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Influence of Water Mist Temperature Approach on Fire Extinguishing Effect of Different Pool Fires

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Abstract: The aim of this paper was to study the suppression influence of water mist on oil pool fires, taking diesel fires and n-heptane fires as experimental objects. The effects of spray pressure and temperature on water mist suppression were examined, and an experimental platform for the suppression of water mist in a small space was set up. Their fire prevention performance and fire extinguishing mechanisms were analyzed by comparing the flame temperature and extinguishing time of diesel and n-heptane pool fire. Three types of spray pressure were set. Water mist was designed at different temperatures and design experiments were carried out for this purpose. The change process of smoke concentration, thermocouple temperature, and flame combustion under different working conditions were analyzed, and the factors affecting the fire extinguishing effect of water mist on oil pool fire were discussed. The results show that 20 °C water mist is more effective at medium and high pressure than at low pressure. Moreover, 80 °C water mist at 9 MPa is more effective in extinguishing n-heptane fire. The flame extinction time is about 10 s, which is more than 40 s higher than that of cold water.

Keywords: water mist; water mist temperature; pressure; oil pool fire; fire extinguishing effect

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1. Introduction

Since the signing of the Montreal Convention in 1987, the international fire safety field has been looking for alternatives to halogenated alkyl fire extinguishing agents [1]. Water mist fire extinguishing technology has the advantages of no pollution, rapid fire extinguishing, less water consumption, and less damage to the protected objects. Water mist has gradually been considered and has been successfully recognized internationally. Against this background, the research on water mist fire extinguishing technology has entered a golden period of development in recent decades [2]. Similarly, great progress has been made in the research on its suppression efficiency [3].

Scholars from all countries pay close attention to water mist fire extinguishing technology because of its suppression efficiency [4]. To comprehensively study the fire-extinguishing conditions of water mist, Liu et al. [5] pointed out that the reason for flame expansion caused by water mist is the thick flammable vapor layer on the oil surface. Ankit dasgotra et al. [6] found that the effect is primarily affected by operating parameters, such as the ratio of the distance between two pools to the diameter of the pool, gap of platform, nozzle ejection rate, and water mist particle size. Zhou et al. [7] added a small amount of newly developed additive named MC to the water mist that can significantly improve the fire extinguishing performance of the water mist system. Liu et al. [8] carried out experiments and simulations to verify that under the smoke exhaust conditions, the water mist can effectively extinguish the fire, but the time required for extinguishing the fire is affected by the ventilation volume. Chelliah et al. [9] explored the quantitative information of the coupling between the optimal droplet size and the flow residence time in suppressing gas flames. Yao et al. [10] studied the interaction between water mist and the heat diffusion flame in a closed environment and found that the small water mist current can increase the flame intensity.

Nevertheless, scholars have researched the temperature factor affecting water mist suppression efficiency less. Most research focuses on the mechanism, additives and surfactants, ventilation conditions and obstacle position, fire heat release rate, and nozzle characteristics [11,12]. This paper measured the fire extinguishing time, flame temperature and smoke change parameters of water mist under low, medium and high pressure at different temperatures. The fire extinguishing effects of water mist at different temperatures on diesel and n-heptane fires were studied through experiments. The influence of temperature on the fire extinguishing effect of water mist can be understood more comprehensively. This paper provides experimental and data support for the engineering application of a high-temperature water mist fire extinguishing system [13], which may influence the developing fields of water mist fire extinguishing technology and fire protection [14].

2. Experimental Setup

2.1. Experimental Platform

The experimental platform is composed of a confined space, water mist system, fire source, temperature measurement system, gas analyzer, and video camera, as shown in Figure 1. The experimental platform space was designed to be 1.8 m × 1.8 m × 3 m. The frame of the confined space is a steel structure. Its bottom is ceramic tile, and the other five sides are tempered glass. This ensures a particular thermal insulation effect, tightness, and safety. In front of the confined space is a 0.8 m × 2 m glass door, which is convenient for entering and leaving the burning dish for experiments. The upper part of the confined space is a smoke exhaust pipe extending outdoors, and a gas analyzer is placed at the tail of the smoke exhaust pipe to record the smoke concentration. The water mist nozzle is placed 2.4 m above the fire source. The bottom thermocouple shall be placed 10 cm above the fire source, and other thermocouples shall be placed every 30 cm upward.

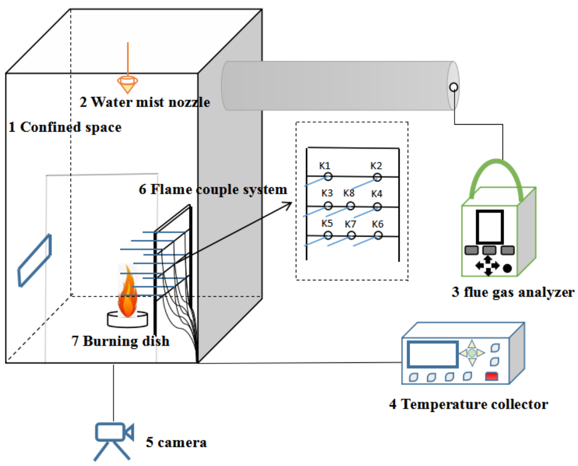


Figure 1. Diagram of the experimental system.

