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Feasibility Study of Fine Water Mist Applied to Cold Storage Fire Protection

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Abstract: The self-built fine water mist fire extinguishing platform studied the fire extinguishing effect of ultra-fine water mist in cold storage fires. The combustible material selected for our experiments is the cold storage insulation material—polystyrene insulation foam board. The combustion characteristics of the insulation board were studied by pyrolysis analysis. We analyzed the temperature, smoke, and other characteristics of the fire scene when a fire occurs in the cold storage and then manipulated the water mist to carry out the fire extinguishing experiment. Experiments aim to change the particle size and pressure of water mist and study the fire extinguishing efficiency of water mist under different conditions. A thorough analysis was used to determine the particle size range of fine water mist most suited for extinguishing fires in cold storage to offer a theoretical foundation for fire protection design.

Keywords: water mist; water mist temperature; pressure; cold storage fires; fire extinguishing

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1. Introduction

The most common fire extinguishing agent in the fire protection industry is the halon fire extinguishing agent [1], but after detailed research, it has been found that it dramatically damages the ozone layer. This is because halon fire extinguishing agents contain chlorine and bromine. When using fire extinguishing agents to put out a fire, the halon gas is irradiated by the sun and will decompose free radicals of chlorine and bromine. These chemically active groups easily remove the ozone molecule's oxygen atoms [2]; as a result, it reduces the ozone concentration and forms the ozone hole. This reduction of the ozone layer will destroy the ecological environment and cause harm to human beings. Continuing to use halon fire extinguishing agents is not in line with the principles of energy conservation and emission reduction in the 21st century. Therefore, a new non-polluting fire extinguishing agent must be developed [3].

Since the 1990s, water mist fire extinguishing has caused wide concern, and in the Montreal Protocol on Substances that deplete the Ozone Layer, it is clearly stated to reduce the destruction of the ozone layer [4]. Furthermore, the United Nations Programme believes that water mist is a clean energy technology with rapid fire-extinguishing capabilities: no pollution, and low water consumption. Therefore, it can be used in fire extinguishing agents and will not cause environmental pollution problems such as ozone layer destruction [5]. Scholars from various countries are also researching water mist fire extinguishing and have made breakthroughs [6]. Due to scholars' continuous in-depth research into water mist, it has been gradually applied to more fields [7], such as tunnels, libraries, and archives [8,9].

People are becoming increasingly concerned about food preservation as the population and economy grow. The construction of the cold storage industry is developing rapidly, with an annual growth rate of 15% in China [10]; the development of the industry has a considerable role in promoting the economic development of the country, but it will also bring related security problems. For example, fire safety issues: although the probability of cold storage fires is low, it cannot be ignored [11] because once the fire gets out of control, the damage will be heavy. The characteristics of cold storage fires are mainly four points: first, it burns violently and forms a three-dimensional fire; second, the burning is concealed, and it is not easy to find the ignition point; third, this burning produces significant smoke, high temperature, and inconvenient firefighting; fourth, There are many toxic and harmful gases, and an explosion is dangerous; therefore, the fire protection of cold storage cannot be ignored. Most of the food stored in cold storage is closely related to people's lives. From the perspective of food safety [12], the fire extinguishing agent used in the fire extinguishing process must be non-toxic and harmless. On the other hand, in the current cold storage fire protection stage, the original nozzle system is still used, which consumes much water and does not meet the principle of saving energy. Therefore, water mist is a suitable extinguishing agent [13].

To sum up, this article aims to apply fine water mist to the cold storage fire protection system. After investigation, many factors affect water mist fire extinguishing, such as the size of the water droplets that specifically influence the fire extinguishing mechanism. The size of these water droplets is different, the specific surface area will be different, and the heat absorbed by the droplets when they evaporate is also different. In general, systems with smaller droplet sizes tend to perform better under the same operating conditions [14,15]. Pressure also has a great influence on fire extinguishing efficiency. In a fire, increasing the working pressure of the water mist system will shorten the duration of the flame, thus speeding up the fire extinguishing [16,17]. In some complex fire scenes, the position of the obstacle also dramatically influences the water mist fire extinguishing. Obstacles reduce the fog momentum of the spray mist, preventing some of the water droplets from reaching the centre of the flame. In an ordinary sprinkler system, the water droplets have a large particle size, and it is difficult to pass through the obstacles to reach the bottom of the flame [18]. When using a fine water mist to extinguish the fire, because of the relatively small particle size, many water droplets bypass the obstacle and surround the flame area like gas to reduce the temperature of the flame. In order to improve the fire extinguishing efficiency, the size of the water droplets can be appropriately reduced, or the momentum can be increased. Ventilation conditions and fog flux also affect water mist fire suppression [19–23].

