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Experimental data on water mist suppression

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Abstract

Action of water mist in suppressing gasoline spray fires, asphalt spray fires and diesel spray fires in confined spaces will be reported in this paper. Relevant experimental works reported earlier are reviewed with key points summarized. Factors affecting the properties of the water mist suppression systems are investigated. The characteristics of water mist are studied using the Phase Doppler Particle Analyzer with key results compiled. Results are firstly applicable in directly drafting out design guides on water mist suppression systems on oil fires. Secondly, it is also useful for justifying numerical models studying water mist suppression on oil fires.

Keywords: Oil fuel; Spray fires; Water mist

1. Introduction

Different spray patterns are designed to suppress different oil fuels. Common oil fuels are gasoline, diesel, kerosene, alcohol and asphalt. Previously, fuel sprays were classified by their area of application in automobiles, marine engine rooms, plant rooms for stand-by electricity, and factories. The discharged oil sprays are specified as low pressure, medium pressure and high pressure sprays according to their working pressure. Leakages in pressurized pipe or fitting, human error, or mechanical damage would lead to emitting of oil fog from those pressurized or damaged containers mixing with air to give a jet flow. The fuel oil fog could be ignited rapidly by hot surfaces of the pipes or boiler walls, electrical arcing, welding, and sparking due to mechanical friction. A fog fire would then rapidly develop within a few seconds after mixing with air to result in a big fire up to 50 MW. Very large fires with high temperatures and high concentrations of carbon monoxide (CO) could occur within 30 s. The emitted radiant heat is extremely high and its effect destructive.

Water mist suppression systems are now commonly installed in marine engine rooms and stand-by electricity generation rooms against such oil fuel fires. Results from intermediate-scale tests have demonstrated the potential capabilities and advantages of water mist technologies for application in machinery space. However, the performance of such systems is dependent on the varying circumstances of fire occurrence. Three scenarios will be reviewed and discussed as examples in this paper to evaluate the performance of water mist sprays in suppressing fuel oil fires in different types of confined spaces. These scenarios are, namely, the action of medium pressure water mist systems in extinguishing gasoline spray fire in a car; the action of high pressure water mist systems in suppressing asphalt spray fire in a factory workshop; and the action of high pressure water mist systems suppressing diesel spray fire within a confined space.

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2. Water mist characteristic parameters

The performance of water mist in fire suppression is dependent on the characteristic parameters of velocity distribution, droplet size distribution and flux. Such parameters can be measured using the Phase Doppler Particle Analyzer (PDPA) system. The working principles of PDPA system are based on the Doppler frequency shift and the associated Doppler phase shift theory [1].

Initial velocity distribution of water mist will affect the performance of the suppression system. The Laser Doppler Velocimetry (LDV) system is a reliable tool for taking measurements of the water mist velocity and the velocity distribution at different positions [2-8]. Example data on the three components u_1, u_2 and u_3 of the velocity vector $\vec{u}$ are shown in Fig. 1. The variation of velocity with operating pressure at different locations is shown in Fig. 2. During all tests the distance from the nozzle to the plane center was fixed at 1000 mm [9]. All testing rig points were placed on the same plane.

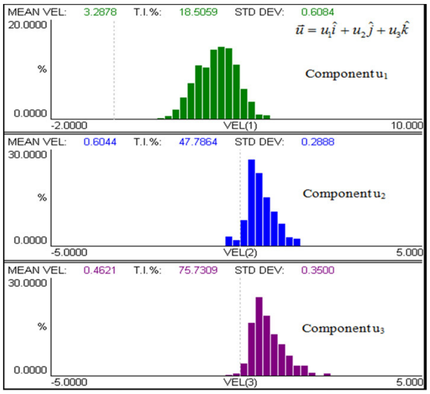


Fig. 1. Velocity components and the distribution of water mist.

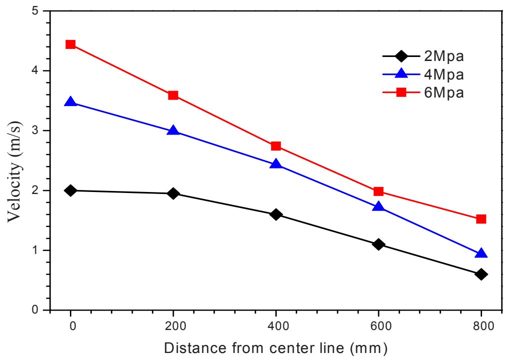


Fig. 2. Variation of water mist velocity with distance at different pressures.

