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Experimental Study on the Wood Combustion Restraining by Ultra-fine Water Mist in Confined Space

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Because of wood is one kind of the basic combustible material, a small scale compartment was built for ultra-fine water mist restraining wood fire, and then the restraining efficiency and related factors were investigated. The study found: the heat release rate and the volume fraction of O_2 decreased quickly, the production of CO_2 increased in a short time and ultimately tended to be stable after discharging the ultra-fine water mist. It showed that the ultra-fine water mist can effectively reduce the heat release rate of wood and components generation rate. It was found that the restraining effect relies on preignition time, mist flux, discharging time and so on.

Keywords: **U**ltra-fine water mist, Mist flux, Preignition time, Discharging time

1 INTRODUCTION

Because of environmental protection and high efficiency advantages, the superiority water mist fire extinguishing technology has become the main alternative technology of halon fire extinguishing agent, and in many fields it has got a wide range of applications(1-3). Last 5 years, the second generation of water mist fire extinguishing technology, ultra-fine water mist(4) has been taken more attention by people. Because of the droplet size is less than 50μm, ultra-fine water mist can suspend and flow easily, and they could bypass the obstacles to reduce the power of the fire source, and the high concentration of droplet can also stay for a long period of time in space, reduce the oxygen concentration in the combustion region, accelerate to cool the flame and smoke. At the same time, ultra-fine water mist has a good heat-absorbing properties. Its bigger surface area can speed up the cooling of smoke, absorb the thermal radiation of flame. In addition, compared with conventional fine water mist, ultra-fine water mistconsumes less water, and it is much securer in some electrified places.

Currently, some foreign countries had already launched studies of some related experiments on ultra-fine water mist technology. British Naval Research Laboratory held an experiment on ultra-fine water mist fire fighting systerm in the submarine. United Kingdom Civil Aviation Authority and the U.S. Federal Aviation Administration studied the effectiveness of ultra-fine water mist in controling the civil aircraft cabin fire.(5-6) Ndubizu(7) and others had done the experiment of ultra-fine water mist to extinguish polymethyl methacrylate (PMMA) flame. The experimental results showed that under a certain speed at the beginning, when the mass fraction of ultra-fine water mist increased to a valid value, the flame became smaller, and gradually weakened, finally extinguished; On the basis of the experiment, Ananth(8) and others had done the numerical simulation of ultra-fine water mist suppression to polymethyl methacrylate (PMMA) flame. It showed that the combustion heat release rate (or reaction rate)

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accompanied by the extinguishment of flame had declined markedly. When the heat release rate lowered to a certain critical value, the inhibition process of ultra-fine water mist came to the end. K.C.Adiga[9] and other people had put out the experiment on the ultra-fine water mist suppression of space-constrained cable fire. The results showed that the ultra-fine water mist can successfully extinguish solid cable fire.

In all kinds of fire accidents, solid combustible materials dominate the leading position, and the quantity of them determines the spreading speed and the final size of fire. Furthermore, wood is one kind of the most normal solid combustible materials. Therefore, avoiding the fire from spreading further by discharging ultra-fine water mist, not only has important practical significance, but also has the typical technology advantage and good application prospect. This paper will construct simulation experiment platform of ultra-fine water mist, inhibit the effectiveness of limited space wood fire, summarize its influencing factors. In order to provide a theoretical basis and data to the ultra-fine water mist suppression system, this article would build a simulation platform for studying the validity of the ultra-fine water mist suppression system and would sum up its impact factors.

2 EXPERIMENTAL PLATFORM AND WORKING CONDITION

2.1 Experimental device

Experimental apparatus and test systems mainly contain ultra-fine water mist fire extinguishing system, smoke analysis system, digital temperature acquisition device, computer workstations and other equipment.

(1) Limited space. In this experiment limited small-scale space is used(length 0.35m, width 0.35m, high 0.62m).The steel structure is used for the framework of limited space, at the same time, in order to ensure a certain degree of insulation and sealing effect, tempered glass is used to pack the faces.

(2) Ultra-fine water mist fire-extinguishing system. Ultra-fine water mist fire-extinguishing system is formed by power source, oscillator circuit, atomizing device (atomization pool, fans, sprinklers and so on). According to the circuit, it contains: power circuit, oscillation circuit, the frequency of automatic tracking circuit and a buffer circuit to improve the main vibration of the peak loss. Internal ultrasound oscillator equipment is used to vibrate water and then it can generate 5~40μm ultra-fine water mist. Its essence is a kind of high-power ultrasonic piezoelectric ceramic oscillator, and its core tablets are atomization device and the corresponding electronic circuit. Oscillator frequency is determined by the natural frequencies of the atomization device.

