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The Effects of Water Mist on the Compartment Fire

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ABSTRACT: The present study investigates the fire suppression characteristics using a water mist fire suppression system. Numerical simulations of fire suppression with water mist are performed with considering the interaction of fire plume and water spray. The predicted temperature fields of smoke layer are compared with those of measured data. Numerical results agree with the experimental results within 10℃ in the case without water mist. In the case of fire suppression with water mist, numerical results do not predict well for temperature field in the gradual cooling region after water mist injection. But the predicted results of initial fire suppression are in good agreement with those of measured data. The reason for the discrepancy between predicted and measured data is due to the poor combustion modeling during the injection of water mist. More elaborate models for numerical simulation are required for better predictions of the fire suppression characteristics using water mist.

Nomenclature

A_f : fire source area [m^2]
C_D : drag coefficient
$c_{p,w}$: specific heat of water [kJ/kgK]
D_p : side length of rectangular pool [m]
F : cumulative volume fraction
g : gravitational acceleration [m/s^2]
h : natural convective heat transfer coefficient [W/m^{2}K]
h_v : heat of vaporization [kJ/kg]
ΔH_C : heat of combustion [kJ/kg]
m_d : mass of droplet [kg]
$\dot{m}_f$: burning rate of fuel [kg/m^{2}s]
Nu : Nusselt number
Pr : Prandtl number
Q : heat release rate [kW]
r_d : droplet radius[m]
Re : Reynolds number
Sc : Schmidt number
Sh : Sherwood number
T : temperature [K]
u : velocity vector [m/s]
Y : mass fraction

Greek symbols

μ : viscosity [kg/ms]
η : combustion efficiency
Γ : diffusion coefficient
ρ : density [kg/m^3]

Subscripts

d : droplet
f : fuel
g : gas phase
m : mean

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1. Introduction

In general, the water based fire suppression system is the most widely used for fire protection agent because of non-toxic, economical merits, easily applicable and environmental issues. The important fire suppression mechanisms are known as direct cooling of flame zone and smoke layer, oxygen displacement and attenuation of thermal radiation. According to the droplet sizes of injected water spray, the water-based fire suppression systems can be classified into the sprinkler system and the water mist system. Also, the main suppression mechanism is different with variable droplet sizes. For instance, the sprinkler system with relatively larger droplets suppresses the fire efficiently through the direct cooling of fire source and pre-wetting of adjacent combustible surface. However, using the sprinkler system may be limited because of the water damages in extinguishing the fire and the pollution problem resulting from the excessive water consumption. Contrary to the sprinkler system, the water mist fire suppression system (WMFSS) uses smaller droplets of water and suppresses the fire by direct cooling of fire source and displacement of oxygen due to evaporation of water droplets. Moreover, WMFSS have become an important area because of alternative agent for Halon 1301 and IMO (International Maritime Organisation) regulations which required the retrofit of the fire suppression systems on commercial maritime vessels.

Recently, many research groups make efforts to investigate on suppression mechanism, performance for various fire scenarios, and interactions of fire plume with water mist. USCG (United State Coast Guard) evaluated the applicability of the IMO test protocol and design requirements to smaller machinery spaces through full scale tests with various commercial water mist systems.(1) They also examined the effects of ventilation conditions and fire sizes on fire suppression characteristics. Kim et al.(2) performed an experimental investigation of fire extinction limit. They suggested that the effective water flux is shown to be more useful parameter than the injection pressure for fire extinction limits and also proposed that the burning rate of fuel increases with pressure for fixed distance. But, their study has some limitations that fire source was too small to examine the fire suppression characteristics and distance between nozzle tip and fuel surface was too close to represent the real fire situation. Hua et al.(3) performed, by extending the field-fire modelling technique, transient simulations of the interaction between water spray and fire plume in order to investigate the effect of several important factor – spray pattern, droplet size, and water flow rate – on fire suppression mechanism. Their results show that the water spray with solid cone pattern and finer droplet size was more effective in extinguishing fires than the one with hollow cone pattern and coarse droplet size. They suggested that the water spray flow rate had to be more than a certain critical value. Chow et al.(4) had numerically studied the interaction a water spray with smoke layer, and a one-dimensional model had been developed by taking smoke and air as two quasi-steady layers. Their predicted results of 1-D model agreed well with the experimental data for a spray in ambient air. Their results provided that a spray of larger droplet size and larger velocity would cause an increase in thickness of smoke layer.

