FEASIBILITY EVALUATION STUDY OF VERY FINE WATER MIST AS A TOTAL FLOODING FIRE SUPPRESSION AGENT FOR FLAMMABLE LIQUID FIRES

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INTRODUCTION

The Navy Technology Center for Safety and Survivability (NTCSS) at the Naval Research Laboratory (NRL) has been examining water mist fire suppression technology since the 1980s. High pressure water mist systems have been a primary focus. Empirical development has led to high pressure water mist systems protecting the five adjacent machinery spaces aboard the LPD 17. However these systems are limited to a minimum 30 μm drop size, making it difficult for the mist to reach highly obstructed fires. New ultrasonic technology has provided a means for creating large amounts of very fine (<10 micron) water mist (VFWM) at ambient pressures [1]. These smaller drops behave more like a gas enabling drops to better remain airborne and to diffuse through clutter with less water loss. This behavior of very fine mist helps approach much closer to the desired uniform total flooding fire suppression agent distribution.

CFD computer fire model simulations on VFWM conducted on a total flooding scale predicted fire extinguishment. The results from these simulations are reported in a companion paper [2]. The compartment modeled, based on an NRL Chesapeake Bay Detachment (CBD) compartment, was 3 m by 3 m by 3 m and unobstructed. A heat source representing a 120 kW heptane fire was used at the compartment center near the deck. Four mist generation units supplied a total of 1.0 L of liquid water per minute to the compartment through eight evenly spaced mist outlets located slightly below the fire base and oriented upward. Temperature and gas concentrations were tracked for comparison to test results. The simulation predicted extinguishment between 5 and 10 seconds. Local flooding results also showed that a 120 kW heptane fire was extinguished in 10 seconds [1]. This paper describes a test series conducted at NRL's CBD facility for comparison with the model and to evaluate the feasibility of very fine water mist as a total flooding agent in Naval applications.

OBJECTIVE

Local flooding and computer fire modeling studies have shown the potential for total flooding extinguishment by very fine water mist. A test series with three objectives was developed to prove the capability using mist generation units developed and provided by NanoMist, LLC. The first objective was to compare the test results with the computer fire model simulation. Gas and temperature measurements were needed for comparisons as well as fire extinguishment times. The second objective was to determine possible limitations of the current systems. Recommendations and suggested improvements are essential for future direction in the development of the technology. The third objective was to compare oxygen measurement techniques to help understand the suppression dynamics of very fine water mist. This increased understanding can lead to significant technological improvements.

FIELD TESTING

The compartment used for test series shown in Figure 1, is a 28 m^3 cubic, steel walled compartment with a standard Navy ventilation system providing one air exchange every four minutes. The supply vent was located near the ceiling while the exhaust vents were split two-thirds low and one-third high. The compartment resembled the simulated compartment as closely as possible.

Figure 1. Picture of 28 m^3 compartment

NanoMist Systems, LLC, supplied the mist generation units used [1]. The power required per unit could be set to either 110 V at 12 A or 220 V at 6 A. Air was supplied to each mist unit through an inlet fan at about 400 L/min. Water was introduced at the base of the mist unit from a reservoir and excess water re-circulated into the reservoir. This system maintained the constant water level needed for efficient mist generation. Four-inch PVC pipes were used to duct the mist from the top of the mist unit to the upward vertical outlets on the deck. Water that "condensed" out in the ducts was collected and measured. A total of six units were used. Initial evaluation by NanoMist, LLC determined the units produce almost 250 mL of mist per minute with a water concentration of 33 mass % in air.

Figure 2. Picture of NanoMist™ mist generation unit

Within the compartment, three mist units with a single outlet each were arranged on both sides of the fire. The fire was located in the center of the compartment. A simple obstruction / partial wall, when used, was half way between the fire and three mist units. A Windows 98 second edition computer using LabView 5.1 and National Instruments hardware served as the data acquisition system. A test control center housed the data acquisition and test controlling equipment.