(3) Burning containers. Burning platform for this experiment is 227mm diameter stainless steel fuel plate with a depth of 10mm. In the experiment, it was placed on the electronic scale.

(4) Electronic weighing system. JA1103-type electronic scale that can be accurate to sub-thousand-bit is placed below the burning containers directly, in order to measure the mass changes of wood during the ultra-fine water mist suppression process of wood combustion.

(5) Temperature acquisition system. In order to grasp the temperature reduction effect of ultra-fine water mist, the digital temperature acquisition device is used to collect and record the temperature on the surface of the combustible wood sample.

(6) Smoke analysis system. It can analyze smoke composition, collect oxygen, carbon dioxide, carbon monoxide and other gas components through the dynamic measurement by using M-9000-type combustion analyzer. Experimental units diagram is shown in Figure 1.

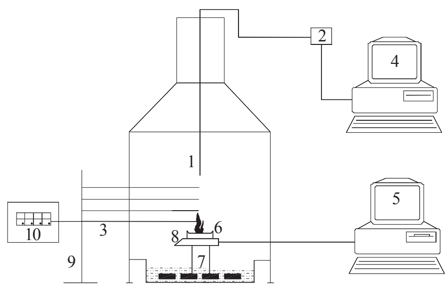

Fig. 1 Schematic of the experimental compartment

1.Smoke analyzer probe; 2.Smoke analyzer; 3.Thermocouple tree; 4.Smoke analyzer workstation; 5.Quality change acquisition workstation; 6.Burning containers; 7.Atomization pool and atomizer; 8.Electronic scale; 9.Thermocouples stent; 10.Digital temperature acquisition instrument

2.2 Experimental cases

By changing the mist flux, preignition time, discharging time, the experimental cases are shown in table 1.

Table 1 tested Cases

Case Number	fuel quantity (g)	discharging or not	mist flux (ml/min)	preignition time (s)	discharging time (s)
1	367	N	—	—	—
2	240	Y	150	25	50
3	240	Y	150	65	50
4	330	Y	50	65	55
5	330	Y	150	65	55
6	342	Y	150	80	40
7	342	Y	150	80	80
8	367	Y	200	50	60

3 EXPERIMENTAL PROCESS OF ULTRA-FINE WATER MIST SUPPRESSION SYSTEM

Poplar wood as the fire source was placed in the center at the bottom surface of the confined space. In order to ensure the stability of combustion, the surface of wood was soaked by 3ml alcohol. The system contained four thermocouples, which was marked 1～4 from bottom to top. No. 1 was 5cm far from the surface of wood, and the thermocouple was 7cm far from each other. The other side of thermocouple was digital temperature acquisiton instrument, which was used to display the temperature of the smoke layer at real time. The mean temperature of smoke layer was calculated by mathematical average method(10).

$$T_{\text{ave}} = \frac{\int_{H_{\text{i}}}^{H_{\text{r}}} T\text{d}y}{H_{\text{r}} - H_{\text{i}}} \tag{1}$$

$$\int_{H_{\text{i}}}^{H_{\text{r}}} T\text{d}y = \frac{1}{2}\sum_{j=k+1}^{L} T_j\left(h_{j+1} - h_j\right) + \frac{1}{2}\left(T_{k+1} + T_{ref}\right)\left(h_{k+1} - H_i\right) \tag{2}$$

Among them, H_{r} is the height of top wall; H_{i} is the height between the smoke layer and the bottom air boundary; h_j is the height between the thermocouple and the top wall; T_j is the temperature reading of each thermocouple; T_{ref} is temperature reading of the boundary between the smoke layer and bottom air; T_k is the temperature of the first thermocouple under the boundary of the smoke layer and the bottom air, here is No.1 thermocouple; T_{k+1} is the temperature of the first thermocouple above the boundary of the smoke layer and the bottom air, here is No.2 thermocouple; L is the quantity of the thermocouple.

JA1103-type electronic scale was placed under the burning container, then the data acquisition system can directly measure the fuel mass changes during the experimental process and convert to the mass loss rate of fuel. The heat release rate can be computed by the following formula:

$$Q = mH_{\mu}\chi \tag{3}$$

m means the coal mass loss rate with the unit kg/s, H_{μ} means the calorific value for wood combustion, here is 1.27×10^7J/kg, χ means the wood combustion efficiency, and its value can be got from the smoke analyzer automatically.

