ABSTRACT: To explore an effective approach for suppressing methane explosions in actual pipe networks, we used a custom-made diagonal pipe network experimental system to assess the suppression of methane explosions using a fine water mist containing KCl and an inert gas. The shock wave pressure, flame wave velocity, and flame wave temperature under different suppression conditions were compared to characterize the effects of explosion suppression under different working conditions, and the mechanism of explosion suppression was analyzed. The results showed that under single-factor explosion suppression conditions the optimal explosion suppression results were achieved when the volume fraction of N\(_2\) was 25\%, the volume fraction of CO\(_2\) was 20\%, and the concentration of KCl was 7\%. The suppression effect of CO\(_2\) on the flame wave temperature was better than fine water mist containing KCl and N\(_2\), and the suppression effect of fine water mist containing KCl on the shock wave overpressure and flame wave velocity was more significant. Under the working conditions of fine water mist containing KCl, which was coupled with an inert gas to suppress the explosion, the suppression effect of the fine water mist containing KCl coupled with 20\% CO\(_2\) on the shock wave overpressure, flame wave velocity, and flame wave temperature was considerably better than fine water mist containing KCl coupled with 25\% N\(_2\).

1. INTRODUCTION

Methane is a colorless and odorless flammable gas, and once an explosion accident occurs, it can cause serious casualties and property damage.\(^1,2\) Therefore, studies on effective explosion suppression methods are of great importance for improving methane transport safety.\(^3\)

Currently, commonly used methane explosion inhibitors mainly include inert gases, fine water mist, and powders. The explosion suppression mechanism of inert gases mainly involves not participating in the explosion branch-chain reaction of the combustible explosion. By diluting combustible gas and oxygen, a flammable gas fire can be extinguished. Many researchers have studied the effects of introducing CO\(_2\) and N\(_2\) into the concentration of combustible gas and oxygen, as well as the effects on the methane explosion limit.\(^4\) These have included a series of experiments in long straight pipes, spherical pipes, and cubic closed containers, which were used to analyze the degree of N\(_2\)/CO\(_2\) suppression on the maximum explosion pressure, pressure rise rate, and flame propagation velocity. The results showed that the explosion intensity decreased with increasing inert gas volume fraction, and the explosion suppression effect of CO\(_2\) was better than that of N\(_2\).\(^5-7\) The explosion suppression mechanism mainly consists of cooling heat absorption, physical inerting, blocking of radiant heat, and chemical explosion suppression, which can be mainly achieved through the elimination of key free radicals by water molecules.\(^10,11\) The main active elements in the methane reaction under high temperatures of methane explosion are H, O, and OH. The water molecules will interact with the active elements, effectively reducing the concentrations of key free radicals, such as H and O in the branch chain of methane combustion. In addition, a large number of water molecules will act as a good third body, and the collision frequency of the three elements will be higher than that of the two elements, allowing for a significant transfer of energy to the water molecules that do not participate in the reaction, thus reducing the activity of the branch chain reaction.\(^12-14\) To enhance the explosion suppression effect, the inhibitors of different phases can be added simultaneously, and the explosion suppression mechanism mainly consists of cooling heat absorption, physical inerting, blocking of radiant heat, and chemical explosion suppression, which can be mainly achieved through the elimination of key free radicals by water molecules.\(^10,11\) The main active elements in the methane reaction under high temperatures of methane explosion are H, O, and OH. The water molecules will interact with the active elements, effectively reducing the concentrations of key free radicals, such as H and O in the branch chain of methane combustion. In addition, a large number of water molecules will act as a good third body, and the collision frequency of the three elements will be higher than that of the two elements, allowing for a significant transfer of energy to the water molecules that do not participate in the reaction, thus reducing the activity of the branch chain reaction.\(^12-14\) To enhance the explosion suppression effect, the inhibitors of different phases can be added simultaneously, and the explosion suppression
properties of various materials can be used to achieve synergistic explosion suppression.\textsuperscript{15−18} Pei et al.\textsuperscript{19} studied the synergistic suppression of methane/air explosions using N\textsubscript{2}, CO\textsubscript{2}, and ultrafine water mist in a semi-closed transparent explosion container. The study found that the maximum flame propagation velocity, the maximum temperature, and the maximum overpressure were significantly reduced with low quantities of the gas−liquid two-phase medium. Jiang et al.\textsuperscript{20} studied the effect of ultrafine water mist containing phosphorus-containing compounds on CH\textsubscript{4}/coal dust explosion flames, using dimethyl methyl phosphonate (DMMP) and phytic acid as additives. The results showed that the ultrafine water mist with phosphorus-containing compounds acted as a thermal barrier and effectively reduced the flame temperature. Liu et al.\textsuperscript{21} used a 20 L spherical explosion system to conduct methane explosion suppression experiments and obtained the explosion overpressure and flame morphology of different methane concentrations under the action of five potassium-containing compound solutions. The results showed that the potassium-containing compounds had a strong ability to suppress the explosion of non-stoichiometric methane.

