Research on key parameters of water mist fire protection in ship cabin

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Abstract. Because of good cooling, heat absorption, attenuation of heat radiation and other functions, water mist is especially suitable for ship fire extinguishing and cooling. The CFD software is used to simulate water mist fire extinguishing and cooling in a ship cabin under the condition of six different parameter combinations. When the grain size is less than 150μm, the cabin temperature can be reduced to 25°C in three minutes after water mist intervention. The larger the flow rate, the smaller the grain size, the faster the cooling rate. Fire extinguishing efficiency test of water mist in small scale ship cabin is carried out. The result shows that water mist with grain size of 100μm-150μm can quickly extinguish fire and reduce cabin temperature to 25°C in two minutes.

1. Introduction
The principle of water mist fire extinguishing is that pressured flow through a nozzle of special structure, which makes pressured water decompose into tiny droplets of a certain speed to extinguish fire. Because of high efficiency, non-toxic, non-pollution, safe and low cost, water mist fire extinguishing has been widely used in civilian and industry construction. Water mist fire extinguishing mechanism includes the following four aspects[1-3]:

(1) Cooling and heat absorption. Due to the small size of water mist droplet, the smaller water mist droplet size of the same mass, the larger surface area is. Therefore, the total surface area of heat absorption and the evaporation rate of water is increased, rate of cooling speed from high temperature gas flame becomes faster.

(2) Isolate oxygen and asphyxia. When water mist is rapidly absorbed heat and evaporated, its volume will expand rapidly, usually up to 1600 times. If water mist is sprayed in a confined space, the droplets will evaporate and expand rapidly, forming water vapor that will replace oxygen. When the oxygen concentration for combustion falls below a critical value, the combustion efficiency will decrease.

(3) Decay thermal radiation. The attenuating effect of water mist on thermal radiation in fire is that water mist forms a barrier around the combustion area to prevent heat transfer of thermal radiation, the other is to prevent flame from spreading to the surface of unburned fuel and reduce evaporation rate on the surface of fuel.

(4) Emulsification. For a fire of insoluble flammable liquid, the impact of water mist can form an emulsified layer on the surface of the liquid. On the one hand, the evaporation rate of liquid is reduced, and on the other hand, the combustibility of emulsified layer reduces the combustion intensity.

With the popularization and application of water mist fire extinguishing, some ships have set up whole ship water mist fire extinguishing system. For ship fire, we should pay attention to the cooling and heat absorption effect as well as fire extinguishing. First of all, steel structure is used to support and separate the interior of the ship. The fire resistance time of bulkheads and decks is generally 1h, which
is a big disadvantage with 3h of land buildings. Secondly, there are a large number of diesel and hydraulic oil equipment in ship power cabin, the risk of Class B fire is higher. Class B fire develops rapidly and fire source power is larger than Class A fire in land buildings, besides, high temperature smoke generated is more likely to pose a threat to the steel structure of ships.

In this paper, the key parameters of water mist fire extinguishing and cooling are proposed according to the characteristics of ships. Numerical simulation of water mist fire extinguishing and cooling performance in a ship cabin is established. A small size fire extinguishing test of water mist is carried out, the cooling and heat absorption effects of water mist flow and droplet size are compared and analyzed.

2. Parameters of water mist extinguishing and cooling

Water mist is a kind of water droplets ejected from nozzle under the minimum design working pressure and formed on the plane 1 meter below the axis of nozzle, which diameter of $D_{v0.5}$ is less than 200μm and $D_{v0.99}$ is less than 400μm.

Water mist fire extinguishing is divided into three pressure levels:

1. High pressure system, with rated working pressure greater than 3.5MPa.
2. Medium pressure system, with rated working pressure greater than 1.2MPa but less than 3.5MPa.
3. Low pressure system, with rated working pressure less than 1.2MPa.

According to NFPA 750[4], the relationship of one single water mist nozzle between flow $q$ (L/min) and pressure $P$ (MPa) is shown as following:

$$q = K\sqrt{10P}$$  \hspace{1cm} (1)

Where, $K$ is the nozzle flow coefficient.

Suppose the area of a protection place is $s$ (m$^2$), and $n$ water mist spray nozzles are arranged, then the spray intensity $I$ (L/min·m$^2$) can be expressed as following:

$$I = \frac{\sum q}{s}$$  \hspace{1cm} (2)

The minimum allowable spray intensity varies greatly with different application places and pressure levels, but the spacing of nozzle is almost constant. Since interior space is divided into various fixed spaces by metal components such as decks and bulkheads, the spray intensity of water mist fire extinguishing in ship is mainly determined by nozzle flow.