Atomization pool was set at the bottom of the experimental platform with the length of 290mm, width of 290mm. Center distance of atomization pool to the wall edges was 175mm, four ultrasonic atomizers were set in the atomization pool, and the flux of a single ultra-fine water mist atomizer was 50ml/min.

Smoke analyzer probe was set 33cm far from the fire source in the experimental chamber. The data from the smoke analyzer would be transported to the smoke analyzer work station. It can collect O_2, CO and CO_2 concentration in the smoke under different cases at real time.

Taking case 8 as an example, in the experiment, 367g wood soaked by 3ml alcohol was ignited and taken into the burning containers at the bottom of the platform, in the meantime, the smoke analyzers, electronic scale, temperature acquisition instrument and its associated workstations were started. 50s later, the power of four atomizers was started to generate ultra-fine water mist, 60s later, the power was turned off. Smoke temperature, O_2 and CO_2 concentration in the smoke were measured. In order to keep original air condition after an experiment in the confined space, 35min would be lasted.

4 RESULTS AND DISCUSSION

4.1 The experiment process analysis

Paragraph 2 is the drawing of the entire process of ultra-fine water mist suppression system, and it includes the scene at 55, 75, 95 and 115s. The ultra-fine water mist was discharged at 50s. Because the water mass concentration was between 3~4%, it had a function of combustion-supporting, and the flame of wood became larger at a short time. After 2~5s, along with the increasing of the discharging time, the flame of the combustible wood gradually became small, and then extinguished at 104s. At the same time, ultra fine water mist was diffused gradually in the confined space. At last, the confined space was full of ultra fine water mist, and the visibility was also reduced.

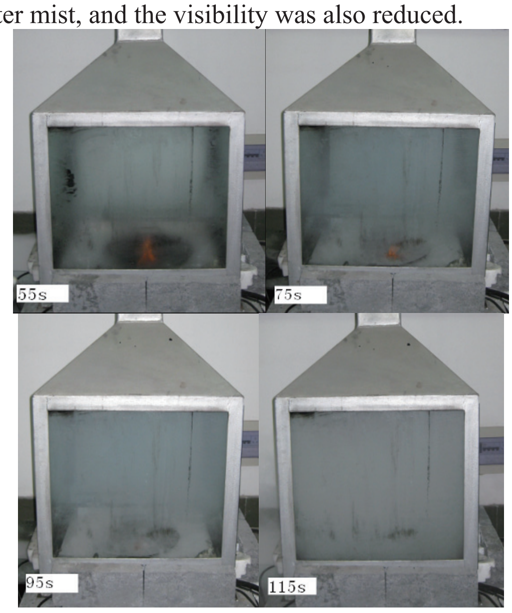

Fig. 2 The process of wood combustion restraining by ultra-fine water mist

K.C.Adiga and R.F.Hatcher(11) considered that O_2 concentration near the fire source was essential for understanding the value of ultra-fine water mist extinguishing fire process, and three oxygen measurements were made of the fire-entrained air in order to compare the different measurement techniques. It included the paramagnetic oxygen analyzer, a dry oxygen molar concentration measurement, a wet oxygen molar concentration measurement. Smoke analyzer was based on the first method to draw the changes in O_2 concentration value. Taking Case 1 and Case 8 as an example, O_2, CO_2 concentration and heat release rate of the wood were compared. It was shown in Figure 3,4,5,6.

First, the wood was ignited and put into the burning container, meanwhile, the temperature in the confined space was gradually increased. High temperature smoke layer was formed in the middle-upper part of the confined space, and then thermal radiation that had a feedback effect was generated. 50s later, the flow rate of 200ml/min ultra-fine water mist was discharged to the fire. d^2 law(12) is fit for ultra-fine water mist as well as normal fine water mist. Formula 2 is shown as follows:

$$\tau = \frac{d_0^2}{k_v} \tag{4}$$

Where τ means the droplets survival time, or completely evaporation time; d_0 means the original droplet diameter; k_v means the evaporation constant; Formula 3 is shown as follows:

$$k_v = \frac{8(\lambda / c_p)}{\rho_1} \ln\left[\frac{q_v + c_p(T_\infty - T_b)}{q_v}\right] \tag{5}$$