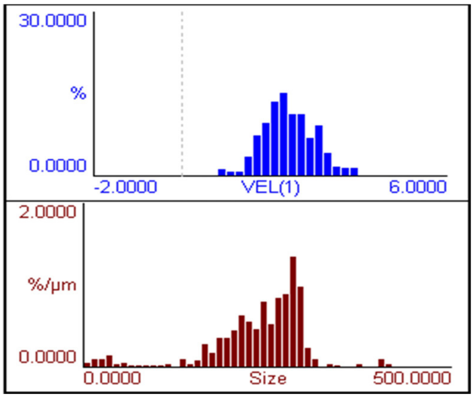


Fig. 3. Water mist size and size distribution.

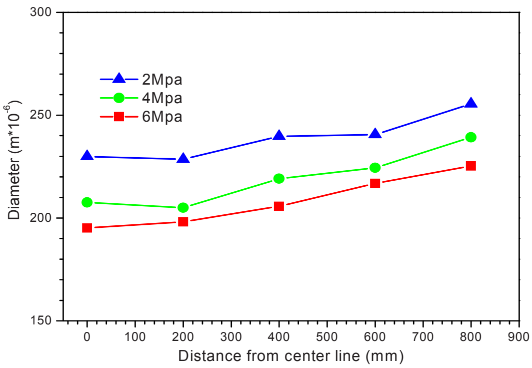


Fig. 4. Variation of diameter of water mist droplets with pressure.

The water mist drop diameter (Fig. 3), size distribution (Fig. 4), size change, as well as distance from the test point to the fog field center are also crucial variable factors that should be considered in evaluation of the performance of water mist systems. All these can be measured by the PDPA system.

3. Gasoline spray fire in a confined space

Fire initiating from an automobile might result in big garage fires, tunnel fires and road transportation fires. Statistics [13, 14] indicate that automobile fires can cause serious deaths and injuries with high economical loss.

Automobile fires mainly start from the engine before igniting tyres and other devices. They constitute 66% of highway transportation fires [13]. The engine is composed of the oil system, the electricity system and other hot sources and has a high breakdown rate and high ignition frequency while the automobile is in motion.

Experiments have shown that automobile fires tend to develop rapidly [15]. During tests, at 5 minutes after flame ignition, the fire at the automobile forepart had already become sizeable. At 13 to 14 min, the fire had spread to the automobile central part. At 21 to 22 min, the fire reached the rear part of the automobile, and at 28.5 min, the gasoline box explosion occurred. The car fire experiment by Mangs and Keski-Rahkomen [16] indicated that during the ignition, the CO and CO_2 densities rose significantly in the cabin. At 4 to 5 min, the fire from the engine spread to the passengers' cabin. From these data, it may be deduced that the engine room fire must be suppressed within 1 to 2 minutes; otherwise the safety of the passengers would be under threat [16]. When a nitrogen foam fire extinguishing system was used for extinguishing the collision car engine room fire [17], no suppression effect could be observed for approximately 10 minutes. Experimental results on the suppression of engine fire by a carbon dioxide fire extinguishing system [14] indicated that the wind velocity had a considerable influence over the extinguishment of fire; the system could not extinguish fire effectively in the presence of wind.

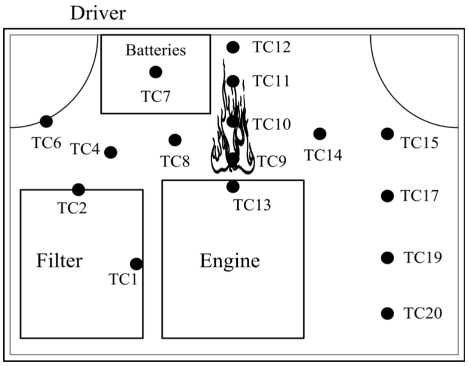


Fig. 5. Thermocouple arrangement in the car engine room with a gasoline spray fire (pressure was 300 kPa). Thermocouples TC3, TC4 and TC5 at 10 cm intervals along vertical direction.

