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Characterization of an effervescent atomization water mist nozzle and its fire suppression tests

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Abstract

A gas-outside-liquid-inside water mist nozzle based on effervescent atomization technology is designed, characterized and tested in this paper. The droplets size distribution, velocity under different operation pressures and gas-liquid-ratios (GLR) are measured with a Phase Doppler Analyser (PDA). The gas flow rate, liquid flow rate of the nozzle with one or seven orifices are also characterized under different operation pressures and GLR conditions, respectively. The results show that all of above parameters are mainly influenced by GLR, i.e., the larger the GLR is, the smaller the droplet size will be, and the liquid mass flow rate is exponentially increased with the increasing of GLR. The test results of fire suppression show that this gas-outside-liquid-inside effervescent atomizer works well for fire extinguishment except the cases where the liquid flow rate is less than about 70 kg/h and the gas pressure is lower than 0.3 MPa.

Keywords: Effervescent atomization; Two-phase flow; Water mist; Fire suppression

1. Introduction

It is well known that the use of water mist for fire suppression was sparked since the first version of the Montreal Protocol which was introduced in 1987. This international commitment to protect the earth's ozone layer from further damage by chlorinated fluorocarbons (CFC's), has driven about 20 years of testing to develop alternative fire suppression technologies to replace the chlorine- or bromine-based gaseous fire suppressants known as Halons. Water mist is not associated with such dangers to people in occupied areas and has received considerable attention as one of the potential methods for replacement of Halon 1301 and 1211 [1,2].

Fire suppression mechanisms of water mist are rather complex. The main mechanisms can be identified as fuel surface cooling, flame cooling and oxygen dilution and displacement. The sub-mechanisms include blocking of radiant heat transfer, reducing mixing concentration ratio of combustibles and oxygen, and dynamical influences [3–8]. The characteristics of mist droplets, such as droplet size distribution, velocity and spray density, are key factors which may mainly influence the fire suppression efficiency of a water mist system [9]. Generally, in order to produce relatively smaller mist droplets, traditional water mist nozzles, such as pressure jet nozzles and impingement nozzles, are applied with higher working pressures. Otherwise, coarser mist droplets should be produced, which may cause poor

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Nomenclature

GLR	gas to liquid mass flow-rate ratio, dimensionless
SMD	Sauter mean diameter, m
P	operation pressure, MPa
M	mass flow rate, kg/h
P_c	pressure inside the nozzle mixing cavity, MPa
P_0	ambient pressure, MPa
R	universal gas constant, J mol^{-1} K^{-1}
d	diameter, m
d_0	diameter of the nozzle orifice, m
T_0	ambient temperature, K
k	specific heat ratio
ρ	density, kg/m^3
μ	viscosity, cP
σ	surface tension, N/m

Subscripts

g	gas
l	liquid
L	ligament

fire suppression effectiveness. However, effervescent atomization technology can generate finer water mist under relatively lower pressures.

Effervescent atomization technology is one of the twin-fluid atomization methods while it has better performance in terms of smaller drop sizes and/or lower injection pressures [10]. Roesler and Lefebvre conducted experiments to visualize the two-phase flow inside an effervescent atomizer as it approaches the exit orifice and the near-nozzle liquid break-up mechanism [11,12]. Huang et al. visualized the two-phase flow patterns inside the effervescent atomizer and studied the effects of superficial liquid velocity and GLR on transition between the flow patterns, known as bubbly flow, annular flow, and intermittent flow [13]. Sovania et al. had discussed the mechanisms of effervescent atomization and studied the effects of ambient pressure on its spray cone angle [14,15]. However, there is few studies have been performed focusing on characterization and its fire suppression efficiency of an effervescent atomization based water mist nozzle. Therefore, a gas-outside-liquid-inside effervescent atomizer was developed, characterized and tested for fire suppression under different operation pressure and GLR conditions in this work.

