Experimental and Mechanism Study of Electrically Charged Water Mist for Controlling Kerosene Fire in a Confined Space

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Abstract

Charged water mist has been widely used in industrial dust controlling due to its charged characteristics. But the study for controlling fire is less. Therefore, in this paper, extinguishing experiments of kerosene fire was carried out with water mist which was charged by a corona discharge in a small-scale and confined space. Water mists with different charge-to-mass ratios was obtained by changing the voltage. The effects on extinguishing time, flame temperature and flame image changes were analyzed. The experiments show that the charged water mist can effectively reduce the extinguishing time, flame temperature and inhibit flame compared with the ordinary water mist. Additionally, the extinguishing efficiency significantly increases with the increase of charge-to-mass ratio.

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1. Introduction

Water mist extinguishing technique has been widely accepted and has a broad prospect. In recent years, researchers at home and abroad have made a large number of studies on the methods and theories of water mist fire extinguishing [1-3], and made a great progress. By the experiments, Acton etc. [4] found that explosion overpressure was significantly reduced by the use of water mist in the industrial environment of partially closed with geometry similarity and obstacles. But it also shorts the time of reaching the explosion overpressure peak due to the use of water mist. Catlin etc. [5] carried on the experiment of water mist suppressing explosive flame effect in the rectangular steel pipe, the results showed that the flame accelerated in the open pipeline than in the closed environment. The accelerating flame overpressure broke the water mist droplets, thus explosion overpressure decreased. Thomas etc. [6,7] thought that water mist only by evaporation was not enough to extinguish the gas explosion flame. The explosion suppression of water mist depended on the increase of heat transfer and mass transfer as a result of the break of the initial water mist droplets due to the induce flow before the flame front in combustion zone. In China, Lu etc. [8, 9] showed that water mainly broke the chain carrier as the third body or inert droplets to reduce the gas explosion reaction capacity through the balance calculation of explosion reaction and experimental verification. Gu and Wang etc. [10] had studied the explosion suppression of different-concentration methane by the unusual volume micro-size sprays, and the critical volume of micro-size spray suppressing methane explosion was determined preliminarily.

On the applied electric field, M.K. Kim, Eric K. Anderson, Mruthunjaya Uddi, Wookyung Kim, K. Criner, M.S. Cha etc. [11-18] found that electric field affected stability and extinguishing of jet fire through changing the electric pulse field

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parameters under applied AC or DC field, which showed that the applied electric field had important influence on combustion.

The water mist that carries some charges by charging in advance called charged water mist and we realize the specific purpose according to charge species. R. G. Maghirang, X.D. Xiang, R. Yadav etc. [19-21] conducted smoke suppression in smoke diffusion process using charged water mist. The similar research indicated that charged water mist is applied to dust, such as J. McCoy, E. Almuhanna and L. F. Gaunt etc. [22-24] improved the contact ability of water mist and industrial dust by using the charged water mist which is charged in advance so as to achieve the goal of dedusting.

Therefore, in this article charged water mists charged by corona charging were used to control a kerosene fire. The mechanisms of flame extinction are analyzed in different forms of charged water mists.

2. The mechanism of water mist corona charged

In the real application, the ways of droplets charged are divided into three types, namely the corona charging, induction charging and contact charging. In this article water mists were charged by corona charging. In this case, when charged electrode were applied high voltage direct current (dc), the electrode tip occurred corona discharge, producing a large number of anion-cation near it. Ions which were in contrast to the electrode polarity absorbed by the electrode turned into the neutral, and the ions which had the same polarity with electrodes rejected by the electrode formed ions area around it. Droplets that went through the ions area were charged by ion collisions. Many factors affected the droplets charged, in which the most important were the electric field intensity, particle concentration and relative dielectric constant of medium.

3. The experimental apparatus and methods

3.1. Experimental device

In this paper, the experimental device consists of the water mist system, temperature testing system and charged system shown in Fig.1. The charge-to-mass ratio testing system was shown in Fig.2.

![Fig. 1. The principle diagram of corona charging](image1)
![Fig. 2. The principle diagram of charge-mass ratio test](image2)

The water mist system is composed of electrical power control board, water tanks, water pumps, steadying pressure-pump, valves, pressure gauge, sprinklers etc.. The hollow cone nozzle of 1/2 LNN-4-SS type was used in this experiment. The spray angle is 90 degrees.

Temperature testing system involves four thermocouples, temperature acquisition card and computer. Thermocouples denoted by 1-4 were respectively placed from the bottom of flame to the top every 10cm. Temperature acquisition system collected a set of data every 4 seconds in this paper.

Charged system is composed of high voltage power supply and electrode. As is shown in Fig.1, the electrode was made by welding from a polar ring 60 mm in diameter and 8 polar needles 5mm in diameter. Its inner diameter(r2) was 50mm. The distance between the nozzle and the electrode was 20 mm.

