WATER MIST FIRE SUPPRESSION STUDIES IN MICROGRAVITY

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Abstract

A research program is underway within CCACS to improve fire suppression systems by conducting experiments in the near absence of gravity aboard terrestrial aircraft and orbital space vehicles, including the Space Shuttle and the International Space Station. The program is focused on developing water mist as a replacement for Halon. By conducting the experiments in microgravity, interference from convection currents is minimized and fundamental knowledge gained. This knowledge is incorporated into models, which can be used to simulate a variety of physical environments. Preliminary experiments have been conducted in the CSM drop tower and are currently being flown on NASA's KC-135 parabolic-flight aircraft. Experiments are being planned for the Space Shuttle and the International Space Station. The research program will be described and preliminary experimental results will be presented.

INTRODUCTION

Fire suppression technologies based on fine water mists are receiving increased attention as replacements for Halon-based systems. Frequently cited potential advantages of water mists over other alternatives to Halons are that they are relatively inexpensive, non-toxic, free of unmanageable environmental impacts, applicable to liquid pool and spray fires, usable in a total-flooding mode and more efficient in terms of water usage than conventional sprinklers.

In order to realize these potential advantages, however, designs must be developed which are based on solid fundamental knowledge of the processes by which a water mist extinguishes a fire. Among these processes are 1) gas phase cooling through heat of vaporization, 2) oxygen depletion by steam expansion, 3) surface wetting and 4) reduction in radiative heat transfer. Important design issues to be considered are water droplet size and distribution, critical concentration, droplet velocity and pattern, and mixing characteristics. There is currently no accepted theoretical basis for selection of any of these design parameters and the current state of the art is simply to extrapolate from large-scale test data on a case-by-case basis. Such an approach makes it difficult to compare studies done under different sets of experimental conditions, to guide improvements or to extrapolate the results.

A project to develop water mist fire suppression technology has been underway within CCACS since 1996. Early results have been reported by McKinnon, etal (1998). The immediate objective of the project is to study the effect of a fine water mist on a laminar propagating flame generated in a propane-air mixture at various equivalence ratios. The effects of droplet size and concentration on the speed of the flame front is used as a measure of the effectiveness of fire suppression in this highly controlled experimental environment. The availability of reduced gravity makes it possible to eliminate the effects of convection and to maintain a homogeneous concentration of water droplets of a nearly uniform size throughout the flame tube. The near absence of buoyancy in microgravity effectively eliminates the effects of convection on flame shape and suppresses complex flow patterns between the flame front and the water mist. Microgravity thus allows for direct and unambiguous measurements of the effect of the water mist on flame speed, flame shape and radiant emission. The experiments coupled with modeling are expected to yield valuable insight into the relative importance of energy removal through latent heat vs. oxygen depletion.

The results of the microgravity measurements are incorporated into a numerical model using the CHEMKIN® code, which was developed by one of CCACS's researchers, Bob Kee. Over 200 elementary reactions can be used in this code to evaluate the relative importance of phase changes and steam expansion in the propagating flame. The critical concentration can be inferred as the point at which the modeled flame fails to propagate. Thus, the effect of water mist loading and water droplet size on the flame speed and the critical concentration of water mist as a function of equivalence ratio can be determined.

As part of the model development, a study of the mechanisms of flame quenching by Bromine-based fire suppression agents was undertaken and has recently been reported by Casias and McKinnon (1998). The purpose of this study was to identify how Halon 1301 (CF_3Br) interacts with a flame at the level of elementary reactions. By studying how Halons suppress flames it is hoped that the knowledge so gained can be used as a benchmark to evaluate alternative agents such as water mist. The contributions of the CF_3Br molecule as well as the CF_3 and Br fragments were identified in this study. Predominant mechanisms identified include trapping of H atoms diffusing against the convective flow, consumption of H atoms through the reaction H + HBR = H_2 + Br, endothermic cooling of the flame by unimolecular dissociation of CF_3Br, and termination of radicals in the preheat zone by the reaction Br + HO_2 = HBr + O_2.

The remainder of this paper will be devoted to a discussion of the experimental details of the water mist project, including flight hardware currently operating in the CSM drop tower and on the KC-135 parabolic aircraft and planned for the Space Shuttle and International Space Station. Early results from the terrestrial laboratory and the KC-135 flights will be presented.

