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Study on Supporting Wood Fire Induced by Mine Methane Explosions

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Abstract

The risk of supporting wood fire induced by methane explosions in roadway was studied by doing some research on the mechanism of it. The thermal environment of methane explosions which include the characteristics of fire flame and the temporal and spatial thermal environment was studied. Based on the research of thermal environment, the fast pyrolysis of supporting wood was carried out by using fast pyrolysis apparatus. The experiment temperature is from 592\textendash{}313 K, and the heat duration were 1 s, 2 s, 5 s, 10 s. Connected with combustion theory, the possibility of supporting wood fire induced by methane explosions was discussed from the following several aspects: fuel, combustion limit, the minimum combustion oxygen limit, and fire period. If the initial methane concentration is between 5.0\textendash{}9.25 \% with someone volume, then the sub-fire may occur at a certain distance from explosion source.

Keywords: methane; explosions; supporting wood; sub-fire

Coal mine methane explosion is a major disasters and accidents, the sub- fire caused by the methane explosion may induce secondary methane explosion again, even for many times of methane explosion, and will lead to much more loss. So, study on the mechanism of sub- fire caused by the methane explosion has great significance for the prevention of such disasters. Supporting wood as one of the main material of coal mine, there are lots of supporting wood fire accidents occurred in the history. Based on
the analysis of thermal environment after methane explosions, and the application of fast pyrolysis apparatus which could satisfy the dynamic thermal environment of methane explosion characteristics, some fast pyrolysis experiments within a temperature and time range were carried out. Combined with the basic theory of combustion to analyze the sub-fire mechanism and possibility, and then get some conclusions. Research on the prevention and control measures related to this kind of disasters could provide some references and proposals to prevent such kind of disasters, it has some practical value[1-3].

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>air concentration, kg/m$^3$</td>
</tr>
<tr>
<td>$g_i$</td>
<td>volume force of direction $i$</td>
</tr>
<tr>
<td>$\delta_{ij}$</td>
<td>unit tensor</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity, Pa.s</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure, Pa</td>
</tr>
<tr>
<td>$h$</td>
<td>enthalpy, K</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat at constant pressure, J/(kg·K)</td>
</tr>
<tr>
<td>$\mu_t$</td>
<td>viscosity coefficient</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>heat exchange coefficient</td>
</tr>
<tr>
<td>$S_h$</td>
<td>equation source</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature, K</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>differential coefficient</td>
</tr>
</tbody>
</table>

1 The thermal environment after mine methane explosion

Do some research on the thermal environment after methane explosion is main to know about the law of products out of supporting wood under methane explosions. Divide the thermal environment into two aspects: (1) first, the heat effect of high temperature and high pressure fire flame to supporting wood; (2) the heat effect of the temporal and spatial changeable thermal environment to supporting wood. Then the two parts will be discussed separately.

1.1 The characteristics of fire flame under methane explosions

1.1.1 Temperature of fire flame

Some experts have done some 9.5 % methane explosions to test the temperature of fire flame after methane explosions, and the experiment results shows that the maximum temperature could reach 1 400
K, and some experts got it to 2 300 K through experiments and simulations\cite{4,5}. As for the convenience of calculation, take the temperature of fire flame changes from 923~1 313 K for deflagration, and 2 000 K for explosions. And presume that temperature of fire flame hold in line when propagating in the roadway.

1.1.2 The heat duration of fire flame to supporting wood

The heat duration is related to the velocity and the width of fire flame. Heat duration of fire flame to one point in roadway is the time of the fire width divides the fire velocity. Some experts have done some 9.5 % methane explosions to test the duration and relating velocity. Because 9.5 % methane explosion is the most serious status, then choose it to study some data \cite{6-8}. The experiment results show that, the fire flame velocity increase from 10 m/s to 125 m/s and the holding time decrease from 400 ms to 35 ms very fast in L/D=80 along with the propagation of fire flame, then holds flat trend. Because the pipe experiment conditions are better than that of roadway, the tested fire velocity in pipe is lager than in roadway. Generally, most of the coal mine methane explosions are weak deflagration. In order to connect the following works tightly, assume that the duration is in 1 s \cite{9}.

