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Extinguishment of Liquid Fuel Fire by Water Mist Containing Additives

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Abstract : An experimental study was presented for extinguishing characteristics of liquid fuel fire by water mist($Dv_{0.99} \leq 200$ μm) containing potassium acetate and sodium acetate trihydrate. To evaluate the extinguishing performance of water mist containing additives, the evaporation characteristics of a water droplet on a heated surface was examined. The evaporation process was recorded by a charge-coupled-device camera. Also, small-scale extinguishing tests were conducted for *n*-heptane pool fire in ventilated space. During the experiments, flame temperatures were measured, and concentrations of oxygen and carbon monoxide were analyzed by a combustion gas analyzer. The average evaporation rate of water droplet containing additives was lower than that of pure water at a given surface temperature and decreased with the concentration increase due to the precipitation of salt in the liquid-film and change of surface tension. In case of using additives, the fire extinguishing times was shorter than that of pure water at a given discharge pressure and it was because the momentum of a water droplet containing additives was increased. And also dissociated metal atoms, potassium or sodium, were reacted as a scavenger of the major radical species OH, H which were generated for combustion process. Moreover, at a high pressure of 4 MPa, the fire was extinguished through blowing effect as well as primary extinguishing mechanisms.

Key words : water mist, additives, fire suppression, alkali metal agent

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1. Introduction

The use of water mist as a fire suppressant was first studied by scientists at Underwriters' Laboratories, Inc. (UL) in the mid 1950 s. Although the UL scientists understood the effectiveness of water mist then, insufficient testing and design standards prevented water mist from developing into the conventional protection system, as did the fixed-sprinkler system. Since the discovery in the 1980 s of the depletion of the upper atmospheric ozone layer and the belief that halons were a major contributor to the damage a renewed interest in water mist technologies has emerged.

A basic description of how water mist extinguishes fires was provided as early as 1955 by Braidech [1] and confirmed by Rasbash et al. [2]. The mechanisms of water mist to extinguish fire can be described as three primary and two secondary mechanisms. The primary mechanisms are heat extraction, oxygen displacement, and blocking of radiant heat. And there are two secondary mechanisms that play a role in extinguishment, but it is difficult to quantity their importance. These are vapor/air dilution and kinetic effects.

The principal problem with very small droplets of water mist is that they do not penetrate through the air easily in low pressure conditions. Large droplets have less air resistance than small droplets; hence, the large droplets travel more easily through air. But the large droplets can pass through a flame with little evaporation since their surface-to-volume ratio is small. The smaller mist droplets can evaporate easily in a flame, making them more efficient than the large droplets.

The use of water mist containing additives might solve this problem, and certain additives can improve its fire suppression effectiveness. Some water-based agents have recently been proven to be more effective than pure water when applied in the form of mist to suppress a small jet fuel pool fire [3].

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The objective of the present work is to examine the extinguishing characteristics of water mist containing alkali metal agents as a fire suppressant. Small-scale extinguishing tests were conducted for *n*-heptane pool fire in a confined space. During the experiments, flame temperatures were measured, and oxygen concentration and carbon monoxide concentration were analyzed by a combustion gas analyzer. And also, the evaporation characteristics of a single water droplet on a heated surface were examined. The evaporation process was recorded by a charge-coupled-device camera. Because of its potentially superior fire suppression ability, water containing potassium or sodium acetate was used in the experiments.

2. Experimental set-up

2.1. Extinguishing tests by water mist

The extinguishing tests were performed in a steel-walled enclosure (0.75 m × 0.75 m × 1.3 m) as shown schematically in Fig. 1. The square fuel pan (0.15 m × 0.15 m × 0.05 m) was placed at the center of the floor and water mist nozzle was installed at 1.1 m high from the floor.

Flame temperatures were measured using a K-type thermocouples per second. The combustion products were all collected by the hood and transferred to combustion analyzer for measurement and analysis. The rate of fresh air flow into the confined space was 0.58m^3/s through the openings on right and left side wall. The burning rate of the pool fire was measured in freely burning conditions without water mist and the heat release rate of the fire source was calculated.