Where λ means the air thermal conductivity; c_p means specific heat at constant pressure; ρ_1 means the density of water; q_v means the latent heat of water evaporation; T_∞ means the flame temperature; T_b means the droplet temperature. The time when the ultra-fine water mist came to the flame region was identified as 1s, and then the original droplet diameter can be got, d_0=3.8mm.When the droplet diameter of ultra-fine water mist was greater than or equal to 3.8mm, the droplet can pass through the flame region to the wood surface and then realize the purpose of cooling the wood. The experimental ultra-fine water mist droplet size was 5 ~ 40 μm, far less than the value. So, when ultra-fine water mist was discharged at the early time, it would be taken to the upper part of the flame region by fire plume. Under the influence of high temperature smoke layer, it would evaporate rapidly. Because the droplet size was smaller than normal fine water mist, the specific surface area was big and the heat absorption was also large. One high concentration water vapor layer was formed outside the flame region, O_2 would not spread into the flame region. And the wood combustion would consume a great deal of O_2, the oxygen content decreased rapidly. With the decreasing of the flame temperature, small size ultra-fine water mist also gradually entrained into the flame region, thereby the flame temperature was effectively lowered, the thermal radiation feedback of smoke layer also significantly reduced, ultimately, wood heat release rate decreased. In addition, on one hand, the combustion of wood consumed part of O_2, on the other hand, ultra-fine water mist rapidly diffused in the confined space, and the living space of O_2 was compressed, thus the concentration of O_2 decreased faster than without discharging ultra-fine water mist. In the pre-50s, the wood still be able to burn fully, and the generation of CO_2 showed a slight increase in the graph. Along with the decrease of temperature in the confined space, ultra-fine water mist gradually entrained into the flame region, the wood can not burn completely, the concentration of CO_2 gradually decreased.

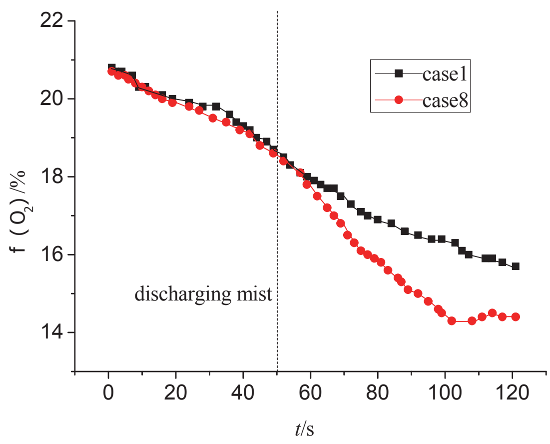

Fig. 3 Oxygen volume fraction variation curve with and without ultra-fine water mist

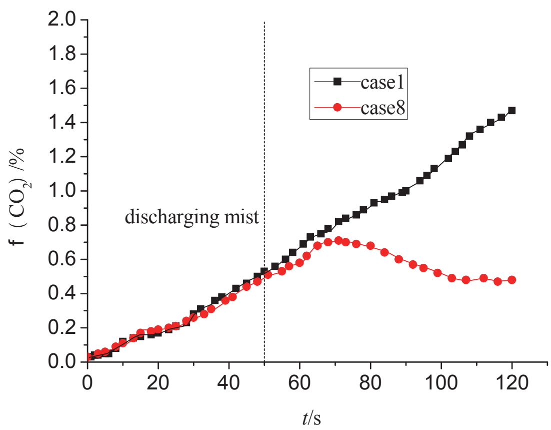

Fig. 4 Carbon dioxide volume fraction variation curve with and without ultra-fine water mist

