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Effects of water mist addition on kerosene pool fire

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The use of water mist to extinguish fire is a problem of particular interest since the banning of halogen-based agents for environmental reasons. This interest is reflected in the large number of researches performed on the main fire-extinguishing mechanisms of water mist: heat extraction, oxygen displacement and attenuation of heat fluxes. In contrast, there are still little known about the chemical and some other aspects of water mist addition on the pool fire. In this paper, a phenomenological study was conducted of the effect of water mist addition on the kerosene pool fire through the measurement of the heat release rate, CO, CO_2 and O_2 species concentration in combustion. The experimental results show that there is a significant enhancement effect at the beginning stage of water mist addition. Then, the flame size was decreased abruptly. By physical suppression effect combined with chemical effect, the experiments' results are explained especially. The study of effects of water mist on pool fire will be useful for optimizing designation of water mist fire-suppression system, improving the fire suppression efficiency and extending their application field.

water mist, Interaction, halon replacement, kerosene fire, fire suppression mechanism

The use of water mist for fire extinguishment and control was firstly studied in the 1950s. Currently, there is a renewed interest in this old technology because the halogen-based agent was limited[1−3]. The fire-extinguishing efficiency of water mist is determined by the drop size distribution, spray location, spray momentum, enclosure geometry and the obstruction within the space[4]. In order to obtain an optimum design, it is necessary to understand both the interactions between the water mist and the flame and the contributions of the various mechanisms of fire suppression by water mist[5,6].

In the aspect of the interaction of water mist and the flame, recent studies were conducted to quantify the gas phase effects of water. In fact, despite some overlaps, these studies are quite different and a comparative analysis is not always possible. Some research works showed that water is not only inert but acts chemically[7,8]. Others found the effect to be thermal[9,10]. Of particular interest are the data of ref. [11]. The authors conducted small scale diffusion flame experiments convenient for both experimental measurements and theoretical modeling. Their experimental device permitted the control of composition, temperature and velocity of the fuel and oxidizer streams. The results mainly showed that the increase of water vapor concentration in the flame zone leads to the oxidation of CO to CO_2. As a result, the combustion became more complete and the flame temperature was increased. The actual magnitude of the chemical enhancement depended on the water concentration, the O_2 concentration and the flame temperature. These data suggested that water vapor should have an important effect on flame chemistry.

Besides that, a large number of studies have been performed on the fire extinguishing mechanisms[12,13]. The research results show that water mist has two physical effects: (i) Cooling of the burning solid by water mist evaporation and (ii) smothering caused by diluting

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the oxidizer and the fuel by water vapor. In addition to these two well-known effects, there are three more effects, namely (iii) enhanced radiative heat loss due to increased vapor concentration, (iv) enhanced mixing as a result of volumetric expansion caused by evaporation, and (v) a little known but significant chemical effect which reduces the soot concentration and decreases the luminous flame radiation. Unfortunately, little is known about the effects (iv) and (v). The study of the effects of water mist on pool fire will enhance the knowledge of such process and be useful for developing the water mist fire suppression system designation, improving the fire suppression efficiency and control efficiency, and extending their application field.

In this paper, a phenomenological study is conducted on the effect of water mist addition on the kerosene pool fire through the measurement of the heat release rate, CO, CO_2 and O_2 species concentration in combustion. By water vapor effect in combined with chemical effect, the experiments' results are especially explained.

1 Experimental

1.1 Generation of water mist

Water mist was generated by a single pressure atomizer as shown in Figure 1. A commercial full cone nozzle with an effective angle of about 90° was used to generate the water mist. Water should be filtered before delivering into the nozzle. The particle size, velocity distribution and mist volume flux of the discharged water mist flow were measured experimentally by Laser Doppler Velocimetry or Adaptive-Phase Doppler Velocimetry system (LDV/APV system). The measurement techniques and the system configuration have been described in detail in refs. [14,15]. This system is based on the light scattering theory of non-conductive spherical particles and the characteristics of water mist. Major components include laser, light beam optics, a transmitting system, a collecting system, photo-detectors, splitting signal processing electronics, an external data input device and a computer with software.

