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Preliminary study on interaction of water mist with diffusion flame of liquid fuels*

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Abstract The chemical and physical interaction mechanisms of the water mist with diffusion flame of liquid fuels are investigated. The difference of the thermograms and the thermal field isograms between ethanol flame and kerosene flame with the water mist application is explained. With the water mist application, the differences between ethanol and kerosene in heat release rate, O_2 and CO concentrations of their combustion products, and the temperature of their smoke are analyzed. At the same time, the interaction mechanism of the water mist with diffusion flame is presented and their relationship to the fuel species and to the concentration of water mist is described.

Keywords: **water mist, diffusion flame, interaction mechanism.**

Since the first version of the Montreal Protocol was introduced in 1987, water mist for fire extinguishment and control have been widely recognized as a halon 1301 replacement[1]. Water mist refers to fine water droplets in which 99% of the volume of the spray is in drops with diameters less than 1000 microns[2]. Extinguishment mechanisms of water mist include thermal cooling, oxygen displacement, fuel surface cooling and attenuation of radiative heat transfer. Factors that contribute to the success or failure of a water mist system include droplet size, velocity, spray pattern, momentum, geometry and other characteristics of the protected area and the type of fuel[3]. So it is very important to study the interaction of water mist with flames. Most of flames are diffusive and occur in confined space with proper ventilation control, and the fuel always varies. The study of the interaction of water mist with a diffusive flame in the confined space will enhance the knowledge of such processes and be useful for developing the water mist fire suppression system, improving the fire suppression and control efficiency and extending their applications.

The interaction of water mist with a diffusive flame in confined space has been investigated in different aspects[4~8], but the enhancement effect of water mist on combustion in some cases is still not understood. Some recent experiments show that the flame by a certain kind of fuel will be enhanced to a larger scale and its temperature will rise when water mist is applied and it seems that this cannot be caused only by physical effect. Some results suggest that the chemical reactions are changed and enhanced within the flames by water vapor[9]. The present work is to study the effect of water mist on suppressing or enhancing the diffusive flames in confined space.

1 Experimental apparatus

The experimental apparatus is shown in Fig. 1. The fuel sample is contained in a circular stainless steel pan with height of 10 mm and inner diameter of 150 mm. The pool was mounted on a steel stand 600 mm above the ground to minimize the effect of surrounding ground surfaces on the behavior of the fire. A downward-directed pressure nozzle was positioned on a square steel plate 300 mm over the fuel sample. The nozzle was operated at pressure of 0.5 MPa, which could be altered by adjusting the pressure regulators to meet different requirements. The water mist was injected into the pool fire downward directly, and the relative flow rate was about 1.0 mL/s. The cone angle of the nozzle was 60°, and the volume mean diameter of the mists was about 80 μm. During the experiment period, the TVS-2000ST infrared thermogram system and a thermal video system were used to record the thermogram and visualize the thermal field of the flame before and after the injection of water mist respectively.

Some K-type thermal couples of 0.5 mm diame-

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ter were arrayed along the centerline and radius to calibrate the TVS apparatus. The radiant heat flux of the flame with and without the application of water mist was also measured by a thermogauge. All of the systems began to receive the data after the automatic ignition started, and the fire was allowed to burn for 100 s to make quasi-steady burning before the spray injection. All the raw data were saved and processed automatically by a computer.

