

THE WATER-MIST FIRE SUPPRESSION EXPERIMENT (*Mist*): PRELIMINARY RESULTS FROM THE STS-107 MISSION

Angel Abbud-Madrid, J. Thomas McKinnon, Francine Amon

Center for Commercial Applications of Combustion in Space

Colorado School of Mines

Golden, CO 80401

Suleyman Gokoglu

NASA Glenn Research Center

Cleveland, Ohio 44135

INTRODUCTION

The deficiency in replacing the chemical fire-suppression agents banned by the Montreal Protocol has led to an increasing interest in fine water mists as fire suppressants since mists pose no adverse environmental or health issues and they offer the promise of meeting the requirements of protecting both water- and weight-sensitive areas due to the low requirements for total water flow. Unfortunately, there is to date no widely accepted interpretation of the critical concentration of droplets or the optimum droplet size required to suppress a flame, or more importantly, of the fundamental mechanisms involved in flame extinguishment by a water mist.

One of the main obstacles to obtaining such understanding is the difficulty of providing a simple, well-characterized experimental setup for the flame front/water mist interaction. A weightless environment provides an ideal place to study this interaction by eliminating the distorting effects of gravity on the prolonged suspension of a uniform concentration of droplets and on the complex flow patterns induced by natural convection between the flame front and the water droplets. In order to take advantage of this environment, the Water-Mist Fire Suppression experiment (*Mist*) was flown on the STS-107 mission of the Space Shuttle on January, 2003. It consisted of a series of microgravity tests that explored the effect of uniformly distributed clouds of polydisperse water mists on the speed and shape of propagating propane-air premixed flames. The results from these tests will be used to assess the feasibility of using water mists on the new generation of fire suppressants on Earth as well as on spacecraft.

DESCRIPTION OF THE *Mist* EXPERIMENT

Figure 1 shows a three-dimensional model of the *Mist* flight apparatus with the main components of the experiment. A mixture of propane (C_3H_8) and air is loaded in a transparent cylindrical tube of 6.3-cm diameter and 49.5-cm length. The two gases are introduced in the tube from separate tanks through a static mixer using mass flow controllers. A polydisperse water mist generated by an ultrasonic atomizer is introduced in one half of the tube separated by an iris from the dry region. A light extinction system consisting of three diode lasers shining radially through the tube into three photodiode detectors is used to obtain droplet concentration data in different parts of the wet section. After the mist injection, the iris opens and the mixture is ignited in the dry section while keeping the valve at that end of the tube open for an isobaric combustion process. In order to measure the fire suppression ability of a given water-mist

droplet size and water concentration, the propagation velocity of the premixed flame is measured by a video camera and by an array of 16 photodiodes installed along the tube. The *Mist* experiment was designed, fabricated, assembled, and tested at the Center for Commercial Applications of Combustion in Space (CCACS) at the Colorado School of Mines and later tested and integrated to the Combustion Module-2 (CM-2) at the NASA Glenn Research Center.