Additionally, the height of 2.4 m is closer to the actual height. The oil pan with a diameter of 60 cm was chosen in accordance with the experimental design of the oil fire. Thermocouples are positioned every 30 cm to ensure accurate measurement of the fire source temperature. Diesel oil and n-heptane were used as fuels in the experiment, which were poured into a container with a diameter of 60 cm and a depth of 3 cm. An external camera recorded and observed the flame image [15].

2.2. Nozzle Properties

2.2.1. Water Flow Rate

The size of droplets will affect the fire extinguishing effect of water mist. The pressure and flow coefficient of the sprinkler will determine the size of water mist particles. This paper studies the characteristics of water mist under different pressures and temperatures. The 0.7 flow coefficient nozzle is used for research in order to regulate the variable. The nozzle's flow coefficient K value is 0.7. The experimental findings are consistent with the following formula. The nozzle flow is obtained by the following Equation (1):

$$q = K\sqrt{10P} \tag{1}$$

where q (in L/min) is the water flow rate; K is the flow coefficient; P (in MPa) is the working pressure.

2.2.2. Particle Size Distribution

The American Fire Protection Association has defined three pressure zones for the fine water mist production technology: low pressure (0–1.21 MPa), medium pressure (1.21–3.5 MPa), and high pressure (>3.5 MPa). The particle size distribution was measured by using the LSP-800 laser particle size analyzer at 1 MPa, 3 MPa, and 9 MPa, respectively. The R-R distribution map measurements are shown in Figures 2–5. Overall, the average volume diameter (VAD), the average mass diameter (NAD), and Sauter average diameter (SMD) of 80 °C water mist are smaller than 20 °C water mist [16]. The particle size distribution of 80 °C water mist is relatively concentrated, while that of 20 °C water mist is more dispersed. Table 1 shows that the particle size of water mist at the same temperature decreases with the increase of pressure. The maximum volume average diameter of water mist is 20 °C under 1 MPa, and the value is 173 μm. The minimum volume average diameter of water mist is 80 °C under 9 MPa, and the value is 105 μm [17].

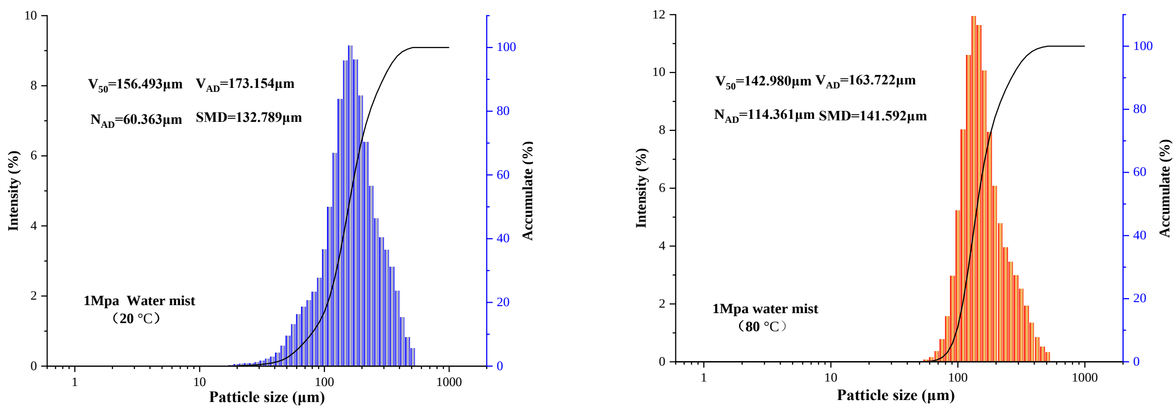


Figure 2. Particle size distribution of 20 °C and 80 °C water mist at 1 MPa.

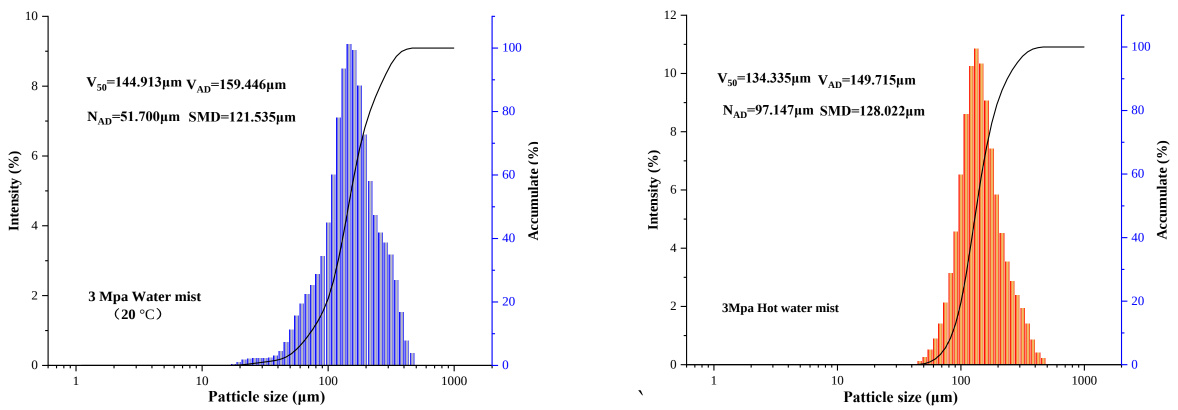


Figure 3. Particle size distribution of 20 °C and 80 °C water mist at 3 MPa.

