STUDIES OF THE EFFECT OF WATER MIST ON SOLID FUEL FLAMES UNDER VARIOUS BURNING CONDITIONS

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ABSTRACT

The focus of this paper is on the numerical simulations and laboratory experiments that are being performed to study the efficacy of fine water mist in suppressing thermoplastic fires in electric/electronic applications. This ongoing work is intended to explore the practical application of fine water mist as a fire suppression agent specifically for enclosed electrical/electronic cabinets. Results show that relatively less water sprayed directly onto the fire is found to lower the local temperature and carbon monoxide (CO) levels, compared with more water sprayed in an enveloping mist. Conversely, an enveloping mist reduces the local oxygen (O_2) levels more effectively.

INTRODUCTION

We are conducting full-scale laboratory experiments[*] and numerical simulations to study the effect of fine water mist in suppressing thermoplastic fires in electric/electronic applications. The objective of this work is to provide a practical basis for water mist fire suppression system design for conditions similar to those described in the following sections. A recent review by Liu and Kim [1] of water mist fire suppression cites several studies showing that water mist is effective in electronic equipment applications and does not cause short circuits or other damage. Water mist may in fact have some advantages over more conventional fire suppressants due to its heat removal mechanisms, which may help to prevent melting of wire insulation and other materials, and due to its nontoxic quality, which may allow uninterrupted human occupation of the compartment. Recent testing by Marioff Oy [2] indicates that water mist may possess the additional benefit of scrubbing smoke and other deleterious gases from burning electronic equipment.

In the larger context of water mist research at the Colorado School of Mines, this work complements a more fundamental experimentation and numerical modeling project in which the interactions of premixed propane/air flames are studied in normal and microgravity [3-5].

WATER MIST SUPPRESSION OF THERMOPLASTIC FIRES

The ongoing real scale laboratory tests and simulations for electrical/electronic cabinets are evolving from relatively simple, low fidelity configurations with very large parameter space to

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[*] These experiments are “real scale” in the sense that the dimensions of the test articles and related apparatus are not scaled down. These are also “laboratory” experiments because they are performed in a laboratory.

more realistic arrangements with reduced parameter space. To date, tests and simulations have been performed with and without ventilation on single, vertically oriented thin sheets of poly-methylmethacrylate (PMMA) ignited along the bottom edge. This work is being expanded to include a "card rack" arrangement with the test article surrounded by nonflammable obstructions and, finally, an enclosure will be included to simulate an electronics cabinet.

There are several reasons why plain, unmodified sheets of PMMA were chosen as test articles. First, the composition of the combustion gas issuing from burning PMMA is more predictable and the gas itself is much less toxic than that coming from an actual printed circuit board (PCB). Second, PMMA is a well-characterized material due to its widespread use in combustion research. Finally, the variety of components found on PCBs differs tremendously, as well as their sensitivity to water mist and elevated temperatures. It is thus beyond the scope of this work to test the integrity of actual PCB components as a result of exposure to fire and water mist.

EXPERIMENTS

The experimental apparatus is shown in Figure 1. Its dimensions are 61 cm on a side by 122 cm from the base to the bottom of the hood. The key features include a positioning rack for the test articles (not shown in Figure 1), a gate valve with which to adjust the ventilation, a secondary carbon dioxide (CO_2) suppression system, and videotaping capabilities. A data acquisition system records gas velocity in the exhaust duct, temperatures at various locations within the enclosure, and CO and O_2 concentrations at one location. Any number of nozzles can be positioned anywhere in the enclosure. A variable pressure pump delivers a measured quantity of deionized water to the nozzles from a large buret.

Tests to date have been conducted with three nozzle configurations: no nozzles (for base-case dry fires), one nozzle spraying vertically downward onto the PMMA sheet from a distance of 33cm, and three nozzles directed horizontally at 120º apart and placed 33 cm above the top edge of the PMMA sheet. The nozzles were operated at 1000 psi and have a flowrate of 0.002 L/s each. The 20 cm x 20 cm PMMA test articles are cut from 1/8" (3 mm) thick commercial grade cast sheets.

