The 6th International Conference on Mining Science & Technology

The characteristic of explosion under mine gas and spontaneous combustion coupling

Qin Bo-tao, Zhang Lei-lin, Wang De-ming, Xu Qin

State Key Laboratory of Coal Resources & Mine Safety, Safety engineering college, China University of Mining & Technology, Xuzhou 221008, China

Abstract

The gas explosions often occur under mine gas and spontaneous combustion coupling in coal mines. The coupling of mine gas and spontaneous combustion is a complex disaster, and the character of the disaster is not clear now. The paper primarily discussed the character of gas explosion under mine gas and spontaneous combustion coupling. The explosion concentration range of mixed gases including CH\textsubscript{4} and CO is studied. And the potential area and the course of explosion detonated by spontaneous combustion of coal is analyzed. When the spontaneous combustion of coal occurs, it can produce plenty of CO and fire-heating air pressure in the goaf. Experiments show that the upper limit of explosion concentration rises rapidly and the lower limit rises slowly with the increase of CO in the mixed gas of CH\textsubscript{4} and CO. The fire-heating air pressure results in continuous mix of the gases and heat convection under vortex action between the combustion zone and non-firing zone. Thus, gas explosion occurs. In order to prevent high-concentration gas in the goaf and spontaneous combustion which detonates gas explosion in the coal mine, three-phase foam with nitrogen is adopted to restrain gas explosion and reduce coal temperature.

Keywords: mine gas; spontaneous combustion of coal; explosion; fire-heating air pressure; three-phase foam

Coal accounts for about 70%\textsuperscript{[1]} of the energy in China. It is estimated that it will still account for more than 50% in 2050. So coal continues to be the main energy for a long period in China. However, 95\% of coal mines in China are underground and the geologic structures are complex. Consequently, fatal accidents often occur. Most accidents are gas and spontaneous combustion of coal. It is dangerous for the safety mining when the coal mine exists high-concentration gas and spontaneous combustion. In China, the majority of coal mines are with spontaneous combustion of coal and high-gas. More than 48\% of state-owned key coal mines are confronted with high-gas and more than 56\% coal seams\textsuperscript{[2]} face spontaneous combustion tendency. If the gas and spontaneous combustion of coal cannot be controlled very well, the gas explosion detonated by spontaneous combustion will occur easily, which results in serious casualties and economic losses\textsuperscript{[3]}. In past ten years, major coal accidents often occurred because the spontaneous combustion detonated the gas. The hidden trouble of mine gas and spontaneous combustion coupling is serious and cannot be prevented effectively by routine technologies.

1. Fire source of gas explosion in Goaf
The gas such as CH₄, CO or the admixture of them in goaf often explode if the environment meets explosion conditions. The gas explosion must meet three basic conditions:

- **Heat.** When the temperature reaches to the ignition temperature, the explosion will possibly occur.
- **Oxygen.** It is essential if the gas explodes.
- **Gas concentration.** All gas explosions occur in certain explosion concentration range.

The explosion in the goaf depends largely on the fire source, which includes external and internal fire source. In underground restricted space, shock waves and flame with high temperature and pressure generated by gas explosion propagate along the roadway, and causes serious destruction. It is difficult to find out the fire source because of the complex dynamic phenomena, wide influence scope and no survivor near the explosion sites. According to the actual situation, the goaf is filled with waste rock and people can’t enter, then the external fire can be eliminated. So the spontaneous combustion of coal and the collision spark of coal and rock are the main heat source. The possibility and mechanism of gas explosion caused by collision and friction of roof rock falling were studied by Uchida in Japan, professor Zhou X Q and Xu J L in china, etc\(^\text{[4-6]}\). The results showed that the temperature and sparks generated by collision and friction can detonate gas, but the probability of occurrence is quite little, so the heat source is produced primarily by spontaneous combustion of coal. However, it is lack of theoretical basis on the mechanism and process of gas explosion detonated by spontaneous combustion of coal. For example, it is lack of convincing conclusions about the fire source for the gas explosion occurred in one coal mine in Ningxia province in China. Now the spontaneous combustion is considered the possible fire source.