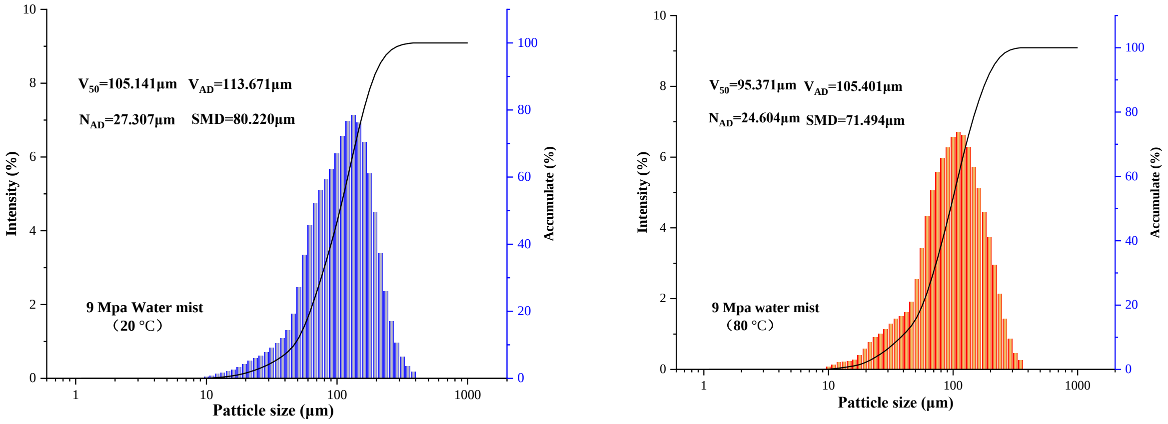
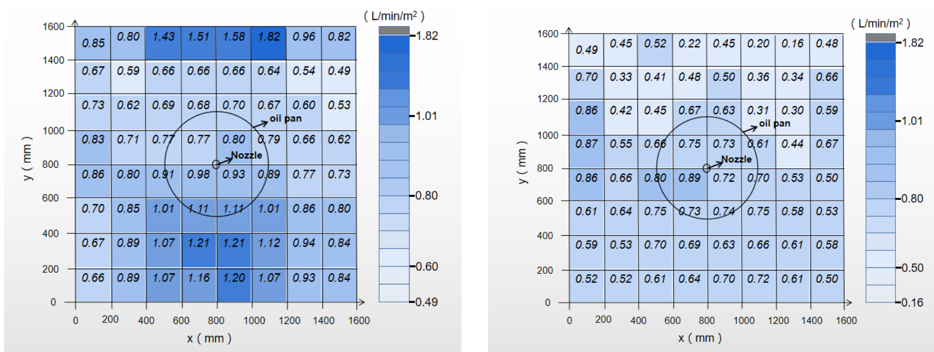


Figure 4. Particle size distribution of 20 °C and 80 °C water mist at 9 MPa.

(**a**) (**b**)



(**c**) (**d**)

Figure 5. The measured front view (**a**) and top view (**b**), and the measured water flux density distribution of hot (**c**) and cold water (**d**).

Table 1. Particle size distribution of cold and hot water mist under various pressures.

Temperature/°C	Pressure/MPa	Volume Average Diameter/µm	Mass Average Diameter/µm	Sauter Average Diameter/µm
20 °C	1	173.154	60.363	132.789
	3	159.446	51.700	121.535
	9	113.671	27.307	80.220
80 °C	1	163.722	114.361	141.592
	3	149.715	97.147	128.022
	9	105.401	24.604	71.494

2.2.3. Water Flux Density Distribution

A bucket experiment was carried out to fully show the characteristics of water mist in the investigation and more intuitively see the adequate water acting on the fire source [18]. As shown in Figure 5, the nozzle is placed 2.4 m away from the ground. Below the nozzle are 64 cubic barrels with a side length of 0.2 m. The barrels are made of acrylic, with a depth of 0.2 m. The average water flux density in each barrel is calculated by the following Equation (2):

$$Q = \frac{V}{t \cdot A_0} \quad (2)$$

where Q (in $L/min/m^2$) is the average bucket density in each bucket; V (in L) is the volume of water collected in the bucket; A_0 (in m^2) is the bucket collection area ($A_0 = 0.2 \times 0.2 = 0.04\ m^2$); t (in min) is the collection time.

Since water splashes into the enclosed space outside the barrel and on the glass, an error of 5–8% can be allowed [19]. As seen in Figure 5c,d, hot water is more effective than cold water in the oil pan. In addition, temperature changes the movement mode of water mist molecules, improving hot water fire extinguishing.