Existing research has mainly focused on experimental research on the suppression of methane explosion in closed containers, such as long straight pipelines and spherical explosion tanks. The experimental systems in these studies were not closely related to the underground roadways of mines; thus, the conclusions obtained were not universal. In actual mine roadway systems, due to the effect of a crisscrossing roadway network structure, the shock and flame waves generated by methane explosions can interact and influence each other in the roadway network, resulting in superposition and opposed-flow effects, considerably increasing the complexity of the changes in the shock and flame waves. Therefore, the effect of the pipeline structure should be fully considered, and effective explosion suppression methods should be studied in more complex pipeline network systems to further ensure and improve the safety of production work.

In this work, we assumed that the explosion source is the underground coal working face, the experimental pipe network is a part of the whole mining area, the water mist containing KCl is used as the liquid explosion inhibitor, and N\textsubscript{2} and CO\textsubscript{2} are used as the methane explosion inhibitors to carry out the explosion suppression simulation experiment in the case of methane explosion in the mining face. Our aim was to provide a theoretical reference for further improving the theoretical system of disaster prevention, mitigation, and relief.

2. EXPERIMENTAL SETUP

2.1. Experimental System. As shown in Figure 1, the experimental system was mainly composed of a diagonal experimental pipe network, a fine water mist generation system, a dynamic data acquisition system, and an ignition system. The fine water mist−inert gas generation system consisted of two parts: the water supply and the gas supply, which were mainly composed of inert gas cylinders, liquid storage tanks, water pumps, vacuum gauges, flow meters, and control. A TST6300 data acquisition system was used to collect the data in real time, which mainly consisted of CYG1721 high precision pressure sensors, NANMAC-E6 series fast-response thermocouples, and CKG100 photosensitive flame sensors. The response times of the pressure, temperature, and flame sensors were 100 $\mu$s, 10 ms, and 1 ms, respectively, and the accuracy of the data acquisition device was 0.2% full scale (FS). The ignition system mainly included a DX-GDH high-energy igniter, high-energy sparkplugs, and high-voltage-resistant and high-temperature-resistant cables, power supply cables, and external trigger devices. The ignition voltage was about 2200 V, and the one-time energy storage was 30 J. Assuming that the distance between two flame sensors was L, the flame front passed through the two adjacent sensors at different moments $t_1$ and $t_2$, and these values were recorded. Then, the flame front velocity was calculated by the following formula

$$v = \frac{L}{t_2 - t_1}$$

(1)

The particle size distribution of the water mist was obtained by a phase Doppler anemometry test, as shown in Figure 2,
which indicated that the particle sizes of the water mist droplets in this experiment were 0–22 μm and that most of the water mist particles were less than 20 μm in size, indicating that the water mist used in this experiment was fine water mist.  