Although there are serveral researches on the fire suppression using water mist, it is yet to be short of quantitative research for WMFSS. Thus, it is important to provide the abundant experimental data through the basic research for WMFSS. The main objective of this study is to investigate quantitatively the characteristics of fire suppression using water mist through the full scale experiments in an enclosure and to verify the numerical simulation results with experimental data. These useful data may be helpful in accomplishing the design and installation regulations for manufacturer and several of certification officials.

2. Experimental apparatus and procedure

The fire tests are conducted in a steel-walled enclosure (4.0 m × 4.0 m × 2.3 m) as shown in Fig. 1. The ceiling had a ventilation duct which is connected with exhause fan. This ventilation duct is closed during the entire fire test. The gas temperatures are measured by 15 aluminum sheathed K-type thermocouples. Two thermocouple trees are used to measure the vertical gas temperature distribution in the test compartment. Each tree consisted of 5 thermocouples positioned at 50 cm, 70 cm, 90 cm, 120 cm and 150 cm above the floor level. The ceiling gas temperatures are measured with 4 thermocouples at 1.8 m above the floor level. Two different rectangular steel pans with 0.3 m ($D_p=0.3$) and 0.4 m ($D_p=0.4$) side length are used to generate the pool fire and the rim height of the pool is 5 cm. The fires are produced using methanol (CH_3OH). The fuel burning rate is measured using a load cell with ±3 g accuracy installed in the bottom of each pan. The burning rates of the pool fire are measured in freely burning conditions without water mist injection in the compartment. The heat release rates of the each fire source considering the combustion efficiency, $\eta=0.7$, are calculated as follows;(5)

$$Q = \eta \cdot \dot{m}_f \cdot \Delta H_C \cdot A_f \tag{1}$$

Details of heat release rate for two cases are summarized in Table 1.

Table 1 Heat release rate of methanol fire

Pool size [m]	Heat release rate [kW]
0.3×0.3 ($D_p=0.3$)	22
0.4×0.4 ($D_p=0.4$)	33

Actually, the injected water droplets above the fuel pan may be possible to dilute the methanol fuel. But, the effect of water accumulation on the fuel pan is negligible because of the hollow cone type of spray pattern, relatively long distance between fire source and nozzle, and rapid evaporation for small droplets.

Five downward directed water mist nozzles of hollow cone type with the single orifice are positioned at 1.8 m above the floor level as shown in Fig. 1. The tested nozzles of the pressurized swirl type have been developed in our previous research as the first part of the

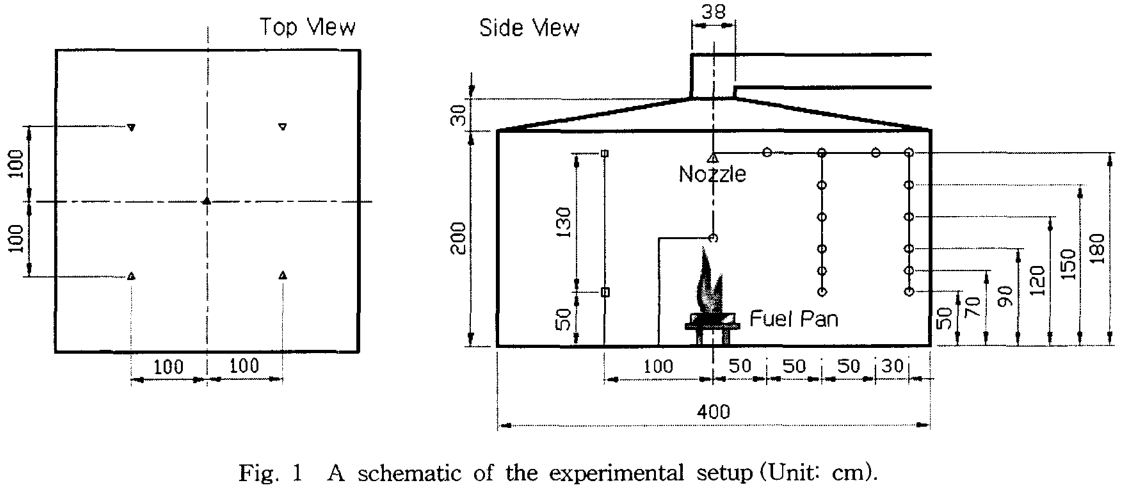


Fig. 1 A schematic of the experimental setup (Unit: cm).