EXPERIMENTAL APPROACH

The basic experimental approach is to study the effect of a fine water mist on the propagation of a pre-mixed flame in a cylindrical tube in the near-absence of buoyancy and convection. The experimental rationale is to use the laminar flame speed as a measure of the effectiveness of suppression by the water mist and to make this measurement as a function of droplet size and concentration. The reduced gravity permits a homegenous and stable distribution of water droplets throughout the flame tube and helps to eliminate the distorting effects of buoyancy on the propagating flame front. Attainable times in microgravity are 1.5 seconds in the CSM drop tower, 10-20 seconds in the KC-135, and hours in the Space Shuttle. Premixed C_3H_8 – air mixtures are used at equivalence ratios varying from 0.7 to 1.3. Water mist is generated in an ultrasonic generator, which produces droplets varying in size from 50 to 100 micrometers. The water mass fraction (Mass of Water/Total Mass) ranged from 0.1 to 0.3. Total water mist volumes ranged from 0.25 to 1.0 ml.

FLIGHT HARDWARE

A schematic diagram of the water mist flight hardware is shown in Fig. 1. The schematic shows all of the features that will be present in the hardware planned for flight on the Space Shuttle. A simplified version is currently flying on the KC-135. Essential differences are in the details of the method of mist generation and flame speed measurement and added features required for recycling of combustion gases and water in the shuttle experiments.

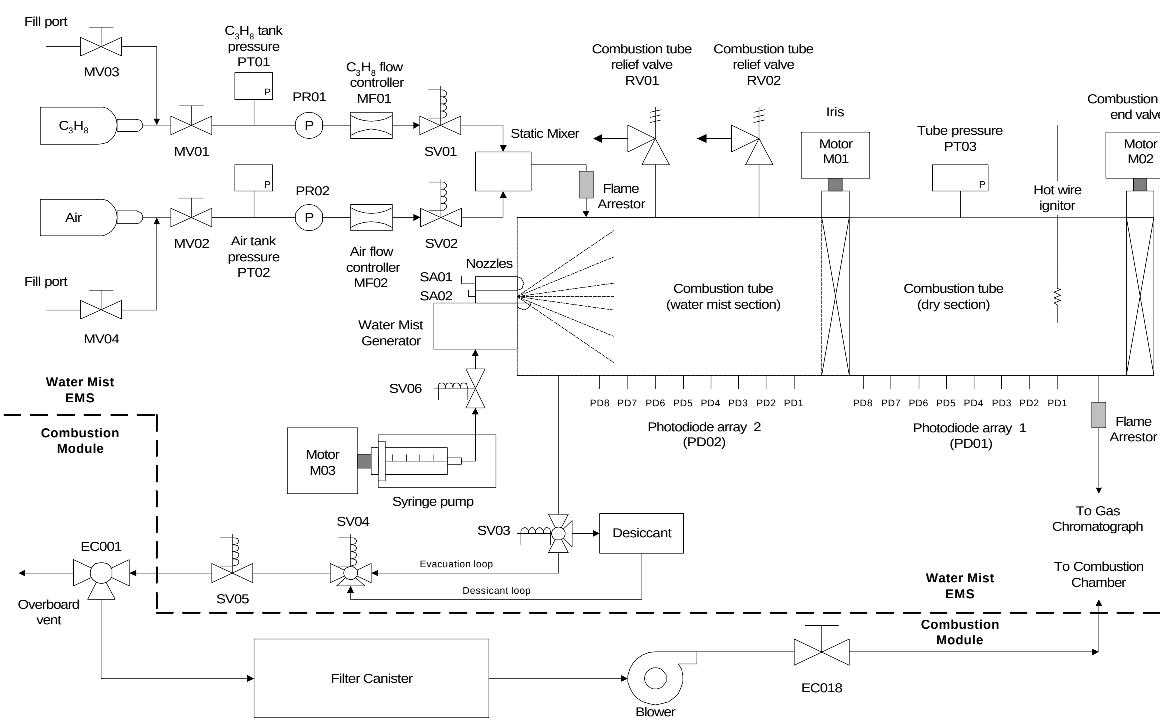


Fig. 1. Water Mist Flight Hardware Schematic.

Figure 2 shows a photograph of the water mist hardware currently flying in the KC-135.