2.3. Experimental Procedure

In the fire extinguishing experiment, the primary fuels were diesel oil and n-heptane. Four kinds of water with temperatures of 20, 40, 60, and 80 °C were used and the water was subject to heat preservation treatment. We added 300 g diesel or 300 g n-heptane to the oil pan, then diesel fuel with a bit of methanol was ignited [20]. To stabilize the flame state, n-heptane fire and diesel oil were pre-ignited for 30 s and 60 s, respectively, then we adjusted the pressure to open the water mist switch. We applied water mist until the flame was extinguished and recorded the extinguishing time. Successful fire suppression is defined as within 60 s after the fire is out, if not recurrent, and there is oil in the plate. Then, the nozzle pressure, fuel, and water mist temperature were changed and the above steps were repeated [21].

2.4. Summary of Working Condition Setting

Based on the above experimental platform and program, 19 comprehensive tests were carried out. All working conditions are listed in Table 2. In addition, the fire extinguishing time of each fuel at various pressures and temperatures was established.

Table 2. Extinguishing time of diesel and n-heptane fires with cold and hot water mist under different pressures.

Condition No.	Fire Extinguishing Species	Pressure/MPa	Water Mist Temperature/°C	Precombustion Time/s	Fire Extinguishing Time/s
1	diesel oil	1	20	60	42
2		3			35
3		9			36
4		1	80		90
5		3			110
6		9			70
7	Heptane	1	20	30	65
8		3			42
9		9			54
10		1	40		42
11		3			31
12		9			17
13		1	60		55
14		3			28
15		9			14
16		1	80		59
17		3			30
18		9			10
19			Free burning		90

3. Results and Discussion

3.1. Analysis of the Experiment Results of Fire Extinguishing Time

According to the fire extinguishing time of the diesel pool fire and n-heptane pool fire under 20 °C water mist, the fire extinguishing effect of medium-pressure water mist is better than the high-pressure and low-pressure water mist. Therefore, the experimental results are consistent with a previous study that found that medium-pressure water mist is more appropriate for class B fires and low-pressure water mist is unsuitable for oil pool fires.

For the water mist at 80 °C, there is no obvious advantage to diesel pool fire; even the fire extinguishing effect is not as good as cold water mist. However, when putting out the fire in the n-heptane tank, the fire extinguishing effect of hot water mist is better than that of cold water mist. Under the pressure of 9 MPa, the fire extinguishing time is more than 40 s earlier, and the fire extinguishing efficiency is several times that of the cold water mist.

Due to the significant effect of the water mist temperature on the n-heptane fire, the middle 40 and 60 °C were also explored and then integrated. Figure 6 shows the extinguishing time of n-heptane fire at different temperatures. It can be seen that the water mist at 40 °C has the shortest extinguishing time under 1 MPa pressure. Under the pressure of 3 MPa, the extinguishing time of 60 °C water mist is the shortest, and the extinguishing time is 28 s. Under the pressure of 9 MPa, the extinguishing time of 80 °C water mist is the shortest, and the extinguishing time is 10 s. Considering the limitations of the low-pressure fire extinguishing system, the comprehensive analysis of the medium- and high-pressure results shows that the temperature with the short overall fire extinguishing time and the highest fire extinguishing efficiency is 80 °C.

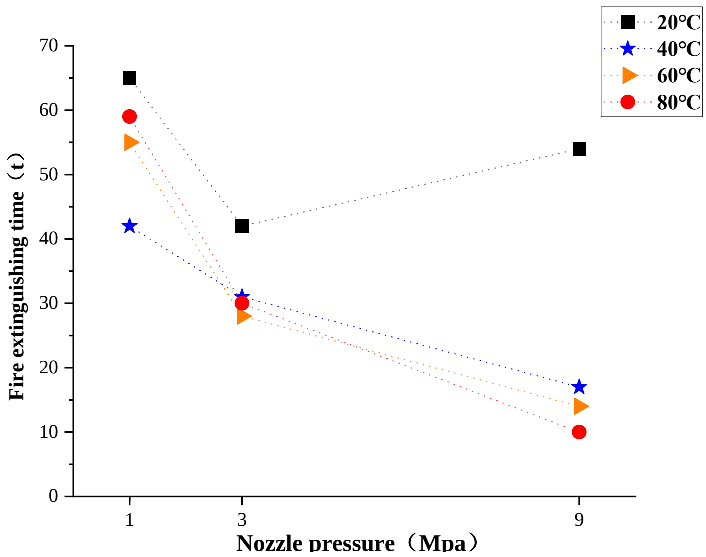


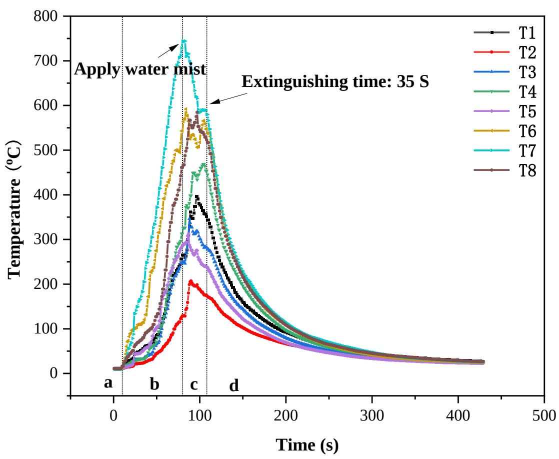
Figure 6. Extinguishing time of n-heptane pool fire by water mist at various temperatures.

