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EXPERIMENTAL EVALUATION OF FIRE SUPPRESSION CHARACTERISTICS WITH TWIN-FLUID WATER MIST UNDER VARYING SUB-ATMOSPHERIC PRESSURE

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ABSTRACT

Sub-atmospheric pressure effects on pool fire behaviors using n-heptane with water mist based on the protection of the ozone layer in aircraft operation safety. Twin-fluid water mist has been evaluated as one of the most promising technologies to replace Halon fire suppressant for cargo fires. N-heptane pool fires with no water mist suppression activated and with water mist fire suppression system activated were tested and analyzed under standard pressure and different depressurization rates (91, 182, 328 Pa/s) in this work. The mass loss of fuel and chamber pressure history were measured. In addition, the suppression time for each test with water mist activated was also analyzed statistically. The test results under different depressurization rates demonstrated the effectiveness of the water mist system, and the average suppression time is less than 25 seconds. The different pressure ratios between water and nitrogen have also been compared and analyzed, and the results show that the suppression is more effective when the pressure of the water and nitrogen is 0.4 MPa and 0.48 MPa, respectively. The outcomes are of great significance for optimizing the design of fire extinguishing systems for aircraft.

Keywords: Twin-fluid Water Mist, Pool Fire, Changed Pressure, Low Pressure, Fire Suppression

1. INTRODUCTION

Cargo fire is one of the major threats to airplane safety, while most of aviation accidents were accompanied by fires [1, 2]. The impetus for Federal Aviation Administration (FAA) to develop fire suppression system for cargo compartments was the crash of a ValuJet DC-9 in the Florida Everglades on May 11, 1996 [3], when all the 105 passengers and 5 crewmembers were killed. Forty percent of the passengers who survive the impact of an airplane accident subsequently die in a postcrash fire [4]. Unless the accident rate decreases, the number of fire fatalities will increase by four percent each year with the expected growth in passenger air traffic. The U.S. FAA has requirements of active fire suppression systems in the cargo compartments of passenger airplanes. Meanwhile, the NTSB has repeatedly issued safety recommendation calling for the broader installation of such systems in the cargo compartments of cargo airplanes.

The Minimum Performance Standard (MPS) tests for cargo fire suppression are conventionally conducted at standard atmospheric pressure (101.3 kPa), however there are dominant cases that cargo fires may occur under high altitude environments, such as cruising airplanes and the numerous high-altitude airports in the world. For a freighter airplane with a Class E cargo compartment on the main deck, the industrial standard firefighting procedure for Class E cargo compartments is to shut off airflow to the cargo compartment, depressurize the airplane, and operate the airplane at an altitude of at least 20,000 ft. (6,096 m) [4-5]. This will reduce the available oxygen to a level that will not support the fire, for which reason the method is also called oxygen starvation. During the depressurization, the airplane cargo compartment pressure decreases significantly. In addition to the cruising airplanes, there are numerous high-altitude airports in the world. The top three highest airports in the planet, Bangda Airport, Elikunsha Airport and Kangding Airport, are all in the Tibet plateau, altitudes of which are all above the typical chamber altitude 8000 ft.

The high-altitude environments should be included in the MPS tests, because experimental evidences [6-12] have

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shown that fire behaviors are inherently different at high altitudes. The spray of fire extinguishing agents from the pipe and the flooding effect in the enclosed chamber may also be influenced by the low pressure. Previous studies have shown that the spray intensity distribution of water mist from the sprinkler is more concentrated on the cone under low pressure. Compared with other potential halon replacements, such as perfluorocarbons, water-based halon replacement is considered is absolutely environmentally friendly with no toxic gas evolution and little potential contribution to global warming [13].

Although water mist is effective in suppression class A fires, pure water without additives is generally considered not suitable for hydrocarbon fires [14]. Water mist system can effectively suppress or extinguish the fires, but a burn-back cannot be guaranteed once the mist system stops. Besides, carriage of a large quantity of water in airplanes is generally prohibited for business profit. For those reasons, water-based foam agents were developed to control fires by warping a foam blanket around the burning cargos to suppress the fires and smoldering for long enough to allow the flight to divert to an alternative airport and conduct a safe landing.

