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A Study of Fire Drone Extinguishing System in High-Rise Buildings

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Abstract: Firefighting in high-rise buildings remains a difficult problem in the world because fire extinguishing equipment and tactics have many deficiencies in dealing with such building fires, especially for buildings higher than 50 m. In the present study, the LY100 fire extinguishing system is taken as an example to introduce the application of the fire drone in the fire control of high-rise buildings. The LY100 fire extinguishing system mainly contains the twin-rotor drone, high-pressure liquid fire extinguishing equipment, pressure fire extinguishing equipment, associated vehicle and extinguishing agent. The LY100 system can be deployed quickly and operated flexibly. Based on such advantages, the indoor fire, exterior thermal insulation layer fire and top platform fire of high-rise building can be extinguished in a timely manner with the LY100 system. In addition, four kinds of firefighting tactics are described in this paper, including one drone operation, double drone cooperative operation, three or more drone cooperative operations, and cooperating with the lifting fire truck. Finally, the experiments are presented to verify the spraying distance of the fire drone system.

Keywords: LY100 system; high-rise building fire; firefighting scenarios; firefighting tactics

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1. Introduction

With the rapid development of China's economy, the number of high-rise buildings has increased dramatically. High-rise buildings stand for the prosperity and civilization of society. However, they also bring serious risks and severe challenges to urban safety. High-rise buildings face a great risk of fire because of their amazing height, complex structure and diverse functions [1,2]. It may cause casualties and property losses [3]. For instance, a fire accident happened in the uncompleted Television Cultural Center (TVCC) on 9 February 2009 in Beijing, which led to one death, eight injured and economic losses of RMB 16.38 million [4]; a fire accident occurred at the Jiaozhou Road in Shanghai on 15 November 2010 which caused 58 deaths and destroyed a 28-story high-rise building [5]; a fire accident caused by fireworks of Shenyang in China brought serious economic loss and social impact in 2011 [6]. The automatic fire sprinklers system is the indoor way to extinguish fire or hold it in check until firefighters arrive [7]. Fire trucks still play a dominant role in fighting high-rise building fires from outside of the building in China [8–10], even though the firefighting robot for high-rise building has been proposed [11–14]. Although the new fire prevention and extinguishing technologies are constantly put forward, high-rise building fires are still frequent and threaten people's lives. For example, 6043 fire accidents of high-rise buildings occurred in China in 2017, causing 102 deaths, and 87 injured [15].

There are five problems as follows in the firefighting of high-rise building due to the working area restrictions and characteristics of lifting fire trucks, financial capacity of local government and so on. Firstly, there is no effective outdoor method for extinguishing fires in buildings higher than 100 m. At present, the maximum working height of fire trucks in China can reach 101 m. Due to the characteristics of fire trucks and the limitation of their working place, the lifting height of the fire truck cannot be significantly increased. Therefore, it is impossible to use the fire truck to extinguish a fire that occurs in buildings over 100 m in height. Secondly, according to the regulations of GB 50016-2014 [16–19], the working area of the fire truck is usually set up along one side or one fourth of the total building's length. Except for the parts corresponding to the working area of fire truck, the remaining parts of the building cannot be protected by the fire truck. Thirdly, the lifting fire truck works at a height of less than 50 m in most fire stations in China. Herein, only the internal firefighting methods can be taken if the high-rise building fire occurs. Taking Henan province as an example, more than 12,900 high-rise buildings exist in the whole province, which exceed 100 m high. However, there are only 2 fire trucks with a height of 101 m in all fire stations, 42 fire trucks with height of over 50 m, and other fire trucks have a height of less than 50 m. Fourthly, the lifting fire trucks need a long time to launch and are greatly affected by the weather, which is not conducive to the rapid firefighting and rescue activities. Taking the fire truck with a height of 78 m as an example, the actual deployment time is more than 3 min, and the platform of the fire truck rises to the top for more than 6 min. Furthermore, it can only work in a wind whose speed is below 10.8~13.8 m/s. Currently, there are no successful rescue cases of lifting fire trucks above 50 m in China. Fifthly, fire of the exterior insulation material of high-rise buildings has no effective means to be extinguished. In China, a large number of flammable and combustible thermal insulation materials are used in the initial stage of building renovation. Once a fire occurs in these buildings, it will spread rapidly. Due to the immovable working position of the lifting truck and the limitation of their working place, the fire cannot be put out in time, causing the whole building to succumb to the fire.