Automobile fire is extremely difficult to extinguish due to its rapid spreading and fierce combustion. The general success rate of extinguishing automobile fires is very low. In the particular case where the car engine is inflamed and the engine room cover is open, the fire would spread further resulting in greater difficulty in control or suppression. However, if the cover is closed, portable fire extinguishers cannot be used for extinguishment of fire. Once the fire occurred in a running automobile, it is seldom possible for fire-fighters to arrive in time to suppress it before great damage. Thus, during the early stage of the fire occurrence in an engine, the fire can seldom be suppressed effectively.

Experiments were carried out by Li and Qin [18] on suppressing an engine fire at the early stage. Their objectives were to extinguish the fire inside the car engine using water mist.

Two points in particular were explored:

- the possibility of suppressing a fire inside the car engine;
- the optimum position of suppressing the fire.

An experimental setup was built to simulate the car engine as shown in Fig. 5. The rig used was of size 132 cm by 82 cm by 62 cm. The 93# gasoline was taken as the fuel to simulate oil spray fire with fog generated by nozzle. Water mist nozzles were arranged to extinguish the fire. The spray position of the water mist, pressure and the nozzle spray angle were considered as influencing factors on the fire extinguishment. The condition of the car engine cover as open or closed was also taken to be a crucial factor. Different car engine fire scenarios, different water mist nozzle operating pressures and cover conditions were studied. Results are summarized below for the experiments studying temperature (Fig. 6), and oxygen concentration (Fig. 7).

The water mist system was proven to be capable of suppressing car engine fires. Water mist could effectively lower the temperature of the flames and the engine. It was also effective in diluting the oxygen content inside the engine to achieve suppression and possibly even complete extinguishment.

The condition of the engine cover was studied as mentioned above. When the engine cover was open, the time required to extinguish the fire was longer than when the cover was closed. With the cover open, the oil fog fire could not be extinguished within 25 s with a water mist with pressure equal to or under 1 MPa.

At the early stage of an engine fire, the heat release rate is smaller as the fire is fuel-controlled. Opening the cabin cover at this point for a short time can lower the temperature of the flames. The fire can then be extinguished. When the engine fire is at the development stage, the heat release rate is higher and the fire becomes ventilation-controlled. If the cabin cover is opened at this stage, the fire would spread because of the increase in oxygen supply. The fire would be out of control. Therefore, the cabin should not be opened at this stage.

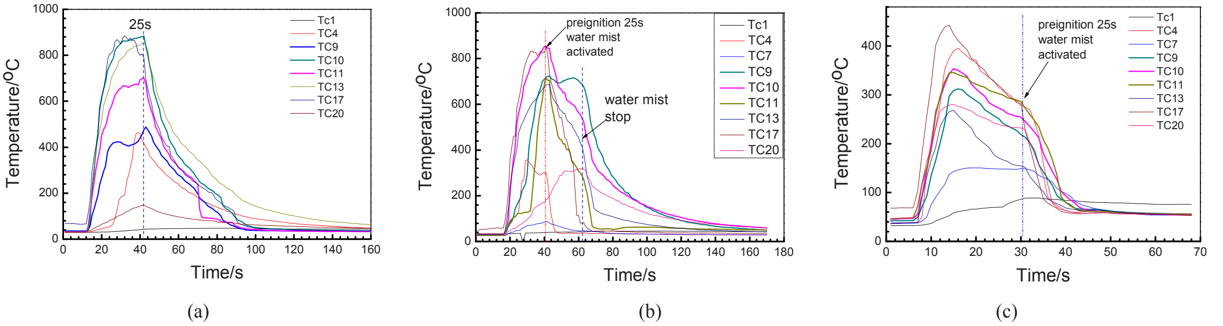


Fig. 6. Results for gasoline spray fire. (a) Free combustion (pressure 300 kPa) with the car engine room cover open; (b) Car engine room cover open, gasoline spray fire (pressure 300 kPa) pre-ignited at 25 s, water mist of pressure 1 MPa; (c) Car engine room cover closed, gasoline spray fire (pressure 300 kPa) pre-ignited at 25 s, water mist of pressure 1.0 MPa.