### 2. Characteristic of gas explosion detonated by spontaneous combustion of coal

For the high-gas coal mine with spontaneous combustion of coal, it is the hidden natural disaster that gas and spontaneous combustion coexist. The main medium of gas explosion is CH₄. However, the spontaneous combustion of coal can produce plenty of index gases such as CO. If CO is mixed with CH₄, the explosion concentration limits of CH₄ can be changed. At the same time, coal spontaneous combustion of coal can raise environment temperature and produce the fire-heating air pressure\(^\text{[7]}\). The mixture of CH₄ and CO in goaf can accumulate at some regions under the interaction of temperature field and fire-heating air pressure. So it may result in a disaster seriously.

#### 2.1. The explosion concentration of mixed gas including CH₄ and CO

For the high-gas coal mine with spontaneous combustion of coal, when the concentrations of CH₄ and CO show abnormal changes on the working face, the dynamic characteristic parameters in the mixed-environment can’t be figured out, and the calamity degree and evolution process can’t be predicted accurately. So it’s often difficult to make the right decision to continue advancing or closing the working face. If the closure is too early, the big loss will be caused, however, if the mine is not closed in time, the spontaneous combustion of coal may be hard to be controlled and the accumulation of gas can’t be eliminated, which result in further deterioration of disasters.

In order to clarify the explosion hazard of CH₄-CO mixtures, the test equipment system of gas explosion (20 L ball-type explosive device)\(^\text{[8]}\) can be used, which mainly includes the explosion chamber (20 L), the ignition device, the explosion control device, data acquisition systems, etc. The explosion chamber is composed of double-wrought steel ball cavity. The water flow in constant temperature can go through inlet and outlet to ensure the constant temperature of the explosion chamber which contains cylinder, top cover and bottom cover. There is an observation hole in the cylinder. The phenomenon of the internal gas explosion can be observed through the observation hole. The explosion control device mainly controls the ignition energy and time, the sampling system and system security, etc. when explosion initiates, data acquisition system includes pressure sensors, signal amplification control circuits and PCI-1710 data acquisition cards, etc. The strong electric spark was used for ignition during the experiment. Then the gas (mixture of CH₄ and CO) explosion concentration limits were determined, which were showed in Table 1. Therefore, in the process of the usual gas analysis, the percentage of CH₄ and CO in the mixed gas in the goaf can be obtained through the chromatographic analysis, which can be used to initial deduction if the mixed gas is in the explosion concentration range.

| Table 1. Explosion limit of mixed gas including different concentration CH₄ and CO |
From Table 1, the percentage of CO is positively related to both the upper and lower limits of explosion concentration of mixed gas. The limits will rise when the percentage of CO increases, which the lower limit will rise slowly while the upper limit rise very quickly. Therefore, the higher the CO content in the gas is, the wider the explosion concentration range will be. The risk degree of explosion is adopted to indicate the danger of gas explosion, the difference between the upper explosion concentration limit and the lower limit is divided by the lower limit\(^9\), namely:

\[
L = \frac{C_{\text{upper limit of explosion concentration}} - C_{\text{lower limit of explosion concentration}}}{C_{\text{lower limit of explosion concentration}}}
\]  

(1)

In the formula (1), it indicates that greater value L means higher explosion risk. If spontaneous combustion of coal takes place in the goaf, a large number of CO which can cause the CO concentration in the mixed gas rising will be generated, thus increasing the margin between the upper limit and the lower limit, then value L will increase. The gas content of the easily spontaneous combustion coal seam in the goaf is large; the explosion risk of CH4-CO mixtures is higher.