With the development of science and technology, the firefighting drone has been gradually used in wildfires [20–25]. Considering the worldwide problem of firefighting and rescue for high-rise buildings, the present paper puts forward the fire drone system to extinguish high-rise building fires from outside. Taking the LY100 system as an example, the application scenarios and firefighting tactics are introduced. This paper is structured as follows. Characteristics related to LY100 system are described in Section 2; advantages and application scenarios are analyzed in Section 3; working process and firefighting tactics of LY100 system are introduced in Section 4; the experiment is presented in Section 5; and finally, the last section is the main conclusion.

2. Description of LY100 System

The LY100 system is mainly composed of the twin-rotor drone, high-pressure liquid fire extinguishing equipment, pressure fire extinguishing equipment and vehicle. In addition, the system is equipped with one 1000 L high-efficiency water-based fire extinguishing agent tank, one 1000 L special fire extinguishing agent tank, four 60 L ultrafine dry powder tanks, four 60 L high-efficiency water-based pressure tanks, generator etc. The detailed information is described in Sections 2.1–2.5

2.1. Twin-Rotor Drone of LY100 System

As shown in Figure 1, the twin-rotor drone is mainly composed of laser, microwave radar, high-definition video, infrared video, etc., which can avoid collision with buildings and aircraft effectively. The drone has a real-time monitoring system, which can raise alarm and return automatically in the case of abnormality. In addition, the drone adopts manual and automatic control, and it can return at one click when it encounters emergency. Its main performance parameters are shown in Table 1. The empty weight and full load weight of the drone are 140 kg and 255 kg, respectively. The maximum velocity can reach 22 m/s. It

can ensure flight safety and stability in the wind with a speed 12 m/s. The drone consumes 16 L of fuel per hour, and it can fly for nearly 2.5 h at its full load (255 kg).

Figure 1. The drone used in LY100 fire extinguishing system.

Table 1. The main performance parameters of the drone used in LY100 system.

Name	Value
Empty weight	140 kg
Full load weight	255 kg
Cruising speed	22 m/s
Average fuel consumption	16 L/h
Control method	Manual and automatic
Maximum wind resistance speed	12 m/s
Maximum load capability	115 kg
Lifting speed	4 m/s

2.2. High-Pressure Liquid Fire Extinguishing Equipment

The high-pressure liquid fire extinguishing equipment is one of the main fire extinguishing equipment equipped with the LY100 system. It includes a fire extinguishing agent tank, gasoline engine, pressure pump, electric reel, high-pressure pipe, automatic aiming servo mechanism, spray gun, etc. Its main performance parameters are shown in Table 2. The working pressure of the high-pressure liquid fire extinguishing equipment can reach 27 MPa. It can continuously extinguish fire and cool down the fire site. The flow rate of the spray gun can be divided into 40 L/min and 70 L/min, and the required diameters of the water belt are 9 mm and 13.6 mm, respectively. The length and weight per meter of the water belt with 9 mm diameter are 120 m and 0.36 kg, respectively. The length and weight per meter of the water belt with 13.6 mm diameter are 70 m and 0.6 kg, respectively. The weight of the spray gun is about 4 kg, while the length of the spray gun is 1.5 m when it is retracted and 4.5 m when it is extended. The shower jet distance and area are 6 m and 28.27 m^2, respectively. In order to extinguish the fire effectively, the direct spray distance of the gun needs to be greater than 16 m.

Table 2. The main performance parameters of high-pressure liquid fire extinguishing equipment.

Name	Value
Weight per meter of the water belt with 9 mm diameter	0.36 kg
Weight per meter of the water belt with 13.6 mm diameter	0.6 kg
Spray gun weight	4.02 kg
Spray gun length	1.5 m
Spray gun stretch length	4.5 m
Shower spray distance and area	6 m and 28.27 m^2
Direct spray distance	16 m

The automatic aiming servo mechanism is equipped with a high-definition camera and thermal imaging aiming mechanism. Through data analysis and manual comparison, the automatic aiming of the target area can be carried out. After the target is locked, the spraying device can realize the angle adjustment of 25 degrees in the hovering of the drone.

2.3. Pressure Fire Extinguishing Equipment

Pressure fire extinguishing equipment is another fire extinguishing equipment of the LY100 system, which is used for the fast suppression and flexible extinguishing of fierce burning fire. As shown in Figure 2, it is mainly composed of a titanium alloy tank, safety valve group, electric slow-release valve, hose and nozzle. The titanium alloy tank can carry 30 kg of ultrafine dry powder or 60 L of a high-efficiency water-based fire extinguishing agent. The working pressure of the tank is 1.2 MPa, the blasting pressure is 2.0 MPa, and the residual quantity of the extinguishing agent is no more than 3 percent of the total amount. The safety valve group has the functions of overpressure relief and emergency rapid relief, which can keep the flight of drone safety. The electric slow-release valve can open and close the equipment in 3 to 5 s.

