EFFECTS OF WATER MISTS ON PREMIXED FLAME PROPAGATION IN A BUOYANCY-FREE ENVIRONMENT

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ABSTRACT

A preliminary investigation of the effect of water mists on premixed flame propagation under buoyancy-free conditions has been conducted to define the scientific and technical objectives for Space Shuttle and International Space Station experiments. The inhibiting characteristics of water mists in propagating flames of propane-air mixtures at various equivalence ratios are studied. The effects of droplet size and water concentration on the laminar flame speed and flame shape are used as the measure of fire suppression efficacy. Measurements and qualitative observations from the low-gravity experiments clearly show the effect of water mist on flame speed abatement, flame shape distortion, and radiant emission changes. For both lean and rich propane-air mixtures, the flame speed increases at first with low water-mist concentrations and then decreases below its dry value when higher water-mist volumes are introduced in the tube. The heating of the unburned mixture ahead of the flame caused by the radiation absorbed by water droplets at low mist concentrations may be partially responsible for the observed behavior.

INTRODUCTION

The use of water mists (very fine water sprays) for fire suppression is currently receiving increased attention as a replacement technology for halogen-based chemical agents—such as Halon 1301 (CF_3Br)—the manufacture of which has been banned by the Montreal Protocol due to their high ozone-depletion potential. Water mist technology has heen found effective for a wide range of applications such as Class B pool fires, shipboard machinery, aircraft cabins, computers, and electronic equipment [1].

There are five distinct mechanisms by which water droplets may interact with a flame. First, the high enthalpy of vaporization of water (2450 kJ/kg) leads to heat removal from the flame front as the liquid droplets turn to steam. In general, a flame will no longer propagate when its temperature drops below around 1500 K, so the simple conversion of sensible enthalpy to phase enthalpy can extinguish a flame. This effect directly corresponds to the endothermic rupture of the C-Br bond in Halon 1301. Second, as water vaporizes its volume increases approximately three orders of magnitude, which leads to the dilution of the oxygen and fuel required to maintain the flame. This effect has no analog to chemical fire suppression systems. The third effect is the recombination of H-atoms and other radicals on the droplet surface. In the gas phase the direct recombination of small radicals is rate limited by the requirement that a third body carry away the reaction energy, e.g., $H + H + M \rightarrow H_2 + M$. However, heterogeneous surfaces can speed these reactions. This effect directly compares to the chemically aided H-atom recombination steps brought about with Halon 1301 [2]. A fourth effect of water mists in fires is the retardation of surface propagation rates due to the wetting of walls and surfaces. The last potential impact of fine water mists affects the radiative propagation of the fire by forming an optically thick barrier to infrared radiation that prevents ignition of the unburned regions. Again, there is no Halon 1301 analog to this behavior. Unfortunately, little fundamental information exists on the interaction of a flame with a water mist. To date, there is no widely accepted interpretation of the critical concentration of droplets required to suppress a flame or of the fundamental mechanisms involved in flame extinguishment by water mists.

One of the main obstacles to obtaining such understanding is the difficulty of providing a simple, well-defined experimental setup for the flame front/water mist interaction. Some of the difficulty stems from the problem of generating, distributing. and maintaining a uniform concentration of droplets throughout a chamber while gravity depletes the concentration and alters the droplet size by coalescence and agglomeration mechanisms. Experiments conducted in the absence of gravity provide an ideal environment to study the interaction of water mists and flames by eliminating these distorting effects. In addition, microgravity eliminates the complex flow patterns induced between the flame front and the water droplets. The long duration and quality of microgravity in space flights provide the required conditions to perform the setup and monitoring of flame suppression experiments.