1.2 The dynamic thermal environment after methane explosions

There are always abnormal, mass and thermal transfer physical phenomena after methane explosions. And the spatial and temporal temperature of air is related to concentration, velocity, and pressure. etc. Then, the following two dimension controlling equations were established \cite{10-13}:

Mass conservation equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0 \tag{1}
\]

Momentum conservation equation:
\[
\frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_j} \left[ \rho u_j u_i - \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] = -\frac{\partial P}{\partial x_j} - f_i - \frac{g_i}{\rho} - \frac{2}{3} \delta_{ij} \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) \tag{2}
\]

Energy conservation equation:
\[
\frac{\partial (\rho h)}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_j h \right) = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial h}{\partial x_j} - \rho u_j \frac{\partial h}{\partial x_j} \right) + S_h \tag{3}
\]

Heat radiation equation:
\[
\nabla q_r = 4 \pi \left( \alpha \frac{G_{4}}{\pi} + E_p \right) - \left( \alpha + \alpha_p \right) G \tag{4}
\]

Based on the research results of the instant temperature distribution after methane explosions by some experts, it was set as an initial temperature state. Then connect it with equations (1)–(4), use Fluent software to calculate the dynamic temperature distribution after methane explosions. The 7.5 %, 100 and 200 m3 conditions are shown as Fig 1, 2.

Tab 1 is the dynamic temperature change law which temperature is higher than 588 K under 200 m3, 7.5 % methane explosions. Choose 588 K is just to fulfill the lowest temperature of fast pyrolysis experiments 592 K. The temperature area which is higher than 588 K is moving far away from explosion source along with the increase of propagation distance. The highest temperature, high temperature area, and the holding time all decrease for period of time. Based on the same theory, the temperature distribution of air after different initial volume and concentration could be got.
Tab.1 The characteristics of spatial and temporal temperature transformation process in the roadway when 200 m$^3$, 7.5% methane explosions

<table>
<thead>
<tr>
<th>Distance/m</th>
<th>Starting time/s</th>
<th>Holding time/s</th>
<th>Temperature range/K</th>
<th>Average temperature/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~4</td>
<td>4</td>
<td>5</td>
<td>588~821</td>
<td>705</td>
</tr>
<tr>
<td>4~10</td>
<td>6</td>
<td>12</td>
<td>588~750</td>
<td>669</td>
</tr>
<tr>
<td>10~17</td>
<td>7</td>
<td>8</td>
<td>588~704</td>
<td>646</td>
</tr>
<tr>
<td>17~23</td>
<td>6</td>
<td>7</td>
<td>588~667</td>
<td>628</td>
</tr>
<tr>
<td>24~30</td>
<td>6</td>
<td>5</td>
<td>588~641</td>
<td>615</td>
</tr>
<tr>
<td>30~36</td>
<td>6</td>
<td>5</td>
<td>588~622</td>
<td>605</td>
</tr>
<tr>
<td>36~43</td>
<td>7</td>
<td>5</td>
<td>588~607</td>
<td>598</td>
</tr>
<tr>
<td>43~55</td>
<td>12</td>
<td>5</td>
<td>588~595</td>
<td>592</td>
</tr>
</tbody>
</table>

2 The products of supporting wood under the thermal environment when methane explosions

Based on the study of thermal environment under methane explosions, high temperature and high pressure fire flame has some heat effect to supporting wood; and supporting wood may suffer some heat effect under the dynamic thermal environment. So, the two aspects will be discussed separately.
Because the fast pyrolysis experiment equipment could fulfill the fire and dynamic thermal environments, some supporting wood fast pyrolysis experiments were carried out. Experiment temperature: 592 K, 673 K, 773 K, 923 K, 1 023 K, 1 173 K, 1 313 K; heating rates: 5 000 K/s; initial supporting wood temperature: 293 K; sample mass: 10 mg(±0.5 mg); sample diameter: 0.1~1 mm; heat time: 1 s, 2 s, 5 s, 10 s; analysis objects: \( \text{CH}_4, \text{C}_2\text{H}_4, \text{C}_2\text{H}_6, \text{C}_3\text{H}_6, \text{H}_2, \text{CO}, \text{CO}_2, \text{tar}, \text{char} \). The sample was deal with industry and chemical analysis before experiments. The sample preparation course and experiment system are shown as Fig 3,4. The sample preparation process is as follows: choose a suitable alloy tinsel, put the powdery sample onto the tinsel, pucker and press the tinsel, put the tinsel into quartz pipe. The experiment process is as follows: connect the curie point fast pyrolysis equipment with GC, open N2, open the analysis software system, set the curie point system to a selected condition, start experiments, collect data and do some analysis.

2.1 The products of supporting wood under fire flame

Take experiment temperature 923~1 313K as the fire flame temperature, and holding time 1 s, the fast pyrolysis experiment results are shown as Fig 5,6.

