N-Heptane Pool Fire Suppression with Twin-Fluid Water Mist

Quan-yi LIU¹,a,*, Yi WU¹, Qiang SUN¹, Yuan-hua HE¹, Rui YANG² and Hui ZHANG²

¹Civil Aviation Flight University of China, Guanghan Sichuan 618307, China
²Institute of Public Safety Research, Tsinghua University, Beijing 100084, China

aquanyiliu2005@126.com
*Corresponding author

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Abstract. As one of the most promising halon alternatives, the merits of water mist have been demonstrated by prior research and tests. Much research done before has been focusing on the improvement of some aspects of water mist systems such as the shape of nozzle, the size of mist particles, and the additive used etc. In order to study the effectiveness of twin-fluid water mist technology and the role of nitrogen in fire suppression, a series of n-heptane pool fire suppression tests were carried out in this paper. The parameters such as fuel mass loss, flame temperature above the centerline of the pool, and axial heat fluxes were measured for assistant analysis of fire suppression during the tests as well as the fire video recorded. All suppression times were analyzed statistically based on the video and they all were under 30 seconds. Results show that the higher Nitrogen pressure is, the less the suppression time is, which means better suppression effect.

Introduction

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer has ceased the production of halons in developed countries since January 1, 1996. As halon will be prohibited from using by 2020, the efforts in finding zero ozone-depleting but effective Halon 1301/1211 replacement are global in scale, spanning government agencies [1-4], industrial companies [5, 6] and academic institutes [7, 8]. The aviation industry has been working to find effective replacements for halon in airplane fire suppression and extinguishing systems since the ban on its production in 1996 [9].

Compared with other potential halon replacements, such as per fluorocarbons, water-based halon replacement is considered as environment-friendly with no toxic gas evolution and little potential contribution to global warming [10]. Water-based fire extinguishing agents can be water with different additives, such as foam agents, to lower the freezing point and improve the fire-extinguishing capability. Mechanisms by water-based fire extinguishing agents include the following [10]: 1) cooling flame temperature, 2) cooling fuel temperature, 3) steam diluting the air, 4) quenching by condensed solid particles, 5) blow off, 6) radiation attenuation [11, 12] and 7) special mechanism by the additive (s).

Water becomes very effective fire extinguishing agent when in the form of mist, whose large surface-to-volume makes them evaporate easily in the flame. Due to the high aerodynamic drag associated with fine droplets in air, a high volume of gas-like
fine droplets of water-based agent can be dispersed throughout a volume, exhibiting a superior ability to diffuse around obstructions without significant loss of mist due to plating and deposition [13, 14]. For full-scale cabin tests, water mist from a small amount of water can efficiently suppress a cabin fire [15]. Research on water mist systems as an innovative technology for halon replacements in fire protection has become quite popular over the last two decades [16, 17]. Early experiments on the extinguishment of liquid fires by water sprays can be traced to the research by Rasbash in the late 1950’s [18, 19]. Since the inevitable phasing-out of halons under the terms of the amended Montreal Protocol in 1987, a reappraisal of traditional fire extinguishing agents, especially the water spray, was undertaken to extend their uses. An overview of the application of fine water sprays and water mist systems was made by Jones and Santangelo et al to analyze the fundamental physical mechanisms related to water mist systems [20, 21]. The comprehensive review by Grant et al has provided some insights into suppression physics of water mist within a broader discussion on the general characteristics of spray-based systems.

One of the promising fire suppression technologies is low pressure twin-fluid water mist technology, which has been evaluated in the recent years and proved to be effective. It has the potential to reduce the weight because the total weight of spacecraft or airplane is strictly restricted. So nitrogen is selected as an additive for water in the twin fluid water mist system in this study. A series of n-Heptane pool fire suppression tests have been carried out to examine the effectiveness of water mist technology and the effect of Nitrogen in fire suppression.

**Experimental Configurations**

The experimental platform designed for the low pressure twin fluid water mist fire suppression is shown in Fig. 1, and the detailed configurations for the experiments will be introduced in the following sections. As presented in Fig. 1(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 electronic scale and the oil pan are all on the top of a steel square desk, which is 0.64 m in height and 0.60 m in width. An array of 18 K-Type thermocouples labeled as T1-T18 from the bottom up to the top was laid on the centerline above the pan to measure the flame temperature. All the thermocouples are 1-mm-diameter; the vertical distance between any two thermocouples is 5 cm, where the first thermocouple T1 is 2.5 cm above the surface of the liquid fuel in pan.