The instrumentation layout detailed in Figure 3 included a thermocouple tree with five thermocouples at 0.76, 1.14, 1.52, 1.90, and 2.52 meters off the deck to characterize the compartment temperatures. Two thermocouples were placed above the fire pan to help determine extinguishment time. Two gas sampling lines were located in the compartment, withdrawing air samples from one high and one low location (heights indicated on Figure 3). A paramagnetic oxygen balance and an IR analyzer measured oxygen and carbon dioxide concentrations respectively in each sampling line. A heated zirconium oxide electrochemical sensor and a tunable diode laser *in situ* multipass absorption gas cell were also used to measure oxygen near the lower gas sampling line (heights indicated on Figure 3). A visible and IR camera were used to observe the fire.

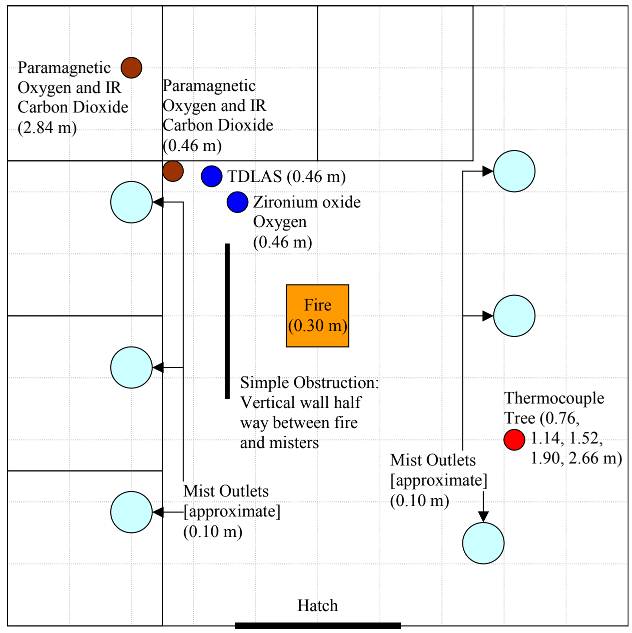

Figure 3. 28 m^3 compartment layout

OXYGEN MEASUREMENTS

Knowing the actual oxygen concentration near the fire is critical for understanding extinction. Three oxygen measurements were made of the fire-entrained air in order to compare the different measurement techniques. The paramagnetic oxygen analyzer (using gas withdrawn from the test compartment) requires almost all of the water to be removed from the gas stream for proper operation. A dry oxygen molar concentration measurement is then produced. The zirconium oxide sensor in contrast operates above 600 ^{o}C; all liquid water (mist) is vaporized. The measurement is thus a wet oxygen molar concentration measurement (fully diluted by water vapor). The TDLAS measures actual oxygen molar concentration directly, without the influence of liquid water. The TDLAS oxygen measurement was a developing technology and the subject of a companion paper [3]. If the difference between the wet and dry oxygen measurements is due to water only, the two measurements can be used to infer the water mass concentration:

$$m_{H_2O} = \frac{MW_{H_2O}}{\sum MW_i x_i^{wet}} \left(1 - \frac{x_{O_2}^{wet}}{x_{O_2}^{dry}} \right) \quad (1)$$

Since the carbon dioxide concentration by IR is also a dry gas analysis, a correction needed to be applied to determine the concentration of carbon dioxide with respect to water.

$$x_{CO_2}^{wet} = x_{CO_2}^{dry} \frac{x_{O_2}^{wet}}{x_{O_2}^{dry}} \quad (2)$$

Where: m_{H2O} is the water mass concentration; MW_{H_2O} is the molecular weight of water; and $MW_i x_i^{wet}$ is the product of and molecular weight and molar concentration of either water, oxygen, carbon dioxide, or nitrogen; $x_{O_2}^{wet}$ is the wet molar concentration measurement of oxygen; $x_{O_2}^{dry}$ is the dry molar concentration measurement of oxygen; and $x_{CO_2}^{dry}$ is the dry molar concentration measurement of carbon dioxide.