2.2. Experimental Process. Various components were connected with pipes using internal threads, and silicone gaskets were installed at the connections between each component and the corresponding pipes to improve the airtightness of the device. After the air in the explosion chamber was pumped out and experimental methane gas was introduced with a volume fraction of 9.5%, with atmospheric air in the pipeline. The spray-jet system was started, the water pump valve and the gas cylinder valve were opened, the airflow and water flow were unchanged, and the water pressure remained unchanged. The spray flow was set at 1 mL/s, and then the spray was started and continued for 15 s. Subsequently, ignition was performed, and the switch for the external trigger device was turned on. At the same time, the igniter and the data acquisition system started working synchronously. After the signal light on the device was on, the trigger button on the external trigger device was pressed to trigger the ignition. After the experiment, the exhaust gas in the pipeline was discharged and gas cleaning was carried out in the pipeline. After the process was complete, the system was ready for the next experiment.

3. RESULTS AND DISCUSSION

3.1. Single-Factor Explosion Suppression Test.  
3.1.1. Experimental Conditions. Fine water mist containing four different concentrations of KCl, four different volume fractions of N₂, and four different volume fractions of CO₂ was used for the single-factor explosion suppression experiments, and the experimental conditions are shown in Table 1.

| No. | Experimental Condition | No. | Experimental Condition | No. | Experimental Condition |
|-----|------------------------|-----|------------------------|-----|------------------------|
| 1   | water mist with 5% KCl | 5   | 15% N₂                 | 9   | 10% CO₂               |
| 2   | water mist with 6% KCl | 6   | 20% N₂                 | 10  | 15% CO₂               |
| 3   | water mist with 7% KCl | 7   | 25% N₂                 | 11  | 20% CO₂               |
| 4   | water mist with 8% KCl | 8   | 30% N₂                 | 12  | 25% CO₂               |

3.1.2. Effect on the Shock Wave Pressure. Figure 3 shows the peak explosion overpressure values at each monitoring point in the pipeline network when the fine water mists with different concentrations of KCl N₂ gases with different volume fractions, and CO₂ gases with different volume fractions acted alone.

As shown in Figure 3, as the volume fraction of N₂ increased from 15 to 25%, the volume fraction of CO₂ increased from 10 to 20%, and the concentration of KCl increased from 5 to 7%. When the peak explosion overpressures at each monitoring point substantially decreased and when the N₂ volume fraction increased to 30%, the CO₂ volume fraction increased to 25% and the KCl concentration increased to 8%, and the peak explosion overpressure almost no longer decreased. Therefore, under the three working conditions, when the KCl concentration was 7%, the N₂ volume fraction was 25%, and the CO₂ volume fraction was 20%; thus, the explosion overpressure suppression effect was the best.

The peak overpressures of the three groups of single-factor explosion suppression under the optimal explosion suppression parameters are shown in Figure 4, which indicated that the fine water mist containing 7% KCl alone had the best suppression effect on the explosion overpressure, followed by CO₂ with a volume fraction of 20%, and N₂ with a volume fraction of 25%.

3.1.3. Effect on the Flame Wave Velocity. Figure 5 shows the peak flame propagation velocity of each branch pipe in the pipe network when the fine water mists with different concentrations of KCl N₂ gases with different volume fractions acted alone. As shown in Figure 5, the concentration of KCl increased from 5 to 7%, the volume fraction of N₂ increased from 15 to 25%, the volume fraction of CO₂ increased from 10 to 20%, and the peak flame wave velocity of each branch pipe decreased greatly. When the concentration of KCl increased to 8%, the volume fraction of N₂ increased to 30%, the volume fraction of CO₂ increased to 25%, and the peak flame wave velocity of each branch pipe almost no longer decreased. We found that the best suppression effect on the flame wave velocity was achieved under three conditions when the KCl concentration was 7%, the N₂ volume fraction was 25%, and the CO₂ volume fraction was 20%.

Figure 6 shows the peak flame wave velocities of the three groups of single-factor explosion inhibitors under the optimal explosion suppression parameters, which indicated that the fine water mist containing 7% KCl was the best single inhibitor for suppressing the flame wave velocity. This was followed by CO₂ with a volume fraction of 20%, and N₂ with a volume fraction of 25%.

3.1.4. Effect on the Flame Wave Temperature. Figure 7 shows a comparison of the peak temperature results for each of the branch pipes in the pipe network when the fine water mists with different KCl concentrations, N₂ gases with different volume fractions, and CO₂ gases with different volume fractions acted alone.