The fire extinguishing mechanism of pure cold water mist mainly includes gas-phase cooling, attenuation of heat radiation, surface cooling, and oxygen isolation [22]. The fire extinguishing mechanism of hot water and fine water mist is different. When the cooling action is carried out, in other words, the heat absorbed by the water during gasification is much greater than when the water temperature rises. For example, the heat required for 1 kg of water to increase from 20 to 100 °C is 80 kcal, while the heat required for 1 kg to be gasified at 100 °C is 539 kcal. Therefore, the temperature gap leads hot water mist to vaporize faster in fire extinguishing experiments and requires a large amount of heat during gasification, resulting in a faster drop in the fire temperature. The cold water mist does not reach the saturation temperature, and no phase change is happening. When the asphyxiation is performed, the hot water reaching the boiling point is continuously vaporized and heated into a large amount of water vapor. Therefore, it reaches the steam extinguishing concentration locally in the fire area. When the concentration of the fire area drops to a specific limit, the flame will be extinguished [23]. Therefore, in this experiment, a large amount of water vapor formed by hot water mist gasification occupies a particular area, locally reducing the oxygen concentration and providing conditions for fire extinguishing.

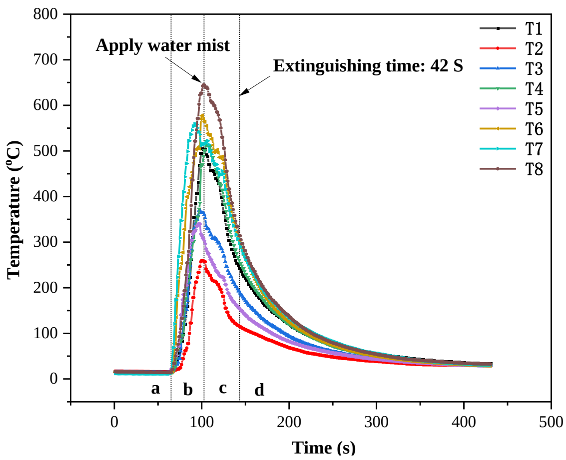
3.2. Analysis of the Changes in the Flame Temperature

Each figure is divided into four stages: a, b, c, and d. Stage a is the ambient temperature before ignition; b is the temperature change of oil pool free combustion after ignition; c is the water mist fire extinguishing stage; d is the stage of free cooling to room temperature.

In Figure 7, this study selected the water mist temperature curve with a good fire extinguishing effect of 3 MPa, including diesel and n-heptane fires. For the diesel pool fire, the violent burning in the free combustion stage and the air roll suction effect are particularly obvious. After applying water mist, it quickly interacts with flame and fuel. However, in the early stage of applying water mist, the flame size and temperature have slightly improved. When fine water mist interacts with pool fires, both mechanisms that promote combustion and inhibit combustion work simultaneously. In some incomplete combustion of the pool fires, the influence of fine water mist can aggravate the combustion process [24]. With the incessant release of water mist, the flame size and temperature decreased significantly, and the flame is completely suppressed and goes out at 35 s. For the n-heptane fire, the initial flame combustion is stable and increased by the temperature. When water mist is applied, the flame temperature gradually decreases until the flame disappears and completely extinguishes at 42 s.



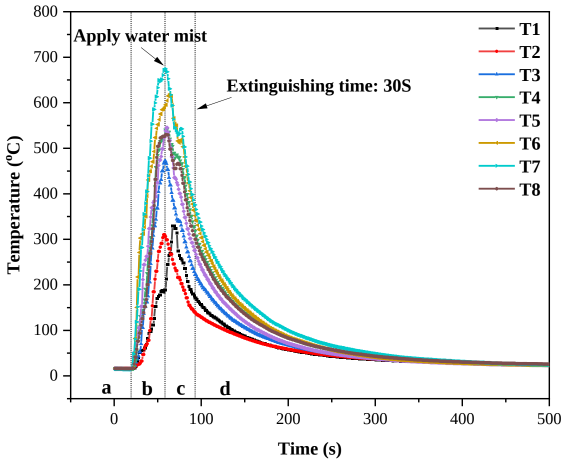
(**a**) condition 2



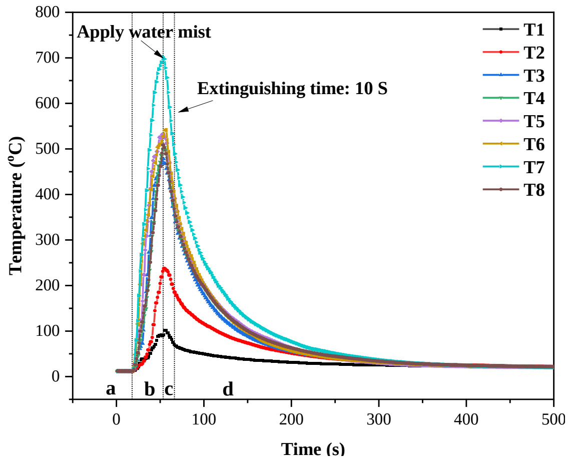
(**b**) condition 8

Figure 7. Temperature curve of flame thermocouple under test conditions 2 and 8.