2.2. The potential area of explosion

In the goaf of the normal advancing working face, under the effect of the spread and dilution of the air flow, CH\(_4\) concentration increases gradually from the surface to inside, that is the CH\(_4\) concentration in the inside of the goaf is higher than that in the surface, the upper higher than the lower. While the oxygen content is opposite, the O\(_2\) concentration in the surface is higher than the inside. There must be a danger zone where gas concentration and oxygen content are suitable for gas explosion, and the zone isn’t very large. But when a large amount of CO mixed into the gas the danger zone will enlarge. Beyond the danger zone the explosion conditions can’t be met. In the scope of the danger zone, electrical equipments are not safe. People are not allowed to enter, which can remove all fire sources made by person and the electrical equipments. So the explosion is basically caused by spontaneous combustion of coal.

According to the laws of spontaneous combustion of coal in the goaf, the goaf can be divided in to three zones that are “No self-ignition zone”, “oxidation zone” and “suffocative zone”. Only in the oxidation zone, the gradual compaction by falling rock reduced porosity, increased wind resistance, and reduced air leakage intensity and the heat generated by oxidation of gradually accumulated coal, which led to coal spontaneous combustion finally. But the spontaneous combustion can’t occur in other two zones. So the explosive area in the goaf is the intersection area of oxidation zone and the area with mixed gas in explosion limit range.

2.3. Explosion process

In the area with coal spontaneous combustion and mixed gas explosion in the goaf, the spontaneous combustion of floating coal will generate explosion gas mixed by a large amount of CO and CH\(_4\). Besides it will increase the ambient temperature to speed up the oxidation rate. As the ambient temperature rises and the density of the surrounding air decreased, it will generate the force (Fire pressure) to make the air rise along coal seam dip angle and to the upper space. And hot air flows up (outside), the temperature of upper coal rises to promote the deep
oxidation rate. At the same time, because of fire pressure, the swirl with low speed may be formed between firing zone and non-firing zone, which causes the troposphere exchange heat. Then the inside and outside temperature rises together. The fire source of floating coal spontaneous combustion plays two roles: (1) the role of local fan. It makes air flow in order to provide fresh air for fire area of coal spontaneous combustion. (2) To enable CH₄ and CO to accumulate in a given region and continuously heat mixed gas around, resulting in expansion of the region of coal spontaneous combustion and more thermal discharge to speed up the oxidation rate of coal.

The process of the explosion is shown in Fig.1. For the goaf of the coal seam with a certain inclination, if spontaneous combustion of coal takes place in zone A (equivalent to a fire zone fan), it will generate a great amount of index gas of coal spontaneous combustion CO and then form the explosive mixed gas including CO and CH₄, which the concentration is always in the explosive concentration range. Due to the fire-heating air pressure, the zone c transport fresh air to zone A, resulting in spontaneous combustion of coal and temperature increasing continually; mixed gas of zone A moves to zone B along inclination under the fire-heating air pressure, and then mixes with gas in zone B, finally, the temperature of the gas in zone B rises. At the same time, the vortex of the heat flow is formed which make the region of spontaneous combustion of coal expand. Because zone C supplies oxygen continuously, oxidization in zone A increases. As the recycle, mixed gas in zone B and C is heated. When the temperature in zone A increases to the critical temperature of gas explosion, explosion in zone A and B and other related areas will occur. While the more gas is involved in, the bigger the explosion region is. Therefore, the consequence of spontaneous combustion of coal detonating gas explosion is serious and power is quite large that might cause significant personal casualties and huge property loss frequently.

3. Restraining explosion technology of three-phase foam with N₂ in goaf

At present, in order to prevent and control the composite disaster occurring in the high gas mines with spontaneous combustion of coal, some single technical methods, such as only gas drainage or prevent spontaneous combustion, is adopted[10-11]. But in fact, due to some in-site conditions, for some high-gas coal mines, especially the low-permeability coal seam, it is difficult to drainage gas effectively and ensure that the concentration is lower than the gas explosion limit. At the same time, a variety of detection equipments and technologies[12-14] are difficult to identify the location and scope of potential fire source in goaf accurately and quickly. As a result, regulation effect is hard to prove effective in a short period.