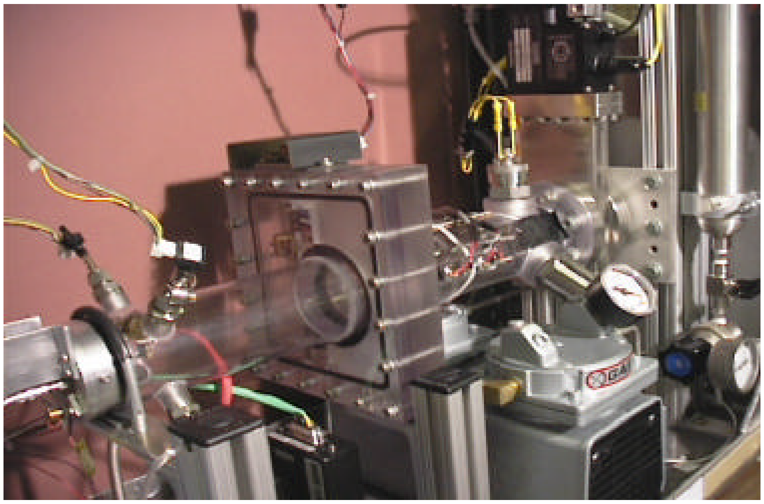


Fig. 2. KC-135 Water Mist Flight Hardware

The flame tube is divided into a section containing the water mist and a dry section. The two sections are separated by a specially designed iris diaphragm. A typical experimental sequence is as follows:

1) the flame tube is evacuated and filled with gas,
2) the water mist generator is actuated,
3) the iris is opened,
4) the gas is ignited (simultaneous with the iris opening) by means of a heated wire and
5) the flame front is allowed to propagate through the iris and into the region containing the water mist.

Gas equivalence ratios representing lean, stoichiometric and rich (C_3H_8)-Air mixtures were used for the KC-135 experiments.

The speed of the flame front is measured by means of a digital camera in the KC-135 experiments, which will be replaced by a photodiode array for the Space Shuttle experiments. The latter gives much greater time resolution in the velocity measurement.

Approximately 60 tests of the water mist hardware have been performed on three KC-135 flight campaigns. Approximately 20 seconds of reduced gravity were available for each test. The goals of these tests were to study the flame propagation speed dependence on air/fuel ratios, atomizer configurations and settings, mist volumes, mist delivery rates, surfactants and gravity. A related goal was to test the hardware as a prototype for the space shuttle.

PRELIMINARY RESULTS FROM KC-135 EXPERIMENTS

Flame speed data at two equivalence ratios is shown in Figures 3 and 4. In each figure, the flame speed is estimated through the iris, which had no thermocouples in it. The iris extends from 18 to 22 cm in the plots. Water mist volume in each case was 0.5 ml.

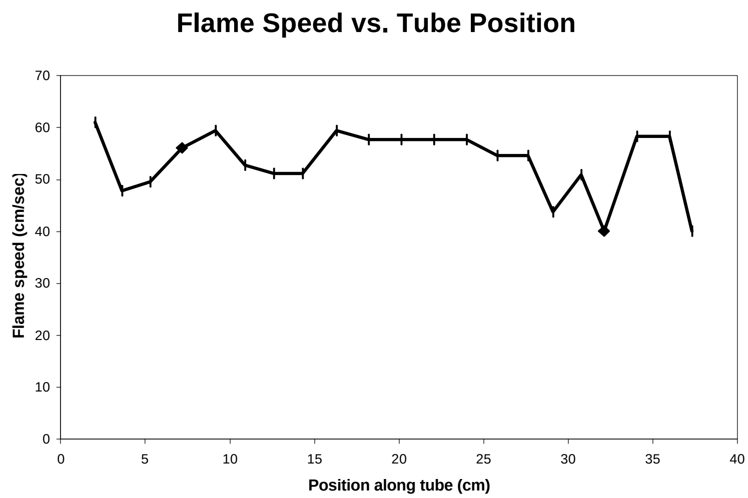


Fig. 3. Flame Speed as a Function of Position along Flame Tube, Equivalence Ratio 0.7.

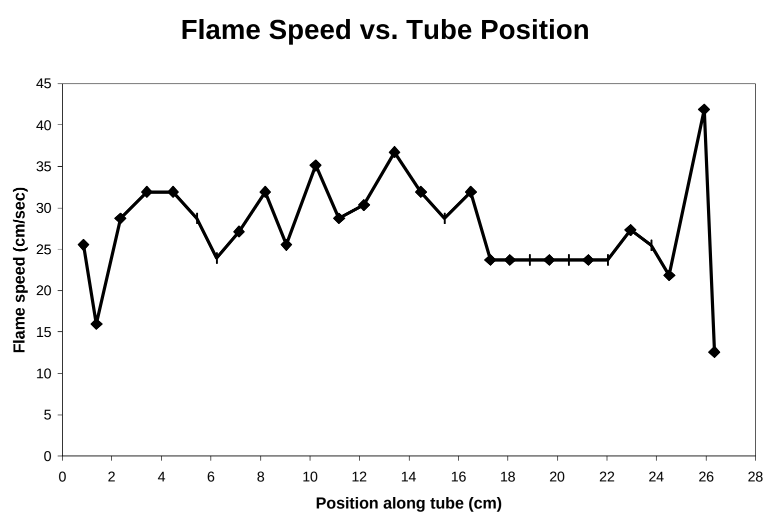
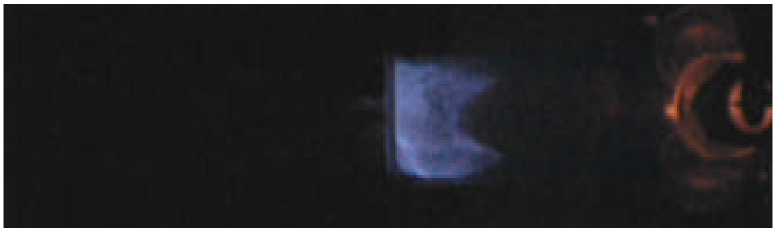