From Fig.5, under the fast heat effect of fire flame, the pyrolysis products include \( \text{CH}_4, \text{C}_2\text{H}_4, \text{C}_2\text{H}_6, \text{C}_3\text{H}_6, \text{H}_2, \text{CO}, \text{CO}_2 \) and so on. CO is much more than other gas, it could get to 23 % when 1 023 K, then \( \text{CO}_2, \text{CH}_4, \text{C}_2\text{H}_6 \). Other gas are very few.

From Fig.6, char decreases along with the increase of temperature, about from 26 % when 923 K to 18% when 1 313 K. The total gas is increases along with temperature, about 30 % when 1 023 K. Tar decreases from 52 % when 923 K to 45 % when 1 313 K. The total loss increases from 73 % when 923 K to 82 % when 1 313 K.

![Fig.5 Supporting wood pyrolysis mass fraction of gas when 1 s](image1)

![Fig.6 Supporting wood pyrolysis mass fraction of gas, tar, char and total loss when 1 s](image2)

2.2 The products of supporting wood under dynamic thermal environment

Take experiment temperature 588~773 K as the fire flame temperature, and holding time 2 s, 5 s, 10 s, the fast pyrolysis experiment results are shown as Fig.7,8.

Fig.7 shows the relationship between output and temperature under dynamic thermal environment. \( \text{CO} \) and \( \text{CO}_2 \) increase linearly with temperature increase. \( \text{CO}_2 \) is more than \( \text{CO} \), \( \text{CO} \) could reach 4 %
when 773 K; Fig. 8 shows the output of CH₄, C₂H₄, C₂H₂, C₂H₆, H₂ under dynamic thermal environment. CH₄ and C₂H₄ change with temperature obviously, and the output turning point is near 673 K. Fig. 9 shows the output of gas, tar, char, total loss under dynamic thermal environment. Except char all decreases with temperature. Char total loss is 50%, and gas 10% when 773 K.

3 Combustion analysis of gas separated out from supporting wood

Based on the analysis of output of supporting wood under fire flame and dynamic thermal environment, and combustion theory, the possibility of supporting wood whether could be fired was discussed. Main from the following several aspects: (1) the fired temperature of gas; (2) the lowest oxygen concentration; (3) the combustion concentration; (4) the fire induced time.

(1) The fired temperature of gas
Based on Fig (5) and (6), the gas out from supporting wood includes CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}, C\textsubscript{3}H\textsubscript{6}, H\textsubscript{2}, CO and so on. As to this kind of flammable mixed gas, the fired temperature is main that of the stable. From the experiment data, CO, H\textsubscript{2}, CH\textsubscript{4} are relatively large, and its fired temperature is about 783 K\textsuperscript{[14]}. So, if the air temperature in the roadway after methane explosions is higher than 783 K, the mixed flammable gas separated out from supporting wood may be fired.

(2) The lowest oxygen concentration

In many cases, flammable gas is mixed gas, no single kind. The lowest oxygen concentration could not substitute that of mixed gas. There are several flammable gases, such as CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}, C\textsubscript{3}H\textsubscript{6}, H\textsubscript{2}, CO. Based on some conference, the lowest oxygen concentration of supporting wood under 1 s heat effect could be expressed as equation (5)\textsuperscript{[15-17]}

\[
C_{O_2\text{ min}} = \frac{5 \times CH_4(\%) + 6.25 \times CO(\%) + 8.25 \times C_2H_4(\%) + 8.75 \times C_3H_6(\%) + 6.98 \times C_2H_6(\%)}{P_T}
\]  

(5)

Tab.2 The minimum combustion oxygen limit of gas out of supporting wood at different temperature under 1 s

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Minimum Combustion Oxygen Limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>923 K/1s</td>
<td>5.09 %</td>
</tr>
<tr>
<td>1023 K/1s</td>
<td>5.61 %</td>
</tr>
<tr>
<td>1173 K/1s</td>
<td>4.98 %</td>
</tr>
<tr>
<td>1313 K/1s</td>
<td>4.44 %</td>
</tr>
</tbody>
</table>

Tab 2 shows the minimum combustion oxygen limit of gas out of supporting wood at different temperature under 1 s based on those experiment data and equation (5). Because the higher the temperature, the lower the oxygen concentration, choose 923 K as the lowest temperature to calculate the minimum combustion oxygen limit is enough. The average minimum combustion oxygen limit is nearly around 4.5 %. Based on some experiment which done by other experts, only the initial methane concentration is between 5.0~9.25 %, the minimum combustion oxygen limit of gas could fulfill the need of Tab 2\textsuperscript{[15]}

(3) The combustion concentration

Two cases: ① the order of gas separated out from supporting wood is based on molecular weight, small molecular weight gas separated out first, then big molecular weight gas such as CO\textsubscript{2}, stratification is obvious; ② all gas mixed equably. Based on the study of thermal environment after explosions, the combustion concentration of supporting wood under 1 s, 2 s, 5 s, 10 s could be got as Tab 3.