TEST VARIABLES

The test plan called for four mist units each producing 250 mL/min to be used with a 120 kW heptane fire near the deck [4]. Two additional mist units were to be used to increase the mist production in attempts to extinguish fires higher in the compartment, better approaching a total flooding scenario. Initial tests in the compartment determined that the mist rate for each unit was well below 250 mL/min. The two additional mist units were therefore used to increase the total mist rate closer to the simulated value of 1,000 mL/min in order to help extinguish the 120 kW heptane fire near the deck,. Since no other mist units were available to further boost the mist generation rate, higher location fire scenarios were not tested.

After modifying the test plan, three variables were tested. The first test variable was the mist generation rate. This was accomplished by varying the number of mist units used, four, five, or six. The second variable was the fire size and fuel. In addition to the 120 kW heptane fire, a 5 kW heptane fire (five 2.5 cm heptane tell-tales placed in the dry fire pan), and 70 kW methanol fires were used. The third variable was the addition of a simple obstruction / partial wall to challenge the mist. Table 1 shows the twelve scenarios tested.

Table 1. Test Matrix

Fire Size (kW) and fuel	Wall	Misters
No fire	-	6
No fire	-	5
No fire	-	4
120 heptane	-	None
5 heptane	-	None
70 methanol	-	None
120 heptane	-	6
5 heptane	-	6
120 heptane	-	5
120 heptane	-	4
120 heptane	Yes	6
70 methanol	-	6

TEST PROCEDURE

A series of pretest procedures were conducted before the start of the test. The test conditions were set up. The analyzers were calibrated. The water recirculation system was filled with clean water. The video camera alignment was checked. The test team was briefed on the test and the emergency plan. The pan was filled with the appropriate amount of fuel. After these tasks accomplished, the video recording and data acquisition system were started to begin the test.

Table 2 details the test sequence of events, the time referenced to the start of the data acquisition. The fire was manually ignited 60 seconds. The compartment was then sealed at about 70 seconds. The mist units were activated and the ventilation was secured at 120 seconds. The fire was extinguished either by the mist or fuel consumption at time, T_x, after 120 seconds. The mist units were secured and the ventilation was activated at time, T_y, after T_x.

At the completion of each test the compartment was vented. Re-entry was made once the space was determined to be "gas-free" by a certified technician. The water loss in the recirculation system and the water condensed out in the ducting were measured to find a total mist generation rate. The remaining fuel in the fire pan was also measured to reaffirm the extinguishment by the mist.

Table 2. Test Procedure

Time (sec)	Event
0	Data acquisition start, test begins
60	Fire manually ignited
~70	Compartment door secured
120	Mist activated, ventilation secured
T_x	Fire extinguished
T_y	Mist secured, ventilation activated

EXTINGUISHMENT RESULTS

Table 3. Selected Results

Fire Size (kW) and Fuel	Wall	Mist Units	Extinguishment Time (sec)	Mist Rate (L/min)
120 heptane	-	6	283	0.64
120 heptane	-	6	301	0.65
120 heptane		6	306	0.66
120 heptane	-	4	357	0.56
120 heptane	-	4	391	0.61
120 heptane	Yes	6	329	0.70
70 methanol	-	6	521	0.62

120 kW heptane fire would burn for more than 480 seconds
70 kW methanol fire would burn for more than 660 seconds

The results show that the extinguishment times do not agree between the computer simulation and the tests. The computer simulation predicted extinguishment times of 5 to 10 seconds, while the tests took more than 5 minutes for extinguishment. Table 3 depicts the extinguishment times for the test scenarios. As seen in Figure 4, extinguishment time decreased with increased mist generation rate.