Consequently, a series of experiments has been identified to be performed on the Combustion Module (CM-2) in the Space Shuttle. These consist of measuring the extinguishing capability of a water mist on a premixed flame propagating along a tube. These experiments should provide the necessary data to obtain further understanding of the water mist suppression phenomena that can be later used to design and manufacture appropriate fire suppression systems. In preparation for the orbital flights, experiments have been conducted on low-gravity ground facilities to obtain the preliminary data necessary to define the scientific objectives and technical issues of the spacecraft experiments.

EXPERIMENTAL APPARATUS AND RESEARCH APPROACH

The experimental apparatus used in both the normal- and low-gravity tests is shown in Figure 1. The low-gravity experiments were conducted in **NASA's** KC-135 airplane in Houston, Texas. Gravity levels down to ±0.01 g are obtained during a typical 20-s parabolic maneuver. Up to 20 tests were conducted in a single flight for a total of 80 tests in a week-long flight campaign.

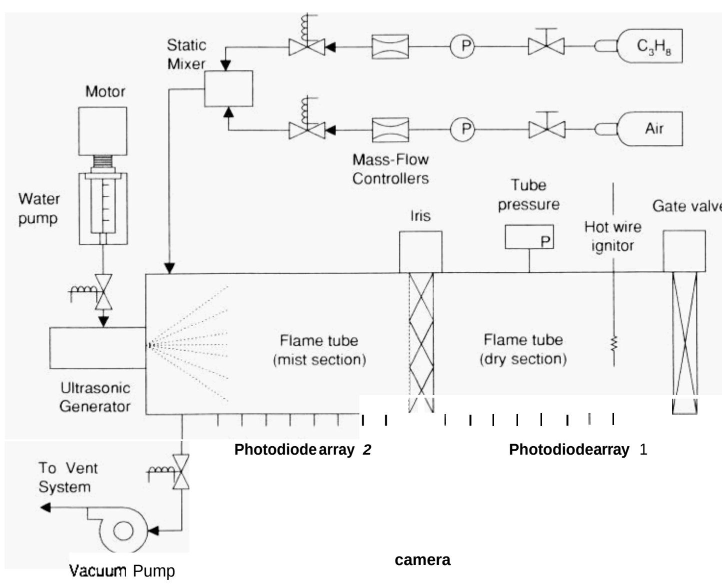

Figure 1. Experimental apparatus.

To characterize the interaction of the water mist with the flame front, *a* premixed gas mixture of propane (C_3H_8) and air is loaded in a transparent cylindrical tube of approximately 6.4-cm diameter and 49.5-cm length. The C_3H_8-air mixture was chosen for its ease of ignition, high flame luminosity, and its wide used in many practical applications. In addition. two types of flame behavior are observed depending on mixture stoichiometry: continuous flames in lean mixtures and wrinkled flame fronts in rich mixtures. This behavior is caused by thermnl-diffusive instabilities that depend on the Lewis number (Le) of the mixture [3]. The Lewis number is defined as the ratio of the thermal diffusivity of the hulk mixture to the mass diffusivity of the scarce reactant into the bulk mixture.

The fuel and oxidizer are introduced in the tube from separate tanks through a static mixer using mass flow controllers. A water mist generated by an ultrasonic atomizing system is introduced in one half of the tube separated by an iris from the dry region. The water concentration is determined by the volume of water delivered by the syringe pump. 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. To measure the fire suppression ability of a given water mist droplct size and concentration, the propagation velocity of the premixed flame is measured.

The flame speed is measured by an array of photodiodes installed along the tube and by a video camera. Experiments are conducted with mixtures of various equivalence ratios (ϕ) ranging from 0.6 to 2.0 and with several water-mist volumes from 0.25 to 1.00 nil. The mean diameter of the water mist droplets is 36 μm.

RESULTS

As mentioned above, the inhibiting characteristics of water mists in premixed propagating tlames of propane-air mixtures are studied. The effects of gas mixture equivalence ratio and of water mist droplet size and concentration on the laminar flame speed are used as the measure of fire suppression efficacy. The influence of water mist on the shape and propagation behavior of flames is also explored.