Fig. 4. Flame Speed as a Function of Position along Flame Tube, Equivalence Ratio 1.3.

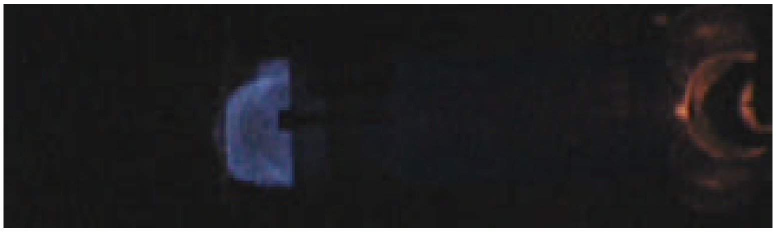
The effects of the water mist on flame speed are evident in these data, as is the dependence of the flame speed on the gas mixture.

Visual records of the flame progression through the tube were taken with a video camera. A typical progression is shown in Figure 5. All images were taken in reduced gravity.

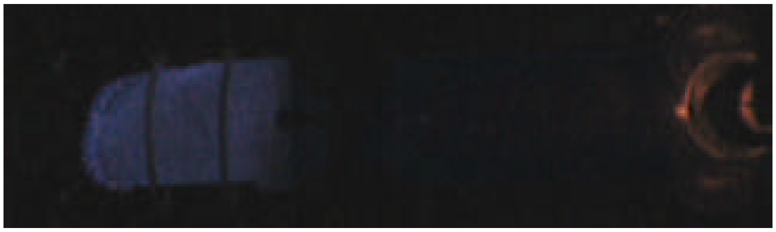
a) Flame Initiated



b) Flame Enters Iris Diaphragm



c) Flame Enters Mist Region



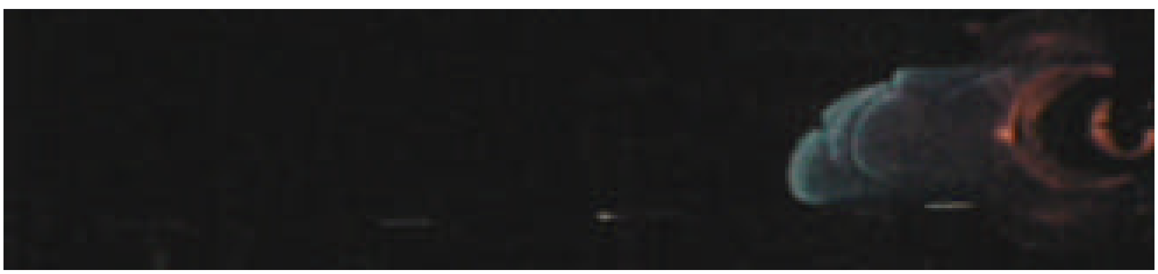
d) Extinction Begins

Fig. 5. Video Record of Flame Progression through Tube.

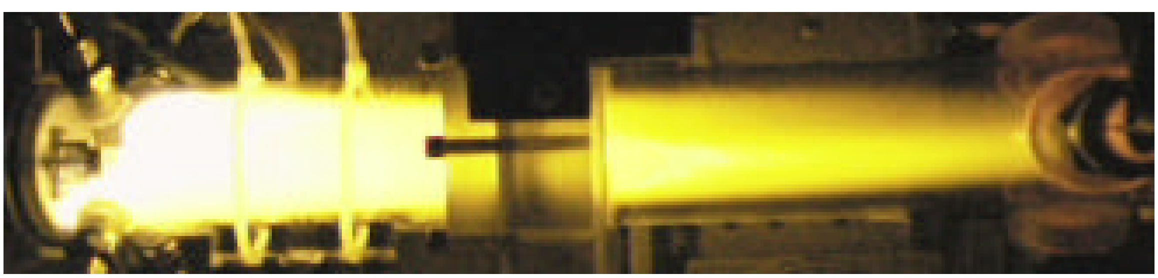
A clearly discernible spherical flame shape can be seen in the images shown in Figure 5. The spherical shape is evidence of a lack of convection within the reacting gases and the water mist in the absence of gravity. Such shapes have been observed many times in reduced gravity experiments. The apparent spreading of the flame upon encountering the water mist is not well understood at present and is in need of further study.