Using LDV/APV system, the radial distribution of the water mist characteristics is shown in Figure 2. The relationship between the droplet size and the radical distance is given in Figure 2(a), and the download mean velocity of the water mist under the pressures of 0.3 and 0.7 MPa is shown in Figure 2(b). From Figure 2, the volume mean diameter was from 90 to 110 μm near the spray centerline and from 120 to 150 μm near the envelope edge. The mean downward velocity was from 1.7 to 2.0 ms^{-1} near the centerline and from 1.0 to 1.4 ms^{-1}

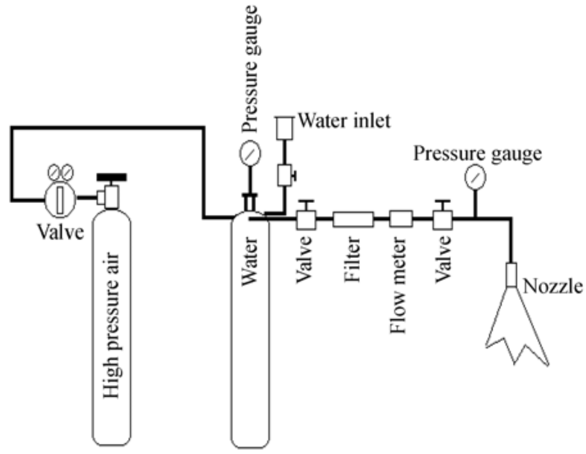

Figure 1 Water mist generation apparatus.

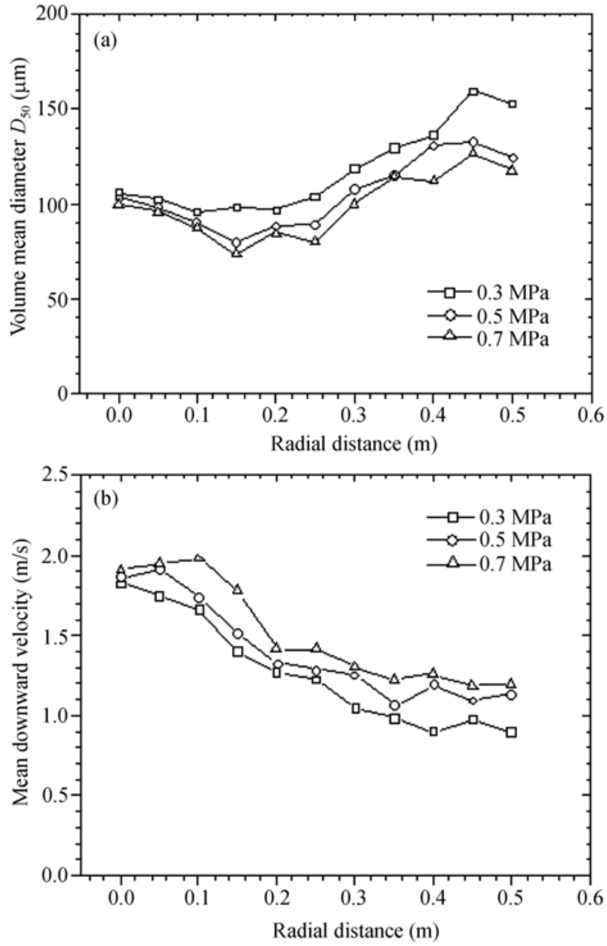

Figure 2 Distribution of volume mean droplet size and mean downward velocity along the spray radial direction. (a) Volume mean diameter of water mist as a function of radial distance from nozzle centerline for different hydraulic pressures; (b) mean downward velocity of water mist and radial distance from nozzle centerline.

near the envelope edge, which accords well with the definition of water mist. The water flux was measured by collecting water with containers placed on the floor 2.5 m away from the nozzle exit, as shown in Figure 3. The water flux increased with the operating pressure, ranging from 2.5 to 3.7 L/(min·m^2) near the center and 0.6 to 1.2 L/(min·m^2) near the envelope edge.