Research shows that the smaller the water droplet size, the better the fire extinguishing effect. However, when the mist particle size is too small, that will lead to insufficient momentum, and it is difficult to penetrate the flame to reach the root of the flame for fire extinguishing. So there should be an optimal particle size fire extinguishing range [24,25]. The primary research of this paper is the influence of pressure and water droplet size on water mist fire extinguishing. Through comprehensive analysis, the particle size range of water mist most suitable for cold storage fire extinguishing is selected, which provides a theoretical basis for cold storage fire protection design.

2. Materials and Methods

2.1. Pyrolysis Experiment

Thermogravimetric Analysis (TG) can measure the relationship between the mass of the sample to be tested and the temperature change under the program's control temperature. Differential Scanning Calorimetry (DSC) is a technique for measuring the relationship between the power difference and temperature of a test sample and a reference sample under a program-controlled temperature. By obtaining the corresponding signal, the curve of the heat change with time during the thermal reaction of the sample can be obtained, which is the DSC curve [26–29].

When dealing with the DSC exothermic peaks of thermal insulation materials, the authors used the Bezier curve to improve the accuracy of the corresponding curves [30,31]. Therefore, the bottom is the baseline for the exothermic peak integration, presented in Equation (1):

$$B(t) = T_0 + T_p(T_e - T_0)\cdot t = (1-t)\cdot T_0 + t\cdot T_e, t \in [0,1] \quad (1)$$

where T_0 and T_e are the onset and end temperatures, and T_p is the peak temperature. The corresponding points of the linear difference between T_0 to T_e and T_e to T_p on the Bezier curve are shown in Equation (2):

$$B(t) = (1-t)^2 T_0 + 2t(1-t)T_e + t^2 T_p, t \in [0,1] \tag{2}$$

The first and second order derivatives of the Bezier curve are shown in Equations (3) and (4):

$$B'(t) = 2(1-t)\cdot(T_p - T_0) + 2t\cdot(T_e - T_p) \tag{3}$$

$$B''(t) = 2(T_e - 2T_p + T_0) \tag{4}$$

TG of thermal insulation materials was carried out on the STA409C synchronous analyzer produced by Netzsch, Germany. The atmosphere was air, the heating rate was 10 L °C/min, and the sample size was ca. 10 mg. After the data processing of the pyrolysis experiment, we can obtain the characterization information of the thermal insulation material, which provides theoretical support for the subsequent fire extinguishing experiments.

2.2. Fire Experimental Platform

The experimental system is shown in Figure 1. The experimental platform comprises a confined space, fine water mist fire extinguishing system, combustion plate, K-type thermocouple, temperature collector, gas analyzer, glass door, and video camera. The size of the confined space is 1.8 m × 1.8 m × 3 m. The nozzle is positioned 2.3 m above the platform, directly over it. The laboratory has an iron frame that will be used to place thermocouples. An iron plate is placed in the centre of an iron frame to retain combustibles. Record the firefighting process with video and thermal imaging cameras (FLUKE–Ti400).

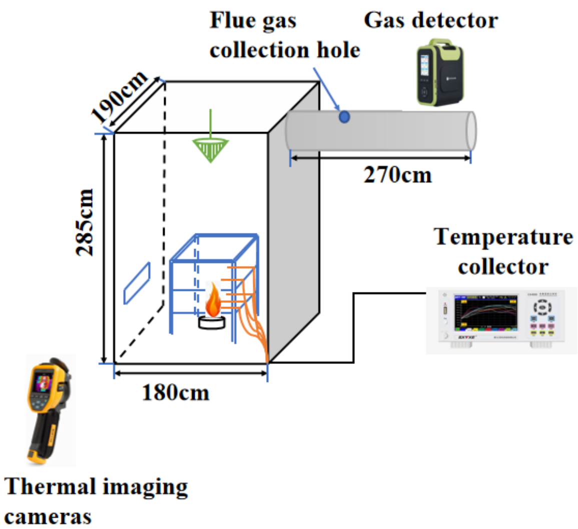


Figure 1. Device diagram of the experimental system.

In the test, a precision thermocouple WRNK–191 was used to measure the internal temperature change of polystyrene. There are 8 thermocouple collection points in total. The location distribution is shown in Figure 1. The accuracy of the thermocouple is 0.4 grade, and the response time is 0.5 s. Therefore, it can effectively cooperate with the temperature sensor to collect data. The model of the temperature acquisition system is the EX4000 multi-channel temperature tester. The equipment converts the electrical and differential pressure signals obtained from the experiment into temperature data for recording. The acquisition frequency was 1 temperature sample per second.