2. Experiment apparatus

As shown in Fig. 1, the PDA system manufactured by TSI Co. in USA is used for mist droplet size and velocity measurement. A 5 W Innova70 Ar^+ laser is used by the system and the light is splitted to 514.5, 488 and 476 nm by a Colorburst unit,

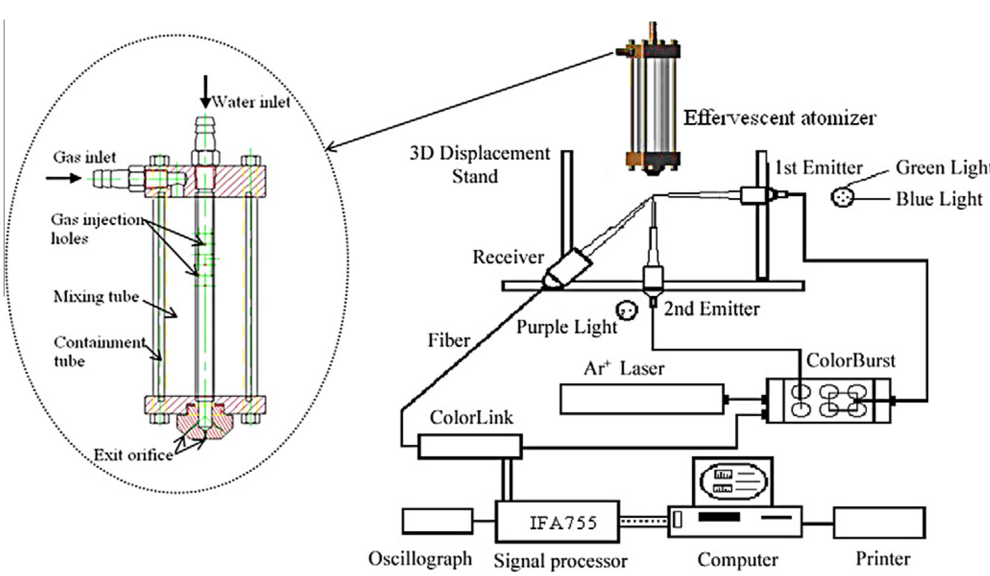

Fig. 1. Schematic diagram of mist droplet characterization with PDA system.

so 3-D velocity of the droplet passing through the measurement volume can be obtained. A 7-hole plain-orifice gas-outside-liquid-inside effervescent atomizer was manufactured and used for fire suppression tests. The overall length of the atomizer is approximately 160 mm. The containment tube has the inner diameter of 40 and 5 mm wall thickness. The mixing tube has 6 mm inner diameter and 2 mm wall thickness. Twenty four gas injection holes with 1 mm diameter are designed for injecting gas into the mixing tube. Each ring is spaced 8 mm apart and rotated 45° from the neighboring ring. The last ring with the injection holes is located 80 mm upstream of the exit orifice. The exit orifice has seven injection holes, where one is set in the center and the others symmetrically mounted around it, and each one with 1.5 mm diameter. To the case for its characterization with PDA system, only the center orifice was considered, while the other six were blocked up.

Figure 2 shows the schematic diagram of the water mist generation system with an effervescent atomizer. Two flowmeters and two pressure sensors coupled with some valves are used for determining flow rate of the nozzle under different operation pressure and GLR conditions.

Fire suppression tests were performed in a $3 \times 3 \times 3$ m confined space as shown in Fig. 3. Six K-type thermocouples are directly placed above the fuel pan to obtain the flame temperature history before and after the application of water mist. A 0.22 m diameter pan with a lip height of 0.04 m is used for test of diesel pool fire suppression. Extinguishing time is determined by using a stop-watch which with a resolution of 1/100 s. At the same time, a JVC DVM801 CCD camera was used to record the extinguishment processes for subsequent frame-by-frame analysis.

3. Results and discussion

3.1. Characterization of the effervescent atomization nozzle

The droplet size and velocity were measured by the PDA system, where the measurement volume was located 0.4 m away from the orifice of the