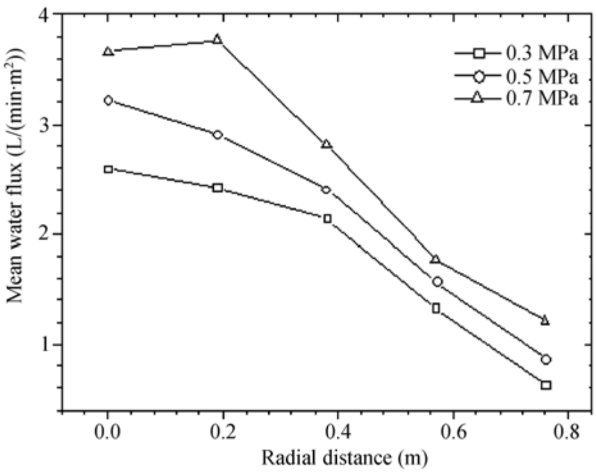

Figure 3 Mean water mist volume flux and radial distance from nozzle centreline.

1.2 Methods

A standard cone calorimeter following ASTM E 1354 with a small water mist system was used, a schematic diagram of which is shown in Figure 4. The cone calorimeter was developed to measure the heat release rate from a burning surface and analyze the combustion products when a constant flow of air is provided into the confined space[16]. The combustion characteristics such as heat release rate, combustion efficiency, burning delay time and gas concentration can be determined. This apparatus was modified in this paper to study the interaction of water mist with kerosene fire in a confined space. Combustion characteristics can be measured without and with water mist. The experiments were performed in a 0.6 m × 0.6 m and 0.7 m high glass walled enclosure which built in a cone calorimeter. The fuel sample was placed on an electronic balance under different radiant heat fluxes. In this paper, radiant heat fluxes of 50 kW/m^2 and 70 kW/m^2 were used for kerosene flame. The combustion products were all collected by the hood and transferred for measurement and analysis. The rate of fresh air flow into the confined space was adjusted by varying the speed of the fan installed. In this study, 24 L/s flow rate of air was chosen.

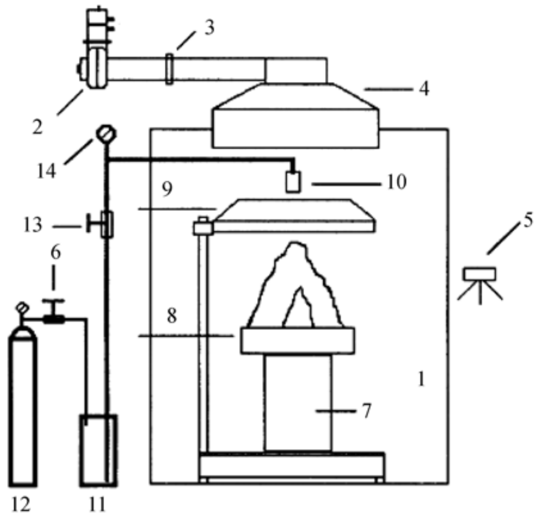

Figure 4 Experimental setup. 1, Test chamber; 2, exhaust fan; 3, exhaust duct; 4, hood; 5, CCD video camera; 6, air valve; 7, load cell; 8, sample holder; 9, radiant heater; 10, water mist nozzle; 11, water tank; 12, compressed air cylinder; 13, water valve; 14, pressure gauge.

A water-proof shield was necessary to protect the load cell from water spray. This shield was made out of 1 mm mild steel galvanized sheet. Also a tray was placed underneath the radiant heater to accumulate the excess and run-off water. Sample of kerosene, whose weight was about 100 g, was poured into a 100 mm×100 mm and 10 mm high stainless-steel tray. The distance between the nozzle tip and the sample was kept at 80 mm to obtain full coverage of the sample surface. At each flow rate, the total amount of water mist applied was controlled by the application time. The actual water mist rate applied in the experiment was obtained before the start of the test. The rate obtained is assumed to be the same as that of the actual test.

Before carrying out the test, the radiant heater was set to the desired value. The sample was exposed to external radiation by placing the sample holder under the radiant heater, and at the same time, the electric spark of the cone calorimeter was operated. Once steady burning with a relatively stable flame appeared on the surface of the specimen, the electric spark was turned off. And then kerosene oil was allowed to burn until their heat release rates were stable. Water mist was then discharged for some time, and was stopped when the flame was extinguished.