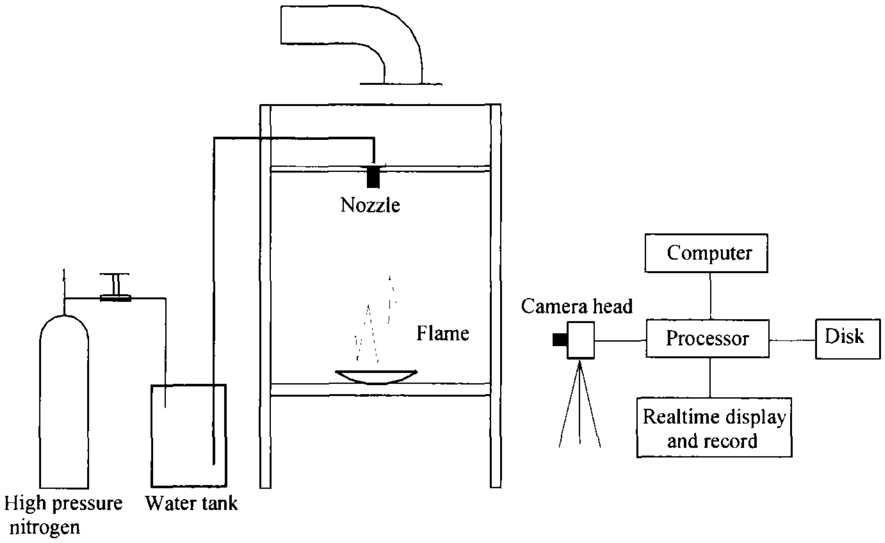

Fig. 1. Schematic of the experimental apparatus.

2 Results and discussion

Fig. 2 shows the thermograms ((a), (b) and (c)) and thermal field isograms ((d), (e) and (f)) of the ethanol flame with and without the application of water mist. It is obvious that the flame was suppressed to a smaller scale and the temperature lowered rapidly due to the application of water mist, and after about 60 s, the temperature lowered to below the boiling point, and then the fire was extinguished quickly. This phenomenon might be caused by physical suppression effect of water mist, and can be explained by the experiments of Yao1). One of his experiments was conducted in the cone colorimeter with a little modification. The heat release rate of ethanol, O_2 and CO concentrations of ethanol combustion products, and the temperature of smoke were measured with the water mist application generated by 5 different water pressure (0.1, 0.2, 0.4, 0.7, 1.0 MPa). The experimental results demonstrated that O_2 and CO concentrations of ethanol combustion products were increased with increase of water mist while the heat release reduced and smoke temperature of ethanol lowered.

Fig. 3 shows the thermograms ((a), (b) and (c)) and thermal field isograms ((d), (e), (f)) of the kerosene flame with water mist application. It demonstrates that the kerosene flame is enhanced to a larger scale and temperature rises at the beginning of the injection of water mist, the high temperature area doubled after 35 s, even after 60 s, the flame structure remained and the combust intensity kept high. These experiments suggest that water mist indeed changes the chemical reactions within the flames. It can also be explained by the experimental results of Yao1), who observed the heat release rate of kerosene, O_2 and CO concentrations of kerosene combustion products, and the temperature of smoke with the water mist application generated by 4 different water pressure (0.1, 0.2, 0.4 and 0.7 MPa). Our experimental results demonstrated that when the water pressure was under 0.2 MPa, the heat release rate and the CO concentration of kerosene combustion products increased with the increase of the water pressure, and the smoke temperature of kerosene rose, while the O_2 concentration decreased with the increase of the water pressure. When the water pressure was higher than 0.2 MPa, the heat release rate and the CO concentration of kerosene combustion products decreased with the increase of the water pressure (but still higher than that under the condi-

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1) Yao, B. A simulative study on the interaction of water mist with a diffusion flame. Ph. D thesis, the University of Science and Technology of China, 1999

tion without the water mist application). The smoke temperature of the kerosene rose as well while the O_2 concentration increased with the increase of the water pressure (but still lower than that under the condition without the water mist applications). These indicate that the chemical enhancement of the water mist is related to the concentration of the water mist and support Jail Suh's conclusion that there is a turning point of the enhancement of water vapor to physical suppression effect on the flame (in this case, it is near 0.2 MPa water pressure).