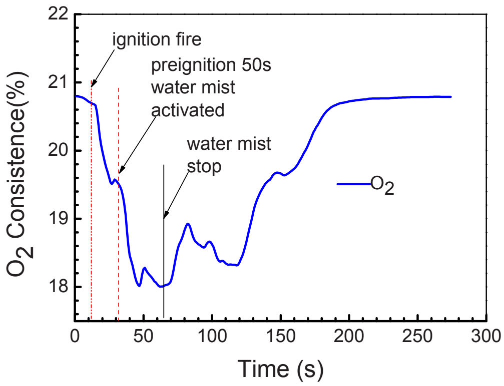


Fig. 7. Oxygen content with engine cover open, gasoline spray fire (pressure 300 kPa), water mist of pressure 0.5 MPa.

4. Asphalt spray fires in a confined space

Asphalt is widely used as building material for roads, bridges, tunnel structures, and roofing for waterproofing. It is also commonly sprayed on underground pipings as antisepsis and for waterproofing. During this spraying process, if the high pressure tube pipeline breaks to result in an asphalt leaking jet, an asphalt spray fog fire will be produced. As the asphalt fog drop is small in size, the hot area will increase to give a large evaporation rate. The resultant fire will spread rapidly and fiercely. It is necessary to study the technique in suppression and extinguishment of asphalt fog fires.

Many works reported on the characteristics of asphalt burning, which include pyrolysis and combustion kinetics of asphalt [19], single drop asphalt combustion characteristics, combustion characteristics of asphalt compounds [20], and water influence to the heavy fuel emulsion droplets [21]. However, few works reported on spray asphalt combustion and the according techniques for suppression.

Experimental studies on suppressing asphalt spray fire can give a better understanding on the performance of burning materials. The yielded results contribute greatly towards the design of fire suppression systems to extinguish real spray asphalt fires. The effect of the water mist on the spray asphalt fire had been studied by Xiang and Qin [22] and Pan et al. [23]. The experiments were carried out in a 3 m × 3 m × 3 m confined space. 10# asphalt was used as the fuel in the experiment. The flash point of the asphalt was determined to be 204.4 °C and the burning point measured as 485 °C. The asphalt used in the experiment was dissolved by dimethylbenzene solution. High pressurized nitrogen was used to drive the asphalt liquid flow and direct it into the nozzle through the pipeline. When the fuel fog sprayed from the nozzle was ignited, a fog fire was formed. In this study, the flame structure and the burning characteristics of the fuel were preliminarily tested. The test data were reported [22] and summarized in Figs. 8 and 9.

The following were observed:

- Extremely vigorous chemical reactions occurred in the interior of the spray fire under temperatures up to 977 °C.
- Water mist discharged had a tendency to interact with spray asphalt fire vigorously. For tests studying the spray fire pressure, the water mist suppressed the spray fire at a low pressure within a short period of less than 10 s.
- Reducing the distance between the water mist and the fuel spray nozzle results in better efficiency in suppression.
- Spray asphalt fire can be suppressed effectively by water mist, depending on the water mist flow and the spray fuel.
- When the water droplets reached the flame interface, there was an initial transient heating period to lower the temperature of the flame.
- With the mixing of the water mist and the spray fuel, the oxygen in air was replaced by the water droplets. Reducing oxygen concentration will stop the combustion.
- If the water mist droplets reached very close to the orifice of the fuel spray nozzle, there would not be enough air space for the combustion reaction. The flame would therefore be extinguished.
- The water droplet would not only cool the fuel vapour, but also reduce the evaporation rate of the fuel.

5. Diesel spray fire in a confined space

Generators and diesel engines of high power are essential installments in marine engine rooms. Diesel fuel is often loaded in the container. The pipeline would direct the oil fuel to the machine. If the pipeline or the container is damaged, the oil could leak out. If these containers or pipelines are pressurized, leaked oil would be ejected rapidly. The ejected oil flow would be atomized when they meet the air to yield an oil fog. Oil fogs in these circumstances are easily ignited by any fire source and develop into big oil fog fire rapidly. As the oil fog is able to mix with the air well, fire combustion is violent. The fire temperature is extremely high and the radiant heat is strong and massively destructive.