Figure 8 shows the flame temperature curve of the hot water mist to extinguish the n-heptane fire under high and medium pressure conditions. Under the pressure of 3 MPa and 9 MPa, the initial flame state is stable, and the temperature keeps rising. After the fine water mist is applied, the flame temperature decreases rapidly. When the flame is extinguished, the fine water mist is stopped, and then the temperature decreases to the end of the room temperature experiment. The fire extinguishing time is 30 s under the pressure of 3 MPa and 10 s under the pressure of 9 MPa. The fire extinguishing efficiency of high-pressure hot water mist is better than that of medium-pressure hot water mist and is far better than that of cold water mist.



(**a**) condition 17



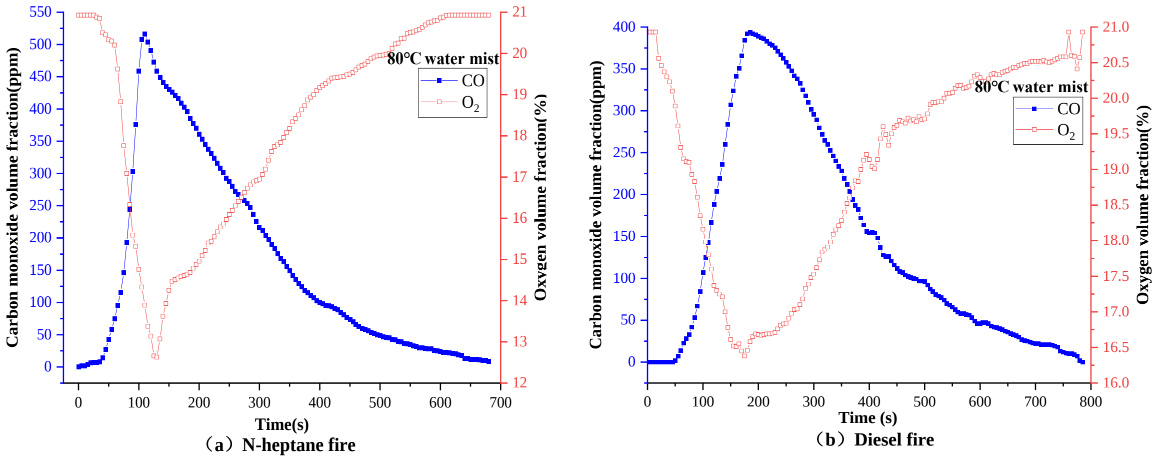
(**b**) condition 18

Figure 8. Temperature curve of flame thermocouple under test conditions 17 and 18.

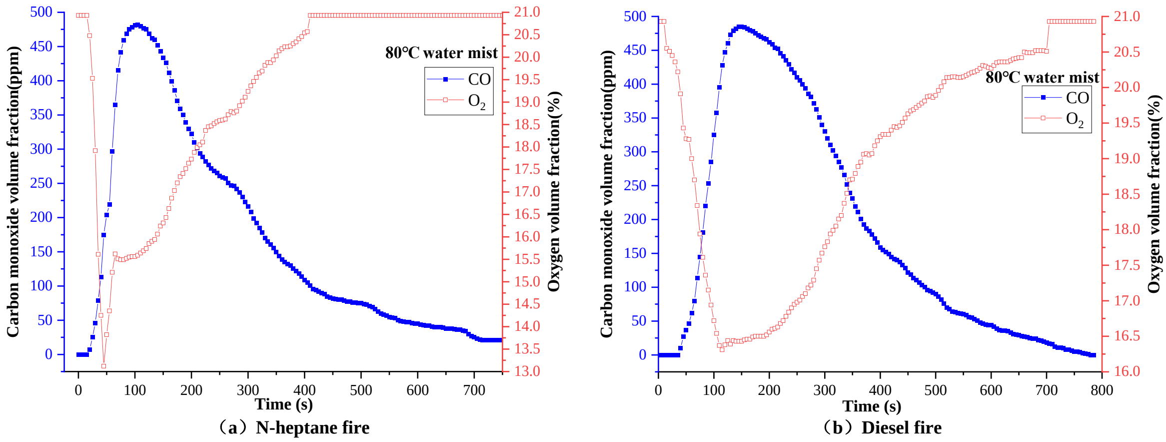
With the increase of pressure, the initial combustion promoting stage of hot water mist will disappear. When the hot water mist acts on the flame and fuel, it absorbs more heat than the cold water mist. The cooling effect is noticeable, and the fire extinguishing efficiency is greatly improved. When the hot water mist acts on fire, it will be vaporized to form steam after reaching the boiling point, expelling oxygen and forming a local anoxic state. The asphyxiation effect is noticeable [25]. In addition, the droplet size of hot water mist is smaller than that of cold water, and the smaller the surface area of water mist droplets, the easier it is for them to interact with the flame, so the fire extinguishing performance of hot water mist is much better than that of cold water mist. The experimental results and temperature curves also reveal that the fire extinguishing effect of hot water mist at high pressure is more significant than that at medium pressure. The atomization effect of high-pressure water mist is more obvious, which can make the water mist fill the entire fire extinguishing space. This makes the impact of water mist on the fire source more effective and has a stronger ability to reduce heat radiation [26]. To sum up, the hot water mist has the best fire extinguishing effect and the fastest fire extinguishing time under the pressure of 9 MPa, which improves safety.