3.2. The testing methods of charge-to-mass ratio

The important index of measuring charging performance of droplets is charge-mass ratio. The greater the charge-mass ratio is, the better the charging performance of droplets is. The charging results, the measuring methods of charge-to-mass
ratio consist of mesh target method, the simulated target and faraday cage method. Mesh target method was selected for this study, as is shown in Fig.2. The distance between target acquisition barrel and nozzle is 200 mm. When the charged water mist reached wire mesh in target acquisition barrel, the electric charge in the wire mesh conducts to the earth after passing the precise microammeter. Therefore the current can be read in the precise microammeter. Electrically neutral water mist flows to the sampling tube along the barrel wall, then the charge-to-mass ratio can be calculated by measuring time and the quality of water mist.

The calculation formula of the charge-mass ratio is

\[
\beta = \frac{Q}{M} = \frac{It}{q_m t} = \frac{I}{q_m}
\]

\(Q\) - charge quantities, C; \(M\) - quality, kg; \(I\) - current, A; \(T\) - time, s; \(q_m\) - mass flow, kg/s.

3.3. The experimental methods

Firstly the testing experiments of charge-to-mass ratio were conducted, as shown in Fig.2. The electric quantity of water mist will change by changing the high voltage power supply output voltage to change electric field intensity of corona field. Then different charge-to-mass ratios were calculated by the different currents value and the corresponding output voltage value was recorded. Contrasting experiments had been carried out by selecting 0mC/kg, 0.5mC/kg, 1.0mC/kg, 1.5mC/kg, 2.0mC/kg five charge-to-mass ratio parameters. The nozzle whose location was constant with the location of water mist was moved to the top of confined space for the next stage fire extinguishing tests.

Dimension of the confined space is 0.8m×0.8m×1.2m and the inner diameter of oil pan is 140mm. The fuel used was kerosene, 30g kerosene each time was ignited by 5g alcohol ignition. The time of pre-combustion was 60s and the time of free burning was 4min. The nozzle pressure of 0.6Mpa and the flow rate of 0.391L/min were used.

4. Experimental results and analysis

4.1. Analysis of fire extinguishing time

In this paper, each experiment was repeated three times under the same conditions and then got an average time of different charge-to-mass ratios water mist for extinguishing kerosene fire. The experimental results are shown in Table 1.

<table>
<thead>
<tr>
<th>Charge-mass ratio of water mist/(mC·kg(^{-1}))</th>
<th>The first time of extinguishing /s</th>
<th>The second time of extinguishing /s</th>
<th>The third time of extinguishing /s</th>
<th>Average time of extinguishing /s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>82</td>
<td>83</td>
<td>87</td>
<td>84</td>
</tr>
<tr>
<td>0.5</td>
<td>79</td>
<td>82</td>
<td>81</td>
<td>80.7</td>
</tr>
<tr>
<td>1.0</td>
<td>77</td>
<td>73</td>
<td>76</td>
<td>75.7</td>
</tr>
<tr>
<td>1.5</td>
<td>72</td>
<td>65</td>
<td>71</td>
<td>69.3</td>
</tr>
<tr>
<td>2.0</td>
<td>56</td>
<td>66</td>
<td>62</td>
<td>61.3</td>
</tr>
</tbody>
</table>

Tab.1 shows that the extinguishing time of charged water mist is shorter than normal water mist. And the greater the charge-to-mass ratio is, the shorter the extinguishing time of charged water mist becomes. This is because the process of fuel combustion produces a large number of free radicals, the producing, disappearing and reproducing, disappearing again of these free radicals which form a chain reaction to maintain the continuation of combustion process until the fuel is burnt out. Free radicals of fuel combustion are electrically charged as a whole, and the amount of positive and negative charges were balanced in the combustion field. Charged water mist is electrically charged, so it can prevent or inhibit the effective combination of free radicals to inhibit flame combustion and accelerate flame extinguishing after approaching the fire. The greater the charge-to-mass ratio of charged water mist is, the stronger the electrostatic interaction will be and the easier to enter the fire and combine effectively with free radicals of the flame, and the stronger inhibition of combustion. So, the fire-extinguishing time is shortened, improving the efficiency of fire fighting.
4.2. Effects of charged water mist on temperature during combustion

The results that effects of charged water mist on temperature during combustion were shown in Figs.3~7. These figures show that charged water mist is more effective to reduce the flame temperature and shorten the time of fire-extinguishing. Due to the gas phase cooling effects of water mist, the vaporization of water mist can absorb part of heat released by the flame. In addition, the water mist can reduce thermal feedback on fuel by decreasing thermal radiation and absorbing part of thermal radiation. Water mist has electrostatic interaction after applied an electric field and charged. It is easier for charged water mist to enter into the fire due to electrostatic force of the positive and negative ions in combustion field and the entrainment of flame. Consequently, there will be more charged water mist entering into the fire. Because charged water mist is better in atomization effect, smaller in water mist particle size, and more uniform in spray effect than normal water mist, it is easier to enter into the fire and evaporate after absorbing heat of flame, further declining the flame temperature. So the cooling effect is further enhanced compared with normal water mist. With the increase of charge-to-mass ratio, charged water mist can enter into the fire and evaporate more easily. The flame temperature is more effectively reduced and the efficiency of fire fighting is improved.