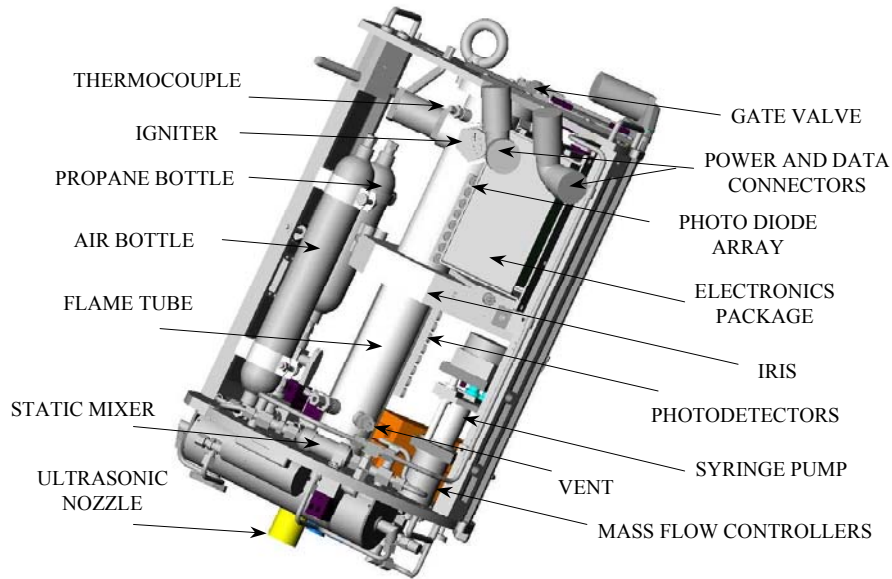


Figure 1. The *Mist* experiment flight unit.

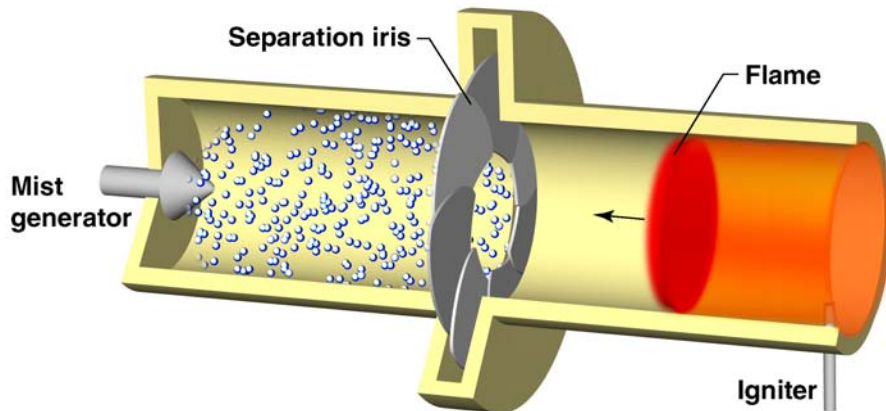


Figure 2. Configuration used in the microgravity tests and in the numerical model.

In this investigation, a computational model has been developed that uses a hybrid Eulerian-Lagrangian formulation to simulate the two-phase, flame/mist interaction. Currently, the model is capable of simulating the free propagation of planar, premixed laminar flames of various stoichiometries and their interaction with monodisperse water droplets as shown in Fig. 2. Gas-phase chemical kinetics, thermodynamic, and transport properties are handled by the PREMIX software [1] and are used in the Eulerian representation of the propagating flame. Various chemical databases are used for the fuel-air reaction mechanisms. This formulation is

then coupled with droplet source terms from Lagrangian equations of mass, momentum, energy, and particle flux fraction. The interaction between the two phases is modeled using an imaginary gas packet that follows the droplet. This algorithm facilitates a stable coupling between the phases, yet permits solving the gas-phase equations and droplet equations separately.

EXPERIMENTAL AND NUMERICAL RESULTS

Numerical simulations have been conducted with both CH₄-air and C₃H₈-air flames. The first simulations consist of two freely propagating, stoichiometric flames—one wet (at 100% relative humidity) and the other dry. In the case of CH₄-air flames, due to the thermal, physical, and chemical effects of the steam, the burning velocity for the wet case is about 34 cm/s, which is considerably lower than the dry flame speed of about 39 cm/s. After establishing the two base cases mentioned above, different droplet sizes and concentrations are introduced in the wet-gas mixture case. These simulations show that larger droplets penetrate further into the post-flame region than smaller droplets which undergo rapid vaporization. Near the end of the droplet lifetime, the vaporization rate accelerates due to the rapidly increasing surface-area-to-volume ratio. Also, as more condensed water is added into the gas mixture, the maximum and post-flame temperatures are reduced. Consequently, the burning velocities are also reduced with increasing water-mass loading. At some point, the amount of water mist is sufficient to extinguish the flame. Figure 3 shows the effect of water concentration and droplet size on the burning velocity of CH₄-air flames. As clearly seen in the plot, very fine mists should be more efficient fire suppressants than larger droplets, although there appears to be a limit around 10 μm droplets.