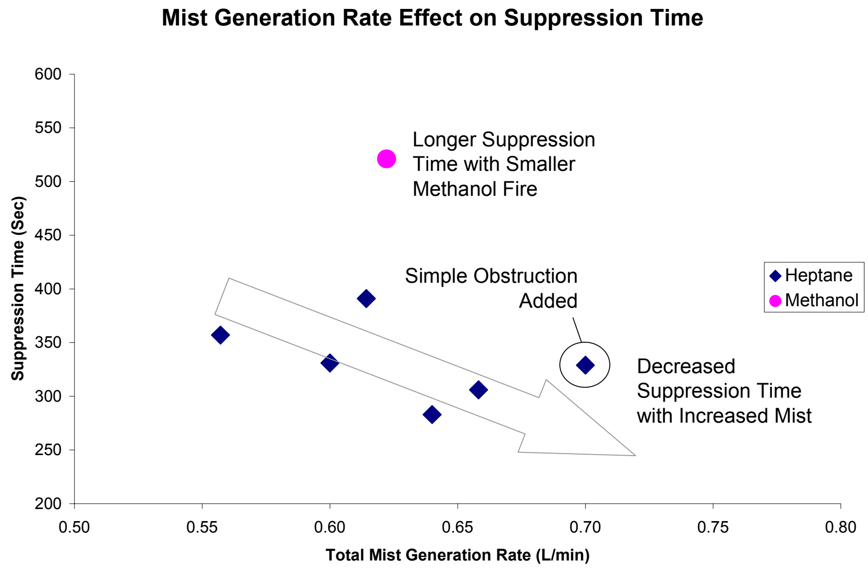

Figure 4. The extinguishment times as a function of total mist generation rate

The total volume of mist generated prior to extinguishment can be found from the mist generation rate multiplied by the generation time to extinguishment. Figure 5 highlights the results of using four mist units, the simple obstruction, and the methanol fire. The simple obstruction and the reduced mist generation rate with four mist units increased the total water volume required.

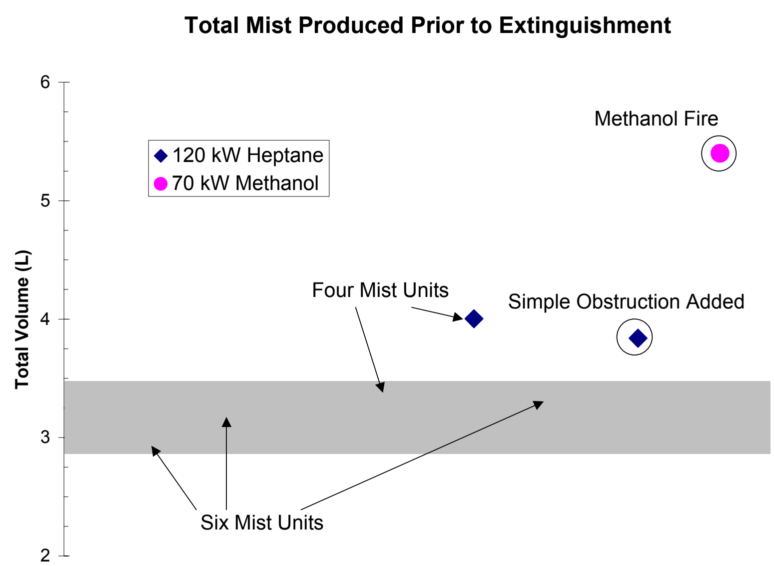

Figure 5. The total volume of mist produced prior to extinguishment for the tests

MIST CONCENTRATION RESULTS

The average water mist throughput was found from measuring the recirculation water volume consumption in the tests. With six mist units, the average value was found to be 0.66 L(liquid water)/min. This is well below the value of 1.0 L/min used in the computer model. The carrier gas flow rate was measured after the test series at 360 L/min per mist unit or 2,160 L total. The resulting mass concentration of water at the mist outlet was therefore ~20 %. Figure 6 compares the water mass concentration (found from equation 1) in three test scenarios: mist only; a 120 kW heptane fire and 5.5 minutes of mist; and a 120 kW heptane fire and 10 minutes of mist. The water concentrations under no fire – fire conditions showed that the fires greatly reduced the water mist density at the sensor positions.