4.3. Effects of charged water mist on combustion flame

Effects of charged water mist on combustion flame are shown in Figs.8~12. Figures show that charged water mist is more effective to inhibit combustion flame and more quickly to extinguish the fire compared to normal water mist. With the increase of charge-to-mass ratio, the stronger the inhibition of charged water mist on the combustion flame, the shorter the time of fire extinguishing. Due to the charged water mist can more easily enter into the fire and evaporate, it is more effective to decrease the flame temperature and reduce the concentration of oxygen in the confined space quickly. As a
result, effect of oxygen suffocation is stronger. In addition, due to the charged water mist could more effectively evaporate and interact with the entrainment of combustion flame. So the stretch and oscillation of flame were strengthened, combustion flame was weakened to extinguishing more quickly. In addition, due to the charged water mist can neutralize a part of free radicals and weaken the chain reaction to make flame shrunk more quickly, so the flame extinguishing was quickened. The larger charge-to-mass ratio is, the stronger weakening effect is, and therefore the shorter the time of extinguishing is, the more quickly flame will diminish, the higher the efficiency of fire fighting is.

Fig. 8. 0 mC/kg changes of flame

Fig. 9. 0.5 mC/kg changes of flame

Fig. 10. 1.0 mC/kg changes of flame

Fig. 11. 1.5 mC/kg changes of flame
The nature of combustion is a redox reaction. Cations and anions from the electron exchange promote the chain reaction of combustion in redox reaction. Since the most compositions of kerosene are hydrocarbons, the free radicals from combustion of kerosene produces are H\(^+\), O\(^-\), OH\(^-\), and the chain reactions are as follows:

\[
\begin{align*}
RH + O_2 & \rightarrow H^+ + 2O^- + R^- \quad \text{(decomposition of combustible, endothermic reaction)} \\
O^- + H^+ & \rightarrow OH^- \\
2OH^- & \rightarrow H_2O + O^- \quad \text{(exothermic reaction)}
\end{align*}
\]

The last step is a strong exothermic reaction. The heat output is greater than the absorbed heat of fuel decomposition in the first step. The O\(^-\) and OH\(^-\) decomposed from the combustible make sustained burning. A large number of free radicals, anions-cations and free electrons are produced due to incomplete combustion and the ionization process in the flame. Because of the charge of water mist, the coulomb force between the anions-cations causes the redistribution of ions in a flame and the chain reaction is weakened due to the mutual attraction of droplets and anions-cations to be neutral in flame and replacing a part of the chain reaction after the charged water mist added. Water mist inhibiting the flame burning spraying has momentum, and ions of droplets repel ions with the same charged polarity in the flame, the flame even more deviated from the direction of the charged water mist. Due to the entrainment effect of the combustion flame, a part of droplets that take the same charged polarity with the flame can enter the fire. The flame moves to the outside by the repulsive force, thereby the stretch and oscillation of flame was strengthened, combustion flame diminishes rapidly and the process of the flame extinguishing was accelerated.

Electron plays a strengthening effect on combustion, charged water mist with a strong positive charge had more cations, the reaction rate of flame chemical ion was effectively reduced by the interattraction of cations and electrons combined into a neutral to consume large amounts of electrons in this process. With the increase of charge-to-mass ratio, the particle size of droplets is smaller and entrainment effect is enhanced, thus charged water mist is more likely to enter the fire and to absorb the flame heat to evaporate, further to reduce the flame temperature. The evaporation of droplets can absorb a lot of heat and thus effectively reduce the flame temperature making the production rate decline. With the increase of charge-to-mass ratio results in cations increasing in the droplets, electrons are more likely to be neutralized, so that the flame will diminish more quickly and is extinguished more easily because there are not enough electrons to keep flame burning.

5. Conclusions

(1) Compared to common water mist, the charged water mist can more quickly extinguish kerosene fire in confined space. With the increase of charge-to-mass ratio, the fire extinguishing speed becomes faster.

(2) Due to electrostatic interaction, charged water mist can enter the fire evaporating more easily and flame temperature is lower. With the increase of charge-to-mass ratio, the cooling effect turns more obvious.

(3) Water mist being charged is more likely to enter the fire and neutralize a part of the free radicals to weaken the chain reaction. It makes the flame smaller quickly, and quickens the flame extinguishing. With the increase of charge-to-mass ratio, the combustion flame diminishes faster and the time of extinguishing is shorter.

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