Video records were also taken of the flame appearance for various equivalence ratios and water mist conditions. Selected images are shown in Figure 6. All images were taken in reduced gravity.

a) No Mist, Equivalence Ratio, 0.7



b) No Mist, Equivalence Ratio, 1.3



c) Mist with Surfactant, Equivalence Ratio 0.7

Fig. 6. Video Records of Selected Flames in Reduced Gravity.

The spherical flame shape is particularly evident in Fig. 6 (a), with no mist present and a lean flame propagating through the tube. The shape is clearly perturbed in the richer mixtures.

The addition of surfactant, which was done to test the effect of a significant change in mist properties, caused the flame to spread throughout the tube and change appearance dramatically. This effect is not understood at present although it is believed to be due to changes in mist droplet sizes. A droplet sizing capability is being designed and will be incorporated into future experiments.

In summary, the KC-135 experiments have shown that there is an inhibiting effect of the water mist on flame propagation speed and that various regimes of flame behavior can be observed. More work needs to be done to relate the inhibiting effect and the various regimes unambiguously to the experimental parameters. It has become clear from our work to date that in order to achieve these goals longer times in reduced gravity are needed. These longer times are only available on the Space Shuttle and the International Space Station (ISS).

PLANS FOR SPACE SHUTTLE AND ISS EXPERIMENTS

The water mist experiment is currently scheduled to fly on the Space Shuttle Columbia (STS-107) in the year 2000. The experiment will be flown as an Experimental Mounting System (EMS) insert into the updated Combustion Module (CM-2), which is the rack used to accommodate combustion experiments aboard the Shuttle. The CM-2 consists of a combustion chamber (primary containment vessel), 5 video cameras for visible and infrared imaging, a laser extinction system for particulate volume fraction measurement, a gas chromatograph for species identification, a flow control system and complete data control, acquisition and telemetry.

Fig. 7 shows a solid model drawing of the water mist EMS.

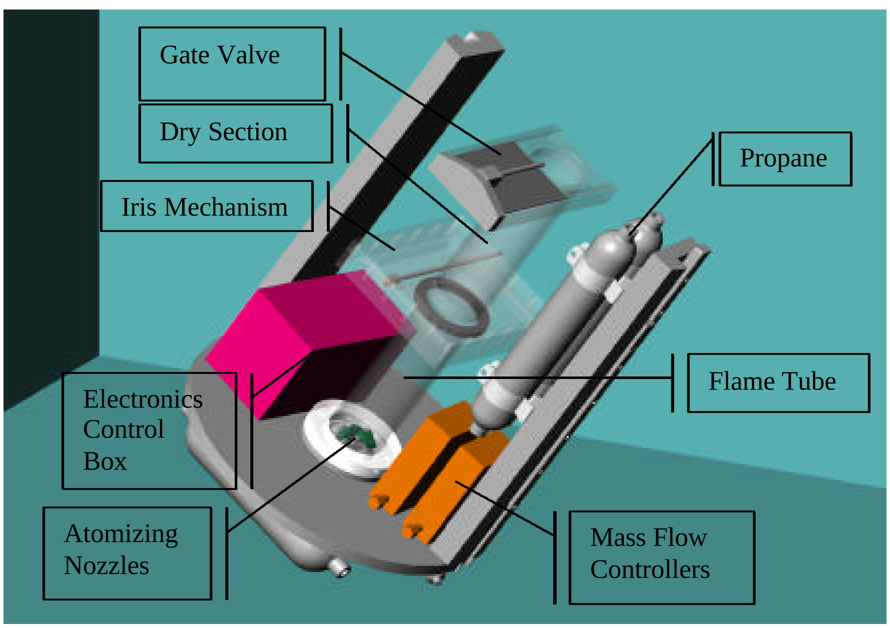


Fig. 7. Water Mist EMS for Space Shuttle Experiments.

All of the components unique to the water mist experiment are self-contained in the EMS. These include the atomizing nozzles, ultrasonic generator, pressure transducers, mass flow controllers, flame tube with gate valve and iris mechanism and an electronic control box. Two atomizer heads, providing two different droplet size distributions, will be incorporated.

ACKNOWLEDGEMENTS

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