Table 2 Specifications of the tested nozzle

Sauter Mean Diameter (SMD)	121 μm
Spray angle	Outer: 90° Inner: 70°
Operating pressure	13 bar
K-factor	1.66
Spray pattern	Hollow cone type

whole project, called "Development of Man-Made Disaster Prevention Technology".(6) The specifications of water mist nozzle are listed in Table 2. The fires are allowed to maintain the pre-burning situation prior to operation of the water mist system, and the water mist system is activated at a specified ceiling temperature, T_{act}, of 85℃.

3. Modeling method

The FDS (Fire Dynamics Simulator, Ver. 2.0) are used to simulate the interaction of fire plume and water mists.(7) Fire-driven flows in the present FDS code are simulated by LES (Large Eddy Simulation) turbulence model, mixture fraction combustion model, finite volume method of radiation transport for a non-scattering gray gas, and conjugate heat transfer between wall and gas flow.

Two-phase flow between water droplets and gas flow is modelled by Eulerian-Lagrangian method and the trajectory of an individual droplet is governed by the following equqation.

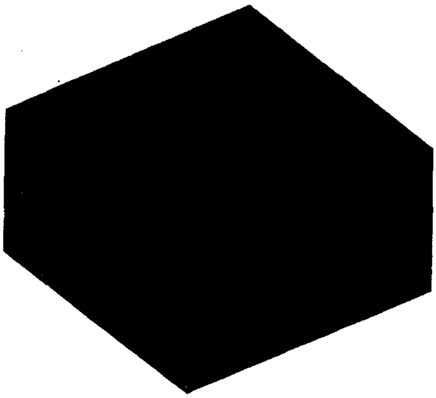


Fig. 2 Grid system of fire compartment.

$$\frac{d}{dt}(m_d \mathbf{u}_d) = m_d g - \frac{1}{2}\rho C_D \pi r_d^2 (\mathbf{u}_d - \mathbf{u}) | \mathbf{u}_d - \mathbf{u} |$$

$$C_D = \begin{cases} \dfrac{24}{\mathrm{Re}} & \mathrm{Re} < 1 \\ \dfrac{24}{\mathrm{Re}}(1 + 0.15\mathrm{Re}^{0.687}) & 1 < \mathrm{Re} < 1000 \\ 0.44 & 1000 < \mathrm{Re} \end{cases} \quad (2)$$

$$\mathrm{Re} = \frac{\rho | \mathbf{u}_d - \mathbf{u} | D_d}{\mu_g}$$

The heat and mass transfer between gas phase and water droplet is calculated by Ranz and Marshell's formula.(8-9)

$$m_d c_{p,w} \frac{dT_d}{dt} = h_d A_d (T_g - T_d) + \frac{dm_d}{dt} h_v \quad (3)$$

$$\frac{dm_d}{dt} = -\pi D_d \mathrm{Sh} \rho D (Y_d - Y_g) \quad (4)$$

$$\mathrm{Sh} = 2 + 0.6\mathrm{Re}^{\frac{1}{2}} \mathrm{Sc}^{\frac{1}{3}}$$

$$\mathrm{Nu} = 2 + 0.6\mathrm{Re}^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}$$