Figure 2. The pressure fire extinguishing equipment.

2.4. Special Command and Transport Vehicle

The special command and transport vehicle of the LY100 system integrates equipment control, consumables supply and equipment storage. The vehicle is composed of cockpit, operational control room and storage cabin (Figure 3). The cockpit can take two people who are mainly responsible for driving. The operational control room is responsible for the control of the drone flight and firefighting operations, as well as the in situ information

summary and transmission. The flight and video information of drone, status and work information of fire extinguishing equipment, firefighting plan of key units, fire field and surrounding vehicles information and others can be transmitted to the screen in the operational control room. The operational control room is convenient for LY100 operators to carry out precise firefighting operations and realize real-time information transmission with the fire command center. The storage cabin can place the devices (such as the ultrafine dry powder tank, high-efficiency water-based fire extinguishing agent tank, and pressure storage fire extinguishing equipment) of the LY100 fire drone system and other firefighting equipment. There is a drone lifting platform installed on the top of the vehicle, which serves as the drone taking-off and landing.

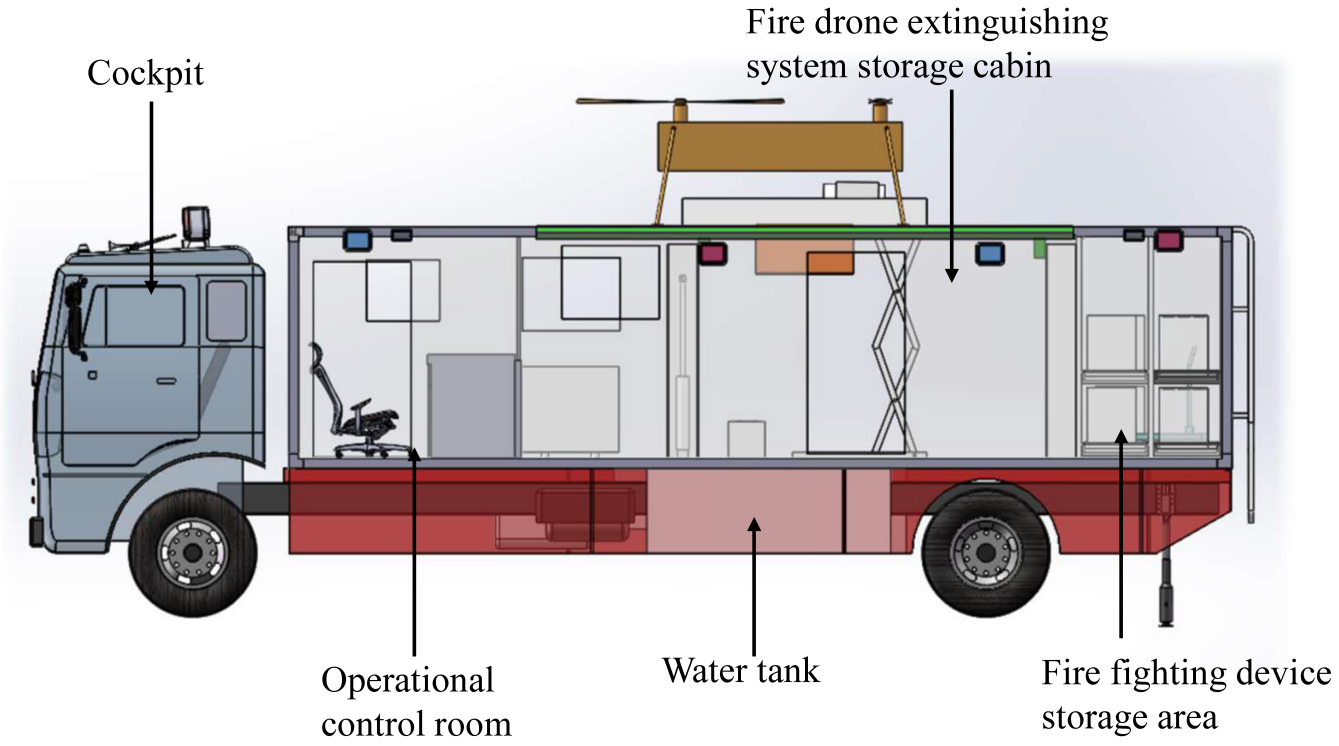

Figure 3. Special command transport vehicles.