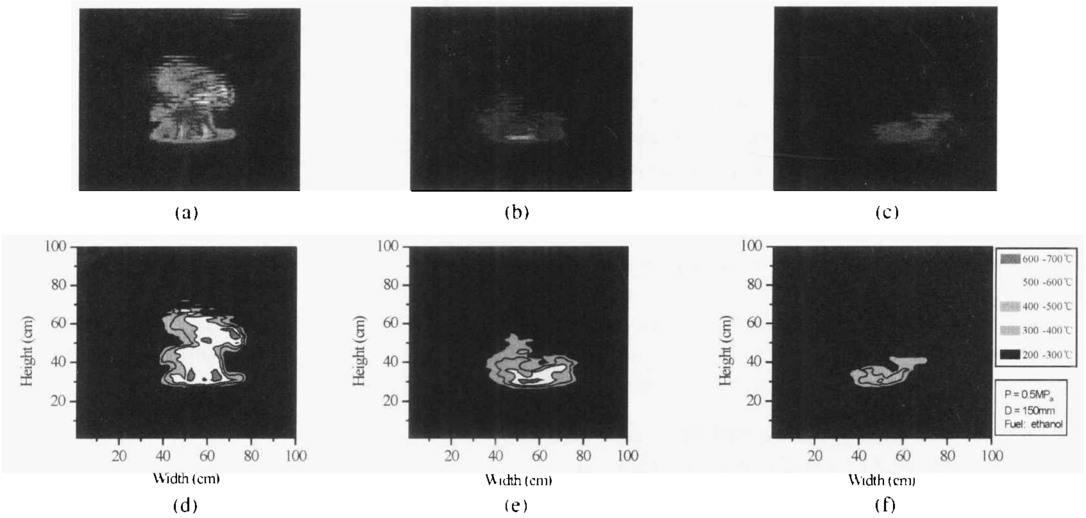

Fig. 2. Thermograms and thermal field isograms of ethanol flame. (a) and (d), without the application of water mist; (b) and (e), with the water mist for 40 s; (c) and (f), with the water mist for 56 s.

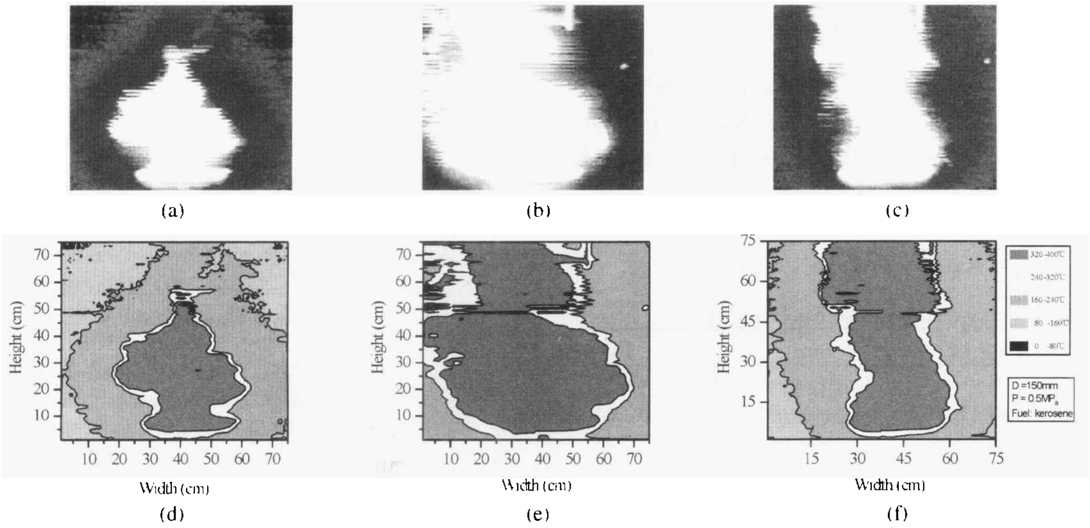

Fig. 3. Thermograms and thermal field isograms of kerosene flame. (a) and (d), without the application of water mist; (b) and (e), with the water mist for 35 s; (c) and (f), with the water mist for 60 s.