$$h_d = \frac{\mathrm{Nu} \cdot \mathrm{k}}{D_d}$$

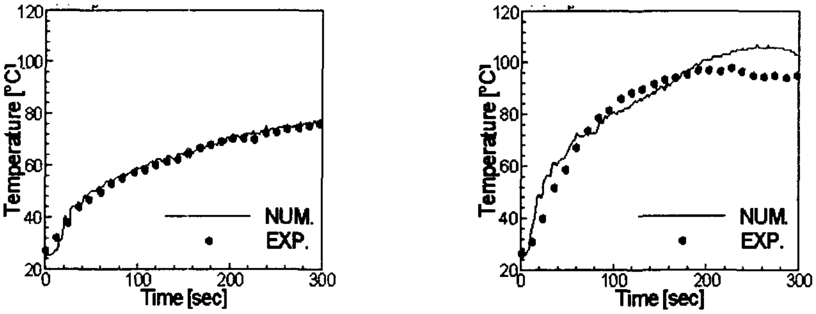
Figure 2 shows the computational domain used in the present study. Because the FDS code is based on the orthogonal grid system, the inclined surface of the fire compartment is represented by stepwise grid approximation. But, the global volume of the computational domain is the same as that of the real compartment. A mesh of 338,688 cells is used to discretise the domain. There are 84 cells in the length and the width of compartment and 48 cells in the height. The measured spray characteristics such as injection velocity and spray angle are applied to the initial injection condition of water droplet. Each simulation is performed up to 600 s after ignition, the computing time is required about 30 hour by P-4, 1.7 GHz.

4. Results and discussion

Prior to simulate the fire suppression, the preliminary tests without water mist are performed for methanol fires. These tests contribute to validate the predictions of FDS code against the experimental data for methanol fires without water mist. Figure 3 represents the mean ceiling temperature over four points along the ceiling and the predicted mean ceiling temperature is compared with the measured data. The predicted results are in good agreement with the measured mean ceiling temperature within 5℃ for D_p=0.3 methanol fire. The predicted result for D_p=0.4 methanol fire shows that the maximum discrepancy is about 10℃ at 200 s after ignition. While the predicted temperatures for each measured position become slightly high near the center of ceiling, they do relatively low near the wall. However, the maximum difference of both results does not exceed 10℃ in the overall ceiling region. Figure 4 shows the comparisons of vertical temperature distribution for D_p=0.3 and D_p=0.4 methanol fire at TC tree 1. It seems that the predicted vertical temperatures agree well with the experimental data. However, the numerical results for D_p=0.4 have some discrepancy within 10℃ at 200 s after ignition. In general, the FDS results are acceptable in predicting the basic fire characteristics dealt with in the present study.

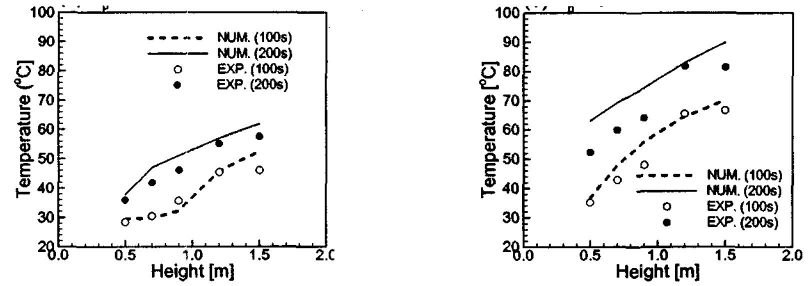
4.1 Fire suppression using water mist

Figure 5 shows the velocity and temperature field at 30 s after water mist injection for 33 kW methanol fire. The discharged water mist passes through the fire plume and consequently affects the cooling of fire plume directly because of heat absorption by the evaporation of



(a) D_p=0.3 m (b) D_p=0.4 m

Fig. 3 Comparison of ceiling mean temperature.



(a) D_p=0.3 m (b) D_p=0.4 m

Fig. 4 Comparison of vertical temperature at 1 m from the fire source.

water droplets. The fire plume is mostly suppressed by injected water mist except near the fuel surface. Figure 6 represents the comparisons of temperature at 1.0 m and 1.8 m from the fire source. When the water mist is discharged from nozzles, generally, water mists absorb heat from the surrounding gas phase and quickly evaporate. At the same time, discharge of water mist makes a strong dynamic mixing in the compartment and consequently temperature gradient between upper and lower layers decreases. Therefore, the temperature of smoke layer decreases abrubtly as time goes on. After the sudden cooling of smoke layer, the ceiling temperature gradually decreases with much lower rate than that of sudden cooling. It results from the fact that the temperature difference between droplets and smoke layers are