As shown in Figure 7, the concentration of KCl increased from 5 to 7%, the volume fraction of N₂ increased from 15 to 25%, the volume fraction of CO₂ increased from 10 to 20%, and the peak temperature of each branch pipe decreased.
considerably. When the concentration of KCl increased to 8%, the volume fraction of N₂ increased to 30%, the volume fraction of CO₂ increased to 25%, and the peak temperature of each branch pipe almost no longer decreased, indicating that under the three working conditions when the concentration of KCl was 7%, the volume fraction of N₂ was 25% and volume fraction of CO₂ was 20%, resulting in the best effect of suppressing the flame wave temperature.

Figure 8 shows the peak flame wave temperatures of the three groups of single-factor explosion inhibitors under the optimal explosion suppression parameters. As shown in Figure 8, CO₂ with a volume fraction of 20% was found to be the best single inhibitor for suppressing the flame wave temperature, followed by water mist with 7% KCl and N₂ with a volume fraction of 25%.

3.2. Explosion Suppression Effect of Coupling Water Mist with an Inert Gas. 3.2.1. Experimental Conditions. According to the above experimental conclusions, N₂ with a volume fraction of 25% and CO₂ with a volume fraction of 20% were coupled with fine water mist containing 7% KCl for explosion suppression experiments. The experimental conditions are listed in Table 2.

3.2.2. Effect on the Overpressure Shock Wave. Figure 9 shows the overpressure−time curves in branch pipe 1 before and after explosion suppression with fine water mist containing 7% KCl inert gas. As shown in Figure 9, under the conditions of no explosion suppression measures, the overpressure shock wave had multiple superpositions and attenuations during the propagation process, and there were multiple overpressure extreme points in the entire process. The peak value of explosion pressure at monitoring point 1 reached a peak value of 0.46 MPa at 0.209 s, and the peak value of the explosion pressure at monitoring point 2 reached a peak value of 0.41 MPa at 0.252 s.

After the explosion suppression experiment was conducted with fine water mist containing 7% KCl coupled with an inert gas, the multiple superpositions and attenuations of the overpressure shock wave almost disappeared compared to the condition without explosion suppression measures, and the overpressure−time curves of the two monitoring points showed single-peak characteristics, where the peak overpressure value declined greatly, and the time needed to reach the peak overpressure value increased considerably. The main reason is that the chemical reaction rate of methane explosion is suppressed in the initial stage of the explosion, some intermediate steps in the chain reaction that characterize its chemical reaction process cannot be carried out normally, coupled with the shock wave in the process of propagation of its own attenuation characteristics, resulting in multiple
superposition of shock waves and attenuation process almost disappeared, the peak overpressure dropped significantly.

Under the working conditions of 7% KCl fine water mist−25% N\textsubscript{2} and 7% KCl fine water mist−20% CO\textsubscript{2}, the peak overpressure values at monitoring point 1 were 0.24 and 0.12 MPa, respectively, and these values were 47.8 and 73.9% lower than the peak explosion pressure values without explosion suppression measures, respectively. Thus, the arrival times of the peak overpressure were delayed by 66.7 and 69.1%, respectively. The peak overpressure values at monitoring point 2 were 0.21 and 0.11 MPa, respectively, and these values were 48.8 and 73.2% lower than those without explosion suppression measures, respectively. Thus, the arrival times of the peak explosion overpressure were delayed by 66.7 and 72.2%, respectively. Under the conditions of fine water mist containing 7% KCl-20% CO\textsubscript{2}, the peak value of the explosion overpressure dropped more significantly, and more time was required to reach the peak value of explosion overpressure.

Figure 10 shows the overpressure−time curves of branch pipe 2 before and after explosion suppression with fine water mist containing 7% KCl inert gas. As shown in Figure 10, under the conditions of no explosion suppression measures, due to the effect of the position of the branch pipe, the number of superpositions and attenuations of the pressure shock wave in branch pipe 2 was significantly higher than the shock wave in branch pipe 1. The maximum overpressure occurrence times at the two monitoring points were delayed compared to branch pipe 1. For monitoring point 3, a maximum overpressure of 0.38 MPa was reached at about 0.57 s, while for monitoring point 4, a maximum overpressure of 0.35 MPa was reached at about 0.61 s.