2.5. Extinguishing Agent Performance

The high-efficiency fire extinguishing agents used in the LY100 system can be divided into three types, including ultrafine dry powder, a high-efficiency water-based fire extinguishing agent and a special fire extinguishing agent for the exterior wall. (1) The ultrafine dry powder adopts the high degree of polymerization of ammonium polyphosphate, which is insoluble in water, as the core component to extinguish fire. It fuses with nano-scale particles with flame retardance, smoke elimination and water repellency to form new functional particles. The average particle size of the powders does not exceed 5 μm. The minimum extinguishing concentration of ultrafine dry powder reaches 50 g/m^3, which is more than 16 times the extinguishing efficiency of the ordinary ABC dry powder. (2) The high-efficiency water-based fire extinguishing agent is stored in a 1000 L tank and 60 L pressure tank. Its main extinguishing principles are moistening, osmosis, cooling, emulsification, foam and emulsion covering, and elimination of free radicals. This kind of fire extinguishing agent can quickly reduce the temperature of the fire site, dilute the oxygen concentration in the fire area, seal the combustion surface, terminate the chain reaction and eliminate the harmful smoke. (3) The special fire extinguishing agent for the exterior wall is stored in a high-pressure tank with the flow rate range from 40 L/min to 70 L/min, which is used for the exterior wall insulation material fire. The agent can shield

the oxygen on the surface of the burning substance, which can asphyxiate the burning substance. Furthermore, the agent can precipitate liquid on the surface of the combustor, cool the combustor and absorb heat so that the temperature of the combustor quickly falls below the ignition point.

Combining the fire extinguishing equipment mentioned in Sections 2.2 and 2.3 with the three kinds of fire extinguishing agents, three kinds of fire extinguishing styles are obtained, which are pressure dry powder fire extinguishing, high-pressure liquid fire extinguishing and pressure water-based fire extinguishing. The pressure dry powder fire extinguishing can control fire quickly and have high fire extinguishing efficiency, but it cannot be used in the space of personnel and it is greatly affected by wind. The high-pressure liquid fire extinguishing can continuously extinguish the fire. The spray distance is long. It can either directly spray liquid fire extinguishing or blossom spraying a special extinguishing agent for the external wall, but it is also greatly affected by wind. The advantage of pressure water-based fire extinguishing is flexibility and can be used in manned space. The disadvantage is that the efficiency of the fire extinguishing is not as high as that of the pressure dry powder fire extinguishing.

3. Advantages and Application Scenarios of LY100

3.1. Advantages Description

The LY100 fire system has strong fire extinguishing capability. The LY100 drone can carry 1000 L of a high-efficiency water-based fire extinguishing agent, 1000 L special fire extinguishing agent for the exterior wall, 240 L pressure dry powder, etc. Furthermore, the LY100 fire system can be continuously supplied by other fire trucks through coupling. The LY100 fire drone system has the following obvious advantages in fighting high-rise building fire compared with traditional fire trucks.

a. Quick equipment deployment and short time in place. It takes less than 30 s for the LY100 fire system to lift the platform hydraulically from opening the cabin roof. The rising speed of the fire drone is from 3 to 5 m/s, and the total time to reach the height of 100 m is no more than 60 s. However, it takes no less than 10 min for the fire truck on the platform whose working height can reach 101 m to expand from working to 100 m height.

b. Widely applicable fire extinguishing agent, high fire extinguishing efficiency. As abovementioned, the LY100 system adopts ultrafine dry powder, a high-efficiency water-based fire extinguishing agent and special fire extinguishing agent for the exterior wall, all of which are suitable to class A, B and C fire extinguishing. In addition, water-based fire extinguishing agents with different proportions can be used to extinguish class A, B, C, D, E and F fires.

c. Various combined firefighting methods. Pressure dry powder fire extinguishing equipment has high fire extinguishing efficiency, which can quickly control the fire. High-pressure water-based fire extinguishing equipment has good effect of cooling and preventing reburning. The high-pressure liquid fire extinguishing equipment can sustainably spray high-efficiency fire extinguishing agents with large flow rate. It can be applied to extinguish an indoor fire by a direct current or an exterior wall fire by blooming. These three kinds of fire-extinguishing equipment can be freely combined to control the fire quickly and put out the fire effectively.

d. Special exterior wall firefighting, broken window cooling and smoke removal. By taking advantage of the flexibility of the drone in air flight, special fire extinguishing agents can be quickly sprayed on the unburned adjacent parts of exterior wall to prevent the fire from spreading and expanding. On this basis, fire extinguishing can be carried out. For rooms requiring cooling and smoke extraction, the outer window glass can be broken by a projectile fired from the LY100 system to achieve natural smoke extraction. In addition, it can also spray water-based extinguishing agent with obvious smoke elimination effect for artificial smoke elimination.