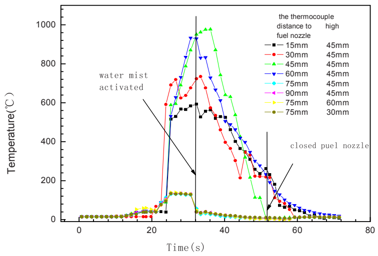
(a) Pressure 0.65 MPa, water mist pressure 0.8 MPa

(b) Water mist activated 20 s, Test 1 of gas pressure: 0.65 MPa, water mist pressure 0.8 MPa

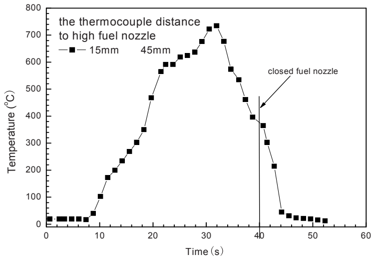
(c) Water mist activated 25 s, asphalt pressure: 0.65 MPa, water mist pressure 1.0 MPa

(d) Asphalt spray fire of pressure: 0.3 MPa, water mist pressure 1.0 MPa

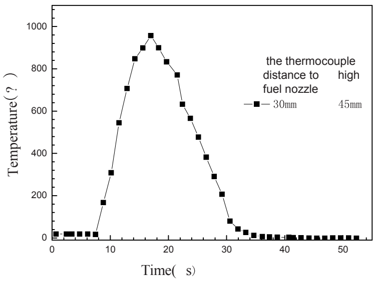
Fig. 8. Pictures of asphalt spray fire.



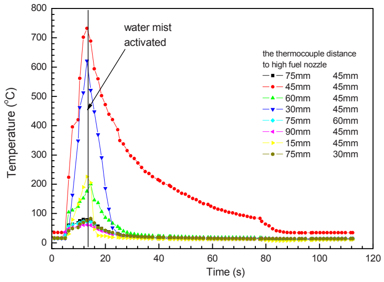
(a) Pressure 0.65 MPa, water mist pressure 0.8 MPa



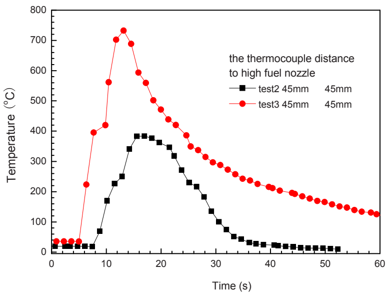
(b) At the point 15 mm from fuel nozzle, asphalt pressure: 0.65 MPa, water mist pressure: 1.0 MPa



(c) Highest temperature of the asphalt spray fire of pressure: 0.65 MPa, water mist pressure: 1.0 MPa



(d) Temperature of the asphalt spray fire of pressure: 0.3 MPa, water mist pressure: 1.0 MPa



(e) Temperature of the asphalt spray fire in the same position, asphalt pressure: 0.65 MPa and P: 0.3 MPa, water mist pressure: 1.0 MPa

Fig. 9. Temperature of asphalt spray fire.

The ship engine room architectural structure is often highly complex [24]. The fire could often spread quickly due to difficulty in detection and efforts to reach the fire for extinguishment would often meet physical barriers. The performance of water mist fire suppression systems on extinguishing the fire in a ship plant room had been reported by Back and Bill et al. [25-28]. The water mist suppression of full-scale class B fire was studied by Lu [29-31]. The relative significance of several influential factors for fire suppression by water mist were studied and documented. The experiments were carried out in a confined space of dimensions 10 m (length) by 10 m (width) by 5 m (height) using the 0# diesel oil as the fuel of the oil spray fire.

References [24-31] were works focusing on principal analysis of the diesel oil fog fire combustion characteristics, burn time of the diesel oil spray fire, water mist velocity and the effect of water mist nozzle position on the effectiveness of water mist in extinguishing the diesel oil fog fire. Some discussions on using water mist to suppress diesel oil spray fire in a confined space had also been endeavored.