After the fine water mist containing 7% KCl was coupled with the inert gas to suppress the explosion, the overpressure−time curves showed single-peak characteristics at both monitoring points, and the peak overpressure value decreased considerably while the time to reach the peak value increased dramatically. Under the working conditions of 7% KCl fine water mist−25% N\textsubscript{2} and 7% KCl fine water mist−20% CO\textsubscript{2}, the peak overpressure values at monitoring point 3 were 0.19 and 0.11 MPa, respectively, and these values were 50.6 and 71.4% lower than those without explosion suppression measures. The arrival times of the peak overpressure increased by 35.9 and 42.4%, respectively. The peak overpressure values at monitoring point 4 were 0.18 and 0.08 MPa, respectively. Compared to the working conditions without explosion suppression measures, the peak overpressure values decreased by 48.6 and 77.1%, respectively, and the arrival times of the peak explosion overpressure values increased by 44.5 and 45.5%, respectively.
Figure 11 shows the overpressure−time curves of branch pipe 3 before and after the explosion suppression with fine water mist containing 7% KCl inert gas. As shown in Figure 11, under the conditions of no explosion suppression measures, the number of superpositions and attenuations of the pressure shock wave in branch pipe 3 showed no obvious upward trend compared to the shock wave in branch pipe 2. However, overall, the rise and fall times of the shock wave in branch pipe 3 slightly increased. This was because there were more pipelines connected to branch pipe 3, and the pressure shock wave was more significantly affected by the shock wave in the other pipelines. The peak overpressure at monitoring point 5 reached a peak value of 0.41 MPa at about 0.50 s, while the peak overpressure at monitoring point 6 reached a peak value of 0.39 MPa at about 0.52 s.

After the fine water mist was coupled with the inert gas to suppress the explosion, the overall changing process of the pressure shock wave at the two monitoring points was similar to each of the monitoring points in branch pipes 1 and 2, with single-peak characteristics. The peak overpressure at monitoring point 5 was 0.22 MPa, while the peak overpressure at monitoring point 6 was 0.12 MPa. The peak overpressure values at monitoring points 5 and 6 were almost the same as those for the inert gas alone.

Table 2. Experimental Conditions of Two-Phase Flow Explosion Suppression

| experimental condition |
|------------------------|
| 1 water mist 7% KCl − 25% N₂ |
| 2 water mist 7% KCl − 20% CO₂ |

Figure 7. Peak temperature of each branch pipe under a single factor. (a) CO₂, (b) N₂, and (c) water mist with KCl.

Figure 8. Peak temperature comparison under the action of a single inhibitor.

Table 2. Experimental Conditions of Two-Phase Flow Explosion Suppression

Figure 9. Overpressure change of branch 1 before and after explosion suppression with water mist containing 7% KCl and inert gas.
explosion suppression measures, the peak overpressure decreased by 46.3 and 70.7%, respectively. The arrival times of the peak explosion overpressure were 0.89 and 0.93 s, respectively, and these values were delayed by 43.2 and 46.0% compared to those without explosion suppression measures. The peak explosion overpressures at monitoring point 6 were 0.21 and 0.10 MPa, respectively. Compared to conditions without explosion suppression measures, the peak explosion overpressure values decreased by 46.6 and 74.3%, and the arrival times of the peak explosion overpressure increased by 34.2 and 53.2%, respectively.

After the fine water mist containing 7% KCl was coupled with the inert gas for explosion suppression, the change trend in overpressure was generally similar to that of other branch pipes. The overpressure shock wave was suppressed to different degrees, and the overall overpressure trends at the two monitoring points were similar to a certain extent. Under the working conditions of 7% KCl fine water mist–25% N₂ and 7% KCl fine water mist–20% CO₂, the peak overpressures at monitoring point 7 were 0.18 and 0.09 MPa, respectively, decreasing by 50.6 and 74.4% compared to the conditions without explosion suppression measures, respectively. Thus, the arrival times of the peak explosion overpressure increased by 12.4 and 14.7%.