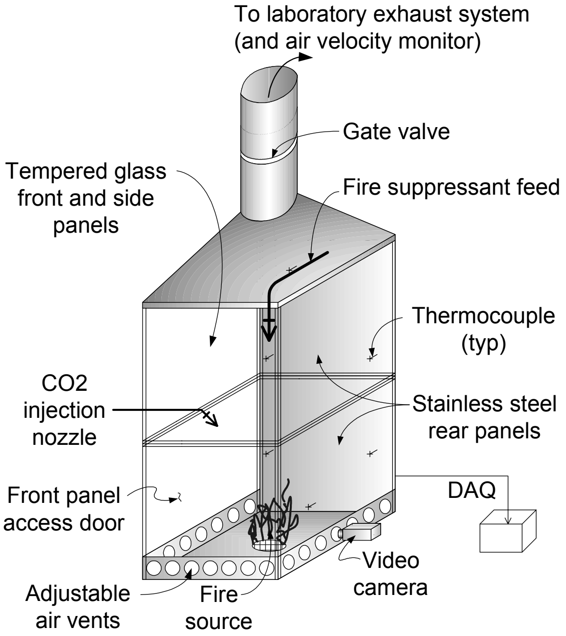

Figure 1. Experimental apparatus for water mist suppression of thermoplastic fires. A pool fire is shown, for PMMA fires the test article is held vertically in a rack above a propane burner which ignites the lower edge of the PMMA sheet

SIMULATIONS

Numerical simulations, using the Fire Dynamics Simulator (FDS) software developed at NIST [6], are used to aid in determining the contributions to fire suppression of thermal cooling, radiation, and oxygen dilution. The numerical simulations have also been used to perform a sensitivity analysis of test parameters, thus providing guidance in exploring the parameter space in order to reduce the experimental test matrix, optimize the nozzle spray characteristics, placement, and to identify key design parameters.

FDS is a useful, flexible tool for fire researchers but, as with most computational fluid dynamics (CFD) based field models, trade-offs must be made between computational expense and accuracy of the results. For the purposes of this project, a rectangular grid was chosen that allowed most cases to be run in under three hours.

There are two categories of measurements taken during a typical test: 1) Temperature- near the fire (T_{loc}), and an average of five other locations in the enclosure (T_{ave}), and 2) Gas Composition- concentrations near the fire of CO (ppm) and O_2 (vol%). Trends in the FDS predictions of these quantities are used to evaluate the effectiveness of various test/nozzle configurations.

Test configurations with zero, one, three and six nozzles placed below and above the test article, both with and without ventilation, have been simulated to date. The orientation of the nozzle in the single nozzle tests was either spraying downward onto the test article from above or spraying upward onto the test article from below. For the three- and six- nozzle tests the spray was directed horizontally, assuming a uniformly distributed radial spray. The nozzle specifications are as follows: in all cases the operating pressure was 1000 psi, the single nozzle K-Factor is 0.114 L/min/bar$^{1/2}$ (x3 for three nozzles, x6 for six nozzles), the geometric standard deviation (σ_g) was 2.6, the Rosin-Rammler parameter (γ) was 0.44, and the initial droplet velocity was 7.0 m/s. The median volumetric droplet diameters (D_{v50}) were 32 and 100 µm, and the cone angles were 20º and 40º. These spray characteristics are derived from data provided by a commercial spray analysis service [7]. A Phase Doppler Particle Analyzer was used to collect and analyze the droplet size and velocity distribution data.