A total of 5 nozzles are selected in this paper: open and closed umbrella centrifugal nozzle, with a diameter of 1 mm. The experimental equipment for measuring water droplet particle size was the Winner9 industrial spray laser particle size analyzer. The principle of the instrument is to measure the scattering spectrum of the particle group and then analyze the particle size distribution law. The particle size distribution of the water droplets of the 7 L/min nozzles under the pressure of 1, 3, and 9 MPa is shown in Figure 2. The particle size distribution of water droplets at 5 nozzles under 9 MPa pressure is shown in Figure 3.

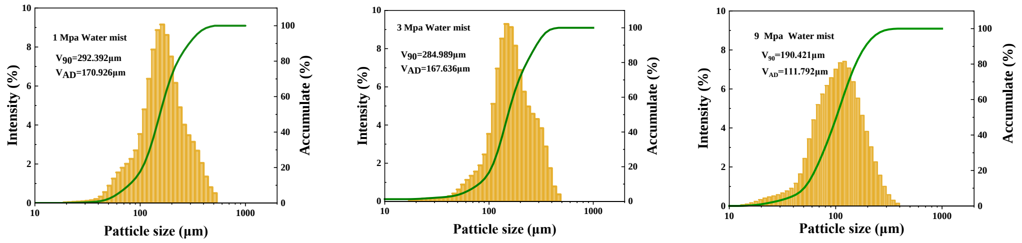


Figure 2. The patticle size distribution of water droplets from the nozzle of 7 L/min under different pressures.

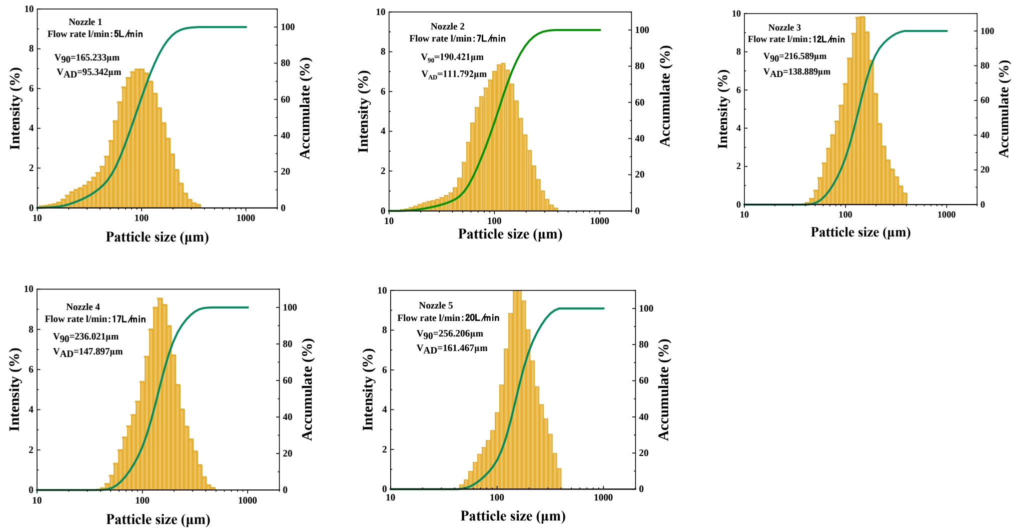


Figure 3. Patticle size distribution of water droplets under different nozzles.

2.3. Fire Experimental Platform

Two preliminary experiments were conducted in fire extinguishing experiments. One used the same nozzle, changing the pressure, and then observing the effects of 1, 3, and 9 MPa on water mist fire extinguishing. Another experiment was where we chose different nozzles to study the impact of water droplet size on water mist fire extinguishing under constant pressure conditions. There were five types of nozzles: 5, 7, 12, 17, and 20 L/min.

The mass of the combustibles used in each group of experiments remains unchanged. All 300 g of polystyrene insulating materials and 10 g of methanol were used for ignition. The water mist device was turned on during the experiment when the thermocouple temperature reached 350 °C and turned off in time when the flame was extinguished.

3. Experimental Results and Analysis

3.1. Analysis of the Experiment Results of the Pyrolysis Experiment

The thermogravimetric analysis of the thermal insulation material is carried out as shown in Figure 4 and Table 1. The thermal decomposition of the thermal insulation material has only one main stage, which starts at 100 °C; the thermal mass loss is about 5%, and a small mass loss peak occurs on the corresponding DTG curve. The heat loss at this stage is mainly because of the gradual volatilization of the residual moisture and blowing agent in the material as the temperature increases, but the molecular chain in the polystyrene foam does not break. The reaction temperature range of the second stage is about 350–480 °C. Thermal mass loss accounts for about 90% of total mass loss. A larger mass loss peak also appears on the corresponding DTG due to oxygen in the atmosphere [32]. At this time, the molecular chains with less energy required in the rigid polystyrene foam are broken to form free radicals and release heat. The polystyrene at this temperature undergoes a combustion reaction, releasing a large amount of gas, and there are a lot of toxic and harmful components in the gas [33,34].