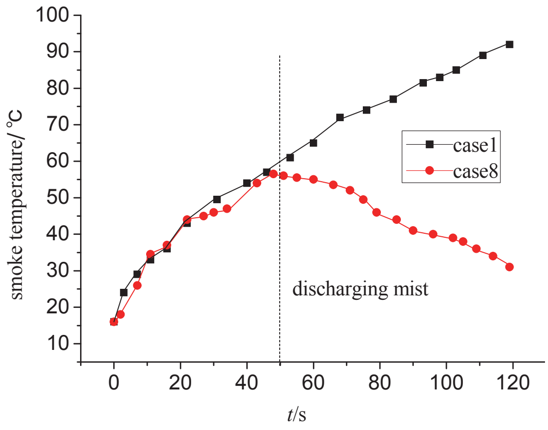

Fig. 5 Smoke temperature variation curve with and without ultra-fine water mist

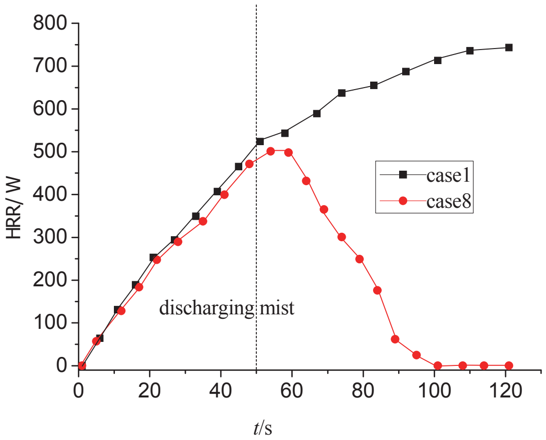

Fig. 6 Heat release rate variation curve with and without ultra-fine water mist

4.2 Related factors analysis

4.2.1 Restraining effects of preignition time

As the application of fine water mist in the other occasions, it is more effective to discharge the ultra fine water mist in the early time of wood combustion.

Taking case 2 and case 3 as the example, the heat release rate of fire source and the temperature of smoke layer are illustrated in Figure 7 and Figure 8. In the experiment, the mist flux was 150ml/min and the discharging time was 50s. In case 2, the ultra fine water mist was discharged at 65s while the smoke temperature reached 67℃. Comparing to case 3, although the mist flux in case 2 was big enough to reduce the smoke temperature and heat release rate, the descending rate of the smoke temperature and heat release rate became obviously slowly. It was seen that the flame length was longer than that in case 3. In case 3, the ultra fine water mist was discharged at 25s when the flame length was short, and the shortest flame length appeared at 59s.

It showed that the preignition time played an important part in the ultra-fine water mist suppression system.

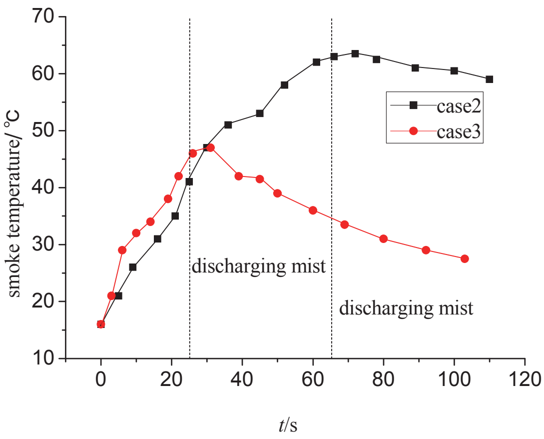

Fig. 7 Smoke temperature variation curve at different preignition time

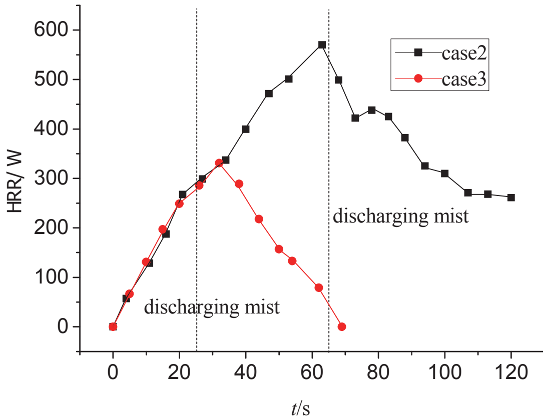

Fig. 8 Heat release rate variation curve at different preignition time

4.2.2 Restraining effects of mist flux

When the fire source power, discharging time and the preignition time were invariable, the volume flux determined the inhibiting effect of wood combustion. The mist flux can be stated by the ultra-fine water mist flow rate. The more the flow rate was, the greater the mist flux was.

Taking case 4 and case 5 as the example, the preignition time was 65s and the discharging time was 55s. The smoke temperature and the fire source heat release rate were compared in Figure 9 and Figure 10.

From the figure, the smoke temperature and the heat release rate have barely changed after discharging the mist for 55s under the flow rate of 50ml/min in case 4. However, for case 5 when the flow rate was 150ml/min, the flame length of wood became shorter. Meanwhile, the descending rate of the smoke temperature and the heat release rate decreased significantly. It indicated that the flow rate of 150 ml/min can restrain wood combustion effectively.

It showed that sufficient mist flux was a key factor in the ultra-fine water mist suppression system.