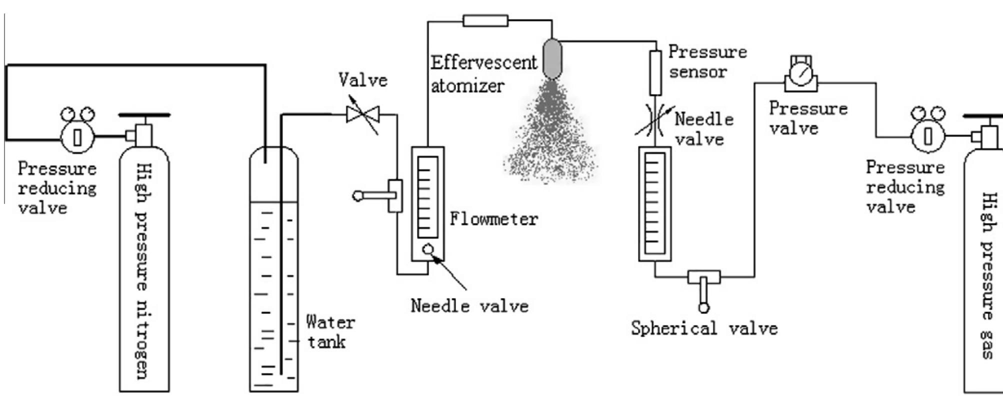

Fig. 2. Schematic diagram of the water mist generation with an effervescent atomizer.

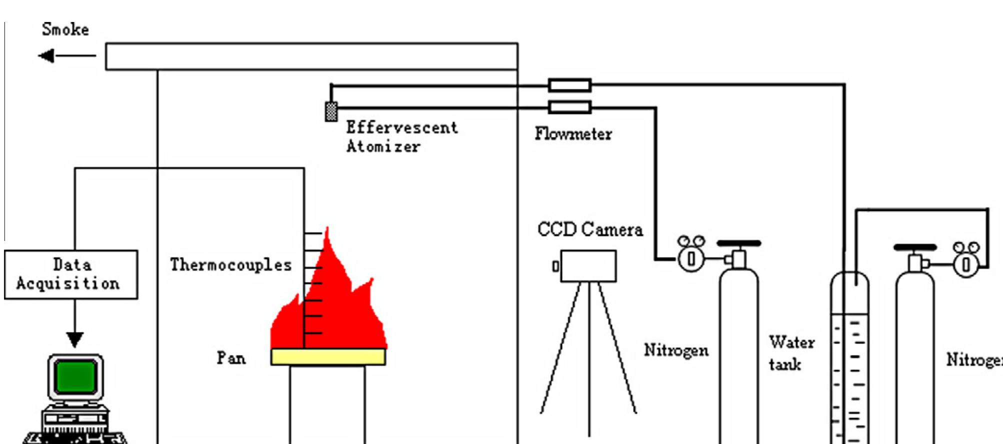

Fig. 3. Schematic diagram of water mist fire suppression test with effervescent atomizer.

atomizer. Figures 4 and 5 show the Sauter mean diameter (SMD) and its droplets size distribution of the atomizer with one orifice measured under different gas operation pressure (P_g) and GLR conditions, respectively. Figure 6 shows the axial and radial mean velocity of the droplets. The results obviously show that both of the droplets size distribution and the mean velocity are strongly influenced by the GLR. This can be explained that the liquid is broken up by the rapidly expanding bubbles on leaving the orifice for effervescent atomization. The higher the GLR is, the higher

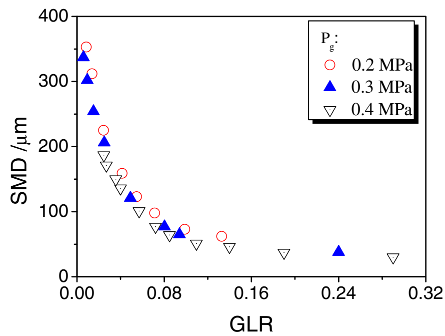

Fig. 4. The Sauter mean diameter measured with PDA under different GLR conditions.

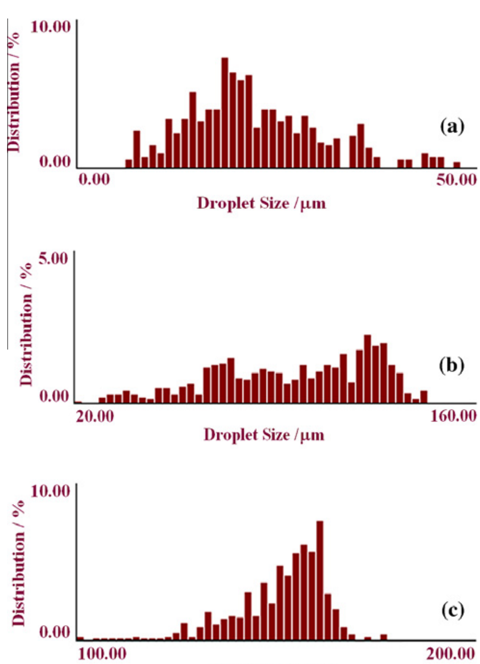

Fig. 5. Droplet size distribution measured with PDA system: (a) $P_g = 0.4$ MPa, GLR = 0.29, (b) $P_g = 0.4$ MPa, GLR = 0.057, (c) $P_g = 0.4$ MPa, GLR = 0.036.