RESULTS

FULL-SCALE LABORATORY EXPERIMENTS

The average mass loss (change in mass/total burning time) is shown in Figure 2 for several test configurations. While the data are somewhat scattered, qualitative results show that the average mass loss is reduced substantially from the base-case of a dry fire when water mist is present. It can also be seen that the average mass loss is reduced more for the single nozzle spraying directly onto the burning test article than for the case of three nozzles (3x more mist) spraying such that the general fire area is enveloped in mist. As an example, for the three nozzle arrangement with fresh air moving upward at approximately 17 L/s through the experimental apparatus, the average mass loss rate dropped by about an order of magnitude from the dry fire base-case but the flames were not extinguished. For a single nozzle spraying directly on the burning PMMA the flames were extinguished within 10s.

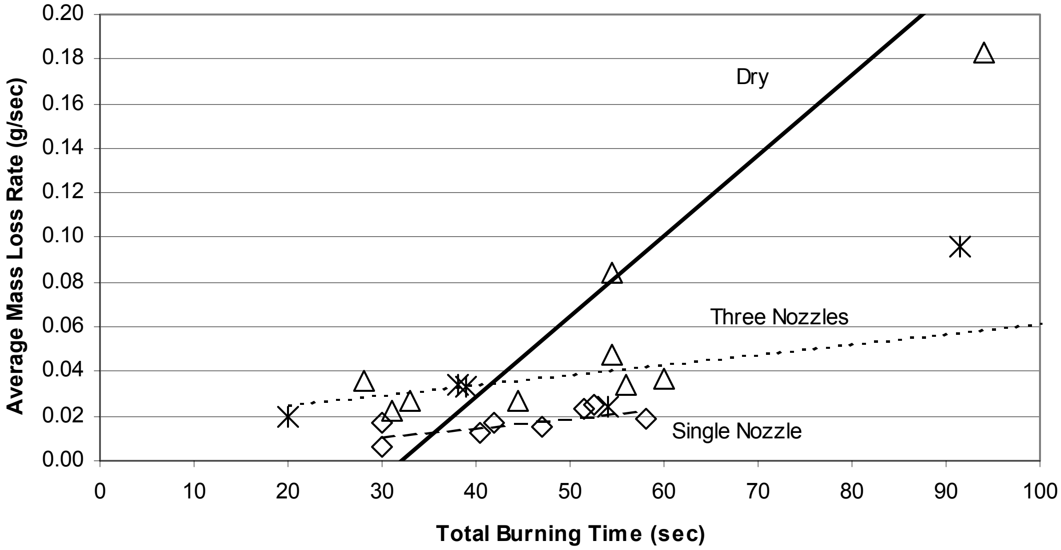

Figure 2. The average mass loss (change in mass/total burning time) of several test configurations and the base case dry fire. The error in average mass loss is estimated to be ±0.01 g/s and the error in time is approximately ±2 s, based on estimations of measurement accuracy

A phenomenon frequently observed in the course of performing these experiments is an immediate, substantial reduction in the vitality of the fire when the water mist is introduced into the enclosure. The suppressed fire continues to burn feebly for a long time; sometimes it is eventually extinguished by the mist, other times it is not. The mist lowers the ambient temperature relatively quickly, which in turn decreases the driving force to evaporate the mist, which then inhibits the oxygen displacement suppression mechanism. This "small fire syndrome" is a result of the fire coming to equilibrium with barely adequate levels of oxygen and heat in its surroundings.

To look more closely at a fire test, Figure 3 shows the evolution of a typical dry test. Compared with Figure 4, which shows the evolution of a typical misted test, several important differences are observed. First, T_{loc} drops quickly upon introduction of the mist. Second, T_{ave} initially rises in response to the fire but returns nearly to the pre-fire value by the time the fire is extinguished. Third, the CO concentration peaks and then decreases with water mist in the system as opposed to increasing monotonically for the dry fire. Last, the O_2 level continues to drop as the dry fire burns, whereas it drops initially when the misting begins but then recovers slowly as the fire shrinks and is eventually extinguished.