In this work, a large-scale altitude chamber with powerful pressure controlling system has been built in order to examine the effectiveness of water-based fire extinguishing agents. Twin-fluid water mist fire suppression system is applied in the research, in which nitrogen is used as the additive extinguishing agent. Up to now, there are few researches on nitrogen aided twin-fluid water mist fire suppression system by commercial aviation companies or other researchers. The working effectiveness of spray systems at high altitudes requires a detailed investigation of the fundamental mechanisms of fire suppression under low-pressure and influencing factors. At this stage, the work are mainly on n-heptane pool fires of low pressure twin-fluid water mist fire suppression under different changed depressurization rates (91, 182, 328 Pa/s) to examine the effect of different ratios of nitrogen/water on water-mist fire suppression. For all the experiments, a fire will be ignited under standard pressure and will be suppressed during the depressurization from 101 kPa with different rates. The results will be helpful to on-flight cabin fire suppression.

2. EXPERIMENTAL APPARATUS

All the tests were performed in the altitude chamber facility, which meets the specifications of ISO9705 full-scale room fire test standards [15]. A simplified schematic and diagram of the the JRC2000 altitude chamber under are shown in Fig. 1.This facility can simulate the pressure observed at different altitudes up to 13,500 m (equivalent pressure 14.5 kPa).

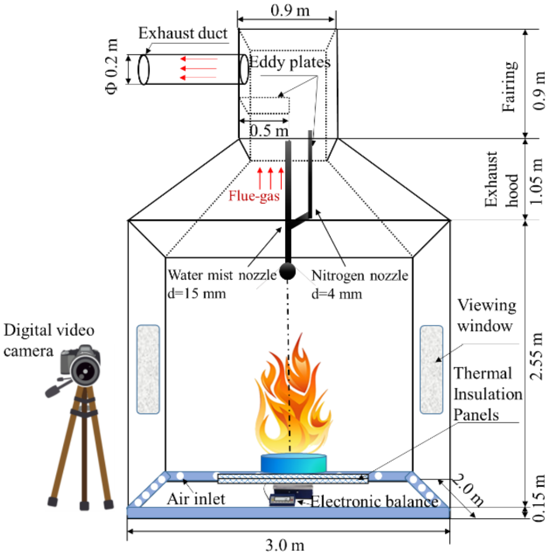

Fig. 1. The schematic diagram of the low-pressure chamber with twin-fluid water mist suppression system.

2.1 Twin–fluid water mist systems

The experimental platform designed for the low-pressure twin-fluid water mist fire suppression is shown in Fig. 2. As presented in Fig. 2(a), the steel fuel pan used is a 30-cm-diameter round and with a height of 15 cm. The pan is placed on the top of a thermal insulation board, below which is an electronic scale. The sampling rates of electronic scale, thermocouples and radiometers are 1 Hz. The twin-fluid sprinkler in the experimental platform is positioned 1.2 m right above the surface center of the fuel pan.

2.2 Fire scenarios and measurements

The present study is directed to provide some insight into the twin-fluid water mist fire suppression effects under the sub-atmospheric pressure. Table 1 shows the experimental configurations of twin-fluid water mist fire suppression tests. The fire suppression by nitrogen aided twin-fluid will be tested firstly under the standard pressure in comparison with those under different depressurization rates which will be carried out in the low pressure chamber. The typical testing fuels i.e. n-heptane, is designed for the fire suppression tests. N-heptane with industrial purity above 99 %. The measured parameters include chamber pressure, mass loss rate, and suppression time. Fire tests will be repeated five times to ensure repeatability for each configuration under changed pressure.

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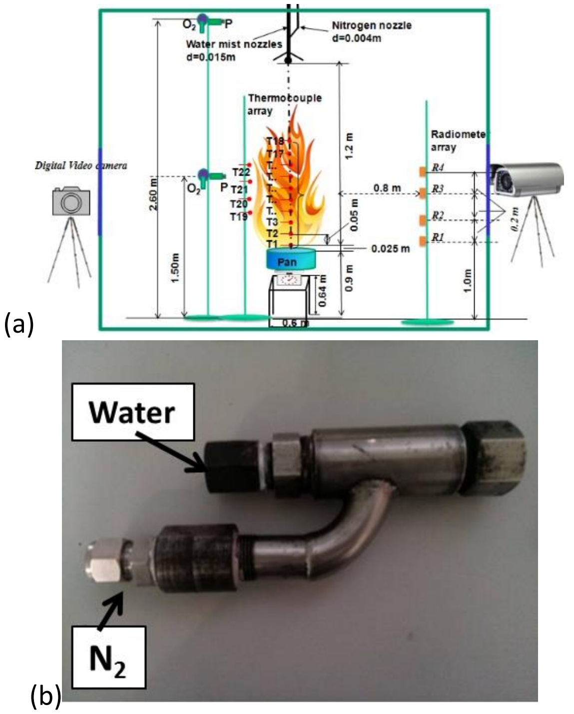

Fig. 2. Schematic diagram of the experimental platform setup for n-heptane pool fires with twin-fluid water mist systems, (a) front view, and (b) water mist nozzle.