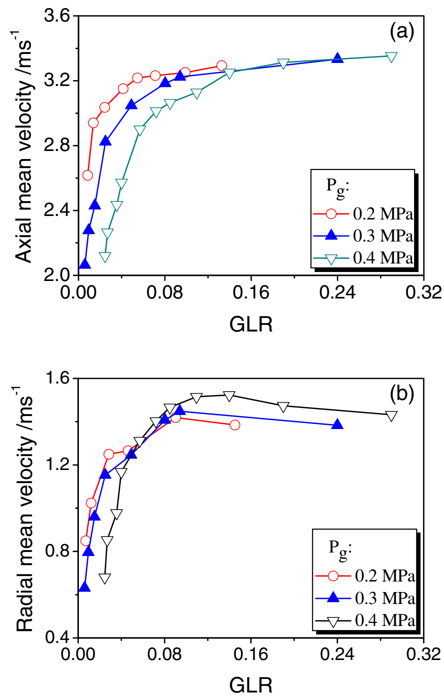

Fig. 6. The axial and radial mean velocity of the droplets measured with PDA system: (a) axial mean velocity, (b) radial mean velocity.

the gas flux will be, then the higher smashing energy can be provided for liquid atomization. Therefore, the droplet size will decrease and its mean velocity will increase as the GLR is increased, especially when the GLR is lower than 0.06.

The SMD also can be predicted with modelling. For instance, Lefebvre considered the effervescent spray is based on bubble and liquid film breakup when the liquid flow inside the nozzle is bubbly flow, and the SMD of the droplets can be predicted with Eq. (1) [16], where C_1 and C_2 are experiment related factors. In this work, $C_1 = 9.30 \times 10^{-2}$ and $C_2 = 3.35$. To the case of annular flow, the SMD prediction model was deduced by Lund et al. as given in Eq. (2) [17]. Figure 7 gives the comparison between the measured and predicted results of SMD. It shows that the measured results agree well with the predicted ones.

$$\mathrm{SMD} = \left\{ C_1 \cdot \mathrm{GLR} \cdot \frac{\rho_l R T_0}{\sigma(k-1)} \left[1 - \left(\frac{P_0}{P_c} \right)^{\frac{k-1}{k}} \right] + \frac{C_2}{d_0} \right\}^{-1} \quad (1)$$

$$\mathrm{SMD} = \left[\frac{3}{2} \sqrt{2} \pi d_L^3 \left(1 + \frac{3\mu_l}{\sqrt{\rho_l \sigma d_L}} \right)^{0.5} \right]^{1/3} \quad (2)$$

The liquid and gas mass flow rate of the effervescent atomizer with one or seven orifices under different operation pressures and GLRs are deter-

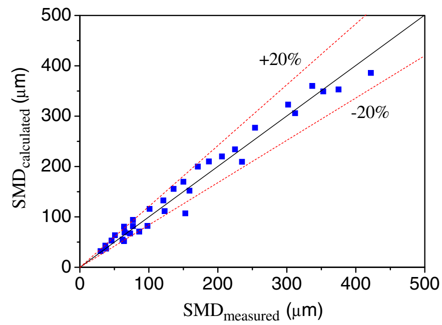

Fig. 7. Comparison of the measured and predicted results of SMD.

mined, respectively. As shown in Figs. 8 and 9, both of the liquid and gas mass flow rate are increased with increasing of the gas operation pressure, while the liquid mass flow rate is exponentially decreased with the increasing of GLR. Based on these experimental data, the relationship among the GLR, the liquid mass flow rate and the gas operation pressure can be derived by the curve fitting method [18]. To the case with one orifice being considered, the relationship between the liquid mass flow rate and the GLR can be expressed as:

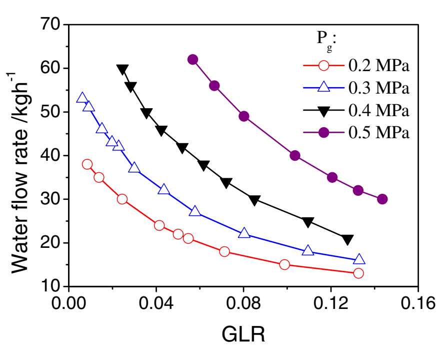

Fig. 8. Water flow rate of the effervescent atomizer with one orifice.

