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Research Paper

Experimental study on the interaction between fire and water mist in long and narrow spaces

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HIGHLIGHTS

- Hydrogen was detected and its concentration increased with the water mist pressure increasing.
- The 20 bar and 30 bar water mist intensified the fire, and a higher mist flow rate resulted in more intense flashover.
- The restraining effect on the fire by the higher pressure water mist improves with the increase of flow rate.
- The 70 bar and K = 1 water mist successfully suppressed the fire in 110 s.
- The radiant heat flux attenuation and the fuel surface cooling effect are the key fire suppression mechanisms.

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ABSTRACT

A series of water mist fire suppression tests were conducted with the rubber ignition as the sign of flashover. An open type nozzle was mounted 1100 mm from the ethanol pan center and activated 8 minutes after the ethanol being ignited. The water mist average velocity and drop size, the fire temperature profiles, the radiant heat flux and the hydrogen, oxygen concentrations were measured. Much hydrogen was detected and its concentration increased with the increase of water mist pressure and flow rate. The 20 bar and 30 bar water mist intensified the flashover and the fire, hydrogen and the sharp increase of the radiant heat flux are the key factors to the intensification. With the 40 bar, K = 1 and 50 bar, K = 0.5 water mist, the rubber still ignited with only a flash flame. The flashover and fire restraining effects are improved with the increase of water mist pressure and flow rate. The 60 bar water mist effectively suppressed the flashover and restrained the fire some extent, and the 70 bar and K = 1 water mist successfully suppressed the fire in 110 s. The radiant heat flux attenuation and the fuel surface cooling effect are the key fire and flashover suppression mechanisms.

1. Introduction

Water mist has been widely recognized as one of the effective halon alternatives especially in total flooding applications. The interactions between fire and water mist are quite complicated although the key fire suppression mechanisms are generally accepted as the gas phase and flame cooling, the attenuation of the radiant heat flux and the dilution of the oxygen [1–7]. The extinguishing capacity is determined by the spray characteristics, spray location, spray start time [7], water mist additions [8,9], enclosure geometry, and obstructions within the space and the type of fuel [10]. The complex fire suppression mechanisms and the extinguishing capacity factors are the main reasons that fire tests are required to evaluate the water mist fire suppression performance and establish design criteria before a manufacturer's water mist system design is accepted in machinery spaces [11] and tunnels [12]. Hansen and Back [13] conducted tests in a simulated 500 m^3 machinery space onboard the U.S. Coast Guard's test vessel STATE OF MAINE and found that water mist systems were more efficient for extinguishing 4 kW/m^3 and greater fires, and some difficult for extinguishing the 1.0 MW obstructed spray fire located on the side of the engine mock-up similar to IMO-6. They concluded that the capabilities of water mist systems cannot be associated with a single parameter such as application rate and must be determined empirically. Jenft et al. [7] conducted experiments in a real-scale room on water mist application to a pool fire. They found an about 10 s fast suppression, and a fast gas cooling and inerting effect when water mist was applied to a developed fire. When the mist was applied early, they found that fire suppression only occurred after a significant cooling of the flame and the liquid pool. Atreya et al. [14], Lu et al. [15], and Wang et al. [16] researched the fire enhancement phenomenon by water mist, and found that the early stage of interaction between water

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mist and pool fire would make the burning more violent and the flame more powerful, and the evaporation of mist drop on the fuel surface was the main factor causing such a phenomenon.

Most experimental researches on water mist suppression techniques were conducted in approximately cubic chambers with various scales. For fires in long and narrow spaces such as tunnel fires with complicated ventilation conditions, due to the stronger thermal feedback to the fuel from the ceiling and walls, the fire heat release rate will be higher, the flame plume and smoke will spread more rapidly along the longitudinal direction [17]. The fire evolution and its interaction with the water mist illustrated special rules. However, the recent fire tests tend to be much larger in scale than the normal performance testing of fire protection systems in traditional industrial applications [18,19]. Because of the high cost of the full-scale testing, the performance of water mist system cannot be adequately explored by conducting repeat tests. Performance standards of water mist fire protection systems in tunnels are still in a state of development.

This study established a 3.6 m long, 1.5 m wide and 0.6 m high test chamber to analyze the interaction between water mist and the ethanol pool fire with the rubber ignition as the sign of flashover. Rubber is frequently involved in chemical industry, road tunnel and garage fires releasing large amounts of combustible and toxic gas and causing much loss of lives and property. There have been some research works on the interactions between water mist and polymers such as Poly (methyl methacrylate) (PMMA), PVC, and many others using a cone calorimeter and other instruments. It was found that polymer fires could be suppressed effectively by water mist system [20–23] with polymers as the single fuel. Santangelo and Tartarini [9] conducted full scale fire suppression experimental tests by 100 bar water mist within a high-rise storage of rectangular shape. Two shelves with solid combustible materials, i.e., wooden pallets, cardboard boxes and plastic glasses, were used as the main fuel suppressed by water mist, and one shelf with the same solid combustible materials was used as the target fuel to compare the fire suppression effectiveness by sole-water mist and water mist endowed with additives. The sole water mist flow appears to even emphasize the fire spread with a rapid temperature growth. The water mist endowed with additives can efficiently control fire spread.