Table 1. Specifications of the tested nozzle

	1.2 MPa	2 MPa	4 MPa
Droplet size, $Dv_{0.5}$ (μm)	•	96	91
Spray angle (degree)	•	55	55
Orifice diameter (mm)	0.7	0.7	0.7
Flow rate (/min)	0.42	0.54	0.72

Water mist was generated by a plunger pump system and the fire was allowed to burn for 180 s to ensure quasi-steady burning before the water mist discharge. The pressure, volume flux, and other characteristics of the water mist nozzle used in the tests are shown in Table 1. Three operating pressures of 1.2, 2, 4 MPa were used in the experiment. The water flow rates under the above pressures are 0.42, 0.54 and 0.72 l/min, respectively.

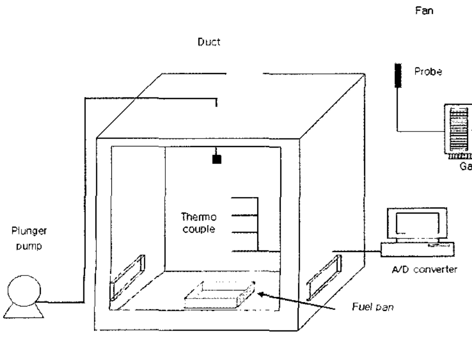


Fig. 1. Schematic of extinguishing experiment set-up.

2.2. A single droplet evaporation tests

Fig. 2 shows a schematic diagram of the experimental set-up for a single droplet evaporation. It consists of a syringe pump for droplet generating, a stainless steel surface, a temperature controller, and a CCD camera. The water droplets were generated using a syringe pump which was programmed at a rate of 0.001 ml/s.

The droplet was formed at the tip of the needle (28 gauge) and detached off the syringe under its own weight. The surface temperature was measured using a thermocouple embedded within the stainless steel surface. The thermocouple was inserted 1mm below the metal surface. All temperatures reported in this study correspond to those in the stainless steel surface. The surface temperature was controlled to within ±1°C using a temperature controller.

A CCD camera (with a framing rate of 120 frames per second) was used to measure the droplet evaporation time. The average water evaporation rate is defined as the initial amount of water in the droplet divided by the evaporation time.

Table 2 displays the physical properties of the aque-

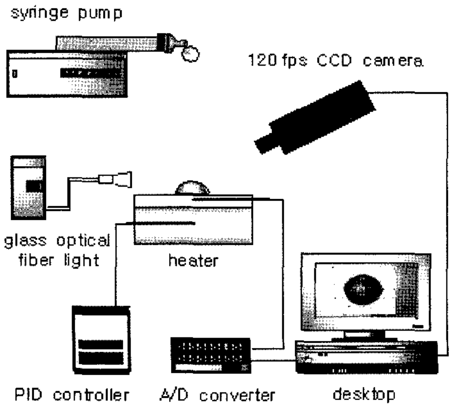


Fig. 2. Schematic of evaporation experiment set-up.

Table 2. Physical properties of the solution

Fluid	Density @20(kg/m^3)	Dynamic viscosity @20(Ns/m^2)	Surface tension @20(Ns/m)	Freezing Point ()	pH @20°C
Distilled water	998.23	0.00089	0.072	0	7.0
10 wt.% K-acetate	1049.56	0.00096	0.073	-7.5	9.8
30 wt.% K-acetate	1157.00	0.00142	0.073	-24.4	10.3
50 wt.% K-acetate	1277.68	0.00305	0.070	-40 $^{a)}$	11.1
10 wt.% Na-acetate	1029.23	0.00100	0.076	-8	8.8
30 wt.% Na-acetate	1082.48	0.00131	0.076	-16	8.9
50 wt.% Na-acetate	1158.31	0.00228	0.075	-16 $^{b)}$	9.1