For the convenience of analysis, it is assumed that diameter of water mist droplets $d$ produced by a nozzle is uniform. According to the conservation of mass, the total number of water mist droplets produced by a nozzle within time $\Delta t$ is:

$$N = q \times \Delta t / [60000 \times \left(\frac{1}{6}\pi d^3\right)]$$  \hspace{1cm} (3)

Total surface area $S$ of water mist droplets is:

$$S = N\pi d^2 = \frac{q\Delta t}{10000d}$$  \hspace{1cm} (4)

Combined with cooling and heat absorption mechanism of water mist, it can be seen that the larger $S$ is, the better the cooling and heat absorption capacity is. Therefore, the key parameters affecting fire extinguishing and cooling of water mist in ship are nozzle flow and droplet diameter.

3. Related Research and Analysis

Liu[2] studied water mist droplet diameter for different types of fire. For Class B fire, different flash point fuels have different requirements for fire extinguishing. The extinguishing mechanism of the fuel with flash point below 60°C is mainly gas phase flame cooling. It is suggested that the fuel with flash point below 60°C is relatively suitable for water mist droplet diameter range of 50μm to 200 μm. The extinguishing mechanism of the fuel with flash point above 60°C is mainly gas phase flame and surface
cooling together. It is suggested that appropriate droplet diameter range for the fuel with flash point above 60℃ is 150μm to 300μm.

Liao[3] studied the influence of nozzle working pressure on droplet diameter and fire extinguishing time. In the same pipe network, nozzle arrangement and burning power, improve nozzle working pressure, not only flow and spray intensity but also initial velocity and momentum of the droplets is increased. The water droplets can overcome resistance of thermal to the root of fire flame, directly cool flame core area. Increasing pressure can significantly reduce fire extinguishing time.

Lu[5] analyzed research status of water mist fire extinguishing on ship in United States and United Kingdom, proposed that to develop a fire extinguishing system suitable for ship cabins, the performance design method must be carried out. Risk assessment of protected sites should be conducted according to actual hazard sources and possible fire scenarios, and then system design plan should be completed.

Liu[6] studied temperature characteristics of water mist extinguishing Class B fire. In experiment, water mist flow rate is 24L/min, droplet diameter size is 300μm, and temperature in a flame center point can be reduced from 1500K to 300K within 8s.

Meenakshi[7] carried out fire extinguishing and cooling test with D\textsubscript{0.5} water mist of 20μm to 30μm, and flame temperature could be reduced from 150℃ to 50℃ within 1min.

Liu[8] used a water mist of 10MPa and 80μm to carry out fire extinguishing and cooling test, and the flame temperature could be reduced from 550℃ to 25℃ within 40s.

Paolo[9] used D\textsubscript{0.5} 80μm water mist to carry out fire extinguishing test of high danger warehouse, which could quickly make temperature below 60℃.

4. Numerical simulation of water mist fire extinguishing

4.1 Model of fire extinguishing with water mist
A fire is supposed to burn in the bottom of ship cabin, and two or three water mist nozzles are arranged on the top of cabin. Firstly, the two-layer regional model is used to calculate the temperature of top smoke layer and bottom air layer as the initial temperature[10]. Secondly, CFD software FLUENT is used to model and calculate water mist fire extinguishing and cooling, as is shown in Figure 1, coordinate O is on the cabin midline plane.

![Figure 1](image)

Figure 1 Schematic of numerical simulation of water mist fire extinguishing and cooling

Six different kinds of water mist parameters are set in the following Table 1.

| Table 1. water mist extinguishing parameter table |
|-----------------------------------------------|
| condition | nozzle | droplet diameter(μm) | one single flow(L/min) |
|-----------|--------|---------------------|------------------------|
| 1         | 3      | 0                   | 0                      |
| 2         | 3      | 100                 | 4.4                    |
| 3         | 3      | 100                 | 13.2                   |
| 4         | 2      | 50                  | 13.2                   |
| 5         | 2      | 100                 | 13.2                   |
| 6         | 2      | 150                 | 13.2                   |
4.2 Simulation result

4.2.1 Influence of nozzle flow rate
Figure 2 is corresponding result of condition No. 1 to 3 in Table 1, the variation curves of upper space, lower space and average cabin temperature with time are given under different nozzle flow rate. In this result, the upper space temperature is taken as average plane temperature which is 3m above cabin midline. While, the lower space temperature is taken as average plane temperature which is 3m below cabin midline.

![Figure 2 Comparison of water mist cooling with different flow rate](image)

(1) no water mist, self cooling
(2) water mist, 100μm, 4.4 L/min
(3) water mist, 100μm, 13.2 L/min

4.2.2 The influence of droplet diameter
Figure 3 is corresponding result of condition No. 4 to 6 in Table 1, the variation curves of upper space, lower space and average cabin temperature with time are given under different droplet diameter.