![Figure 1](image.png)

Figure 1 Schematic diagram of the experimental platform setup for n-heptane pool fires, (a) front view, and (b) top view

The axis heat flux is measured by an array of radiometers, which are all placed 1.5 m horizontally from the center of the pan to characterize the axial radiation output from the flame. The vertical distance between any two axial radiometers is 20 cm, where the first radiometer R1 is 100 cm above the floor. Mass loss rate is calculated based on the mass loss measured through high accuracy electronic scale placed beneath the pan but
separated by thermal resistance plasterboard. The fire videos are recorded along with other parameters. Fire videos are recorded by a hi-speed camera for the whole burning process. The sampling rates of electronic scale, thermocouples and radiometers are 1 Hz.

A layer of 10 cm cold water bed will be added beneath the fuel layer to cool the pan and avoid the boiling of the fuel. N-Heptane is selected as the fuel, of which purity is above 99% (the impurity contents: volatile ≤ 0.05%, water ≤ 0.05%, unsaturated compounds in Br+ ≤ 0.032%), density is 683–685 kg/m³, boiling range is 96.5–98.5 °C, self-ignition temperature is 223.0 °C and the explosion limits is 1.05–6.7%. The measured parameters include axial flame temperature, mass loss, axial heat flux, and fire video recording and suppression time.

The water mist nozzle in the experimental platform is a twin fluid nozzle, positioned 1.2 m right above the surface center of the fuel pan. The twin fluid nozzle uses two streams of fluid, one of water and one of compressed nitrogen, which increases the energy available for the atomizing process. During the atomization, the compressed nitrogen is injected into the water stream at the nozzle, and shear the water into fine water drops in the mixing chamber and discharging from one or several orifices. When it is discharged from the discharging orifices, it could break up to the water mist with expected water droplet sizes.

### Results and Discussion

A high accuracy electronic scale placed beneath the pan is utilized to measure the mass loss of the fuel during the tests, and mass loss rate will be calculated based on these data. However, taking into consideration that there is a large amount of the ejected water mist on the weight loss measurement of the fuel by electronic scale, the high accuracy electronic scale is only used in the tests with no suppression activated to measure weight and the mass loss of the fuel. The general status of fire suppression tests is given in Table 1. It can be seen from Table 1 that Fire tests of each combination of different configurations will be repeated at least three times to ensure repeatability.

**Table 1. Configurations for tests with and without fire suppression.**

<table>
<thead>
<tr>
<th>case No.</th>
<th>Water (MPa)</th>
<th>N₂ (MPa)</th>
<th>Measured Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pres. (MPa)</td>
<td>Q₁ (L/s)</td>
<td>Pres. (MPa)</td>
</tr>
<tr>
<td>Baseline</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case A</td>
<td>0.25</td>
<td>0.057</td>
<td>0.32</td>
</tr>
<tr>
<td>Case B</td>
<td>0.35</td>
<td>0.093</td>
<td>0.43</td>
</tr>
<tr>
<td>Case C</td>
<td>0.40</td>
<td>0.13</td>
<td>0.48</td>
</tr>
</tbody>
</table>

**Baseline Case without Water Mist**

The high accuracy electronic scale is only used for the baseline case without using water mist to measure weight and the mass loss of the fuel in the tests. Mass loss rate (MLR) is obtained through derivation to the mass curve of the fuel for the entire burning time. Fig.2 shows the variation of weight, mass loss rate for the baseline case.

It can be seen in Fig.2 that repeatability of tests of baseline case is generally good. The initial weights of two tests of baseline case just before ignition are 620g and 590g, respectively. Time from ignition to nearly 80s is the growth period while time from 80s to about 400s is the fully developed fire period or stable stage. The duration for the
stable burning is approximately more than 300s. After that, fire comes to the decay period. Mass loss rate in stable stage is between 1.4 g/s and 1.6 g/s.

![graph](image1)

![graph](image2)

Figure 2. Variation of (a) weight and (b) mass loss rate for the baseline case.

**Cases with the Suppression System Activated**

For cases with suppression activated, the high accuracy electronic scale is no longer used to measure fuel mass loss due to the influence of ejected water mist on the weight loss measurement, but the initial weight for each test is more or less the same to that of the baseline case tests. For the cases with water mist system activated, the fuel burning from ignition to the time discharging the water mist during the stable stage can be considered approximately the same with that for baseline case. Nitrogen is selected as an additive for the twin fluid water mist system in this study. A series of n-Heptane pool fire suppression tests have been carried out to examine the effectiveness of water mist technology and the role of Nitrogen in fire suppression.