Table 1. The experimental configurations of twin-fluid fire suppression tests

Case No.	Changed Pressure	Water		N₂	
		Pressure (MPa)	Flow (L/min)	Pressure (MPa)	Flow (L/min)
BaselineA	101 kPa	0	0	0	0
A1		0.25	3.4	0.32	14.2
A2		0.35	5.6	0.43	9.6
A3		0.40	7.7	0.48	14.1
BaselineB	91 Pa/s	0	0	0	0
B1		0.25	3.4	0.32	14.2
B2		0.35	5.6	0.43	9.6
B3		0.40	7.7	0.48	14.1
BaselineC	182 Pa/s	0	0	0	0
C1		0.25	3.4	0.32	14.2
C2		0.35	5.6	0.43	9.6
C3		0.40	7.7	0.48	14.1
BaselineD	328 Pa/s	0	0	0	0
D1		0.25	3.4	0.32	14.2
D2		0.35	5.6	0.43	9.6
D3		0.40	7.7	0.48	14.1

3. RESULTS AND DISCUSSION

3.1 Description of water mist suppresses fire process

After two minutes of n-heptane burning, a stable combustion state was reached, and then the twin-fluid water mist fire extinguishing system was artificially opened, as shown in Fig. 3(b). Water mist was formed at the nozzle and sprayed toward the flame, so that the flame fluctuation jumped obviously, resulting in suppression of the combustion reaction. Furthermore, water mist of good form was applied to the surface of flame, and the flame was disturbed and widened as indicated in Fig. 3(c). The area and height of flame decreased as the mist continues to be applied. Over this time, the water mist became water vapour, and a closed water vapour loop was formed around the flame, as displayed in Fig. 3 (d~e). The closed water vapour circuit displaced the oxygen in the combustion zone on the surface of the flame, eventually extinguishing n-heptane pool fire, as described in Fig. 3(f). The duration of the entire extinguishing process lasted for less than 25 s.

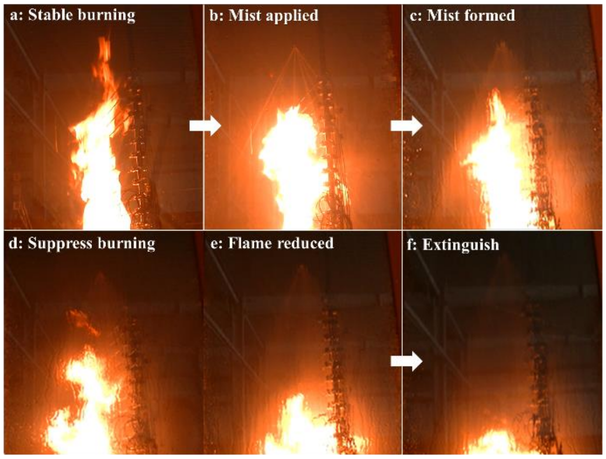

Fig. 3. The interaction of n-heptane pool fire with twin-fluid water mist.

3.2 Baseline case without water mist

3.2.1 Chamber pressure

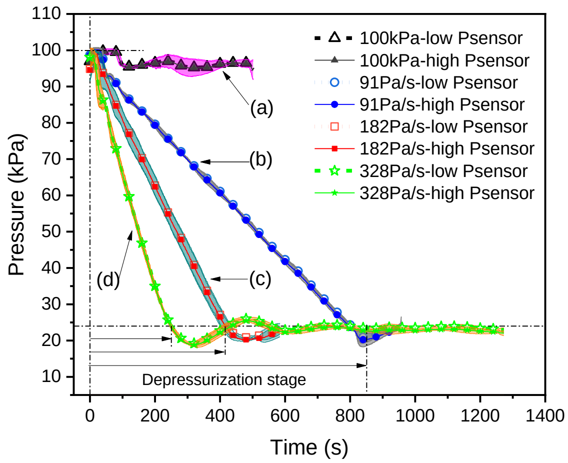

Fig. 4. Pressure variations for baseline cases: (a) baseline case A, (b) baseline case B, (c) baseline case C, (d) baseline case D. Shaded regions indicate estimated error bounds.

Figure 4 shows the changes of chamber pressure for baseline cases under standard pressure and changed depressurization. It takes more than 800 s, more than 400 s and approximately 230 s, respectively, to reach 24 kPa for

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the depressurization rate is 91, 182 and 328 Pa/s. The greater the depressurization rate is, the shorter time is for the pressure in the chamber dropping to 24 kPa.