![Figure 3 Comparison of water mist cooling with different droplet diameter](image)

(1) water mist, 50μm, 13.2 L/min
(2) water mist, 100μm, 13.2 L/min
(3) water mist, 150μm, 13.2 L/min

4.3 Simulation results analysis
Based on the time of average cabin temperature dropping to 25°C, the cooling effect of six water mist working conditions is compared in Table 2.

| nozzle | droplet diameter(μm) | one single flow(L/min) | cooling time (min) |
|--------|----------------------|------------------------|-------------------|
| 3      | 0                    | 0                      | >10               |
| 3      | 100                  | 4.4                    | 2.1               |
| 3      | 100                  | 13.2                   | 1.1               |
| 2      | 50                   | 13.2                   | 1.4               |
| 2      | 100                  | 13.2                   | 1.6               |
| 2      | 150                  | 13.2                   | 2.8               |

In self cooling state, cabin temperature drops slowly, after water mist is intervened, cabin temperature drops rapidly in about 3 minutes. While simulation flow is increased 3 times, cooling time is shorten to about 50%. According to equation (4), the greater water flow is, the better ability of oxygen insulation
and heat radiation absorbing will be, and temperature of flame surface is lowered down, effectively restrain flame heat release rate to achieve purpose of fire control.

The decrease of droplet diameter can accelerate temperature dropping rate in cabin, and the cooling time of 50μm water mist is about 50% shorter than 150μm water mist. According to equation (4), the smaller droplet diameter is, the larger surface area will be, therefore, interface area between atmosphere and liquid is increased to speed up evaporation heat of water.

5. Small size water mist fire extinguishing test of ship cabin

A small size ship cabin water mist fire extinguishing experiment system is set up. The cabin area is 11m², three water mist nozzle is located on the top, apart from 2.8m of ground, water mist nozzle pressure is 5MPa, spray angle is 120°, average droplet diameter is 100 to 150μm, an oil pan of 600mm in diameter is placed on the ground in the center of three nozzle. The test schematic is shown in figure 4.

In the test, after 30 seconds of pre-burning, water mist fire extinguishing is started. The test result is shown in Table 3, cooling time is total minutes of cabin temperature dropping to 25°C. Indoor temperature changing curve during the test is shown in Figure 5.

After oil pan is burned, the cabin temperature rises to 50°C - 60°C in 30s. Then water mist system is started to spray, oil fire is impacted by water mist momentum, flame is flickered. After spraying continuously, due to the effect of water mist evaporation under high temperature of the fire, fire is quickly cooled and extinguished in about 2min, while indoor temperature is reduced to 25°C.
6. Conclusions
(1) Based on the characteristics of ship, key parameters of water mist fire extinguishing and cooling are proposed in this paper. Numerical simulation and fire extinguishing test of water mist in small-size ship cabin are carried out, and cooling effects of water mist flow rate and droplet diameter are compared and analyzed.

(2) Six kinds of water mist fire extinguishing numerical simulation show that cabin temperature decreases to 25°C within 3 minutes. When the simulated flow rate is increased by 3 times, cooling time is shortened to about 50%. The decrease of droplet diameter can quicken temperature decline rate in the cabin, and the cooling time of 50μm water mist is about 50% shorter than 150μm.

(3) The small size water mist fire extinguishing test shows that water mist of 100-150μm can extinguish fire quickly and reduce cabin temperature to 25°C within 2 minutes.

(4) In the next step, according to the characteristics of fire scenarios in different ship cabin, we will continue to study the influence of different water mist parameter combinations on fire extinguishing and cooling performance, propose the optimal scheme of water mist fire extinguishing and guide system design in ship.

References
[1] Niu Guoqing. (2007) Theoretical and experimental study of compartment fire suppressed by water mist.
[2] Liu Xin, Deng Xiaoli, Wei Dong. (2012) Discussion on different extinguishing mechanism of water mist relative appropriate particle size. Fire technology and product information, 6:67-70
[3] Liao Yide. (2008) Research on High pressure fine water mist fire suppression system key problems and its performance.
[4] NFPA 750. (2019) Standard on water mist fire protection systems. NFPA.
[5] Lu Qiang, Liao Guangxuan, Huang Xin. (2004) Review of study of water mist fire protection systems on shipboard. Engineering science, 6(9):88-94
[6] Liu Xin, Deng Xiaoli, Wei Dong. (2012) Study on the temperature and concentration diffusion characteristics of water mist extinguishing liquid fire. Fire technology and product information, 6:67-70
[7] Meenakshi Gupta, Amit Pasi, Anjan Ray. (2013) An experimental study of the effects of water mist characteristics on pool fire suppression. Experimental thermal and fluid science, (44):768-778
[8] Liu Yinshui, Jiang Zhuo, Wang Dan. (2014) Experimental research on the water mist fire suppression performance in an enclosed space by changing the characteristics of nozzles. Experimental thermal and fluid science, (52):174-181
[9] Paolo E. Santangelo, Paolo Tartarini. (2012) Full-scale experiments of fire suppression in high-hazard storages: A temperature-based analysis of water-mist systems. Applied thermal engineering, (45-46):99-107
[10] Tang Fang, Li Pan, Chen Guofeng. (2020) An estimation method of fire extinguishing time in closed ship cabin, 2nd International Conference on Civil Architecture and Energy Science.