The large flux with high-quality three-phase foam is adopted as one of effective methods to control gas explosion and spontaneous combustion coupling in goaf of high gas mines.

- Absorbing heat and cooling temperature

Solid incombustible matter and water in three-phase foam has lower temperature. When three-phase foam is poured into the goaf, it has the characteristic of absorbing heat and cooling temperature.

When in the condition of thermal equilibrium, the heat absorbed that water and the solid incombustible matter temperature rising is:

\[ Q_1 = m_1 c_{p1} ( T_2 - T_1 ) + m_2 c_{p2} ( T_2 - T_1 ) \]  

(2)
In the formula: $Q_i$ is the heat that raise the temperature of water and solid incombustible matter, kJ; $m_1$, $m_2$ are the weight of water and solid incombustible matter which need absorb heat and raise temperature, kg; $C_{p1}$, $C_{p2}$ are the specific heat at constant pressure of water and solid incombustible matter, kJ/(kg·K); $t_1$, $t_2$ are the temperature before and after heating.

The specific heat at constant pressure of water and solid incombustible matter is usually big. For example, the specific heat at constant pressure of water is 4.868 kJ/(kg·K), for every ton of water, the temperature elevate $10\,\degree$C, it will absorb heat about $4.868\times10^4$ kJ. Therefore, the heat absorbed from three-phase foam through is large. Pouring three-phase foam into the goaf, a large quantity of heat may be absorbed and the temperature of coal and environment may decrease. Cooling the coal rapidly restrains the spontaneous combustion of coal effectively.\cite{15}

- Restraining the gas explosion

The foaming multiple of three-phase foam has relation to the amount of N$_2$. The greater the amount of nitrogen is, the higher the foaming multiple is. In the current mine, the foaming multiple of three-phase foam can achieve to 20 to 30 times generally. N$_2$ wrapped in three-phase foam releases slowly as the bubble burst of three-phase foam. Then the N$_2$ mixed with CH$_4$ and CO of environment and the mixed gas play the important role in suffocating the goaf and restraining gas explosion.

The explosion equipment introduced above was adopted to study the explosion limits of gas, the results show that the range of explosion concentrations in the different percentage of CH$_4$ and CO (Table 2).

<table>
<thead>
<tr>
<th>Percentage of N$_2$ in the mixed gas(%)</th>
<th>0</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>26</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$:CO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>=3:2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower limit of explosion concentration (%)</td>
<td>7.19</td>
<td>7.29</td>
<td>8.01</td>
<td>8.68</td>
<td>9.3</td>
<td>9.68</td>
<td></td>
</tr>
<tr>
<td>Upper limit of explosion concentration (%)</td>
<td>19.94</td>
<td>16.03</td>
<td>13.05</td>
<td>12.20</td>
<td>10.30</td>
<td>9.68</td>
<td></td>
</tr>
<tr>
<td>CH$_4$:CO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>=4:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower limit of explosion concentration (%)</td>
<td>6.08</td>
<td>6.13</td>
<td>6.51</td>
<td>6.82</td>
<td>7.03</td>
<td>7.04</td>
<td>7.06</td>
</tr>
<tr>
<td>Upper limit of explosion concentration (%)</td>
<td>16.51</td>
<td>12.30</td>
<td>10.12</td>
<td>9.13</td>
<td>7.82</td>
<td>7.63</td>
<td>7.06</td>
</tr>
</tbody>
</table>

From the Table 2, the range of explosion diminish significantly with the addition of N$_2$ in the mixed gas including N$_2$ and CH$_4$; when the content of CO in the mixed gas is higher, the lower limit increases more rapidly; the addition amount of N$_2$ is smaller when the mixed gas loses the ability of explosion. At the same time, the results of experiment show that upper limit of explosion concentrations decrease and the lower limit increase quickly; as the CH$_4$ contents in the mixed gas increase, the N$_2$ is needed when the mixed gas loses ability of exclusion. The reason is that the activation center in oxidation and chemical characteristics of free radical are inerter than CH$_4$ in the environment surrounding of N$_2$, and then the oxidation rate is slower. The result shows that the effect to restrain explosion of N$_2$ is notability than CH$_4$. So, when the higher the CO concentration of the mixed gas including CH$_4$ and CO is, the lower the additional amount of N$_2$ to restrain explosion is.