Experiments [29-31] showed that water mist performed most satisfactorily in extinguishing the diesel oil fog fire, among all scenarios. When comparing with an oil pool fire scenario, applying the same water mist system in fire control, extinguishing a diesel oil fog fire required a higher work pressure than extinguishing an oil pool fire of the same flame power and the velocity of the water mist was increased. As shown in Fig. 10, the operating pressure of the water mist fire suppression system should be equal to or above 2 MPa to extinguish a 1 MW oil fog fire. When the water mist operating pressure increased, the system extinguished fire more effectively. When the water mist system nozzle operating pressure was 2 MPa, the thin water fog grain attained an average velocity of approx. 2.1 m/s. To put out a 1.6 MW oil fog fire, a minimum period of 85 s was required. When the water mist system operating pressure increased to 6 MPa, the average velocity of the fog reached approximately 4.5 m/s. The time required to extinguish the 1.6 MW oil fog fire was only 40 s, as shown in Fig. 11. Therefore, a high pressure water mist can put out the diesel oil spray fire more efficiently. The major rationale behind this is that a higher operating pressure of the water mist system spray will result in a higher velocity of water mist. The fog flux of the unit area increment would break the equilibrium of the oil fog fire combustion more easily and hence extinguish the flames. There is also the advantage that high pressure water mist system creates a smaller fog drop, entraining more air into the flames. In putting out the oil fog fire with water mist, the thin fog of water would enter an important path of the flame area. Therefore, the high pressure water mist system is more effective in extinguishing the oil fog fire. The water mist discharged from high pressure system having a higher velocity and momentum is able to penetrate the fire plume to act at the flame.

Testing with the same water mist system, extinguishing an indoor oil fog fire is relatively easier than outdoors. For an indoor oil fog fire, the evaporation rate of the oil fog drop is slower and the combustion is fuel-controlled. Temperature at the inner part of the flame area is higher than the exterior. Water mist entering the inner flame would have a higher temperature difference with the flame. The amount of heat absorbed per unit time is considerably greater. Evaporated water mist would absorb the heat to lower the flame temperature, cool down the oil fog drop, and limit the evaporation rate of the oil fog drop. Therefore, the same water mist system can control an indoor oil fog fire with greater ease and effectiveness than an outdoor oil fog fire.

From the experimental results, it could be deduced that the direction of the water mist nozzle spray plays a crucial role.

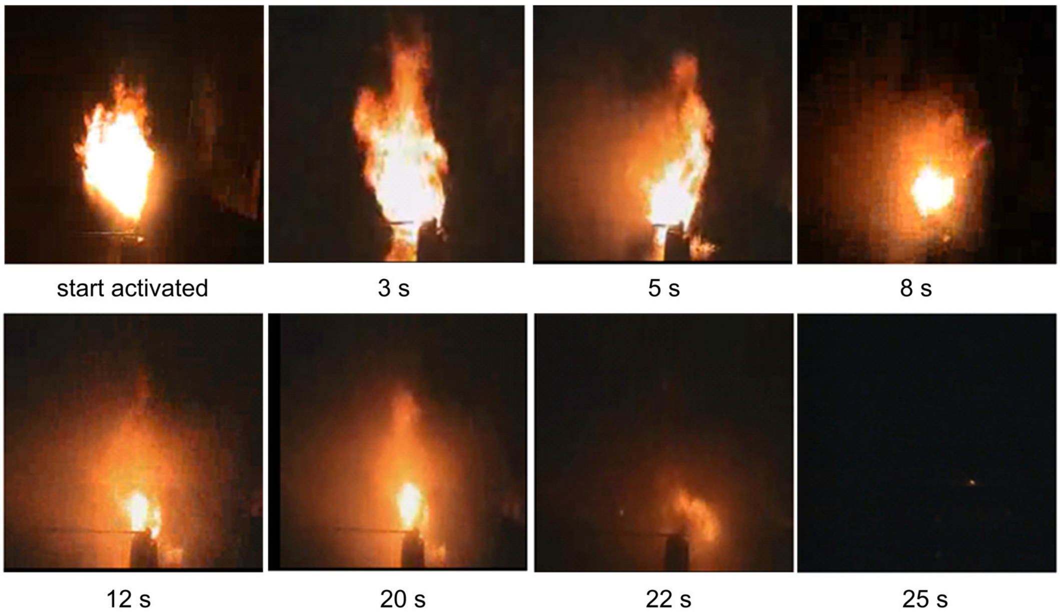


Fig. 10. The dynamic process of suppressing the diesel oil spray fire with water mist in a confined space (diesel oil spray fire power: 1 MW, water mist pressure: 2 MPa).