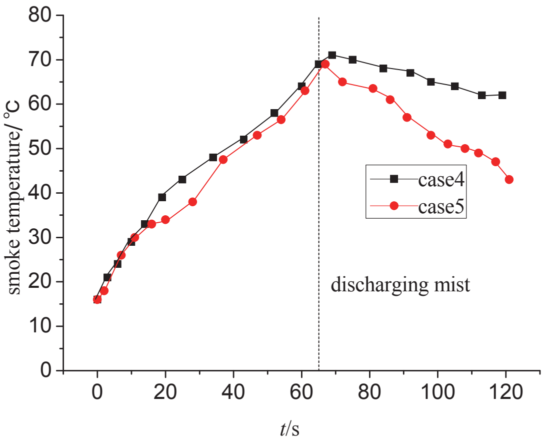

Fig. 9 Smoke temperature variation curve at different mist flux

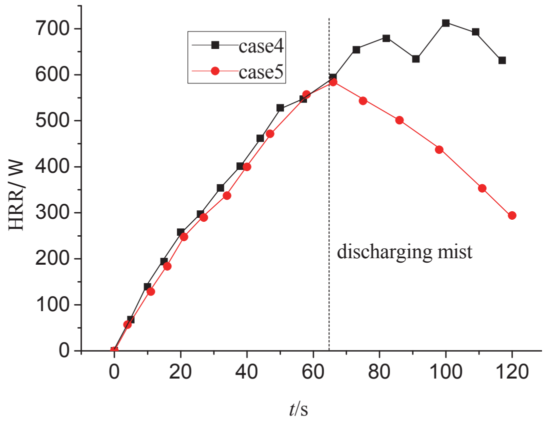

Fig. 10 Heat release rate variation curve at different mist flux

4.2.3 Restraining effects of discharging time

The experiment also discovered that different discharging time may lead to different suppression effects. Taking case 6 and case 7 as an example, the smoke temperature and the heat release rate were described in Figure 11 and Figure 12. In the first 40s, after discharging the ultra fine water mist, the wood combustion can be suppressed under two cases. In case 6, the ultra fine water mist was stopped discharging at 120s. Because the evaporation and heat absorption function disappeared, the smoke temperature stayed the same. However, in case 7, the discharging of ultra fine water mist was continuative, the smoke temperature kept downtrend. Along with the increase of time, the ultra fine water mist was accumulated on the surface of the wood. Compared to case 6, the heat release rate decreased obviously.

It was seen that the discharging time was another factor to affect the function of ultra fine water mist suppression system.

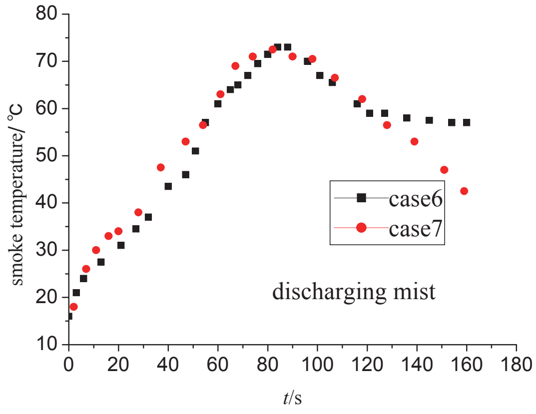

Fig. 11 Smoke temperature variation curve at different discharging time

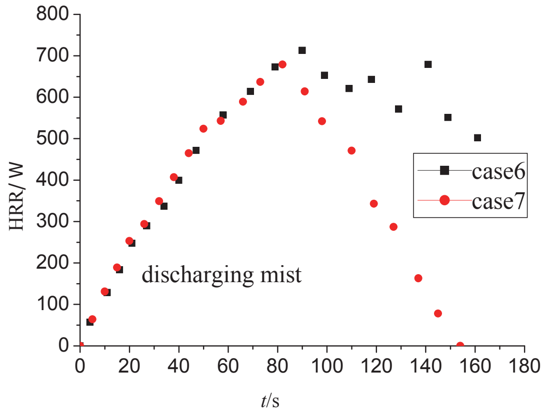

Fig. 12 Heat release rate variation curve at different discharging time

5 CONCLUSIONS

1. By the function of ultra fine water mist, the concentration of O_2 in the smoke decreased continuously, the concentration of CO_2 decreased slowly until becoming stable. Along with the extinguishment of the flame, the heat release rate decreased, and finally, it became zero.
2. The ultra fine water mist suppression system was related to the preignition time, the mist flux, the discharging time and so on. In order to suppress the wood combustion, the mist flux should be big enough.
3. For the sufficient mist flux, the shorter the preignition time was, the better to suppress the wood flame.
4. When the preignition time and the mist flux was feasible, the more the discharging time was, the better to extinguish the wood flame.

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