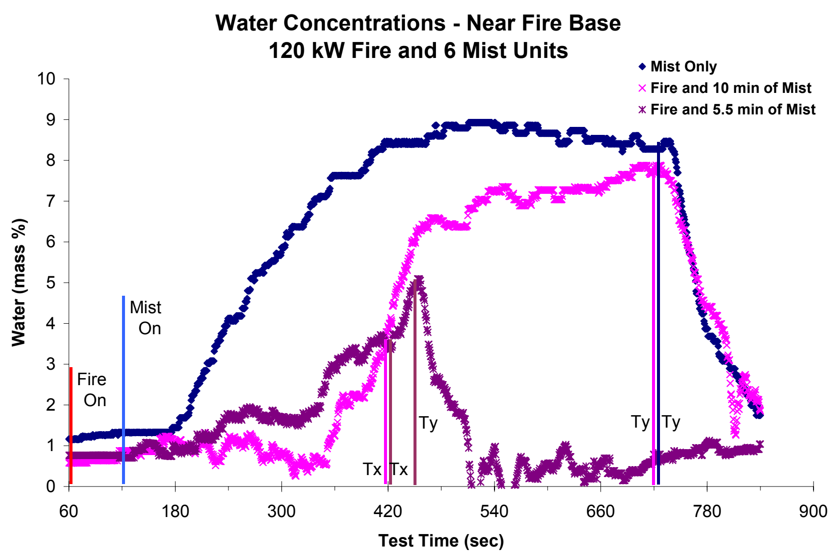

Figure 6. Water mass concentration from several 6 mist unit tests

The time delay in attaining the peak concentration of mist is related to transport process. The water mass concentration begins to plateau and eventually reaches about 9 %. This is less than half the concentration at the outlet of the mist units. The difference between the mist only and fire and mist tests is large. Less than half of the water at fire extinguishment is present compared with the mist only test. Mist depletion processes, without and with fire present, were not the focus of this initial exploration. Observations made during preliminary testing showed that the mist throughput was decreased by the presence of soot entrained into the mister water supply. Ensuring only clean water was used at the start of each test minimized this decrease.

CONCLUSIONS AND RECOMMENDATIONS

The very fine water mist (VFWM) was able to successfully extinguish all pool fires. The average extinguishment time of a 120 kW heptane fire was around five minutes with six mist units operating at 0.66 L/min total. The extinguishment time decreased with increasing mist injection rate. The addition of a simple obstruction required more mist input to extinguish the fire. A 70 kW methanol fire was extinguished in approximately eight minutes. Some telltale fires continued to burn past 10 minutes. The measured volume of water consumed by the misters differed from the predicted rates used in the computer model.

In order for this technology to be used in total flooding applications improvements are needed. The mist units need to extinguish fires in a reasonable time frame and need to extinguish fires in any location. Mist concentrations reached steady state levels well below input mist concentration. Preliminary testing also showed significant decreases in mist generation in sooty environments. These relationship needs to be understood. Further research into the ability of the mist to penetrate more complex obstructions is needed. The influence of oxygen depletion and carbon dioxide concentrations on extinguishment need to be quantified. The effect of fresh air introduction into misters needs to be explored.

With the improvements suggested, the technology should be ready for further feasibility studies. These studies are important to potentially develop a new useful technology for the Navy and to better understand the mechanisms of very fine water mist in fire suppression. Unlike high pressure water mist, very fine water mist is produced with very little momentum making the suppression dynamics very different. The mist transport dynamics and mist – fire interactions are very different and need to be understood for a better understanding of water mist fire suppression.

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