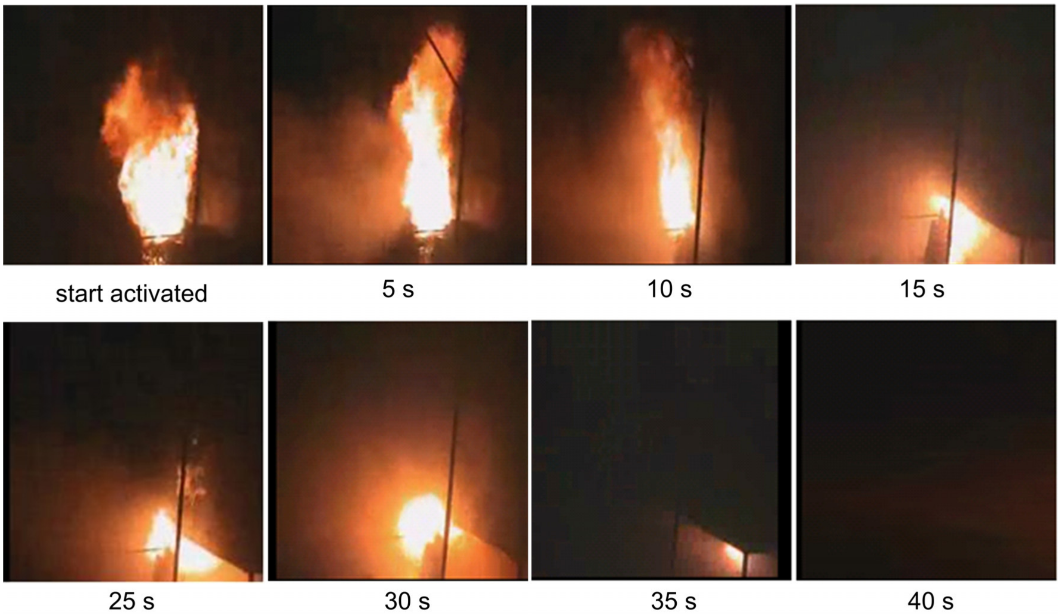


Fig. 11. The dynamic process of suppressing the diesel oil spray fire with water mist in a confined space (diesel oil spray fire power: 1.6 MW, water mist pressure: 6 MPa).

When the water mist nozzle was arranged for side spray, the time needed to put out the oil fog fire was reduced. A possible explanation is that it may not be necessary for water mist to overcome the smoke plume. It is more advantageous that the flames root entrainment could absorb the thin fog of water and water mist. As the water fog entrained by the flames is continuously evaporating, more heat could be absorbed.

There is also the fact that oil fog next to the nozzle often does not evaporate completely. The water mist evaporating in the root of the flames is able to cool down the oil fog. The steam generated can then block the flame radiation. This contributes towards deceleration of the evaporation rate of the oil fog drop, resulting in lowering the amount of fuel fume produced per unit time. The combustion chain reactions could then be broken down.

In the oil fog fire experiment, pre-ignition time of the oil fog fire has been observed to change. The time required to extinguish the oil fog fire by water mist is very different from that for pool fire. Under the same conditions, the pre-ignition time for an oil fog fire was shorter (less than in 18 s) as shown [29] in Fig. 12. A longer time is needed for the water mist system to put out the fire. But the oil fog fire pre-ignition time increases rapidly after 20 s. The time required to achieve extinguishment is shortened. A possible explanation for this phenomenon is that the oil spray fire, especially at the root of the oil fog flames, entrains a much larger quantity of air. Upon discharging the water mist, the air near to the side of the oil fog nozzle would be saturated with steam due to the water mist.

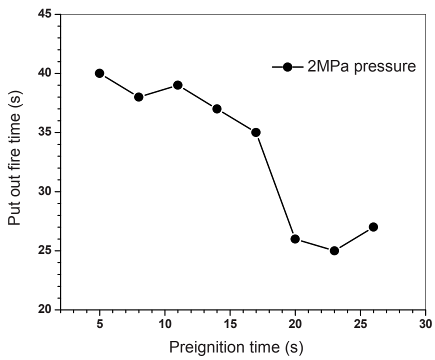


Fig. 12. Effect of pre-ignition time of the diesel oil spray fire on the effectiveness of extinguishing spray fire (1 MW oil spray fire).