The suppression time is an important parameter for the analysis of suppression efficiency. Table 2 provides the statistics of the suppression data for cases A-C. The suppression time ranges from 11 s to 27 s, the average suppression time for cases A, B and C are 25 s, 20 s and 14 s, respectively, which indicates that pool fire is suppressed or extinguished in less than 30s after the low pressure twin fluid water mist suppression system was activated. The total mass of water and nitrogen consumed for suppression for case A1, A2 and A3 are 1709 g, 1590 g and 1414 g, respectively.

<table>
<thead>
<tr>
<th>CASE</th>
<th>Water pressure (MPa)</th>
<th>Water flow rate (L/min)</th>
<th>Nitrogen pressure (MPa)</th>
<th>Nitrogen flow rate (L/min)</th>
<th>Suppression time (s)</th>
<th>Average time(s)</th>
<th>Total weight of water and nitrogen(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>0.25</td>
<td>3.4</td>
<td>0.32</td>
<td>14.2</td>
<td>23</td>
<td>25</td>
<td>1708.9</td>
</tr>
<tr>
<td>A-2</td>
<td>0.25</td>
<td>3.4</td>
<td>0.32</td>
<td>14.2</td>
<td>27</td>
<td>25</td>
<td>1708.9</td>
</tr>
<tr>
<td>A-3</td>
<td>0.25</td>
<td>3.4</td>
<td>0.32</td>
<td>14.2</td>
<td>25</td>
<td>25</td>
<td>1708.9</td>
</tr>
<tr>
<td>B-1</td>
<td>0.35</td>
<td>5.6</td>
<td>0.43</td>
<td>9.6</td>
<td>20</td>
<td>20</td>
<td>1590.7</td>
</tr>
<tr>
<td>B-2</td>
<td>0.35</td>
<td>5.6</td>
<td>0.43</td>
<td>9.6</td>
<td>18</td>
<td>18</td>
<td>1590.7</td>
</tr>
<tr>
<td>B-3</td>
<td>0.35</td>
<td>5.6</td>
<td>0.43</td>
<td>9.6</td>
<td>22</td>
<td>22</td>
<td>1590.7</td>
</tr>
<tr>
<td>C-1</td>
<td>0.4</td>
<td>7.7</td>
<td>0.48</td>
<td>14.1</td>
<td>11</td>
<td>11</td>
<td>1414.9</td>
</tr>
<tr>
<td>C-2</td>
<td>0.4</td>
<td>7.7</td>
<td>0.48</td>
<td>14.1</td>
<td>16</td>
<td>16</td>
<td>1414.9</td>
</tr>
<tr>
<td>C-3</td>
<td>0.4</td>
<td>7.7</td>
<td>0.48</td>
<td>14.1</td>
<td>15</td>
<td>15</td>
<td>1414.9</td>
</tr>
</tbody>
</table>

Note: density used in the calculation is 1kg/L(water) and 1.251g/L(N2).

The suppression time for each test with the system activated is analyzed statistically based on the videos recorded. STDEV function is employed to estimate the standard deviation based on the statistics of suppression time and its average. The standard error is used to calculate the error bars to show how confident the average represents the true suppression time in the experiments. Fig.3 shows the suppression time analysis of cases A, B and C.

It can be seen from Fig.3 (a) that the suppression time ranges from 10s to 27 s, which indicates that pool fire is suppressed in less than 30 s after the low pressure twin fluid water mist suppression system is activated. The average suppression time is increasing.
with the pressure of nitrogen rises, and the suppression effect is better relatively when
the pressure between the water and nitrogen is more closed, but the error bars shown in
the line graph are large due to the loose distribution of suppression time.

As shown in table 2 and Fig.3, it can be obtained that the higher Nitrogen pressure is,
the less the suppression time is, which means better suppression effect. When the water
pressure is 0.40 MPa and the nitrogen pressure is 0.48 MPa, the suppression time is
shortest (14 s) and the total weight of water mist is least (1414.9 g).

![Figure 3. Suppression time analysis of cases A-C: (a) statistics of suppression time distribution,
(b) STDEV error analysis of suppression time.](image)

**Conclusions**

A series of n-heptane pool fire suppression tests with twin fluid water mist were studied
in the paper and some preliminary conclusions are obtained as follows:

1) Mass loss rate is obtained by using the derivation method, and the repeatability of
weight and MLR is generally good. The mass loss rates of n-heptane pool fire in the
stable stage are between 1.4 g/s and 1.6 g/s.

2) N-heptane pool fire is suppressed in less than 30s for all the tests once the twin
fluid water mist suppression system is activated, which shows the effectiveness of the
twin fluid water mist system with the nitrogen pressure lower than 0.5 MPa and a better
suppression effect with a higher nitrogen pressure.

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