Yao's work gives another example, e.g. when the water mist was applied, the radiant heat flux of ethanol flame decreased while that of kerosene flame increased.

Then, why can the water mist enhance the chemical reactions inside the kerosene flames?

The main differences between the combustion of ethanol and kerosene are the flame temperature, CO concentration and carbon particles in the smoke. As to the flame temperature, it is lower for kerosene than ethanol, it makes no contribution to the enhancement of the combustion, so CO might be the main reason. Kerosene combustion generates more CO than ethanol. Dry CO is hard to be oxidized (only when the temperature is higher than 1000 K, at which the gas phase flame can be seen), but when water mist was applied the oxidation of CO becomes easier because more OH radical will be generated by the following reaction:

$$O + H_2O \rightarrow 2OH.$$

Then the following reactions will occur:

$$OH + CO \rightarrow CO_2 + H,$$
$$H + O_2 \rightarrow OH + O,$$
$$CO + O \rightarrow CO_2.$$

When the combustion intensity increases rapidly, the flame and smoke temperature will increase rapidly, then the following reaction may occur:

$$H_2O + C \rightarrow CO + H_2.$$

The H_2 can bring more H and OH through the following reactions:

$$H_2 + O_2 \rightarrow 2OH,$$
$$H_2 + M \rightarrow 2H + M.$$

H and OH are extremely active radicals, one H radical can generate three H radicals and one OH can bring two OH in the following chain branching reactions:

$$OH + H_2 \rightarrow H_2O + H,$$
$$H + O_2 \rightarrow OH + O,$$
$$O + H_2 \rightarrow OH + H.$$

The global combustion reaction rate can be expressed in terms of the rates of the elementary reactions given above, some of them are shown in Table 1[10]. The rate constants are expressed in the Arrhenius form:

$$K_k = A_k T^{N_k} \exp(-E_k/RT).$$

Table 1. The elementary reaction rate coefficients

No.	Reaction	A_k	N_k	E_k
1	$H + O_2 \rightarrow OH + O$	1.20×10^{17}	-0.91	69.10
2	$O + H_2 \rightarrow OH + H$	1.50×10^{7}	2.00	31.60
3	$OH + H_2 \rightarrow H_2O + H$	1.00×10^{8}	1.60	13.80
4	$O + H_2O \rightarrow 2OH$	1.49×10^{10}	1.14	71.14
5[a)]	$H + O_2 + M \rightarrow HO_2 + M$	2.00×10^{18}	-0.80	0.00
6	$OH + CO \rightarrow CO_2 + H$	4.40×10^{6}	1.50	-3.10

a) Catalytic efficiencies are taken from Ref. [5]

It is obvious that, in the process of kerosene combustion, the water mist (and H_2 which may be generated during the reaction) has catalyzed the chemical reaction. But when the water mist addition exceeds a certain amount, the physical suppression effect will produce, the combustion enhancement will decrease, so there should be a turning point at which the concentration of water mist and the chemical enhancement reach the top.

3 Conclusions and future work

A series of experiments were performed to investigate the interaction mechanism of flame with water mist using ethanol and kerosene. It was found that the interaction mechanism is related to the fuel species for different fuels have different flame temperature, product components (especially the CO concentration) and smoke components. In the case of ethanol, physical suppression effect is dominant, but in the case of kerosene, chemical reaction is dominant. The reason that the water mist can enhance the chemical reaction is because it can help generate extremely active radical H and OH. Combustion enhancement is also related with the amount of the water mist, there may be a turning point at which the effect of water on the flame changes from dominant chemical to dominant physical.

Further work will consider: (1) Performing the same experiments using the water mist at different concentrations to investigate the relationship between the concentration and the effect; (2) using a special apparatus to detect the H and OH radical concentrations in the flame; (3) doing the same experiments using different fuels, and with some additives which can help suppress flame (for example NaCl).

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