3.2. Scenarios Analysis

3.2.1. Indoor Fire

The indoor construction area is less than 100 m^2 and has outside windows. The LY100 equipped with pressure dry powder extinguishing device can carry 30 kg of ultrafine dry powder at one time. The effective fire extinguishing concentration of ultrafine dry powder is 50 g/m^3 according to the standard storey height (3 m) of the building and safety coefficient (0.5), which can effectively put out a space fire occurred in 100 m^2.

When the glass of the outside windows has burst and fallen off (or opened) and no one has been identified, the LY100 carries out firefighting from the outdoor space of the building through the window, provided that the exterior window glass has been blown off (or opened) at high temperature and no one is confirmed. Generally, it takes more than 10 min from the fire brigade receiving an alarm to fight the fire. According to the "fire standard temperature rise curve", the fire has developed to the violent phase at this time. At this stage, the window glass will burst and fall off, and the indoor temperature will no longer be suitable for survival. When extinguishing a fire, it should be decided whether to adopt a pressure dry powder fire extinguishing device after video investigation and comprehensive information analysis. Otherwise, water-based fire extinguishing equipment with pressure or high-pressure liquid fire extinguishing equipment should be adopted. If the indoor temperature does not reach the temperature condition of glass bursting, it shows that the indoor temperature is not high. At this time, the fire belongs to ventilation-controlled combustion. The air will enter the room if the window is broken, causing rapid expansion of the fire. Only with the permission of people can drones break the windows. Therefore, the windows can only be broken under the direction of the fire commander. Otherwise, the LY100 drone will not be allowed to break the windows.

3.2.2. Exterior Thermal Insulation Layer Fire

The characteristic of fire that occurs on the exterior thermal insulation layer is that the fire spreads rapidly and mainly upward in the initial stage. As the fire develops to a violent stage, the fire spreads downward as the molten matter falls off, and a new "fire point" is formed at the lower platform. The speed of horizontal spread is affected by the combustion performance, laying mode and structure of thermal insulation materials. Based on the characteristics of the exterior thermal layer fire and LY100 system, the operation of LY100 in high-rise buildings is mainly divided into three steps. Firstly, a special fire extinguishing agent is sprayed on the platform connecting the fire area and the wall below to prevent the fire from spreading downward. Secondly, special fire extinguishing agents are sprayed from bottom to top along the left and right sides of the fire area to prevent the fire from spreading. Finally, it is necessary to keep the LY100 at a safe distance from the building, and the propeller airflow of LY100 will not disturb the smoke airflow in the fire site. Then the special fire extinguishing agent can be sprayed on the unburned part of the combustion area or sprayed directly to extinguish the fire.

In order to ensure the continuity of spraying fire extinguishing agents, the combination method should be adopted to implement fire extinguishing. High-pressure liquid fire extinguishing equipment should be used in fire-fighting operations at the lower part and both sides of the combustion area. When spraying or extinguishing the upper part of the combustion area, the pressure liquid extinguishing equipment should be used. Therefore, the high-pressure liquid pipe can be avoided by high temperature, and the maneuverability of LY100 can be maintained. It is worth noting that the LY100 system is not suitable for the thermal insulation layer fire of exterior stone of cavity structure. The fire will spread quickly in this kind of insulation layer. The exterior stones are usually destroyed after a certain duration of fire. Therefore, the fire cannot be extinguished or prevented because the fire extinguishing agents cannot be directly sprayed on insulation materials.

3.2.3. Top Platform Fire

The top platform fires of high-rise buildings are usually caused by mechanical and electrical equipment, cooling towers and sundries. The fires usually do not harm the below buildings because of their location. The drone extinguishing system can provide a decision-making basis for firefighters through detecting and monitoring high-rise building fires effectively. The special extinguishing agent is sprayed on the connection of the top platform and wall by the fire drone when there is a possibility of spreading downward along the exterior insulation layer. Accordingly, the fire spreading downward along the exterior insulation layer can be prevented.

4. Description of Working Process and Firefighting Tactics

4.1. Working Process

The standard staffing of the LY100 fire drone extinguishing system is four, which are the operators of the fire drone and fire-extinguishing device, respectively, device mounter and ground watchman. The fire drone operator is responsible for the flight control. The fire extinguishing device operator is responsible for the operation of the fire extinguishing device. The main task of the device mounter is to load and replace the firefighting device. The job of ground watchman is to set up the operation warning area, observe during operation time, and to be responsible for driving the vehicle. After receiving the alarm, the work of the squadron is mainly divided into five parts. Firstly, the equipped vehicles are driven to the fire scene and parked under the fire building, followed by the warning area set on the ground. Secondly, the hydraulic support leg of the equipped vehicle is lifted, then the roof of the equipment cabin is opened, and the drone base is raised. After that, the firefighting equipment can be mounted according to the needs of the site. Thirdly, the fire drone operator should ensure that the fire drone reaches the outside of the fire room and is kept in good flight condition. Fourthly, the fire extinguishing device operator cooperates with the fire drone operator through visual observation and video confirmation, and then aims at releasing the fire extinguishing agent or spraying the fire extinguishing agent on the exterior wall. Finally, the drone is returned to the drone platform, and the fire extinguishing equipment is replaced by the device mounter.