If only take the flammable gas into account, the combustion concentration increase first, then decrease, then increase again. As to all gas, the combustion concentration increase along with temperature and then become clam gradually. Contrast to each other, the max and min combustion concentration range of all gas is narrower than that of flammable gas. This could explain the reason of inert gases or incombustible gas could increase the combustion difficult of flammable gas. The min combustion concentration of supporting wood under fire flame is only 5.5 %, it will be very possible to be fired.

Tab.3 The concentration limit for combustion of mixture gas out of supporting wood when heating 1 s, 2 s, 5 s, 10 s
The combustion concentration limit of flammable gas

<table>
<thead>
<tr>
<th>Heat conditions</th>
<th>592 K/2 s, 5 s, 10 s</th>
<th>673 K/2 s, 5 s, 10 s</th>
<th>773 K/2 s, 5 s, 10 s</th>
<th>923 K/1 s</th>
<th>1023 K/1 s</th>
<th>1173 K/1 s</th>
<th>1313 K/1 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>10.5</td>
<td>67.0</td>
<td>9.3</td>
<td>61.1</td>
<td>6.6</td>
<td>46.5</td>
<td>5.8</td>
<td>46.2</td>
</tr>
<tr>
<td>15.1</td>
<td>75.3</td>
<td>12.4</td>
<td>68.3</td>
<td>8.2</td>
<td>57.6</td>
<td>6.1</td>
<td>49.3</td>
</tr>
</tbody>
</table>

The combustion concentration limit of all gas

<table>
<thead>
<tr>
<th>min</th>
<th>max</th>
<th>min</th>
<th>max</th>
<th>min</th>
<th>max</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1</td>
<td>75.3</td>
<td>12.4</td>
<td>68.3</td>
<td>8.2</td>
<td>57.6</td>
<td>6.1</td>
<td>49.3</td>
</tr>
</tbody>
</table>

(4) The fire induced time

The fire induced time refers to the time of separated gas to be fired. There are many effect factors, such as component, pressure, temperature. Etc. As to carbon-hydrogen fuel, its fire induced time is about 1 min when 573 K, about 1 s when 623~673 K. It will be much shorter if temperature is much higher. Because the fired temperature of gas 783 K is much higher than 623 K, the gas separated out from supporting wood must be shorter than 1 s, or even 0.1 s [14].

Based on the four aspects analysis above, there are several conclusions as follows: if the initial methane concentration is between 5.0–9.25 %, there are three conditions could be satisfied: ① there are mixed flammable gas; ② the lowest oxygen concentration of mixed gas could be fulfilled; ③ there is a dynamic thermal environment which has a temperature area higher than 783 K. If all those three conditions satisfied at the same time and the same place, the sub-fire of supporting wood could be induced. So, it’s necessary to do some prevention and preparation to prevent such kind of disasters.

4 Conclusions

Based on analysis of the characteristics of fire flame, and the dynamic thermal environment, by used fast pyrolysis equipment to do pyrolysis experiment under different heat effect and different temperature, connected with combustion theory, the fired mechanism of the gas separated out from supporting wood was studied. The main conclusions are as follows:

(1) Most of the mine methane explosions are weak deflagration, and the heat holding time is between tens of MSEL to hundreds of MSEL.
(2) The dynamic thermal environment was studied, there is high temperature and high temperature holding time area.
(3) Choose supporting wood to do some fast pyrolysis experiment to study the law of gas separated out from itself under methane explosions. The gas out from supporting wood under fire flame is much more than that of under dynamic thermal environment.
(4) The possibility of gas to be fire was discussed from four aspects: ① the fired temperature of gas; ② the lowest oxygen concentration; ③ the combustion concentration; ④ the fire induced time.
(5) If the initial methane concentration is between 5.0–9.25 %, there are three conditions could be satisfied: ① there are mixed flammable gas; ② the lowest oxygen concentration of mixed gas could be fulfilled; ③ there is a dynamic thermal environment which has a temperature area higher than 783 K. If all those three conditions satisfied at the same time and the same place, the sub-fire of supporting wood could be induced.

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References