3.3. Comparison of the Volume Fraction Change of the Flue Gas Fraction

Figures 9 and 10 respectively show the change of flue gas composition of diesel and n-heptane fires extinguished by hot and cold water mist measured by the flue gas analyzer under the pressure of 3 and 9 MPa. At the beginning of combustion, because n-heptane has a higher combustion calorific value than diesel, it needs to consume more O_2, and complete combustion will produce more CO_2 accordingly. Therefore, the volume fraction of each flue gas component of n-heptane fire changes more obviously and faster than that of diesel fire. We started spraying after 30 s of n-heptane and 60 s of diesel combustion. The space temperature of n-heptane pool fire is higher than that of diesel pool fire, so the rate of water mist entering and evaporating with the flame is faster, resulting in insufficient oxygen supply and easier flame extinction. However, the diesel pool fire is more complex and has a higher boiling point, which makes it easier to carry out incomplete combustion and produces more CO [27]. After the flame is extinguished, we closed the water mist generator, and the flue gas test was completed when each flue gas component drops to normal.



3 MPa



9 MPa

Figure 9. Change diagram of flue gas composition of diesel and n-heptane under the action of hot water mist at 3 MPa and 9 MPa.

The longitudinal comparison (Figure 9) shows that the pressure acting on the n-heptane fire of 9 MPa consumes more oxygen than 3 MPa. As a result, less CO is produced, so the fire extinguishing effect is better under the pressure of 9 MPa. Although the CO produced by diesel fire under 3 MPa pressure is relatively small, the rate of oxygen reduction is not as apparent as 9 MPa, so the fire extinguishing effect of hot water mist under 3 MPa pressure on diesel fire is not obvious. Figure 10 shows that the change rate of O_2 volume fraction of cold water mist on n-heptane and diesel fires at 3 MPa is faster than that at 9 MPa because the CO produced is also less. Therefore, the cold water mist under 3 MPa pressure can control the fire more, and the fire extinguishing time is also shorter [28].

Comparing all working conditions in Figures 9 and 10, the n-heptane pool fire under hot water mist is easier to vaporize and form water vapor when it acts with the flame, consuming oxygen. In addition, the water vapor eliminates part of the oxygen to form local anoxia, resulting in a faster change rate of O_2 than that of cold water. Therefore, the fire extinguishing efficiency of hot water mist is superior. On the other hand, when the cold water mist acts on the diesel pool fire, the production of CO decreases, and the change rate of O_2 accelerates [29]. Furthermore, the boiling point of the diesel fire is also very high, so the cold water mist fire extinguishing efficiency is dominant. That is to say, cold water mist is more effective for diesel fire, and hot water mist is more effective for n-heptane fire.