4.2. Firefighting Tactics

Five kinds of firefighting tactics in high-rise building fire are presented as follows.

One drone operation. According to the situation of the fire site, the pressure dry powder fire extinguishing equipment can be selected to suppress and extinguish the fire quickly in the case that there is no life in the indoor area. For larger fires, fires in multiple rooms, or fires in the exterior insulation layer, high-pressure liquid fire extinguishing equipment can be used for continuous and uninterrupted firefighting. For high-floor fires or large horizontal spacing between fire area and vehicle, pressure fire extinguishing equipment can be chosen to fighting fire. Pressure dry powder fire extinguishing equipment should not be applied under the condition that personnel may exist.

Different fire extinguishing equipment can be used to carry out round-trip liftoff and multiple firefighting operations as the fire scene needs. During the firefighting, the advantages of the aforementioned three fire extinguishing equipment and agent should be given full consideration so as to maximize the overall efficiency of the fire drone system.

Double drone cooperative operation. This fire tactic requires two drones to participate in the same firefighting action. The two drones' operation can be divided into four modes, including partition operation, subregion operation, division of labor operation, and cross operation. Partition operation means that the two drones should be parked in different sides of the building to carry out the operation independently when two or more sides of a building are on fire. When a fire occurs on one side of the building, the subregion operation can be adopted. The two drones should be parked at intervals with each other along one side of the building. In this way, the two drones can be used to carry out firefighting operations independently and prevent mutual interference. Division of

labor operation is suitable for building the exterior insulation layer fire. Both drones should be responsible for fire control on the side of the burning area. Cross operation refers to when the two drones take off in turn for fire in the same area when a fire breaks out on one side of the building.

Three or more drone cooperative operation. When three or more drones participate in the same firefighting operation, they should carry out a multi-unit joint operation under the same command. This tactic can comprehensively adopt the methods of partition operation, subregion operation, division of labor operation, and cross operation of one drone operation and double drone cooperative operation to fight the fire so as to control the fire quickly and extinguish the fire completely.

Cooperating with the lifting fire truck. The LY100 extinguishing system for high-rise building fire and the lifting fire truck both belong to external fire extinguishing equipment. They have their own advantages and can work together. This firefighting mode can control fire quickly. It takes a long time to carry out fire extinguishing by a lifting fire vehicle because hydraulic legs need to be stretched and fixed in operation. However, the LY100 can quickly get to work. The LY100 system can not only use the pressure fire extinguishing equipment to fully extinguish the fire, but also quickly change the site by means of connecting the motorized coil. Considering the fast deployment speed and high fire extinguishing efficiency of the fire drone system, LY100 can used to control the fire before launching the lifting fire truck. Therefore, LY100 can gain time for the lifting fire truck through suppressing and controlling the spread of the fire in the building. At the same time, this tactic can adopt high and low partition operation to fight the fire. The height of LY100 can reach 120 m. It can be used to fight fire above the maximum height of the lifting fire vehicle. Herein, the upper fire of the building can be put out by LY100, and the lower fire can be put out by the lifting fire truck in this firefighting tactic.

5. Experiments

5.1. The Experimental Site

The experiments were conducted to verify the spraying distance of the LY100 fire extinguishing system. The in situ test of spray distance of the high-pressure liquid fire extinguishing equipment is shown in Figure 5 for 26 January 2019 in Zhengzhou, Henan province. The temperature of the test day was about 10 °C and there was no wind. Three groups of experiments using water were carried out with different fire extinguishing tank whose flow rates are 40 L/min and 70 L/min respectively. The experiments were conducted at the 15th floor of ordinary residential buildings, with a brick–concrete structure, second-level fire resistance, and 3.3 m in height. The layout was set according to the apartment-style one-bedroom and one-hall. The bedroom was 22.78 square meters, and the room was equipped with a double bed, mattress and quilt, wardrobe, bedside table, curtains and other daily necessities. The living room was 48.39 square meters, equipped with sofas, coffee tables, TV cabinets, tables, stools, computers, curtains and other conventional household items, as shown in Figure 4.