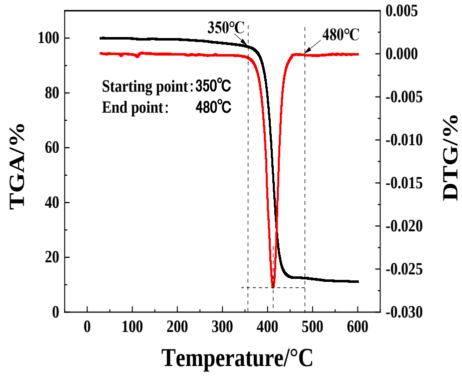


Figure 4. Thermal pyrolysis analysis chart of thermal insulation material.

Table 1. Thermal mass-loss table.

Sample	5% Mass Loss Temperature/°C	95% Mass Loss Temperature/°C	Maximum Mass Loss Rate/°C	Pyrolysis Residual/%
Heat insulation materials	195	350	480	9.8

In daily life cold storage is usually used to store food, and so the gas released from the combustion of the insulation material will inevitably pollute the food in the cold storage. From the perspective of food safety, the most effective way to extinguish the fire in cold storage is to extinguish the fire before the polystyrene material burns in a large area. Therefore, in the follow-up water mist fire extinguishing experiment, the temperature at which the water mist started spraying was set before 350 °C.

3.2. Analysis of the Results of the Pyrolysis Experiment

3.2.1. Study on the State of Natural Combustion to Extinction

Figure 5 is the process map of the combustion process, showing the thermal images when the combustibles are burned for 0, 20, 30, and 200 s. When the brazier is ignited, the flame expands rapidly, and as time passes, black smoke appears in the experimental glass device, and the polystyrene begins to burn to release carbon monoxide and nitrogen oxides.

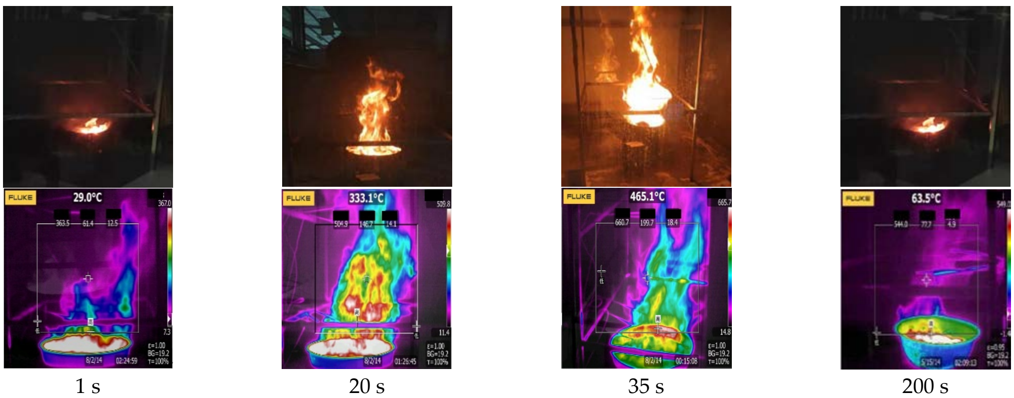


Figure 5. Thermal images of the combustion process.

Figure 6a is a graph of the natural combustion-to-extinction temperature curve of polystyrene. When the temperature of other thermocouples reaches room temperature, the temperature of thermocouple 2 suddenly rises, and the temperature drops to room temperature after a while. This experiment reflects the characteristics of cold storage fires to a large extent, and it is prone to reignition.

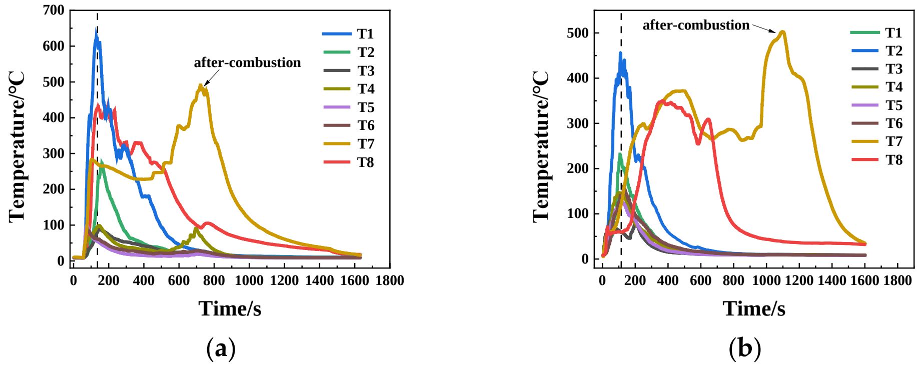


Figure 6. Temperature curve of thermal insulation material under natural combustion state: (**a**) where the materials are placed horizontally, (**b**) where the materials are placed vertically.