When three-phase foam including N$_2$ were poured into the goaf, according to the reference\cite{3}, half-life of three-phase foam is $t_{1/2} = \frac{38}{e^{-0.052n}}$, and $n$ is foaming multiple. According to characteristics of three-phase foam, it is assumed that the rate of foaming distinction is $k$ (release rate of N$_2$), the flow of three-phase foam is $q_f$ (m$^3$/h), and the total time of pouring three-phase foam is $t$ (h). The three-phase foam in a given volume is $V$ and the half-time of foam is $T_{1/2}$, so it can be seen linear damage and the rate of foaming distinction is:

$$k = \frac{1}{2T_{1/2}} V \quad \text{(3)}$$

Through series of derivation, the results show that the released quantity of N$_2$ in the period when pouring three-
Combined with the actual situation, if the foaming multiple is 30 times, and the half-life of three-phase foam is $T_{1/2}$ (about 8h), when the quantity of slurry is $20 \text{ m}^3/\text{h}$, the numerical $Q$ is substituted into the equation (4):

$$Q = 600(t + 16e^{-\frac{t}{16}} - 16)$$ (5)

Therefore, the three-phase foam poured into the goaf should be mainly in the area of explosion under mine gas and spontaneous combustion coupling. In the area, the released amount of $N_2$ increases quickly with pouring three-phase foam continuously. At the same time, existence time of $N_2$ in the goaf is long. As a result, $N_2$ mixes with mixed gas fully during the release time changing the explosion range of the mixed gas; with the increase of $N_2$ concentration, mixed gas loses explosibility when $N_2$ concentration achieves a specific level. At last the goal of restraining explosion in goaf can be achieved effectively.

4. Conclusions

It is dangerous in high-gas coal mines with spontaneous combustion because of the coexistence of $CH_4$ and CO (flammable gas) in goaf. The paper provides theoretical analysis and control technology for preventing gas explosion through the analysis of mechanism on spontaneous combustion of coal detonating gas.

- The explosion concentration range and hazards resulted from mixed gases concluding $CH_4$ and CO is studied by experiments. The result shows that the upper limit of explosion concentration increases rapidly and the lower limit increases slowly with the increase of CO in the mixed gas including $CH_4$ and CO, then the risk increases.
- The potential area and process of explosion detonated by spontaneous combustion of coal is analyzed. The explosion often occurs at the area of spontaneous combustion zone meeting explosion concentration range of $CH_4$. At the same time, fire -heating air pressure produced by spontaneous combustion of coal results in the full mix of $CH_4$, CO and fresh air and the heat convection between the combustion zone and non-firing zone. So, the gas explosion accident occurs.
- Three-phase foam with nitrogen is adopted to prevent spontaneous combustion of coal detonating gas explosion in the high-gas coal mine with spontaneous combustion of coal. On one hand, three-phase foam may reduce temperature of the coal and the environment greatly and cool the high-temperature coal rapidly. It is effective to prevent the spontaneous combustion of coal. On the other hand, the nitrogen released from three-phrase foam mixes with the gases including $CH_4$ and CO, it can effectively suffocate the goaf and restrain the gas explosion. And the mixed gases can not explode thoroughly when the concentration of $N_2$ reaches to the degree.

Acknowledgements

Financial support for this work, provided by the Authors of National Excellent Doctoral Dissertation of PR China (2007B53) and Jiangsu Provincial Natural Science Foundation (BK2008123), is gratefully acknowledged.

References