$^{a)}$not able to measure below this temperature, $^{b)}$ not frozen but saturated

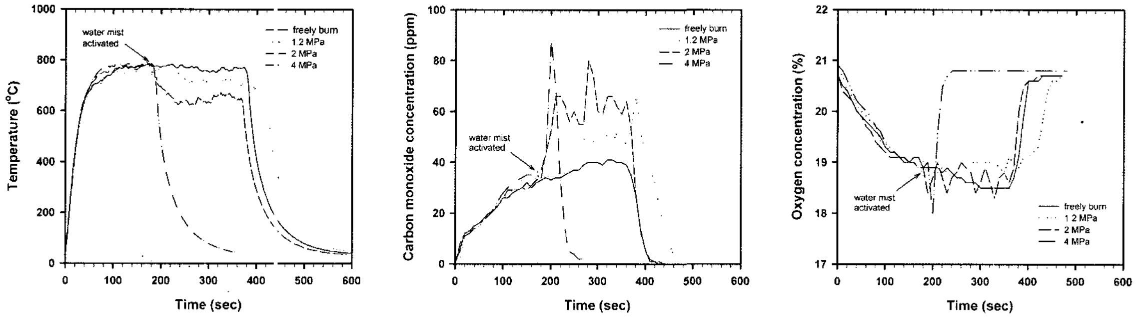
ous solution studied. The surface tensions of the aqueous solutions were determined by using a tensiometer (SEISAKUSHO, LTD. 514-B2) which measured the force required to withdraw a platinum-iridium ring from the surface of the liquid. The density, viscosity, and normal freezing point of the solutions were also measured experimentally.

3. Results and Discussion

3.1. Extinguishing Characteristics

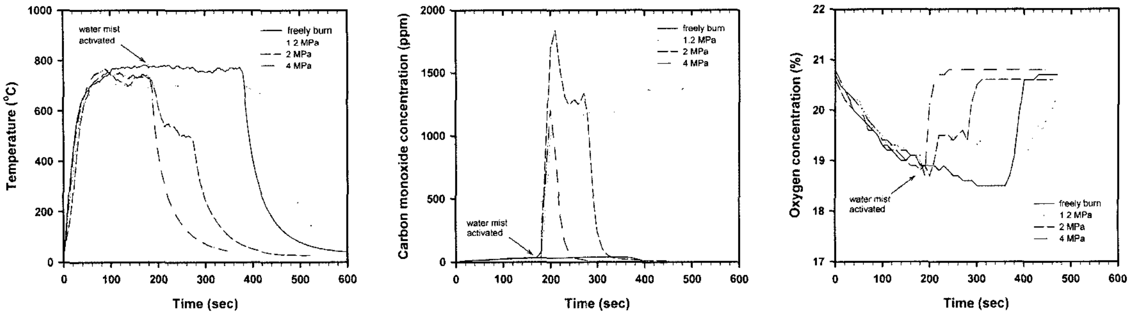
The burning rate of the pool fire was 0.025 kg/m^{2}s in freely burning conditions without water mist in the confined space and the heat release rate of the fire source was about 25 kW. The average combustion time of 300 m *n*-heptane was 380 s (6'20") in freely burning conditions. When the momentum of droplets discharged from the nozzle was not enough to penetrate the fire plume, most of the droplets were deflected away from the fire [4]. As a result, the deflected droplets covered the fire reducing the fire size and the heat release rate and combustion rate were decreased. The curves of the temperature variation, carbon monoxide concentration, and oxygen concentration with water mist application are shown in Fig. 3 (a), (b), and (c), respectively. A liquid pool fire is sometimes intensified by water mist injection. A flare-up often occurs in the first second of contact with the water mist, and it is evident that the burning rate is increased for longer periods. In Fig. 3 (a), the combustion time with the pressure of 2 MPa was about the same with the freely burning conditions under the influence of flare-up.