EFFECT OF WATER MISTS ON LEAN C_3H_8-AIR PREMIXED FLAMES

In the case of lean premixed flames, a curved. continuous flame front propagates at a constant speed down the dry section of the cylindrical tube after ignition. Interestingly, after the flame reaches the mist section of the tube, the flame speed increases at first with low water-mist volumes and then decreases helow its dry-region value lor high water-mist volumes. This phenomenon is observed in all lean mixtures tested. This effect is shown in Figure 2 for a C_3H_8-air mixture of $\phi = 0.8$. The speeds shown correspond **to** the flame front propagation velocity in the tube and not to the burning velocity of the mixture.

This reversal of tlame speed with water-mist volume may be due in part to the heating of the unburned mixture ahead of the flame as a result of radiation absorption by the water droplets. At sufficiently low water-mist concentrations. this preheating of the mixture may overcome the heat loss experienced by the flame due to the phase-change cooling and mixture dilution caused by the water mist. Alternatively. this behavior may be due *to* the short duration of reduced

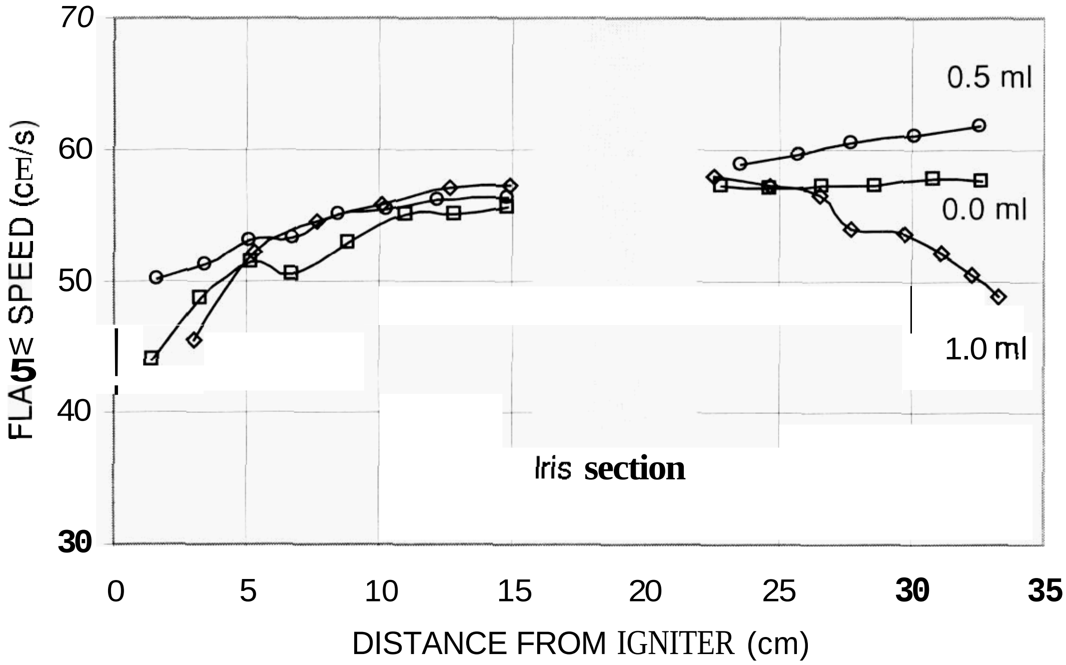

Figure 2. Effect of water mist (mean droplet diameter of *36* μm) on the flame speed of a C_3H_8-air premixed flame with equivalence ratio of 0.8.

gravity in the airplane. The brief time allowed for water injection and dispersion in the airplane is not enough to generate a uniform mist concentration and may also lead to residual convective currents generated by the mist injection. In addition, the fluctuations of the gravity level (g-jitter) present in parabolic flight may also contribute to the inability to obtain the desired experimental conditions.

