Numerical Simulation of Ultra-fine Water Mist Extinguishing Mechanism

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Abstract

Ultra-fine water mist (UMF) had good performance in extinguishing fire caused by electric or flammable liquid. This paper studied the extinguishing effect of UMF in total flooding experiment in confined space, and used FDS fire dynamics simulation software to simulate the entire process in order to explore the extinguishing mechanism of UMF. The simulation results showed that UMF could not only cool the fire rapidly but also isolate the fire from oxygen to cause suffocation which was the main reason for extinguishment because of its characteristics.

Keywords: UMF, FDS, extinguishment, suffocation, cooling.

Nomenclature

| Symbol | Description |
|--------|-------------|
| u      | velocity of fluid phase (m/s) |
| u_p    | velocity of particle (m/s) |
| d_p    | particle diameter (m) |
| C_D    | drag coefficient |

Greek symbols

| Symbol | Description |
|--------|-------------|
| μ      | kinetic viscosity |
| ρ      | density of fluid |

1. Introduction

In recent years, scholars at home and abroad has studied the mechanism of fire extinguishment with ultra-fine water mist (UMF) and the results indicated that UMF had excellent capability on fire suppression[1-5]. UMF with extremely small particle size had excellent flowability and was easier to suspend than conventional water mist. Its large surface area increase the rate of evaporation, which accelerates its heat absorption speed. The mechanism of fire extinguishment by UMF is mainly reflected in the following aspects:

- Cooling effect. First, all of the water evaporates into high temperature steam. Second, it takes extremely short.
- Suffocation. The UMF evaporated thoroughly and rapidly which resulted in massive production of UMF would reduce the volume fraction of oxygen in the space, or isolated the fire from oxygen in local area to suffocate it.
- Absorption and barrier of radiant heat. Some molecules of water vapor and carbon dioxide produced by burning fire has a strong absorption effect to some spectrum, which can prevent the radiation heat transfer to the combustion itself or to destroy other combustion equipment.

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The absorption and barrier of radiant heat by UMF was less important to the fire extinguishment, cooling and oxygen suffocation were the main causes to lead the fire extinguished. To explore which one was the most important factor, we could use FDS fire dynamics simulation software to simulate the whole process of UMF total flooding fire extinguishing experiment, in order to study the cooling effect and the suffocation effect.

2. Formulae for UMF

In Lagrange coordinate system using discrete phase model (DPM) to simulate the transportation of UMF, the motion equations of single particles or droplets can be obtained by the force equilibrium. The equilibrium equation is [6]:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_s$$

(1)

$F_D(u - u_p)$ means the drag force per unit mass of particle, and $F_D$ could be expressed as:

$$F_D = \frac{18\mu}{\rho_p \cdot d_p^2} \cdot C_p \cdot Re / 24$$

(2)

3. FDS model setting

3.1. Space setting

The space setting is shown in Fig. 1 [7]. The confined space was surrounded with fire-proof heat insulation board with the size of 1.2m*1.2m*1.2m and division of 85184 grid (the minimum size of 0.01m and the maximum size of 0.03m), including the atomization system, pool fire and all kinds of measuring equipment (including the thermocouples above the fire and the oxygen sensor). A small vent was set on one side of the wall to release the pressure in the space.

3.2. Setting of atomization system

The transportation of UMF would be simulated by discrete phase model (DPM) in Lagrange coordinate system. The UMF extinguishing system was set by 4 nozzles, each of which had an equal massflow. The average diameter of UMF is about 50μm with the vaporization heat of 1.6966*10^4J. And the average vaporization time of each droplet is 0.002682 [8], which is shortened by 16 times compared with the ordinary water mist. The total mist flux is 0.1L/min with the velocity of 0.3m/s, released after the fire burn for 60s.
3.3. Fire source setting

There were two ways to set the fire: liquid fuel plate and liquid fuel nozzle. In order to be more close to the experimental conditions, the former way would be adopted in the simulation. The evaporation process of liquid fuel was controlled by the Clausius-Clapeyron equation, which meant the liquid would burn up immediately after evaporation without ignition device. The liquid was set in accordance with the properties of heptane and the heat release rate of fire was set to 500 kW/m², about 2 kw.

4. Extinguishing mechanism of UMF

4.1. Cooling effect

By comparing the temperature above the fire in the extinguishment process to which in the process without UMF shown in Fig. 2, we could study the cooling effect of UMF in extinguishment. The fire could burn for around 1000s without UMF in the confined space, the temperature measured by the thermocouple above the fire was about 600°C with no obvious downward trend. The fire would be extinguished at 403s when started the UMF device. The temperature declined with a certain downward trend, but the trend was not obvious.

![Fig. 2. Temperature above the fire in extinguishment process and process without UMF.](image)

By comparing the temperature variation condition under different heat release rate of fire, we could study the cooling effect of UMF from another perspective. The values of heat release rate were 500 kW/m², 700 kW/m², 1000 kW/m². Fig. 3 showed that greater the power was, shorter the extinguishing time would be. The two main reasons were: firstly, larger flame area caused larger heat transfer area and heat absorption of UMF, which would speed up the cooling and evaporation process; Secondly, more oxygen consumption and suffocation effect led by the evaporation of UMF resulted in incomplete combustion which would shorten the extinguishing time. But on the other hand, it could be seen from the figure that the temperature above the fire still had a small downward trend, and the difference between 3 conditions was not obvious.

In summary, the cooling effect of UMF was not the main factor of fire extinguishment.
4.2. Suffocation effect

By comparing the volume fraction of oxygen near the fire in the extinguishment process to which in the process without UMF shown in Fig 4, we could study the suffocation effect of UMF in extinguishment. The oxygen concentration decreased at a certain rate even if without UMF because the space was confined. When started the UMF device, the fire would be extinguished at 403s and the volume fraction of oxygen was 0.164mol/mol at the time with a greater downward trend. The oxygen concentration would decrease continually after the fire was extinguished because the evaporation of UMF was not stopped yet.

Similarly, changing the heat release rate of fire could also explore the suffocation effect of UMF from another perspective. As shown in Fig 5, the downward trend of oxygen concentration was increased with the increasing of fire power, and the oxygen concentration at the time when the fire was extinguished under 3 conditions were very closed, was about 0.16mol/mol. The main reason was the suffocation effect which caused by the greater consumption of oxygen and faster evaporation speed shortened the extinguishing time. The increasing of the decline of oxygen concentration proved that the suffocation effect of UMF was significant.

The average diameter of UMF could also be used for exploring the extinguishing mechanism of UMF. The values of diameter were 50μm, 200μm, 500μm. The extinguishing time was increased with the increasing of average diameter of UMF as shown in Fig 6, 7. The reason was small diameter meant more UMF droplets and larger heat transfer area which
accelerated the evaporation and led to stronger cooling effect and suffocation effect. The downward trend of temperature under 3 conditions was still not obvious as shown in the figure, which further explained that the main reason for extinguishment was suffocation but not cooling.

![Figure 5: Volume fraction of oxygen in extinguishment process under 3 different heat release rate of fire.](image)

5. Conclusion

By using FDS to simulate the total flooding experiment in confined space with UMF, it could be concluded that fire would be extinguished at a short time by the twofold effect of cooling and suffocation. The cooling effect was the secondary cause while the key factor of extinguishment was suffocation. Moreover, the smaller average diameter of UMF also determined that it had more excellent extinguishing efficiency than the general water mist, which enabled UMF to have good application and development prospects in extinguishing technology.

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