From the measured thermocouple data near to the flame, in the short period of time before the ignition of the oil fog, the temperature of the air entrained by the oil fog fire was very close to the ambient temperature of about 25 °C. After 18 s, the oil fog fire was ignited due to flame radiation. The temperature of air entrained by the oil fog fire near the flame area became as high as 60 °C.

Under standard circumstances, when the ambient was one atmospheric pressure and 20 °C, the saturated steam pressure of the water was 0.02338 MPa. At 60 °C, the saturated steam pressure of the water increased to 0.2 MPa. The saturated moist air would have a low percentage of oxygen 16%. Oxygen supply became insufficient after discharging water mist. As the combustion was under fuel-rich condition, the free radicals would induce polymerization of the fuel molecules to form hydrocarbon polymers. Under heating, these hydrocarbon compounds would decompose into hydrogen and solid carbon materializing as soot.

If liquid fuel is used, the oil drops would vaporize when heated by the surrounding flames. Simultaneously, the oil molecules also decompose and polymerize under heating. Frothing and solidification can co-occur in the oil drops. Soot particles with high porosity were formed with even larger volume than the oil fog droplets. The production rate of soot is extremely high with characteristic formation time as short as below 10 s. Once soot has been formed, its oxygenation rate or complete combustion rate is much slower than its production rate. The quantity of soot formation is determined by the fuel and its constituents. Heavy fuel would produce more soot. The produced soot could only be burned completely with the suitable temperature, sufficient time and air supply.

Results indicated that presence of steam can lower the soot content significantly. This is due to the reaction between steam and carbon resulting in the creation of water coal gases. The temperature in this process is about 1400 K. However, in a fire, the flame area temperature is generally approximately 1100 K. This value is lower than the heat condition necessary to create water coal gases. Therefore, water stream entering the flame area cannot effectively hinder or prevent the formation of soot. The saturated wet air would cause reduction of oxygen concentration in the flame area. The oil fog fire temperature would not usually be very high in a larger confined space. A certain amount of soot would be produced for an incomplete combustion. In liquid fog combustion, the output soot will be adsorbed on the surface of the oil fog in great quantities to obstruct the evaporation of oil fog drops. This breaks the equilibrium of the oil fog fires and further decelerates their burning rate. Therefore, under these circumstances, the oil fog fires are relatively easier to extinguish by water mist. When the pre-burning time of oil fog exceeds certain duration, the extinguishing time would decrease. This is particularly observable for an indoors oil fog fire. In the case of an oil fog fire, a large amount of soot would be formed due to the great quantity of oil fog drops surrounded by the flames. This would assist fire extinguishment by water mist.

6. Conclusions

From the above review on suppressing three scenarios of oil spray fire in a confined space by water mist, the following can be concluded on drafting the associated design guides:

- The water mist must be able to penetrate the flame and reach the burning surface.
- Water mist extinguishes the oil fog fire mainly through lowering the temperature of flames, reducing thermal radiation and lowering the flame area oxygen concentration.
- Performance of the water mist in extinguishing the oil fog fires depends on their locations in the engine room. However, when the nozzle work pressure increased, the system extinguished the fire more quickly. It is more effective for the nozzles to be placed sideways to extinguish the oil fog fires.
- When the pressure is greater than 2 MPa, water mist can extinguish rapidly oil fog fires lower than 1 MW.
- When the pressure is greater than 6 MPa, water mist can extinguish rapidly oil fog fires up to 1.6 MW.
- Effect of pre-burn time duration on suppressing fire by water mist is due to the temperature increase of the air entering the flame area. The partial pressure of water mist in the saturated wet air would increase and the oxygen concentration would decrease, resulting in an incomplete combustion and production of a large volume of soot. The soot would be absorbed on the oil surface and hence prevent oil vaporization, achieving fire extinguishment.
- High pressure water mist system is more effective in fire suppression in a confined space than a system with medium or low pressure. A high pressure water mist system with lower water delivery rate would also lengthen the protection time for the oil spray fire in locations including the automobiles, marine engine rooms, architectural stand-by electricity plant rooms and certain places in a factory workshop. This type of water mist system with appropriate nozzles layout should be the most effective and applicable in most scenarios.

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