During the STS-107 mission, 32 tests were conducted with four different stoichiometries ($\phi=0.6, 0.7, 1.0, \text{ and } 1.3$), various water concentrations ranging from water mass fractions of 0 up to 0.40, and with two different droplet size distributions with 20 and 30 μm mean droplet sizes. A mist behavior characterization study was also performed that showed a consistent generation and suspension of an extremely uniform and quiescent cloud of droplets for several minutes as a result of the low microgravity levels (with negligible jitter or oscillations) experienced in the Space Shuttle. Preliminary results show that the leanest propane-air flames exhibit progressively lower burning velocities with increasing water loadings and decreasing droplet size (as predicted by the model) with final extinction at the highest water concentrations. Stoichiometric and rich flames show additional flame distortion and cellular break up as the flames traverse the misted section of the tube. Pulsating flames were also observed for lean mixtures under certain water loadings. It is important to point out that none of these observations have been possible on the ground or on the KC-135 airplane due to the inability to form a uniform cloud of droplets prior to the passage of the flame. Thus, the jitter-free environment of the Space Shuttle was absolutely essential to conduct a controlled study of the effect of water mist on propagating premixed flames.

CONCLUSIONS

An investigation of the effect of water mists on premixed flame propagation has been conducted onboard the Space Shuttle to take advantage of the prolonged microgravity environment to study the effect of uniformly distributed clouds of polydisperse water mists on the speed and shape of propagating propane-air premixed flames. The suspension of a quiescent and uniform water mist cloud was confirmed during the microgravity tests. Preliminary results

show good agreement with trends obtained by the numerical predictions of a computational model that uses a hybrid Eulerian-Lagrangian formulation to simulate the two-phase, flame/mist interaction. Effective flame suppression is observed at progressively higher water loadings and smaller water droplet sizes. Other unusual flame behavior, such as flame front breakup and pulsating flames, is still under investigation. The promising results from the microgravity tests will be used to assess the feasibility of using water mists as fire suppressants on Earth and on spacecraft.

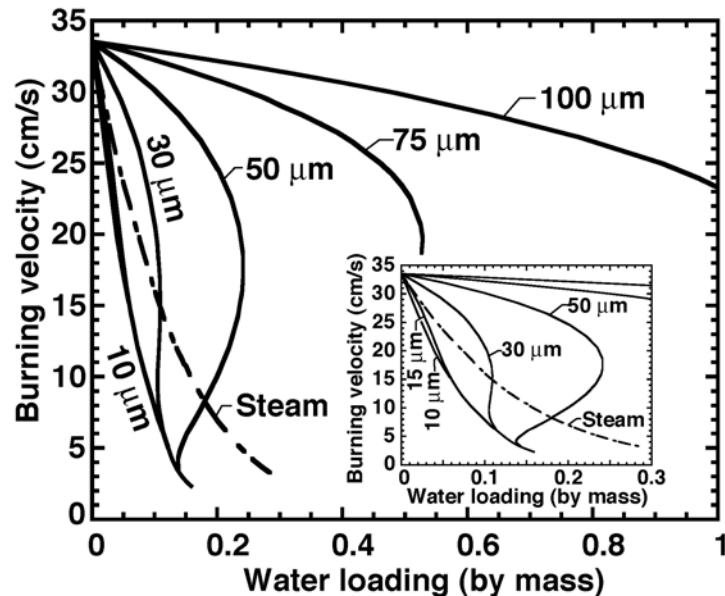


Figure 3. Effect of droplet diameter at various mass fractions of water on the flame speed of a planar, stoichiometric CH₄-air premixed flame obtained by numerical simulation (from [2]).

ACKNOWLEDGMENTS

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