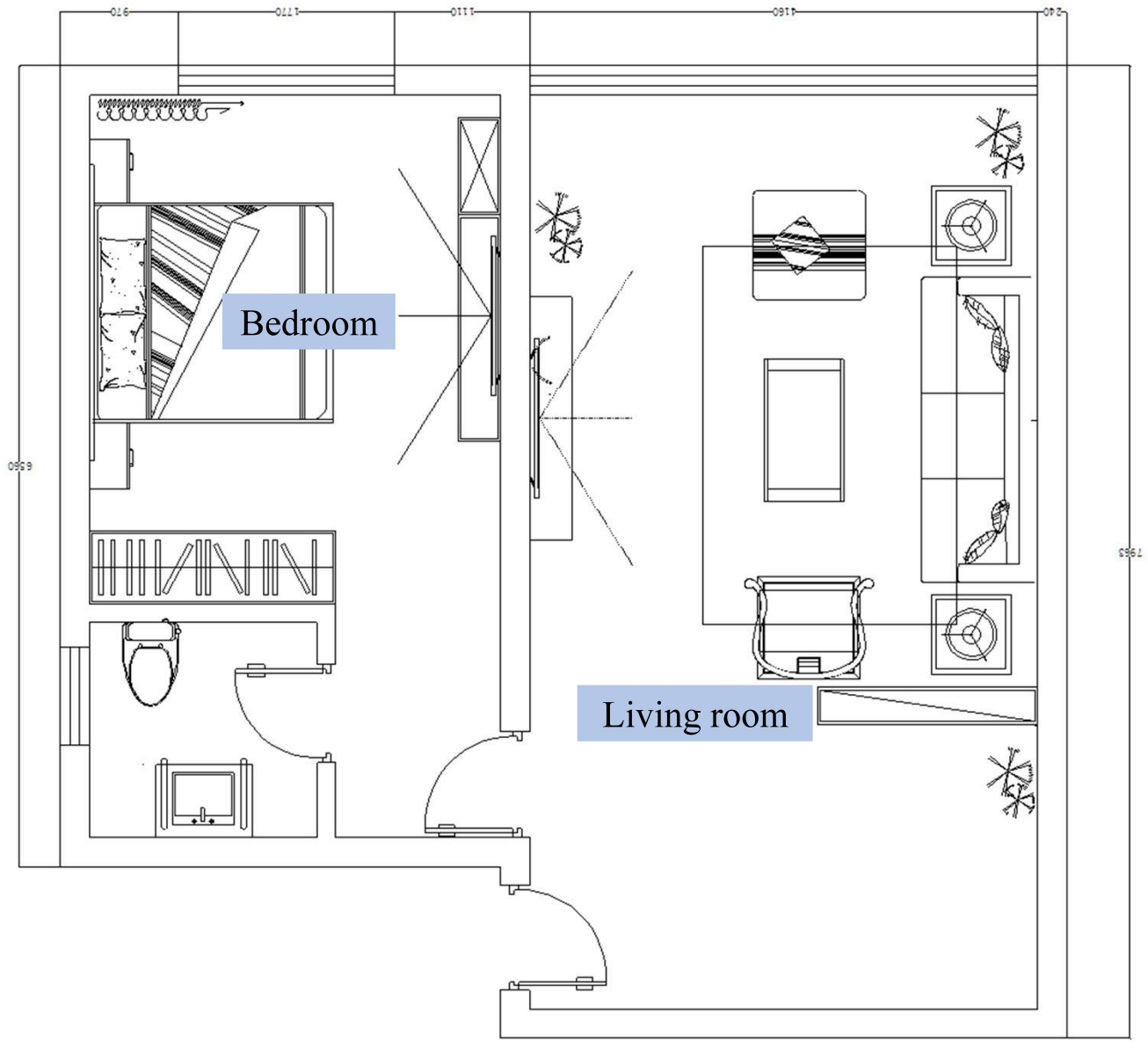

Figure 4. Layout of experimental site.

5.2. Experimental Measurement System

The data required for this experiment are mainly to measure temperature and collect on-site conditions. The temperature measurement and collection use thermocouple beams, and the image and video information collection use digital cameras.

5.3. Experimental Methods and Procedures

A total of six experiments were carried out. The bedroom and living room were respectively carried out with a storage pressure dry powder fire extinguishing device and a high-pressure liquid fire extinguishing device. The dry powder was military-grade superfine dry powder, and the water-based fire extinguishing agent was FA2000.

The specific experimental process of the bedroom is repeated according to the following steps.