2 Results

2.1 Flame change with water mist addition

Information about the evolution of the flame was obtained by the parameter of heat release rate in these tests because the quicker heat release rate, the more turbulent fire. As shown in Figure 5, before the water mist was activated, the kerosene oil combusted stably and the heat release rate almost has no change until the total fuel is consumed completely. But after the water mist was activated, the heat release rate was increased abruptly. After a few seconds, the heat release rate was greatly reduced. Figure 5 also shows that the higher operating pressure, the less the heat release rate.

2.2 Yield of CO and CO_2

A typical example of the evolution of CO_2 concentrations is shown in Figure 6. It is worth noting that the general characteristic of these evolutions is in a qualitative agreement with the turbulent of flame. Before the water mist sprays out, the yields of CO_2 are almost steady. After the water mist activated, the yield of CO_2 shows an abrupt increase followed by a subsequent progressive decrease until fire extinction.

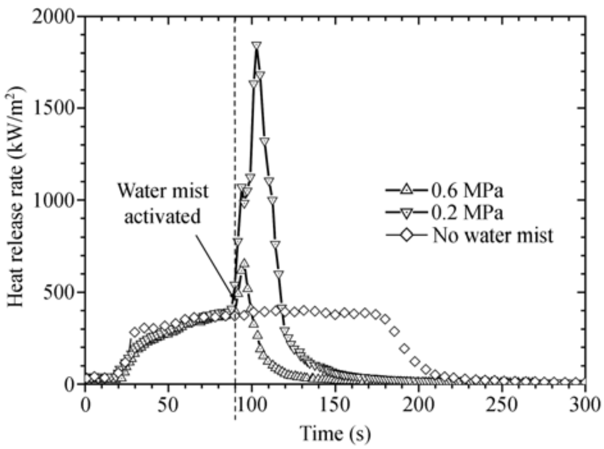

Figure 5 Heat release rate of kerosene fire with and without water mist application.

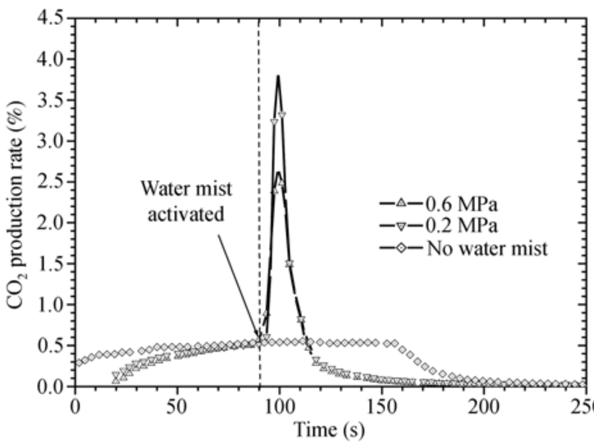

Figure 6 CO_2 production rate with and without water mist application.

As shown in Figure 7, when the water mist is added, the CO production rate is increased quickly. Then, the production rate decreased abruptly. Besides that, the higher operating pressure, the less CO production rate, and if there is no water mist added, the CO production rate was almost sustained. Comparing with the change of CO_2 produced rate with the water mist addition, the production rate of CO had less change, but with discharge pressure increased, the produced rate of CO decreased more violently than that of CO_2.

2.3 Consume of O_2

As shown in Figure 8, the evolution of O_2 concentration is contrary to the evolution of CO and CO_2. Before the water mist sprays out, the concentration of O_2 is also steady. After the water mist activated, the concentration of O_2 shows an abrupt decrease followed by a turbulent increase. After the fire was extinguished, the concentration became stable again. It is because that with the fire flare up, the consume rate of O_2 is greatly increased, and

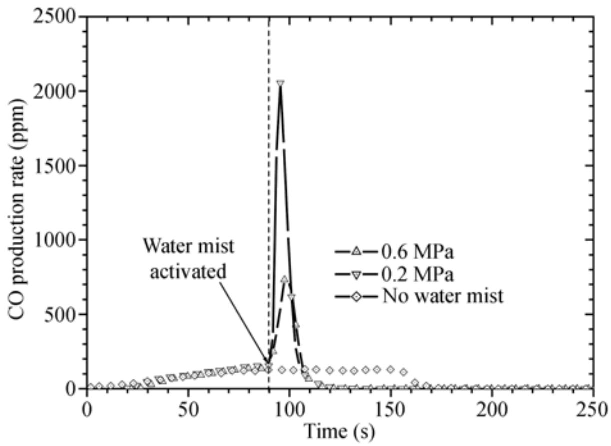

Figure 7 CO production rate with and without water mist application.