Fig. 4-9 shows the curves of the temperature variation, carbon monoxide concentration, and oxygen concentration with the water mist containing additives. The flame temperature decreased immediately after the application of water mist. The higher the operating pressure, the faster the flame temperature decreased, and as the concentration of dissolved salt increased, the flame temperature decreased rapidly. The oxygen concentration decreased after ignition and increased quickly after the application of water mist. When water mist was injected into the confined space, it absorbed the heat more quickly than the large droplets did and slowed down the combustion intensity so that the total oxygen consumption decreased [5]. The carbon monox-



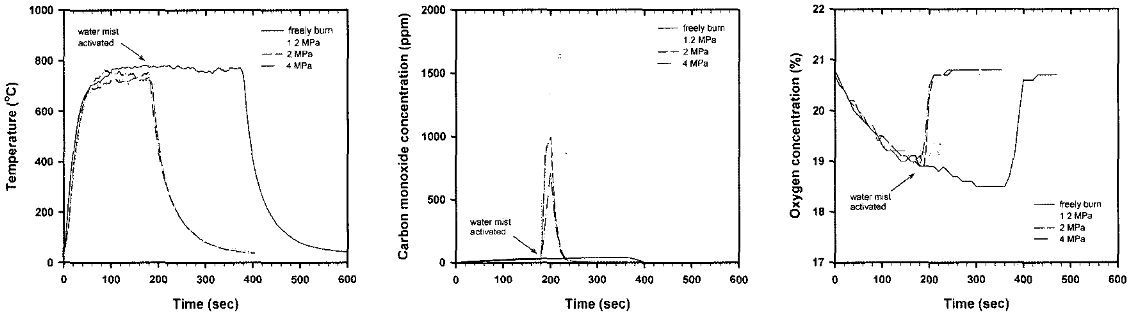
(a) Temperature variation (b) CO concentration (c) Oxygen concentration

Fig. 3. Results of extinguishing liquid fuel fire by pure water mist.



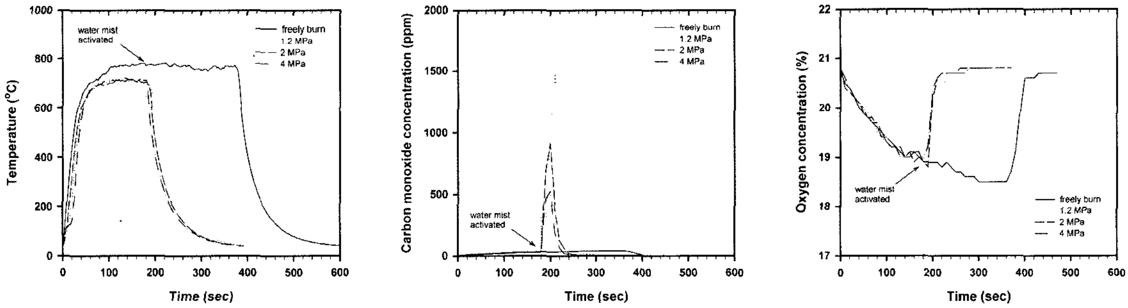
(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

Fig. 4. Results of extinguishing liquid fuel fire by water mist containing 10 wt.% K-acetate.



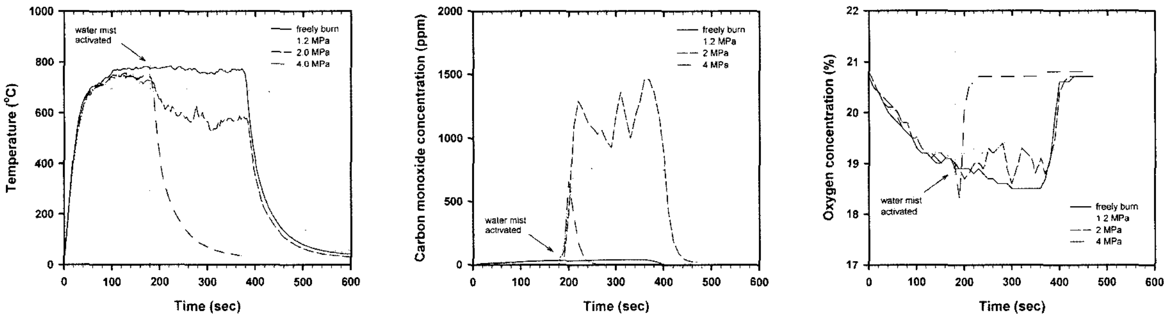
(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

Fig. 5. Results of extinguishing liquid fuel fire by water mist containing 30 wt.% K-acetate.