Regarding monitoring point 8, the peak overpressures were 0.20 and 0.10 MPa. Compared with the working conditions without explosion suppression measures, the peak explosion overpressures decreased by 50.6 and 74.4%, and the arrival times of the peak explosion overpressure values increased by 51.9 and 57.2%.

Figure 12 shows the overpressure–time curves of branch pipe 5 before and after explosion suppression with fine water mist containing 7% KCl inert gas. As shown in Figure 13,
under the conditions of no explosion suppression measures, the change trend in the overpressure in branch pipe 5 was similar to branch pipe 2. Both monitoring points reached their maximum overpressure value due to the action of a positive shock wave. A peak pressure of 0.40 MPa appeared at 0.435 s, while the overpressure value at monitoring point 10 reached a peak value of 0.37 MPa at 0.495 s.

After the fine water mist containing 7% KCl was coupled with the inert gas to suppress the explosion, the overpressure shock wave was suppressed to varying degrees. Because the position of monitoring point 10 was close to the explosion venting outlet, the degree of overpressure suppression was greater than at monitoring point 9. Thus, the occurrence time of the pressure peak was further prolonged. Under the working conditions of 7% KCl fine water mist, the peak value of overpressure at monitoring point 9 were 0.20 and 0.10 MPa, respectively. Compared to the conditions with no explosion suppression measures, the peak explosion overpressures decreased by 50.7 and 76.1%, respectively, and the arrival times of peak explosion overpressure increased by 42.9 and 50.2%, respectively. The peak overpressure values at monitoring point 10 were 0.17 and 0.08 MPa, respectively. Compared to the working conditions without explosion suppression measures, the peak explosion overpressure values decreased by 54.1 and 78.4%, respectively, while the arrival times of the peak explosion overpressure values increased by 48.5 and 55.0%, respectively.

According to the changes in the peak explosion overpressure curves in branch pipes 1 to 5, we concluded that the fine water mist containing 7% KCl inert gas coupling had a good suppression effect on the explosion overpressure. Under the working conditions of the fine water mist containing 7% KCl–20% CO₂, the peak overpressure values at monitoring point 9 were 0.20 and 0.10 MPa, respectively. Compared to the conditions with no explosion suppression measures, the peak explosion overpressure values decreased by 54.1 and 78.4%, respectively, while the arrival times of the peak explosion overpressure values increased by 48.5 and 55.0%, respectively.

According to the above experimental phenomena, the single peak characteristic of the time history curve of pressure shock wave after coupling explosion suppression is mainly due to the suppression of the chemical reaction rate of methane explosion in the initial stage of explosion, the failure of some intermediate steps in the chain reaction characterizing its chemical reaction process, and the attenuation characteristics of shock wave itself in the propagation process, resulting in the multiple superposition and attenuation process of shock wave almost disappearing. The peak value of overpressure decreased significantly.

3.2.3. Effect on the Flame Wave Velocity. Figure 14 shows a comparison of the peak flame wave velocity in each branch pipe under the working conditions of 7% KCl fine water mist with 25% N₂ and 20% CO₂ for explosion suppression. Under the working conditions of fine water mist containing 7% KCl and 25% N₂, the peak flame velocities in branch pipes 1 to 5 were 10.96, 18.35, 20.08, 16.33, and 13.79 m/s, respectively, resulting in decreases of 96.8, 95.2, 94.9, 95.5, and 96.1%, respectively, compared to without explosion suppression measures. Under the conditions of fine water mist containing 7% KCl and 20% CO₂, the peak flame wave velocities in branch pipes 1 to 5 were 7.29, 9.28, 9.95, 8.35, and 7.93 m/s, respectively, resulting in decreases of 97.9, 97.6, 97.5, 97.7, and 97.8%, respectively, compared to without explosion suppression measures. For water mist containing 7% KCl–20% CO₂, the peak values of the flame velocities in each branch pipe showed larger decreases than water mist containing 7% KCl–25% N₂, indicating that the water mist containing 7% KCl–20% CO₂ coupling had a better suppression effect on the flame wave. 31,32