(1). The bed is ignited by an open flame (lighter to ignite the paper) and starts burning;

(2). With the continuous burning, the scope (area) of the burning becomes larger and larger, and the material becomes greater and greater. The flame rises, the flue gas rises, and

the temperature of the fire field gradually rises. The height of the flame and the temperature of the fire field are recorded;

(3). The combustion has entered a fully developed stage. The curtains and the surrounding combustibles are ignited, and the flame rises. The temperature of the fire field rises, the smoke fills the roof and then presses down. The window glass is burned and burst, and the smoke rolls outward at the cracked place. It gradually reaches the crash stage, at which time the entire surface of the combustible material in the room is fully involved in the combustion, and the temperature reaches the highest point; the flame height and the temperature of the fire field are recorded.

(4). After the fire lasts for 15 min, the window glass bursts. The LY100 extinguishing system sprays the fire-extinguishing agent or water with flow rates of 40 L/min and 70 L/min, respectively, from below the neutral surface of the smoke from the ruptured window, as shown in Figure 5.

(5). During the spray is processing, the spray distance, the spray time, flow rate, and nozzle pressure is recorded.

Figure 5. The fire extinguishing equipment at high heights.

5.4. Experimental Results

The results are shown in Tables 3 and 4. The spray angle, spray gun height and the spray time were 0°, 1 m and 5 min, respectively, in all six experiments. When the flow rate was 40 L/min and the working pressure of the pump was 10 MPa, 13 MPa and 15 MPa, the measured pressure at the nozzle of the spray gun was 4.4 MPa, 5.2 MPa and 6.2 MPa, respectively. At this time, the flow rates of the water were 53.3 L/min, 60.8 L/min and 65.6 L/min, and the corresponding spray distances were 16 m, 17 m and 18 m. When the flow rate was 70 L/min and the working pressure of the pump as same as the 40 L/min, the measured pressure at the nozzle of the spray gun was 5.8 MPa, 6.5 MPa and 7.2 MPa respectively. At this time, the flow rates of the water were 60.5 L/min, 67.8 L/min and

72.4 L/min, and the corresponding spray distances were 16 m, 17 m and 18 m. All spray distances of the six groups of tests are no less than 16 m, meeting the requirement of the direct spray distance mentioned in Section 2.2.

Table 3. Experiment results of the high-pressure water fire extinguishing equipment.

Name	Unit	40 L/min			70 L/min		
		1	2	3	1	2	3
Pump working pressure	MPa	10	13	15	10	13	15
Nozzle pressure	MPa	4.4	5.2	6.2	5.8	6.5	7.2
Spray angle	Degree	0	0	0	0	0	0
Spray gun height	m	1	1	1	1	1	1
Flow rate	L/min	53.3	60.8	65.6	60.5	67.8	72.4
Spray distance	m	16	17	18	16	17	18
Spray time	min	5	5	5	5	5	5

Table 4. Experiment results of spraying dry powder of the pressure fire extinguishing equipment.

Name	Unit	Test Number			
		1	2	3	4
Agent weight	kg	20.45	21.25	20.2	20.15
Tank weight	kg	23.45	23.45	23.45	23.45
Spray time	s	26.56	24.87	23.73	23.25
Spray distance	m	20	18	18	18

In addition, four experiments of the pressure fire extinguishing equipment sprayed dry powder were conducted in this study. The spray angle and spray gun height were 0° and 1 m, respectively. The results of spraying dry powder of the pressure fire extinguishing equipment are in Table 4. It can be seen that all the spray distances of the four groups of experiment were greater than 16 m, too. The results meet the requirement of the spraying dry powder of LY100 fire extinguishing system.

6. Conclusions

Considering the difficulties that exist in high-rise building firefighting, a new extinguishing system named the LY100 system is developed in this study. Its outstanding advantages are its rapid deployment and flexibility in operation. The LY100 system is mainly composed of the twin-rotor drone, high-pressure liquid fire extinguishing equipment, pressure fire extinguishing equipment, vehicle and extinguishing agent. In addition, the firefighting ability of LY100 system is strong since it can bring 1000 L of a high-efficiency water-based fire extinguishing agent, 1000 L of a special fire extinguishing agent, 240 L dry powder, etc. The system is suitable for two kinds of indoor fires, including cases where the indoor area is less than 100 m^2 and has outside windows, and the windows of the fired room has burst and fallen off with no people in the room. When the LY100 system is used in fighting exterior thermal insulation layer fire, it is affected by the influence of smoke and temperature, structure of the insulation layer, and performance of the fire extinguishing agent. For firefighting tactics, the LY100 system can adopt one drone operation, double drone cooperative operation and three or more drone cooperative operation. Furthermore, it can also cooperate with the lifting fire trucks to control and extinguish high-rise building fires quickly and effectively. The spray distance of the high-pressure liquid fire extinguishing equipment and spraying dry powder of the pressure fire extinguishing equipment have proved that the proposed LY100 fire extinguishing system is effective. The results will be analyzed in separate papers.

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