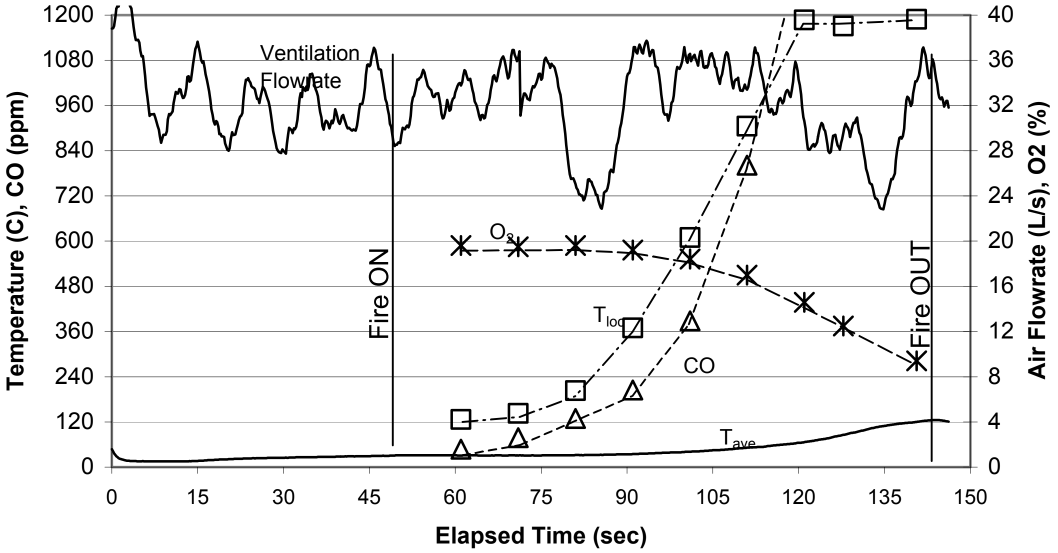

Figure 3. Evolution of a typical dry fire showing increased CO and local temperature levels and decreased oxygen concentration.

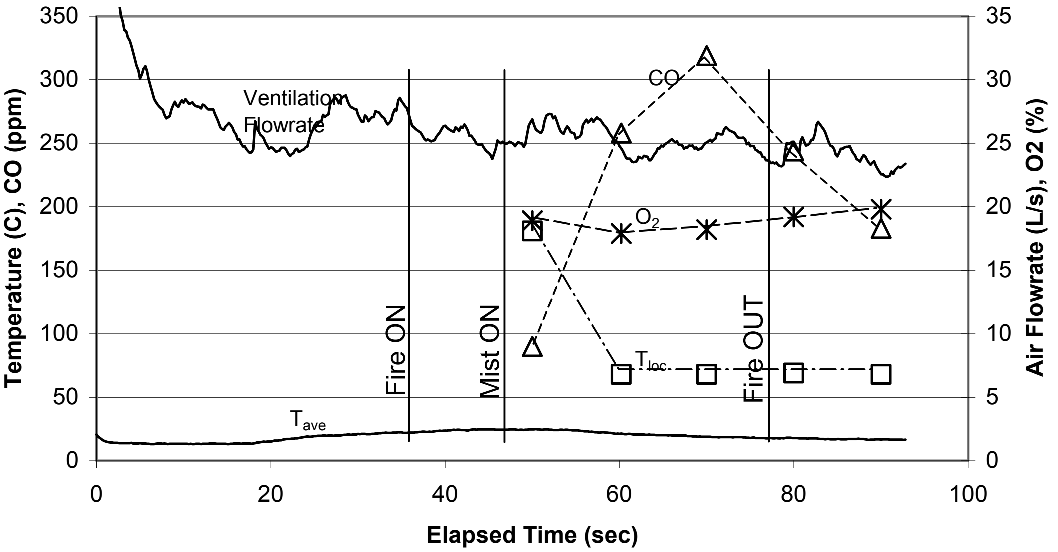

Figure 4. Evolution of a typical misted (single nozzle) fire showing a peak in CO concentration, a minimum in O_2 concentration, and depressed local temperature level. Note that this fire was extinguished by the water mist after burning at a very slow rate for approximately 15 s.