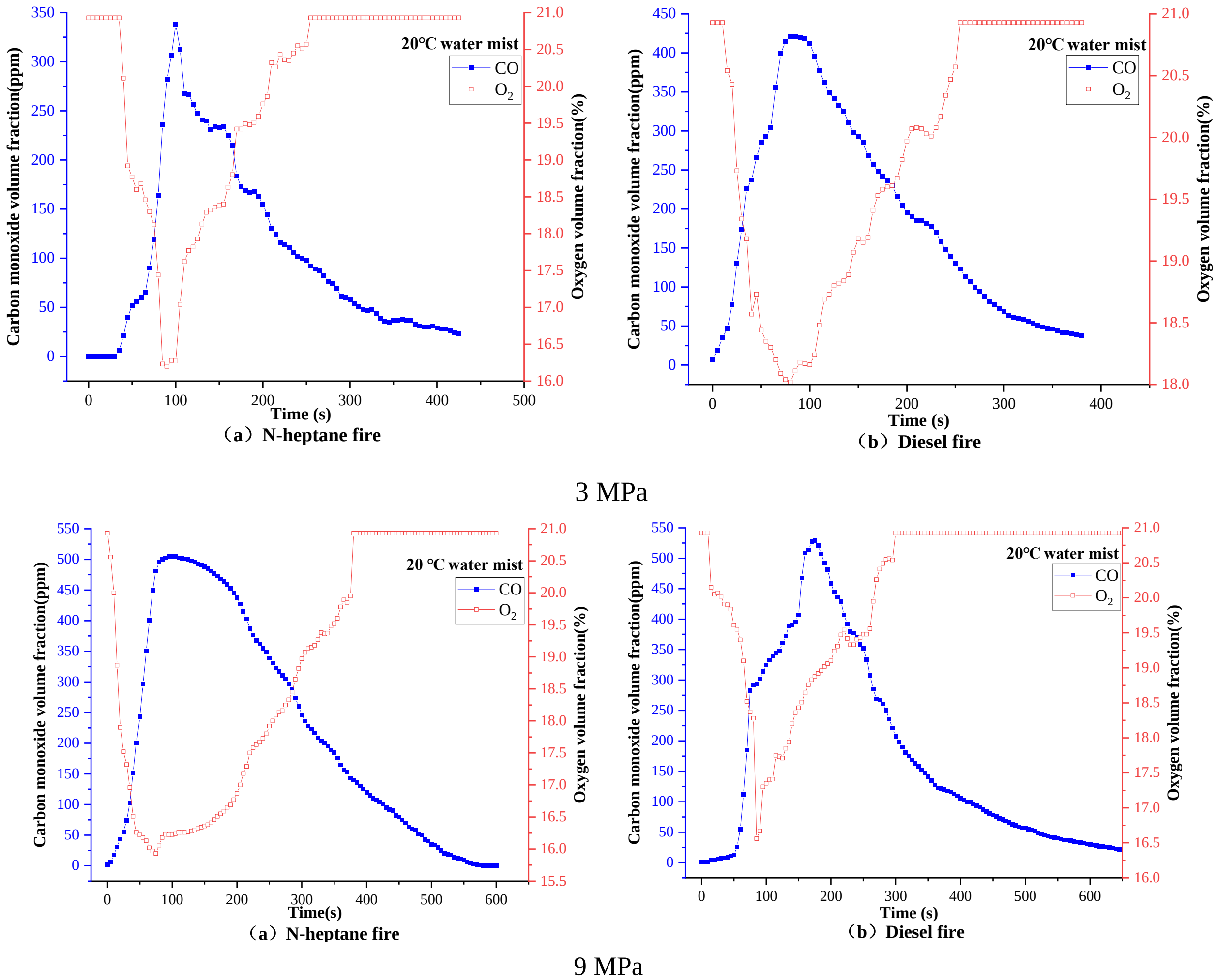


Figure 10. Change diagram of flue gas composition of diesel and n-heptane under the action of cold water mist at 3 MPa and 9 MPa.

3.4. Flame Status Analysis

Figure 11a,b show the flame diagram before water mist is applied; Figure 11c,d show the flame diagram when the cold and hot water mist extinguishes the fire for 3 s; and Figure 11e,f show the flame diagram when the cold and hot water mist extinguishes the fire for 8 s. When the water mist is applied, it has a combustion-supporting effect, and the flame keeps jumping and rolling [30]. The fire size and height of hot water mist fire extinguishing are relatively small at the beginning and near the end of the fire. The lower surface tension of hot water than that of cold water occurs since the temperature of cold water is low, the activity of water molecules is poor, and the ability to overcome intermolecular attraction is weak, while hot water molecules have good activity and strong ability to overcome intermolecular attraction. Surface tension is the intermolecular attraction and the weaker the ability to overcome the intermolecular attraction, the greater the surface tension, so the surface tension of hot water is small. When the water mist is applied, the hot water is more likely to form a wrapping system, which hinders the interaction between the oil pool and the oxygen, and the flame size and temperature are greatly reduced until it is extinguished [31].

(**a**) cold water mist

(**b**) hot water mist

Flame diagram before the action of cold and hot water mist

(**c**) cold water mist

(**d**) hot water mist

Flame diagram under the action of hot and cold water mist for 3 s

(**e**) cold water mist

(**f**) hot water mist

Flame diagram under the action of hot and cold water mist for 8 s

Figure 11. Comparison of flames at different times under the action of hot and cold water mist.

4. Conclusions

Through the experimental study of inhibiting confined space n-heptane and diesel fires, the following conclusions are drawn:

(1) Medium- and high-pressure water mist is better than low-pressure water mist in extinguishing oil pool fires, but for hot water mist this is not the case.

(2) N-heptane pool fire has the best fire extinguishing effect under the pressure of hot water mist of 9 MPa, which is better than medium pressure hot water mist and much better than cold water mist, but the effect on diesel fire is not significant.

(3) When water mist acts on n-heptane flame, the fire extinguishing effect is susceptible to temperature. The higher the water mist temperature, the better the fire extinguishing effect.

(4) The particle size of high-temperature fine water mist is generally less than that of cold water fine water mist, and the fire extinguishing effect is the best when the particle size of 80 °C fine water mist under 9 MPa pressure is 105.4 μm.

(5) The hot water mist distributes water more effectively on the fire source than the cold water mist, and the water flux density distribution on the fire source is also higher. Therefore, the hot water mist saves more water and has higher fire extinguishing efficiency.

(6) The fire extinguishing mechanism of hot water is more optimized for cooling and suffocation than cold water. When cooling, the heat absorbed by hot water is much larger than when the water temperature rises, resulting in a faster reduction in the fire-fighting temperature; when suffocating, the hot water reaching the boiling point is continuously evaporated and heated into a large amount of water vapor. As a result, it eliminates the surrounding oxygen and forms local hypoxia. This causes the flame to have no combustion conditions and eventually go out.

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