With ethanol as the main fuel and the rubber ignition as the sign of flashover, the present work was carried out to study the mechanisms by which water mists suppress, restrain or enhance fires in the long and narrow test chamber. The mean velocity and the water mist drop size SMD on the interface zone between the fire and the water mist were measured by the PIV system. The fire temperature profiles, the radiant heat flux received by the floor and the smoke composition with various water mist pressures (20–100 bar) and various flow rates ($K = 0.5$ and $K = 1$) were measured to analyze the kinetic and thermal dynamic interactions between water mist and the fire. The study will enhance the developing of the performance based water mist fire suppression system evaluation, improve the fire suppression and control efficiency and extend their application field.

2. Theoretical model of the interaction between water mist and the fire

The global energy conservation equations between the fire and the surroundings in the confined space can be expressed as Eq. (1) and Fig. 1 [24]:

$$Q_{\mathrm{fire}} = Q_{\mathrm{g}} + Q_{\mathrm{w}} + Q_{\mathrm{V}} + Q_{\mathrm{d}} \tag{1}$$

where Q_{fire} refers to the fire heat released by the combustion of fuel; Q_{g} notes the heat gained by the gases within the control volume; Q_{w} means the heat transferred to component boundaries by radiation and convection from the fire plume, hot gases with the action of water mist spray systems; Q_{v} means the heat transferred through the vent openings; Q_{d} refers to the total heat absorbed by the droplet of water mist for heating and vaporizing them.

The fire heat released by the combustion of the fuel Q_{fire} depends on the combustion efficiency χ, the fuel surface A_{f}, the combustion heat h_{c}, the heat flux feedback to fuel q'', the vaporization heat of fuel h_{vap}, and the mass loss rate of the fuel m_{f}, and can be evaluated by formulation (2).

$$Q_{\mathrm{fire}} = \chi A_{\mathrm{f}} \left({q''}\big/{h_{\mathrm{vap}}} \right) h_{\mathrm{c}} = \chi m_{\mathrm{f}} h_{\mathrm{c}} \tag{2}$$

Among which, the heat flux feedback to fuel q'' mainly depends on the radiant heat flux feed back by the component boundaries, the flame plume and the hot gas. Dramatic heat flux feed back to fuel will enhance the fuel vaporization and the fire combustion process. Flashover, a typical fire thermal instable phenomenon, will occur and it becomes very difficult to suppress the fire hereafter. Many studies have been done on the fire thermal instabilities by the compartment boundaries, including the thermal inertia characteristics of boundaries, the component geometry and the discharge coefficient. Beard [25] created a model named *FLASHOVER A*1 to explore the effect on flashover by the compartment geometry with the vent on one side of the component with length L_1. By varying the aspect ratio of the compartment $\gamma = L_1/L_2$ while keeping the total internal surface areas constant, the critical heat release rate at $\gamma = 1$ is always bigger than that at $\gamma > 1$ or $\gamma = 0.35$ if the discharge coefficient C_{d} is lower than 0.76 although the difference is not too much. If C_{d} is higher than 0.84, the critical heat release rate at $\gamma = 1$ is always smaller than that at $\gamma > 1$ or $\gamma = 0.35$ and the difference is dramatic. Overall, the chamber geometry does influence the fire development and thus influence the interaction between fire and the water mist.

The gas heat gain Q_{g} can be got by the temperature evolution of the hot gas within the control volume in Eq. (3):

$$Q_{\mathrm{g}} = \frac{\partial}{\partial t} \int_{V} \rho c_{p} T_{g} \, dV \tag{3}$$

where dV is the elementary volume of a control volume.

The heat Q_{w} transfers to component boundaries by convection heat flow $Q_{\mathrm{cv,w}}$ between the gas and the boundaries, the radiation

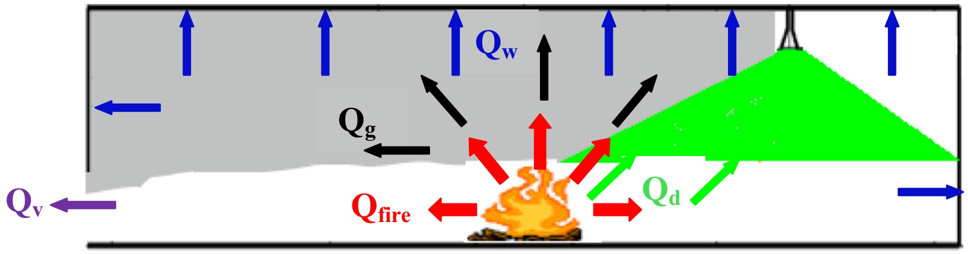

Fig. 1. Theoretical model on interaction between fire and the surroundings.