Put the insulation material sideways and then carry out the combustion experiment. As seen in Figure 6b, thermocouple 2 rises suddenly when the temperature of the other thermocouples drops because of a reignition phenomenon. It shows that the reignition of the insulation material has nothing to do with the placement.

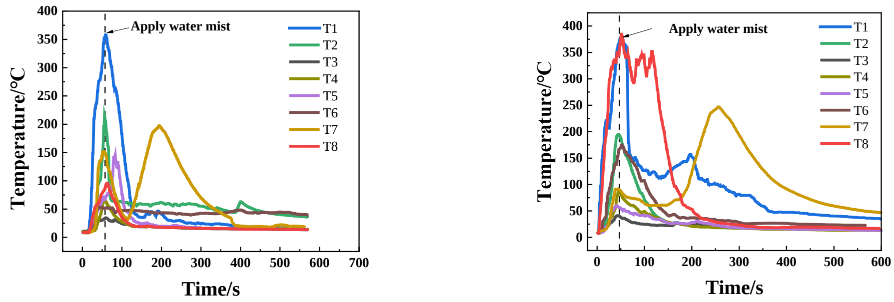
3.2.2. Apply Water Mist of Different Pressures

Figure 7 is a graph of temperature changes during the water mist fire extinguishing process under different pressure conditions. Figure 7a shows that when the water mist is applied for a while, the flame extinguishing temperature decreases, but two minutes after the flame is extinguished, thermocouple 1 shows a growth curve, and the flame appears to reignite. This reignition phenomenon shows that although the fine water mist of 1 MPa can extinguish the flame, it cannot prevent the problem of reignition of the thermal insulation material.

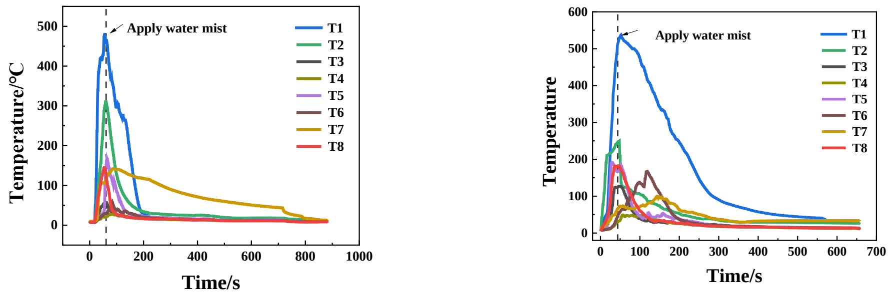
When the pressure is 3 MPa, Figure 7b illustrates that thermocouple 4 measures the temperature outside the flame, and the change is noticeable. There is no reignition phenomenon during the whole fire extinguishing process. According to the combustion temperature diagram and the experimental phenomenon, when the pressure is 3 MPa, the fine water mist can effectively solve the combustion characteristic of the thermal insulation material being easy to reignite. When the pressure is 9 MPa, Figure 7c shows no reburning phenomenon during the entire flameout process.

During the combustion process, burning the thermal insulation material will generate a large amount of smoke, making the visibility very low. The generation of smoke can reduce escape efficiency. According to statistics, 80% of casualties in fires are related to toxic and harmful gases [35]. A large amount of smoke generated during the combustion of combustibles can also pose a threat to life [36]. Therefore, the smoke change in the fire is also a way to investigate the fire extinguishing efficiency.

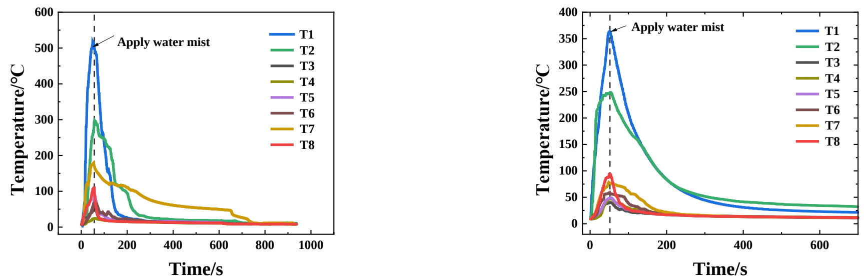
As seen in Figure 8, the application of water mist can effectively reduce the CO content compared to the application without water mist. When the pressure is different, the change in CO concentration is different. The maximum value of CO concentration is lower than in other conditions when the pressure is 9 MPa. Because when the pressure is 9 MPa, the fine water mist can extinguish the fire quickly, stop the combustion reaction, and reduce the production of CO gas. It shows that the high-pressure water mist can reduce the CO concentration during the experiment. Therefore, when high-pressure water mist is used to extinguish the fire, it can play a good role in protecting the people from the fire.