SIMULATION RESULTS

With respect to CO concentrations, the FDS simulations show that the levels are reduced most effectively by direct impingement of a single nozzle oriented to spray downward onto the burning test article. Water loading and droplet size for the three- and six-nozzle configurations is important, but the cone angle appears to have no effect.

An important mechanism of water mist fire suppression is the dilution of oxygen levels below that which will sustain a fire, this level is about 15 vol% [8]. The ability of a mist to prevent oxygen from being accessible to the fire is a measure of its effectiveness as a suppressant. Simulations show that the three- and six-nozzle systems located below the burning test article are most effective in preventing oxygen intrusion into the local fire area. Among these systems, cone angle and droplet size had no effect. The single nozzle systems were not effective.

The local temperature (near the fire) is also a good indication of a suppression system's effectiveness because fire is not viable below about 1600 K [9]. The temperature measured in the experiment is not the actual flame temperature but is instead a gas temperature in the vicinity of the flame. The FDS "thermocouple" is positioned to mimic this measurement. The results indicate that direct impingement of smaller droplets reduces the local temperature more quickly and to a greater degree than other arrangements. Larger droplets don't work as well unless they are more concentrated.

Although the average temperature in the enclosure is not important in the sense of being indicative of a fire suppression mechanism, but there may be cases in which sensitive equipment in proximity to a fire must be kept cool. To this end, it was found that the three- and six-nozzle systems were approximately equally effective in reducing the average enclosure temperature, with little dependence on cone angle or droplet size.

CONCLUSIONS

This work has shown that a well-directed spray (impinging upon the surface of the burning test article) with a relatively small droplet concentration of relatively small droplets, is the most effective way to reduce the local temperature and the average mass loss of the test article, and to extinguish the fire. However, this system is ineffective at reducing O_2 levels, in fact both the simulations and experimental results show that this "best case" configuration actually enhances O_2 recovery when compared with a dry fire.

Incidents of the "small fire syndrome" were much more prevalent in experiments utilizing the three nozzle configuration, compared with single nozzle tests. The simulations indicate that the three- and six-nozzle arrangements are effective at displacing O_2 while single nozzle arrangements are in fact counterproductive for this purpose.

The results of the simulations and experimentation performed to date indicate that heat effects and surface wetting are the most important fire suppression mechanisms, oxygen dilution is not as important for the cases studied.

This work is intended to explore the viability of fine water mist as a fire suppressing agent for enclosed electrical/electronic applications. It is anticipated that the outcome of this endeavor will help to validate whether water mist is a suitable fire suppressant for sensitive electrical/electronic equipment and, if so, identify the key design parameters.

FUTURE WORK

After the single PMMA sheets have been tested a "card rack" will be constructed to mimic a generic shelf of printed circuit boards. It is recognized that there is no standard card rack design; therefore the rack will be configured in such a way as to maximize card placement flexibility. The test article will be placed in various locations relative to the other cards in the rack, which will be nonflammable. The experimental apparatus will also be fitted with instrumentation to measure fire radiation and instantaneous burning rate.

In the last set of experiments the card rack will be enclosed in a metallic cabinet. The top of the cabinet will be a solid obstruction while the bottom will be fitted with screens of varying open area. Nozzle configurations will include overhead, under and inside the cabinet placements. Similar tests have been performed by Grosshandler et al. [10], who found that nozzles external to the cabinet were not effective at extinguishing internal fires.

It is expected that knowledge gained from each of the previous sets of experiments, along with corroborating simulations, will further fine-tune the test matrix.

ACKNOWLEDGMENTS

The authors are grateful to their commercial partners at the Center for Commercial Applications of Combustion in Space: MicroCool International and Fogco, Inc. for sharing their equipment and expertise with us on this project.

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