3.2.2 Mass burning rate

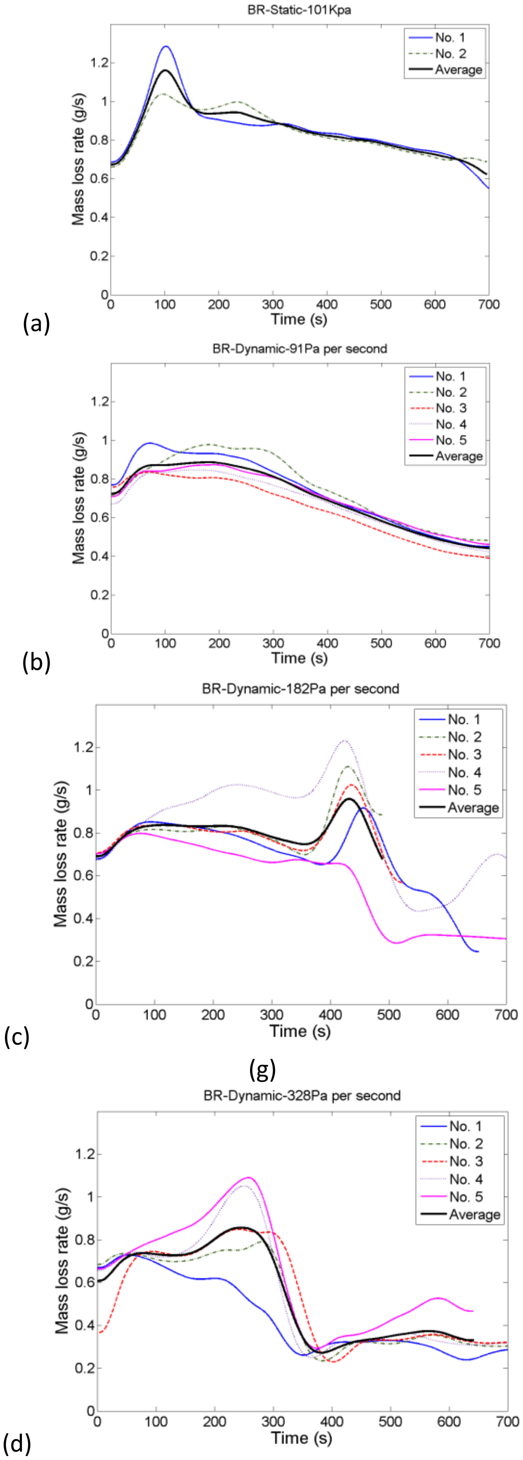

Fig. 5. Variations of (a) 101 kPa (b) 91 Pa/s (c) 182 Pa/s (d) 328 Pa/s mass loss rate for the baseline cases.

Figure 5 shows the variations of mass loss rate for the baseline case A-D. Tests of baseline case selected here are those with all thermocouples working. Mass loss rate (MLR) is obtained through derivation to the mass curve of the fuel for the entire burning time. It can be seen from that the mass loss rate is stable under standard pressure and the depressurization rate of 91 Pa/s, while it fluctuates greatly under the depressurization rates of 182 Pa/s and 328 Pa/s because of the great turbulence of airflow caused by the pump.

3.3 Analysis of the suppression time

The suppression time ranges from 11 s to 30 s, which indicates that pool fire was suppressed in less than 30 s after the twin-fluid water mist suppression system was activated. The correlation curves were obtained by fitting a polynomial to the discrete points, and the correlation fitting formulas were shown in Figs. 6~7 for case A, B, C and D. Fig. 6 indicates the relationship of the second polynomial between the extinguishing time of n-heptane pool fire and the nitrogen pressure in the water mist. The fitting relationship of the 30 cm oil pan fire at the standard pressure of 101 kPa is: $t = -113.6 \cdot \varDelta P^2 + 23.4 \cdot \varDelta P + 27.9$ (R^2=1). Fitting formula at rate of changed pressure of 91 Pa/s is: $t = -168.2 \cdot \varDelta P^2 + 57.0 \cdot \varDelta P + 20.2$($R^2$=1). When changed pressure drop rate is 182 Pa/s, the fitting formula is: $t = -322.7 \cdot \varDelta P^2 + 185.7 \cdot \varDelta P - 7.6$ (R^2=1). The fitting formula at the changed pressure drop rate of 328 Pa/s is: $t = -305.7 \cdot \varDelta P^2 + 170.2 \cdot \varDelta P - 4.9$ (R^2=1), where $\varDelta P$(MPa) is the pressure of nitrogen. It can be seen from the Fig. 6 that the binomial fit relation between the extinguishing time of 30 cm oil pan fire and nitrogen pressure is better.