3.2.4. Effect on the Flame Wave Temperature. Figure 15 shows a comparison of the peak flame wave temperature in each branch pipe under the working conditions of 7% KCl fine water mist with 25% N₂ and 20% CO₂ for explosion suppression. Under the conditions of fine water mist containing 7% KCl and 25% N₂, the peak flame temperatures in branch pipes 1 to 5 decreased by 79.8, 79.3, 79.3, 79.7, and 79.5%, respectively, compared to without explosion suppression measures. Under the working conditions of fine water mist containing 7% KCl and 20% CO₂, the peak flame temperatures in branch pipes 1 to 5 decreased by 82.4, 82.3, 82.3, 82.3, and 82.2%, respectively, compared to without explosion suppression measures. The above findings showed that the coupling of fine water mist containing 7% KCl and 20% CO₂ had a better suppression effect on the temperature of the explosion flame wave.

The qualitative conclusions obtained in this study are consistent with the relevant descriptions in refs 31, 39, and 42. It demonstrates that the conclusions obtained in this paper can describe the effective method of suppressing methane explosion in the pipeline network and can also provide...
theoretical reference and support for suppressing the methane explosion event in the actual mine roadway network.

4. EXPLOSION SUPPRESSION MECHANISM

According to the analysis of the explosion suppression mechanism, both inert gases (N\textsubscript{2} and CO\textsubscript{2}) and the fine water mist underwent physical and chemical reactions in the process of suppressing explosions.\textsuperscript{37} The inert gas mainly reduced the oxygen concentration in the reaction process. At the same time, according to the molecular collision theory, the inert gas could effectively reduce the free radical concentration that maintained the reaction during the reaction process, thereby affecting the chain reaction in the methane explosion process and slowing down the reaction rate. As a result, the entropy energy in the reaction was further reduced and finally, explosion suppression was achieved. CO\textsubscript{2} not only had the physical explosion suppression mechanism of the inert gas but also participated in the branch reaction of the methane explosion. According to the branch-chain-transfer process of the methane explosion reaction, the key steps were

\[
\begin{align*}
\text{OH} + \text{CH}_4 & \rightarrow \text{CH}_3 + \text{H}_2O \\
\text{H} + \text{CH}_4 & \rightarrow \text{CH}_3 + \text{H}_2 \\
\text{O} + \text{CH}_4 & \rightarrow \text{OH} + \text{CH}_3
\end{align*}
\]

The reaction chain-transfer processes after adding CO\textsubscript{2} were

\[
\begin{align*}
\text{O} + \text{CO} + \text{M} & \rightarrow \text{CO}_2 + \text{M} \\
\text{O} + \text{HCO} & \rightarrow \text{H} + \text{CO}_2 \\
\text{O} + \text{CH}_2\text{CO} & \rightarrow \text{CH}_2 + \text{CO}_2 \\
\text{O} + \text{CO} & \rightarrow \text{O} + \text{CO}_2 \\
\text{OH} + \text{CO} & \rightarrow \text{H} + \text{CO}_2 \\
\text{H}_2\text{O} + \text{CO} & \rightarrow \text{OH} + \text{CO}_2 \\
\text{CH} + \text{CO}_2 & \rightarrow \text{HCO} + \text{CO}
\end{align*}
\]

Because CO\textsubscript{2} itself was one of the products in the methane explosion reaction, the addition of CO\textsubscript{2} could affect the direction of the reaction and CO\textsubscript{2} was converted into CO through the reaction, which reduced the concentration of important free radicals O, H, and OH that maintained the methane explosion reaction, thereby reducing the methane explosion reaction and burning rates.