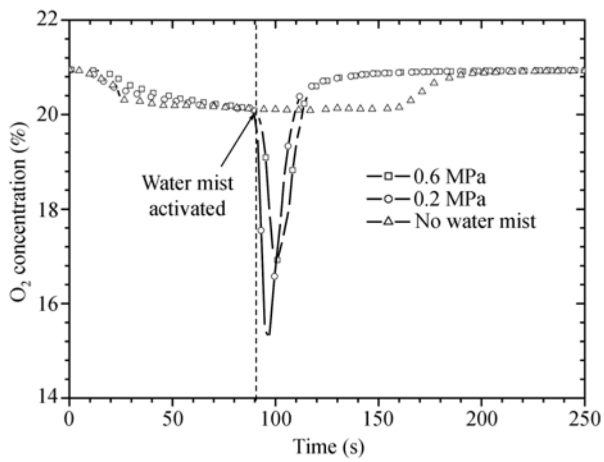

Figure 8 O_2 production rate with and without water mist application.

the fresh air cannot be poured into the protection area immediately. A few seconds later, the fire was controlled and the air change rate can keep balance between the burning area and the atmosphere, so the O_2 concentration becomes stable again.

2.4 Mass change of kerosene oil

As shown in Figure 9, if there is no water mist addition, the mass of the fuel in the pan is gradually decreased because the oil is consumed in combustion. If water mist is applied to the kerosene pool fire, the mass of the kerosene oil is increased. It is because that some of the water mist which has enough discharge momentum break through the flame and dissolve into the kerosene oil.

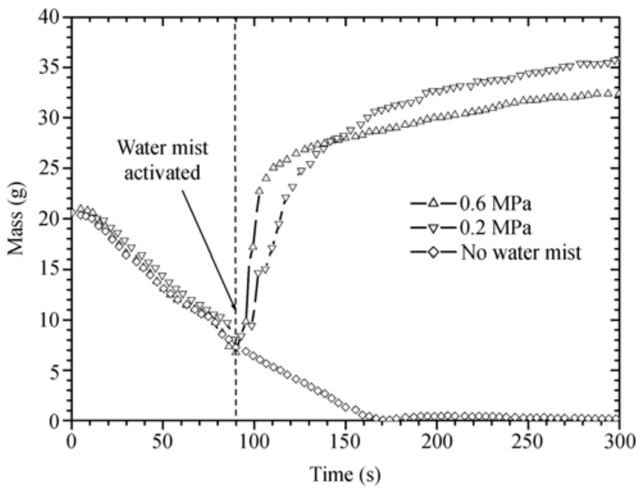

Figure 9 Mass change of kerosene oil with and without water mist application.

3 Discussion

There are a variety of ways in which water mist acts in inhibiting hydrocarbon flames. Most of these effects are intimately related. For example, the heat loss of flame means temperature decrease. Temperature decrease causes the combustion reaction to become slower. The slower combustion rate means less product formation and heat generated, which results in flame temperature decrease and so on. For the water mist, the fire suppression mechanisms of water mist include at least three aspects[17,18]: (i) Gas phase and fuel surface cooling; (ii) Local and global oxygen depletion; (iii) Radiant heat blocking to surroundings and fuel surface.

By these mechanisms' coupling effect, the fire was quickly controlled and then extinguished with the water mist spraying. However, experimental results indicated that when water mist was injected, the pool fire made a violent outburst, followed by a quickly knocking-down and extinguished in a few seconds. It is because that the conflicting influences of cooling, inerting, dilution, enhanced turbulence and fuel mixing, led to a degree of unpredictability in the effects of water mist on gas phase burning[19]. The particular process is discussed as below.