(**a**)

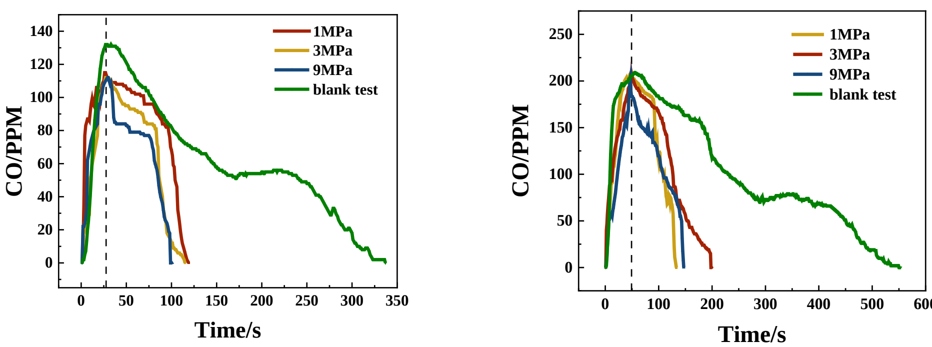


(**b**)



(**c**)

Figure 7. The temperature chart of fire extinguishing under different pressures and different placement positions: (**a**) is temperature changes at 1 MPa include horizontal and vertical placement, (**b**) is temperature changes at 3 MPa include horizontal and vertical placement, (**c**) is temperature changes at 9 MPa include horizontal and vertical placement.



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

Figure 8. Change curve of CO concentration under different pressures: (**a**) materials are placed horizontally, (**b**) materials are placed vertically.

From the change curve of O_2 concentration in Figure 9, we can see that the oxygen concentration after the application of water mist decreases faster than that without water mist. The oxygen concentration after the water mist was applied was always lower than the oxygen concentration without the water mist, which indicated that the water mist could reduce the oxygen concentration in the event of a fire. This principle is due to the small volume of high-pressure water mist, which can quickly absorb heat. When the water mist enters the fire field, it can vaporize promptly to form water vapor, increasing the water vapor volume [6]. When the volume of water vapor increases by more than 170 times, it can form an air curtain, which covers the flame in the fire field, preventing the surrounding air from entering the flame, thereby playing the role of isolating oxygen and reducing the oxygen concentration in the combustion flame area. On the other hand, when the water mist droplets evaporate quickly, more water vapor will be formed, and the oxygen concentration around the fire will decrease. Because oxygen is essential in the combustion process, when the oxygen concentration decreases, the combustion efficiency also decreases, thereby achieving the effect of extinguishing the fire.

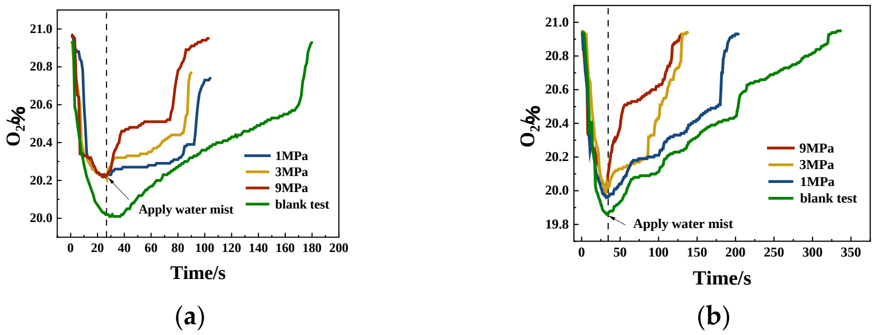


Figure 9. Change curve of O_2 concentration under different pressures: (**a**) materials are placed horizontally, (**b**) materials are placed vertically.

As implied in Figure 9, the oxygen concentration of the fine water mist applied under different pressures changes accordingly. For example, the oxygen concentration drops the fastest at 9 MPa, and the oxygen concentration at 9 MPa is always higher than in other pressure conditions, which also shows that the high-pressure water mist can effectively extinguish the fire, reduce the interaction between combustibles and oxygen, and the fire extinguishing effect is better.

Table 2 shows the fire extinguishing results of water mist under different pressures. The comprehensive comparison was made from the aspects of fire extinguishing time, CO produced during combustion, and O_2 consumed during combustion. The fire extinguishing effect was the best when the pressure was 9 MPa. The material will not become a reignition phenomenon under 9 pressures, effectively solving the problem of reignition during the cold storage fire extinguishing process. In light of this, cold storage fires can be put out using high-pressure water mist.

Table 2. Fire extinguishing results from water mist under different pressures.