(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

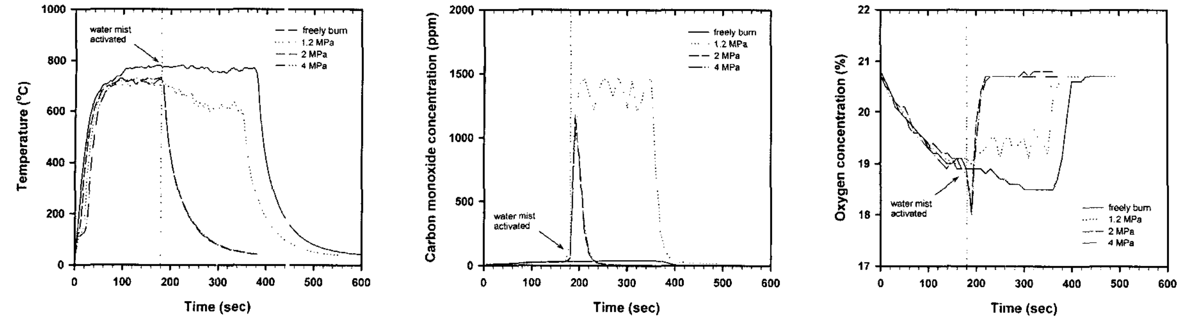
Fig. 6. Results of extinguishing liquid fuel fire by water mist containing 50 wt.% K-acetate.



(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

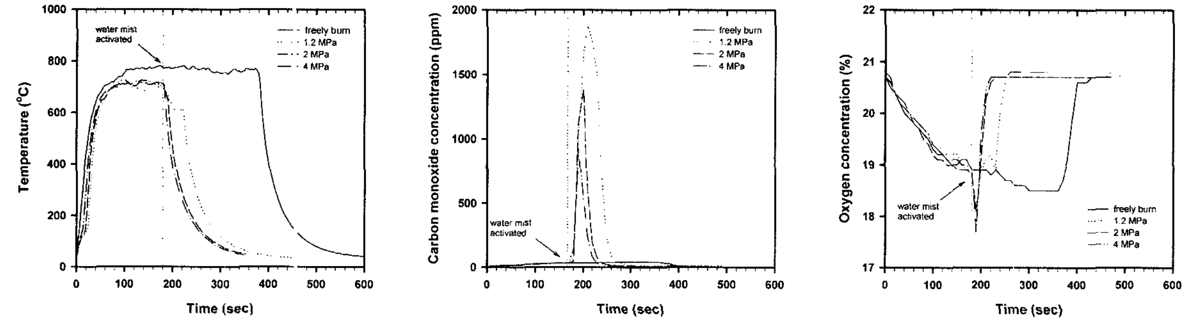
Fig. 7. Results of extinguishing liquid fuel fire by water mist containing 10 wt.% Na-acetate.

ide concentration after the application of water mist increased quickly. In case of using additives, the fire extinguishing times was shorter than that of pure water at a given discharge pressure and it was because the



(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

Fig. 8. Results of extinguishing liquid fuel fire by water mist containing 30 wt.% Na-acetate.



(a) Temperature variation **(b) CO concentration** **(c) Oxygen concentration**

Fig. 9. Results of extinguishing liquid fuel fire by water mist containing 50 wt.% Na-acetate.

momentum of a water droplet containing additives was increased, and also because dissociated metal atoms, potassium or sodium, were reacted as a scavenger of the major radical species OH, H which were generated for combustion process. Under these conditions, combustion was less efficient and as a result, more carbon monoxide was produced.

