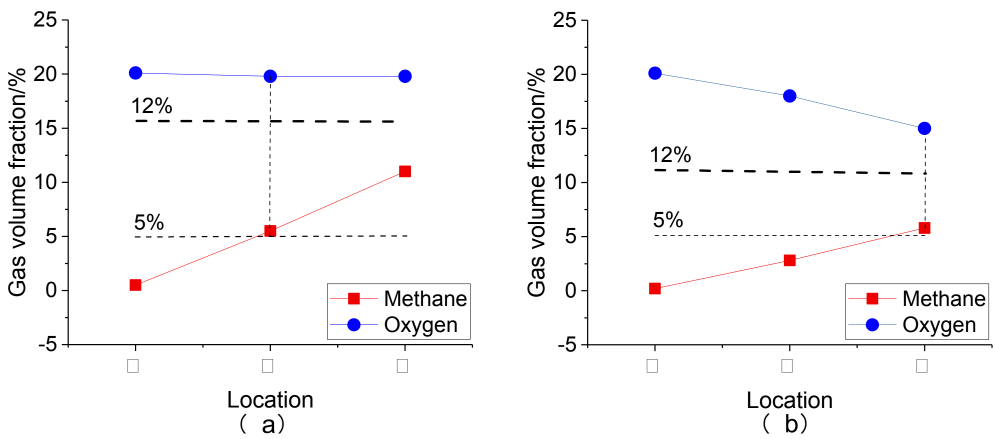

Figure 6: Variation in methane and oxygen volume fraction (a) the first gas explosion (b) the second gas explosion

3.3 The emergency disposal

To obtain the methane distribution in the air roadway during the blackout, the methane volume fraction *c* can be calculated as:

$$c = \frac{V_1}{V_1 + V_2} \times 100\% \qquad (1)$$

Where V_1 is the methane volume (V_1=ut); V_2 is the air volume (V_2=Sl); u is the absolute gas emission rate of the air roadway; t is the time of no wind; S is the cross-section area of the air roadway; l is the length of a tunnel containing a certain volume fraction of methane. Based on Eq(1), l can be calculated as:

$$l = \frac{(1-c)ut}{cS} \tag{2}$$

Before the first gas explosion, the absolute gas emission rate of the air roadway was 1.5 m^3/min. Considering the no wind time (53 minutes), there were about 79.5 m^3 methane seeped from the coal into the air roadway. According to Eq(2), these methane would fill up the air roadway within about 179.8m from the working face if the volume fraction of methane mixed uniformly with air was 5%. In fact, the methane volume fraction was relatively higher in locations close to the working face and the roof. Thus, an explosive mixed gas was formed once the ventilation was recovered. This means it is improper to recover ventilation without removing the explosive mixed gas beforehand.

The first gas explosion accident was handled by the customary way of gas discharging. The rescue team tried to detect the fire with an infrared thermometer, but failed to find any fire. Without considering the concealed fire, the rescue headquarters ordered the rescue team to discharge the potentially explosive mixed gas, and the order was accepted without any argument. It is exactly the rash gas discharging that caused the second gas explosion. The second accident was reported to the government immediately, followed by the establishment of the robust emergency organization. Under the premise of preventing another gas explosion, the seven rescuers in distress were carried out of the disaster area. Finally, the air roadway was sealed up to extinguish the concealed fire. Overall, the key disposal measures include scientific safety evaluation, making the mixed gas inert, saving the dead rescuers and sealing up the disaster area.

4. Discussions

4.1 The causes of the poor emergency rescue

The poor emergency rescue is caused by two major reasons. The first cause lies in the customary emergency response mechanism. Unwilling to report sudden events like blackout to the government, coal mine mangers tend to adopt emergency response measures based on their own experience. In this case, some gas explosions which cause no casualty may be wrongfully treated as minor sudden events. The absence of prudent evaluation of the disaster situation is not conducive to the emergency work, which is well proved by the incorrect measures leading to the second explosion. The other cause is the lack of emergency knowledge. Albeit the abundant experience on coal mining, the coal mine mangers did not necessarily have enough knowledge on emergency response. The blind and rash accident handling style of Shanmushu Coal Mine increased the risk level. This is evidenced by the findings of previous research (Brændeland and Refsdal, 2013; Vaught et al., 2006). In our case study, the emergency response was undermined by poor emergency organization, unscientific emergency decision and improper emergency disposal. For example, the first gas explosion might not happen if the mixed gas had been removed before the ventilation was recovered.

4.2 Emergency organization of the rescue team

When a gas explosion happens in coal mines, the rescue team is always ordered to enter the disaster area and report the situation, discharge the gas, recover the ventilation, rescue the trapped, etc. The team leader has to decide whether or not to execute the emergency orders. According to China's Coal Mine Safety Regulation, the leader of a rescue team, in the event of a sudden event, has the right to withdraw from the dangerous area and report the situation to the underground rescue base and rescue headquarters (SAWS and SACMS, 2016). Unfortunately, this provision is often overlooked in actual practice. The rescue team is often forced to enter the disaster area under severe dangers. After receiving an emergency order from the rescue headquarters, the team leader commonly has the following options (Table 3).

Table 3: The options of the team leader after receiving an emergency order

No.	Disaster Situation	Option
1	Not dangerous	Execute the emergency order
2	Dangerous	Execute the emergency order at risk.
3	Dangerous	Execute the emergency order, report the danger to the rescue headquarters, and ask for safe measures.
4	Unclear	Execute the emergency order which is too difficult to be finished.

In Table 3, the first option poses no danger to rescuers; the third option can ensure the rescuers safety with scientific measures; the second and fourth options may put rescuers' lives at stake. The second option is featured by blindness, while the fourth one consumes too much physical strength of rescue team members. In Shanmushu Coal Mine, the leader of the rescue team selected the second option after the first gas explosion, and chose the third option after the second gas explosion. The most favourite options should be the first and the third one for coal mines.

5. Conclusions

The first gas explosion was handled much more poorly than the second one. The improper disposal of a blackout resulted in a series of mistakes in the early phase of emergency response. During the emergency response in a coal mine, the ventilation recovery and gas discharging must be executed with safety measures. Besides, the poor emergency response can be attributed to the customary emergency response mechanism and the lack of emergency knowledge. Facing a fatal gas explosion, the responders should avoid using the customary emergency response mechanism, and abide by standard rescue procedures. The acquisition of emergency knowledge is also vital to improving emergency ability. Furthermore, the leader of the rescue team must adopt the first and third options to prevent the casualty of the rescuers.

Acknowledgments

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