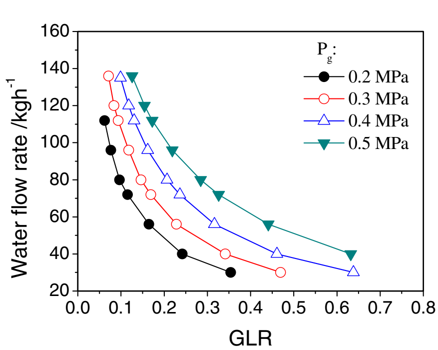

Fig. 9. Water flow rate of the effervescent atomizer with seven orifices.

$$M_l = k_1 + k_2 e^{-\mathrm{GLR}/k_3} \tag{3}$$

where k_1, k_2 and k_3 are fitting coefficients. Based on fitting the experimental data of liquid mass flow rate and the GLR under different gas pressures, they can be determined as [18]:

$$\begin{cases} k_1 = 7.44 + 19.2P_g \\ k_2 = 15.7 + 6.29e^{P_g/0.191} \\ k_3 = 0.0411 + 0.00113e^{P_g/0.156} \end{cases} \tag{4}$$

substitute Eq. (4) into Eq. (3), we can obtain

$$M_l = 7.44 + 19.2P_g + (15.7 + 6.29e^{P_g/0.191}) \times e^{-\mathrm{GLR}/(0.0411+0.00113e^{P_g/0.156})} \tag{5}$$

with the similar way, the relationship between the liquid mass flow rate and the GLR of the effervescent nozzle with seven orifices can be determined as shown in Eq. (6), while two exponential functions are considered for data fitting due to a wide range of GLR values occurs to this type nozzle [18].

$$M_l = 22.1 + (73.0 + 268P_g - 241P_g^2)e^{-\mathrm{GLR}/(0.0556+0.0349e^{P_g/0.256})} + (186 + 65344e^{-P_g/0.0360})e^{-\mathrm{GLR}/(-0.0266+0.275P_g-0.232P_g^2)} \tag{6}$$

3.2. Fire suppression tests with the effervescent atomization nozzle

Tests of diesel oil fire suppression were conducted using the effervescent atomization nozzle with seven orifices. High pressure nitrogen was adjusted to 0.2, 0.3 and 0.4 MPa as gas operation pressures. The nozzle was set 1.50, 1.75 and 2.00 m above the fuel surface. Figure 10 gives the fire extinguishment time under different gas operation pressures and water flow rates, where the distance between the nozzle and the fuel surface is about 2.00 m. Figure 11 gives a summary of the fire suppression test results which were averaged with at least three data. It is obviously shown that, to same gas operation pressure, the

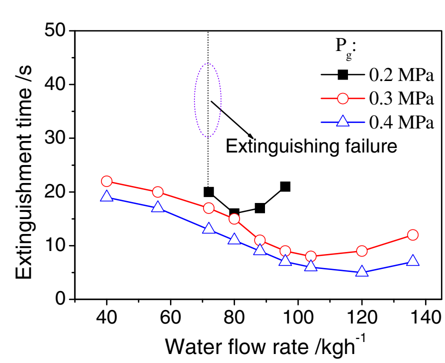

Fig. 10. Extinguishment time under different gas operation pressures and water flow rates.

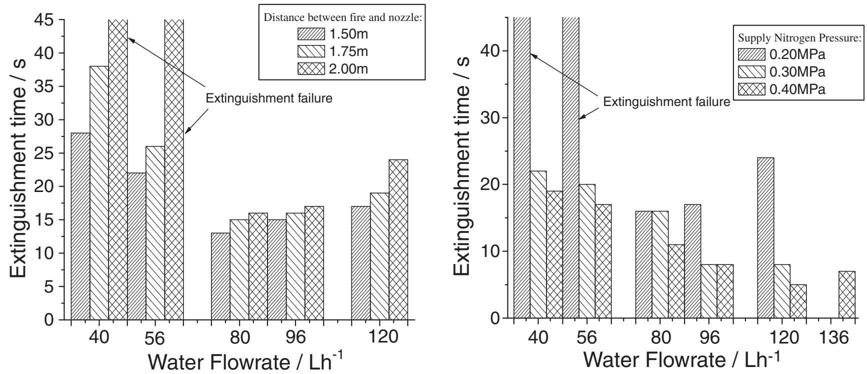

Fig. 11. Test results of fire suppression with different water flow rates: (a) gas operation pressure is 0.20 MPa, (b) distance between the fire and nozzle is 2.0 m.