3.2. Droplet evaporation

Fig. 10 shows the evaporation lifetime as a function of surface temperature for a distilled water droplet with an initial diameter of 2.4 mm. The droplet evaporation lifetime was recorded in 20°C intervals. At each temperature, three sequential experiments were performed and the evaporation time at each temperature represents the average of the three runs.

Fig. 11 shows the average water evaporation rates at different surface temperatures for pure water, 10, 30, 50 wt.% sodium acetate solutions. The average water evap-

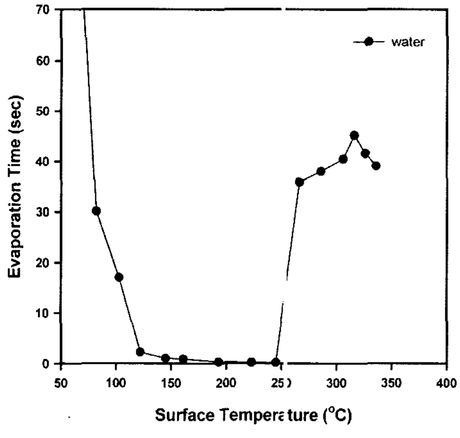


Fig. 10. Evaporation lifetime of water by the temperature.

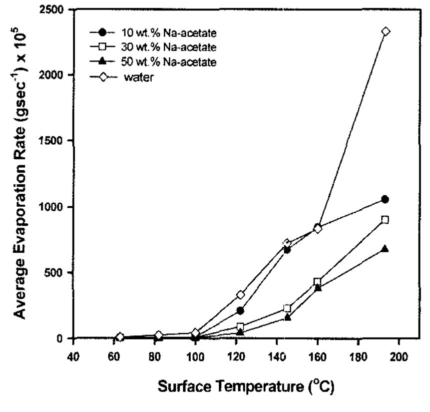


Fig. 11. Average evaporation rates at different temperatures.

oration rate at each temperature is defined as the initial amount of water in the droplet divided by the evaporation time. The addition of sodium acetate to water decreased the evaporation rate below that of pure water. The average evaporation rate of water droplet containing additives was lower than that of pure water at a given surface temperature and decreased with the concentration increase due to the precipitation of salt in the liquid-film and change of surface tension. If the droplets penetrate the fire plume and reach the flame, the chemical suppression action of the alkali metal agent could be fully utilized, and the reduction in water evaporation rate would not be a governing factor. On the contrary, if most of the droplets were deflected away from the fire, the chemical effect of the salt would be minimized or lost, and the reduction in water evaporation rate would impose an additional penalty because for a given time less water vapor would be generated and entrained into the adjacent fire for suppression [6].

4. Conclusions

An experimental study was presented for extinguishing characteristics of liquid fuel fire by water mist containing potassium acetate and sodium acetate trihydrate. To evaluate the extinguishing performance of water mist containing additives, the evaporation characteristics of a water droplet on a heated surface was examined.

It was effective to suppress the *n*-heptane pool fire with the application of water mist containing additives. In case of using additives, the fire extinguishing times was shorter than that of pure water at a given discharge pressure and it was because the momentum of a water droplet containing additives was increased, and also because dissociated metal atoms, potassium or sodium, were reacted as a scavenger of the major radical species OH, H which were generated for combustion process. But more carbon monoxide was produced, giving adverse effects in using water mist for extinguishing fires. The average evaporation rate of water droplet containing additives was lower than that of pure water at a given surface temperature and decreased with the concentration increase due to the precipitation of salt. When most of the droplets were deflected away from the fire in case of low pressure of 1.2 MPa, the chemical suppression effectiveness of the salt was minimized, and the reduction in water evaporation rate caused the combustion time to be longer than freely burning conditions.

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