Figure 7 reveals the quadratic polynomial fitting relationship between the 30 cm oil pan suppression time and the depressurization rates. The fitting formula for nitrogen pressure at 0.32 MPa is: $t = 6.5 \times 10^{-5} \cdot \delta P^2 - 0.04 \cdot \delta P + 23.9$, the fitting error is R^2 = 0.99. The fitting formula for nitrogen pressure is 0.43 MPa: $t = 6.8 \times 10^{-5} \cdot \delta P^2 - 0.04 \cdot \delta P + 16.9$, the fitting error is R^2 = 0.98. The fitting formula for nitrogen pressure is 0.48 MPa: $t = 9.0 \times 10^{-5} \cdot \delta P^2 - 0.05 \cdot \delta P + 12.9$, the fitting error is R^2=0.99. Here δP(Pa/s) is the depressurization rate. The binomial fitting relationship between the extinguishing time and depressurization rate is better.

The fire extinguishing time in the experiment is negatively related to the nitrogen pressure of twin-fluid water mist. When the nitrogen pressure reaches 0.48 MPa, the extinguishing time of the twin-fluid water mist is the shortest. The extinguishing time is inversely proportional to the depressurization rate. The suppression time is 6~25 s under different water mist ratio parameters within the three pressure drop rates. When the pressure drop rate

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increases, the fire extinguishing time is shorter. When the pressure drop rate is large enough, the extinguishing time tends to a constant value, which is about 5 s. It reveals that the twin-fluid low-pressure water mist system can extinguish the n-heptane oil pool fire within 25 s in case of emergency. It provides an important reference for aviation and high-altitude fire protection.

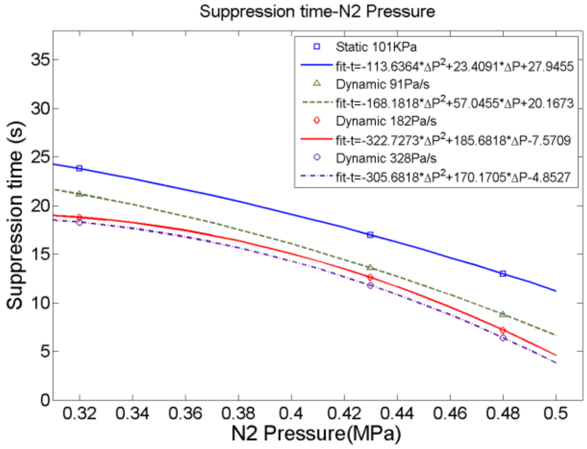

Fig. 6. The suppression time VS N_2 pressure under different ambient pressure environment.

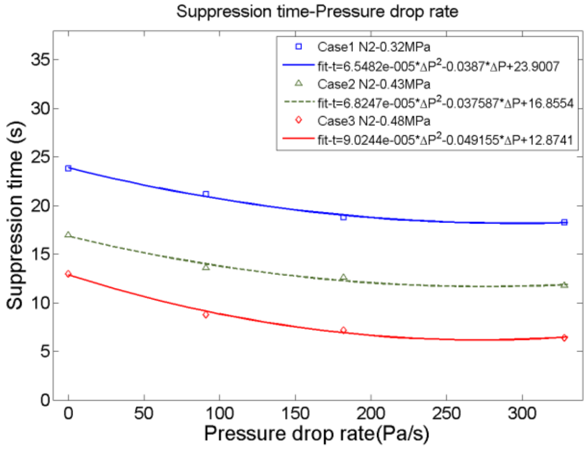

Fig. 7. The suppression time VS different depressurization rates involved in 0, 91, 182, and 328 Pa/s.

4. CONCLUSION REMARKS

The experiments of twin-fluid water mist fire suppression under the standard pressure and different depressurization rates were carried out with three different pressures of water and nitrogen are applied for all cases with suppression. Some preliminary conclusions are obtained as follows.

1) The mass loss rate fluctuates greatly for depressurization rates of 182 Pa/s and 328 Pa/s than that standard pressure and 91 Pa/s, resulting from the great disturbance of reducing pressure to airflow.

2) Considering the time needed to extinguish fire and the total weight of water mist, the ideal suppression condition is: low-pressure water mist generated by the water pressure of 0.40 MPa (flow rate: 7.7 L/min), nitrogen pressure 0.48 MPa (flow rate: 14.1 L/min) for the depressurization rate of 328 Pa/s.

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