Figure 5 shows that the heat release rate is very quick at the beginning stage of water mist application, so the water mist vaporizes instantaneously when it meets the high temperature flame and large volume of vapor generate immediately. This sudden increase in vaporization intensity accompanied by the air entrainment took place and two phases (the air and the kerosene) were intensively agitated. Therefore the fuel-oxygen interface is significantly increased[20]. Corresponding to this effect, the combustion rate is increased greatly. The experimental result in Figure 8 shows that fresh air around the flame is poured into the burning area uninterruptedly in the process of water mist application. It is coincidental with the above air entrainment hypothesis.

As shown in Figure 9, the mass of the kerosene oil is increased with water mist addition. It means that some of the water mist which has enough momentum breaks through the kerosene layer and dissolves in the oil. Because the temperature of the oil is high, the water mist is vaporized under the kerosene oil. The expansion effect leads to an intense liquid motion. The fuel is then intensively agitated by the growing and rising of the vapor and fuel surface is dynamically unstable[21]. These stirring effect and disruptive burning continue until the fire is controlled by the water mist. These results greatly accelerate the combustion rate of kerosene fire.

Comparing with Figures 6 and 7, it is shown that the increase of CO produced rate was slower than the increase of CO_2 produced rate when the water mist is added. The reason is that with regard to the combustion products, the reaction $\cdot OH+CO \rightarrow H\cdot +CO_2$ is a significant reaction to which CO is oxidized. When water mist is added into the kerosene flame, the reaction $H_2O+H \rightarrow H_2+OH$ becomes an important source of $\cdot OH$ formed and the concentration increases[22,23]. Therefore the combustion becomes more complete and the increase of CO produced rate is less than that of CO_2 produced rate. At the same time, the combustion rate of kerosene fire was also accelerated while the combustion becomes more complete.

Besides that, the actual magnitude of the enhancement effect of water mist, however, depends on the operation pressure, the O_2 concentration and the flame temperature. In experimental results, it is shown that the higher operating pressure, the less turbulent flare up and the CO, CO_2 production rate also changes greatly with the water mist addition. It can be explained by the following theory.

Clearly, there are two competing mechanisms[22]: (i) physical and chemical increase effects, and (ii) the fire suppression effects. The fire extinguishing ability of water mist is affected by the drop size distribution and spray momentum greatly. With the increase of operation pressure, the drop size decreases and the spray momentum increases. Therefore the fire suppression ability is stronger. With the increase of operation pressure, the enhancement degree of flame is weakened.

On the other hand, the experimental result also shows that the water mist discharge pressure has a more violent influence on the CO produced rate than the CO_2 production rate. The answer to this is clear from the O_2 concentration and the water mist discharge rate. Firstly, with the increase of the burning rate, oxygen concentration decreases greatly, so the burning process changes into incomplete combustion partly and more amount of CO produced comparing with enough oxygen exists in the burning area. Secondly, the total unburned hydrocarbon always increases with the increase in the fire extinguishing time. This implies that lower fuel oxidation is consistent with experiment results.

However, at this stage of investigation, some of the interpretation can only be qualitative and speculative. No measurements are made of the radicals and other species present in the flame. In addition, there are rather complex combinations of mixing and reaction processes, neither of which are stationary in space and time. Time-averaged data, as those obtained here, cannot be expected to give deeper insight into the detailed mechanisms. Therefore the measurement of radicals in the flame will be immediately required and more detailed research should be done in the future.

4 Conclusion

These tests are to further enhance our understanding on the interaction of water mist and pool fire. Firstly, the results demonstrated that at the beginning stage of the water mist addition, the pool fire produced an initial flare-up and made the flame very turbulent. The reason was that the water mist has enhanced effect when it vaporized quickly, which made the oil burn more completely. Secondly, a few seconds later, the flame size was reduced because the fire extinguishing ability of water mist played a leading role at this stage. Thirdly, the experimental results also showed that the more operation pressure, the less burning rate change. It is because that with the increase of operation pressure, the drop size decreased and the spray momentum increased. That is, the fire suppression ability is stronger. Finally, the experimental results also showed that the water mist discharge pressure has a more violent influence on the CO produced rate than the CO_2 production rate. It can be explained by insufficient O_2 in the burning area and the fire extinguishing time is increased with the discharge pressure augment. This study results will be useful for developing the water mist fire suppression system designation, improving the fire suppression efficiency and control efficiency, and extending their application field.

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