Placement	Nozzle Pressure/MPa	Droplet Particle Size/μm	Extinguishing Time/s	Whether Reignition Has Occurred
Vertical	Burns naturally	–	–	yes
	1	170.926 ± 2	36	no
	3	167.636 ± 2	24	no
	9	112.792 ± 2	16	no
Horizontal	Burns naturally	–	–	yes
	1	170.926 ± 2	34	yes
	3	167.636 ± 2	26	no
	9	111.192 ± 2	15	no

3.3. Analysis of Fire Extinguishing Effect under Different Water Droplet Sizes

Figure 10 is a temperature diagram of the combustion reaction. The illustration shows that although the cooling speed of nozzles 4 and 5 is fast, the re-combustion phenomenon has occurred. Table 3 shows the fire extinguishing time under different nozzles. For example, although nozzle 1 did not reignite, the fire extinguishing time was longer than that of nozzle 2.

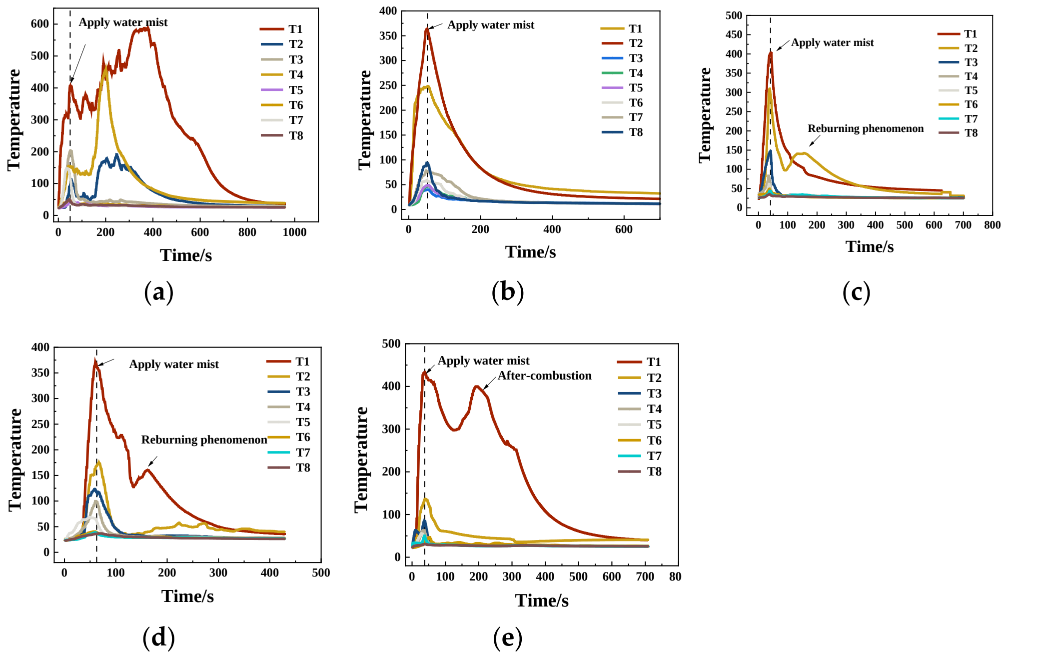


Figure 10. Temperature change diagram under different particle sizes: (**a**) is nozzle 1, (**b**) is nozzle 2, (**c**) is nozzle 3, (**d**) is nozzle 4, (**e**) is nozzle 5.

Table 3. Fire extinguishing results from water mist under different nozzles.

Placement	Nozzle Flow L/min	Pressure/MPa	Droplet Particle Size/μm	Extinguishing Time/ s	Whether Reignition Has Occurred
Vertical	5	9	95.342 ± 2	18	no
	7	9	111.792 ± 2	15	no
	12	9	138.889 ± 2	19	no
	17	9	147.897 ± 2	23	yes
	20	9	161.467 ± 2	14	yes

From the thermokinetic perspective, the fire extinguishing efficiency of different nozzles was analyzed. Applying the first law and the second law of thermokinetic to the two-phase equilibrium system, if the system has surface work in addition to expansion work and chemical work in this process [37], then there is Equation (5):

$$dU = TdS - PdV + \gamma dA \sum_{i} \mu_i d_{n_i} \tag{5}$$

where μ_{i} is the chemical potential of component i, according to the above formula, Equation (6) can be obtained:

$$\gamma = \left(\frac{\partial U}{\partial A}\right)_{S,V,n_i} \tag{6}$$

From the formula, we can see that under the conditions of constant entropy, constant volume, and constant system composition, the increase in the internal energy of the system when the unit surface area is increased is the surface free energy γ [38]. Under the same pressure, change the properties of the nozzle so that the particle size of the water droplets sprayed out is different, and the surface area of the water droplets is also different. For the same mass of water droplets, the particle size of these droplets decreases, the total surface area of the droplets increases, the overall surface free energy of the water droplets also increases, and the absorption can take away more heat during evaporation.