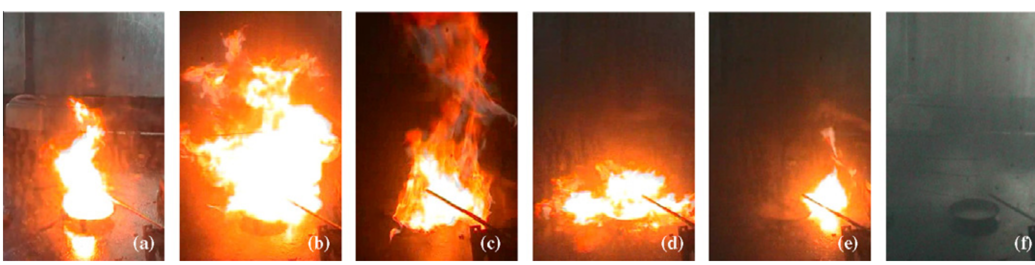

Fig. 12. Diesel pool fire behavior before and after the injection of water mist (gas pressure: 0.30 MPa, distance: 2.00 m, water flow rate: 80 kg/h): (a) before water mist injected, (b) water mist injection started, (c) 6s after water mist injection, (d) 11 s after water mist injection, (e) 14 s after water mist injection, (f) 16 s after water mist injection.

larger the distance is, the more difficult the fire can be extinguished. And to same distance, the fire can be extinguished easily when the gas pressure is higher. The reason is that the momentum of the nitrogen and the droplets are larger under higher pressure or smaller distance. Then the "blow out" effect of the nitrogen is enhanced and the droplets are easy to penetrate into the flame or reach the fuel surface. In addition, the droplet size is smaller with higher operation pressure, so the flame cooling efficiency is enhanced. The results of the tests also show that an optimization value of the water flow rate for fire extinguishing exists, and this value increases as the gas operation pressure increases, while larger water mass flow rate is better for single fluid water mist nozzle [19]. The reason is that droplet size is increased and gas flow rate is decreased by the increase of water mass flow rate for effervescent atomizer, while larger droplets have worse effects on flame cooling and smaller gas mass flow rate has worse effect on blow out and oxygen dilution.

Figure 12 shows the video pictures of the diesel oil fire before and after the interaction of water mist. Unlike the extinguishing process with a single fluid water mist nozzle, the flame can be enlarged at the beginning of water mist injection as shown in Fig. 12(b). This can be explained that the stirring of the nitrogen gas and the evaporative expansion of water mist droplets enhance the mixing of the fuel vapor and the fresh air which being entrained by the injecting water mist. So the combustion will be enhanced before the temperature of the fire plume is cooled down. Generally, the fire can be extinguished within one minute except the cases under which the nitrogen pressure or the water flow rate is not large enough. For instance, to the test cases of this work, it is difficult to extinguish the fire when the water flow rate is less than about 70 kg/h and the gas pressure is lower than 0.3 MPa.

4. Conclusions

A new kind of effervescent atomization based water mist nozzle was designed and its fire suppression efficiency was tested in a 3 × 3 × 3 m confined space. The droplets size distribution and velocity were measured with a PDA system, while the flowmeters and pressure sensors coupled with some valves were used for determining of the flow rate.

Following conclusions can be drawn from the experimental results: (1) Both of the droplets size distribution and the mean velocity are mainly influenced by the GLR, i.e., the droplet size will decrease and its mean velocity will increase rapidly as the GLR is increased, especially when the GLR is lower than 0.06. (2) The liquid and gas mass flow rate are increased with increasing of the gas operation pressure, while the liquid mass flow rate is exponentially decreased with the increasing of GLR. (3) To the test cases of this work, there is an optimum water flow rate with which the fire suppression effectiveness is best, and when the water flow rate is less than about 70 kg/h and the gas pressure is lower than 0.3 MPa, the fire can not be extinguished.

Acknowledgments

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