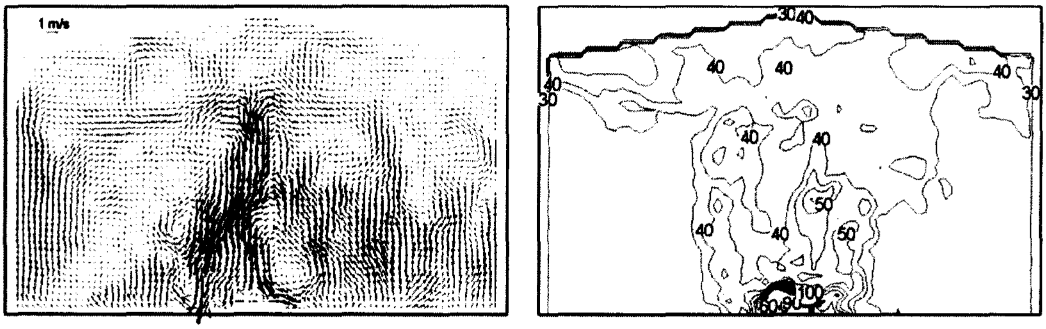
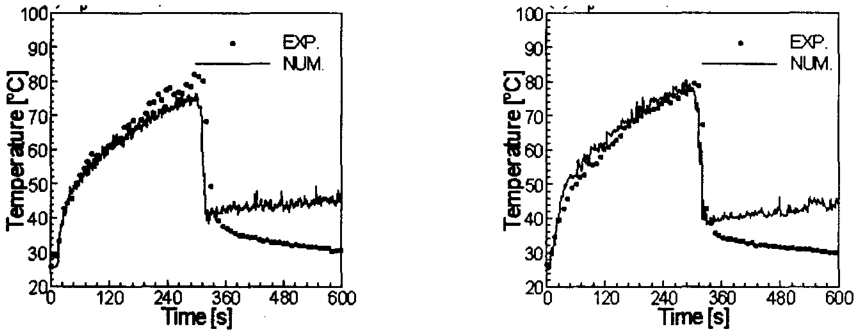
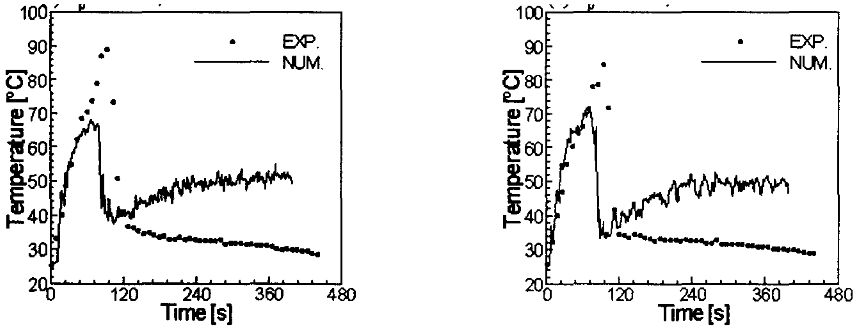


Fig. 5 Velocity and temperature field at 30 sec after mist injection.



(a) D_p=0.3 m, R=1.0 m (b) D_p=0.3 m, R=1.8 m



(c) D_p=0.4 m, R=1.0 m (d) D_p=0.4 m, R=1.8 m

Fig. 6 Comparison of ceiling temperature with water mist.

relatively lower than that in sudden cooling period because thermal energy accumulated in initial fire plume is mostly lost in the sudden cooling process. As shown in Fig. 6, The trends of numerical result are similar with experiments in the initial fire growth and sudden cooling process, but the numerical simulations are fail to predict the temperature field in gradual cooling process. The discrepancy may be due to the combustion modeling used in FDS code. As a matter of fact, the burning rate is highly affected by the water mist in the real situation because of additional factors such as air entrainment due to water mist injection and strong interactions between fire source and water mist. Nevertheless, FDS code does not consider this variation of burning rate. Thus, further theoretical and experimental studies for the burning rate variations should be performed as a future work in order to complete the present combustion model. The FDS results give reasonable predictions in the initial fire growth and sudden cooling process in the present study.

5. Conclusions

The characteristics of fire suppression using the water mist have been investigated numerically and experimentally for methanol pool fire. The conclusions are summarized as follows:

(1) The numerical results without water mist injection are in good agreement with experimental data. The maximum discrepancy between them does not exceed 10℃ in the overall ceiling region.

(2) The initial fire growth and sudden cooling process are successfully predicted by the numerical simulation, while it is difficult to predict the graudual cooling process using the present FDS model.

(3) Further theoretical and experimental studies for the present FDS model are required to predict more accurately the fire suppression using water mist.

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