Figure 11 shows the CO concentration map of different nozzles, which reveals that the CO concentration produced by nozzle 2 is lower than that of the other nozzles. After nozzle 5 is turned on, the CO concentration drops rapidly, and the decline is greater than that of nozzle 2. However, after the subsequent stop of water mist spraying, the phenomenon of reignition occurred. CO concentration rises again due to the large particle size produced by nozzle 5, which greatly inhibits the flame in the early stage of the fire. However, because the thermal insulation material is covered with a protective layer, the fine water mist does not enter the inside of the thermal insulation material during the fire extinguishing process. When the flame on the surface of the thermal insulation material is extinguished, the water mist-generating device is turned off. Since the residual temperature remains inside the thermal insulation material, it will re-burn after reaching the ignition point.

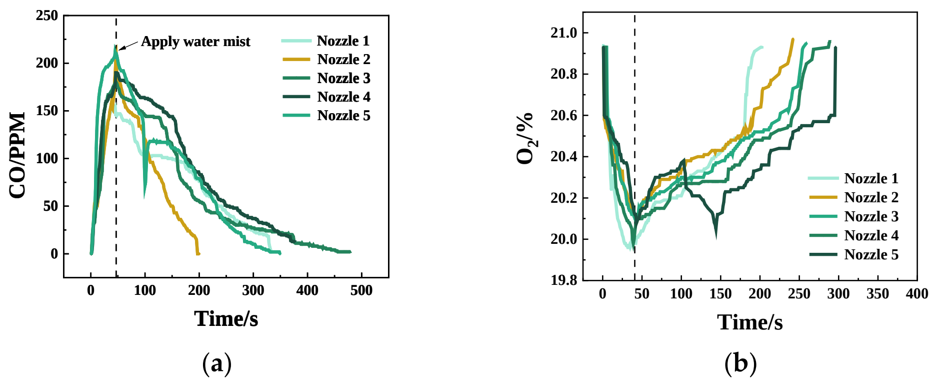


Figure 11. Variation diagram of gas concentration under different particle sizes: (**a**) is a graph of the change in CO concentration, (**b**) is a graph of the change in O_2 concentration.

The O_2 concentration map shows that the O_2 concentration of nozzle 2 is higher than the other nozzles, which suggests that this nozzle is more effective at extinguishing fires, attributed to the reduction in burn time. When the combustion reaction time is shortened, the enclosed space retains more oxygen concentration in an enclosed space.

Experimental results show that nozzle 2 has the best fire extinguishing effect. The optimal particle size of the extinguishing insulation material is between 110–140 µm. The conclusion of Liu et al. [15] can also be verified according to the experimental results. Within a certain range, the smaller the particle size of the water droplets, the better the fire extinguishing effect, although the fire-extinguishing action will be lessened when the water droplets' particle size is very small due to insufficient momentum.

4. Conclusions

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

1. When a fire occurs in the cold storage reignition is prone to occur, and it is not affected by the placement of the insulation material. When the nozzle pressure is 1 MPa, the phenomenon of reignition will still occur, and when the nozzle pressure is 3 MPa and 9 MPa the phenomenon of reignition will not occur so that the high-pressure water mist can be used in cold storage fires. If the cold storage fire–fighting uses water mist to extinguish the fire, the extinguishing effect is good, and water resources can be saved. It provides an innovative idea for energy saving and environmental protection;
2. In the process of water mist fire extinguishing, it can effectively reduce the CO concentration generated in the fire. When the nozzle pressure is 9 MPa, the effect of reducing the

CO concentration is more obvious. Therefore, high-pressure water mist has a good suppression effect on cold storage fires. At the same time, it can also reduce the concentration of O_2, which can suffocate the flame and help to control the fire;

3. As the pressure increases, the water droplet size gradually decreases for fine water mist droplets size. During the fire extinguishing process, the smaller the water particle diameter, the more water droplets vaporize, and the greater the volume expansion. However, it is not that the smaller the particle size is, the more suitable it is for firefighting. This research studied the particle size range of water droplets within the scope of 100–200 µm and found a particle size range that has better effects and is more suitable for cold storage fire protection. After experimental research, it was found that when the water droplet size is between 110–140 µm, it is more suitable for cold storage fire protection.

This study still has potential for improvement, because the experimental setting was constrained and the actual cold storage environment may include obstructions, poor ventilation, and other elements. A full-scale replica of an actual cold storage facility should be built, and additional influencing factors should be included to explore the fire-extinguishing properties of water mist with various particle sizes. In addition to providing more precise experimental data for the later design of the cold storage fire prevention system, this will increase the credibility of the experimental results.

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