The fine water mist had a good endothermic effect, effectively reducing the ambient temperature. Due to the dispersion of droplets, the flame wave could be divided into many small units, which weakened the heat-transfer effect between the flame fronts and weakened the reaction intensity.\textsuperscript{38,39}

The reaction chain-transfer process after the addition of water mist was

\[
\begin{align*}
\text{2H} + \text{H}_2\text{O} & \rightarrow \text{H}_2 + \text{H}_2\text{O} \\
\text{HO}_2 + \text{CH}_4 & \rightarrow \text{OH} + \text{CH}_3\text{O} \\
\text{H} + \text{O}_2 & \rightarrow \text{O} + \text{OH} \\
\text{O} + \text{H}_2\text{O} & \rightarrow \text{OH} + \text{OH}
\end{align*}
\]

After the water molecules participated in the explosion reaction, the concentration of H with the highest degree of activity was reduced, and water acted as the third body, and the gas-phase destruction of the active free ions in the flame increased (H + OH + M = H\textsubscript{2}O + M). Therefore, energy was transferred to the water molecules, and the reactivity of the branch chain was greatly reduced, which was not conducive to the methane explosion reaction.

KCl itself has shown anti-explosion properties. KCl was brought into the explosion pipeline through fine water mist and due to the ionization of water and the high temperature of the explosion system, anions and cations decomposed faster, and the decomposed anions and cations (K\textsuperscript{+} and Cl\textsuperscript{−}) and the free radicals (H\textsuperscript{+}, O2\textsuperscript{−}, and OH\textsuperscript{−}) generated by the chain reaction produced a chemical reaction that generated more stable chemical molecules. This blocked the chain reaction of the methane explosion, and the synergistic suppression of methane explosion was achieved.\textsuperscript{40,41} The chemical reactions involving K\textsuperscript{+} and Cl\textsuperscript{−} were as follows

\[
\begin{align*}
\text{K}^+ + \text{OH}^- & \rightarrow \text{KOH} \\
\text{KOH} + \text{H}^+ & \rightarrow \text{K}^+ + \text{H}_2\text{O} \\
\text{Cl}^- + \text{H}^+ & \rightarrow \text{HCl} \\
\text{HCl} + \text{OH}^- & \rightarrow \text{Cl}^- + \text{H}_2\text{O}
\end{align*}
\]

According to the experimental results and theoretical analysis, the explosion suppression mechanism of the fine water mist containing KCl inert gas could be obtained as shown in Figure 16.
5. CONCLUSIONS

The explosion suppression effect and the explosion suppression mechanism of fine water mist containing the KCl inert gas were studied in a diagonal pipe network, and the following conclusions were obtained.

1. Within a certain range, increasing the volume fraction of inert gas and the concentration of KCl additive significantly improved the explosion suppression effect. When the volume fraction of N₂, CO₂, and KCl additive concentration increased to 25, 20, and 7%, the overpressure peak, the flame wave velocity peak, and temperature peak were suppressed to the greatest extent. Continuing to increase the volume fraction of the inert gas and the concentration of KCl additive had no obvious effect on suppressing the explosion.

2. The suppression effect of CO₂ on the flame wave temperature was better than the fine water mist containing KCl and N₂, while the suppression effect of the KCl fine water mist on the shock wave overpressure and the flame wave velocity were superior to CO₂ and N₂.

3. Under the conditions of fine water mist containing 7% KCl coupled with an inert gas for explosion suppression, the multiple superposition—attenuation processes of the overpressure shock wave almost disappeared, and the time—overpressure curves of all monitoring points showed single-peak characteristics. The time required to reach the peak overpressure increased considerably, and the peak overpressure, the peak flame wave velocity, and the peak flame wave temperature all significantly decreased.

4. The suppression effect of coupling the water mist containing 7% KCl with 20% CO₂ on the explosion overpressure, flame wave velocity, and flame wave temperature was considerably better than the coupling of water mist containing 7% KCl with 25% N₂.

5. The conclusions obtained in this paper can describe the effective method of suppressing methane explosion in the pipeline network and can also provide a theoretical reference and support for suppressing the methane explosion event in the actual mine roadway network.

In future works, the effective detonation inhibitor should be organically treated by chemical means to improve its chemical properties, so as to obtain a better detonation suppression effect.

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Notes
The authors declare no competing financial interest.

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