A few experiments were conducted with water volumes above 1.00 ml. In these cases the flame front was distorted, slowed down, and eventually extinguished before reaching the end of the tube. Even under these extreme conditions of flame distortion and stretch, the flame front remains remarkably coherent and resilient due to the high ***Le*** number (1.78) of these lean mixtures.

EFFECT OF WATER MISTS ON RICH C_3H_8-AIR PREMIXED FLAMES

The rich mixtures tested exhibited a wrinkled flame front immediately after ignition. This unstable behavior is caused by the unequal rates of diffusion of thermal energy and mass characteristic of **a** mixture with lower-than-unity Lewis number (***Le*** = 0.87). These instabilities are later on accentuated by the quenching action of the water mist. Multiple local extinctions on the wrinkled flame front by water droplets result in increased flame curvature and consequently in larger reactant diffusion rates versus heat loss rates. **As** a result, the flame front breaks up into various cellular fronts that tend to propagate independently of each other. The highly curved cells acquire a higher temperature and higher resistance to extinction by water droplets. This in turn promotes faster flame speeds for low water-mist concentrations. The inability to obtain a uniformly distributed water concentration in the airplane experiments, results in the formation of flame cells separating from the flame front and traveling at different propagation velocities. This non-coherent propagation makes it difficult to define a uniform flame front speed.

A few tests were conducted with very rich mixtures (higher than $\phi=2.0$) and high water volumes (higher than 1.0 ml). In these extreme cases, a few small cellular flames propagated through the non-homogeneous misted section at speeds lower than 5 cm/s.

CONCLUSIONS AND FUTURE WORK

A preliminary investigation of the effect of water mists on premixed flame propagation in a cylindrical tube under reduced-gravity conditions has been conducted to define the scientific and technical objectives of the experiments to be performed on the Space Shuttle microgravity environment. The inhibiting characteristics of several water mist concentrations in premixed propagating llames of propane-air mixtures at various equivalence ratios are studied. Two different types of flame behavior are found depending on the mixture stoichiometry. In the case of lean C_3H_8-air mixtures, the tlame speed increases at first with low water-mist concentrations and then decreases below its dry value when higher water-mist volumes are introduced in the tube. This phenomenon may be due in part to the heating of the unburned mixture ahead of the flame as a result of radiation absorption by the water droplets. For rich C_3H_8-air mixtures, similar behavior of tlame speed vs. water concentration is found hut, in this case. is mostly due to the formation of cellular flames, which become more resistant to extinction by the water mist.

It is suspected that the unusual behavior observed in both of the above cases may be also due in part to the short duration and low quality of the reduced gravity available in the airplane. The brief time allowed for water injection and dispersion in the airplane is not enough to generate a uniform mist concentration and may also lead to residual convective currents generated by the mist injection and g-jitter. Consequently, the next stage of the Water Mist project (MIST) is the development of an experiment that will take advantage of the long duration and high-quality microgravity experienced in orbital flight. The MIST experiment is scheduled to fly on the STS-107 mission of the Space Shuttle in early 2001. During that mission, the MIST apparatus will be installed inside the Combustion Module (CM-2) along with other two combustion experiments. Under this configuration the effect of droplet size will be added to the water-concentration and equivalence-ratio parameters. A laser extinction system will provide measurements of water concentration and several cameras positioned at different angles and with different spectral sensitivities will give a more accurate view of the mist/flame interaction phenomena. In addition, analytical and numerical models are being developed to complement the experimental approach hy providing useful preliminary information for test parameter selection. These models will be significantly refined by the experimental information obtained under microgravity conditions. The final objective of the MIST experiment is to create a detailed map of flame speed, droplet diameter, water concentration, and equivalence ratio, which will give the appropriate set of parameters required for flame suppression.

ACKNOWLEDGMENTS

This research is funded through the NASA Center for Commercial Applications of Combustion in Space (CCACS) at the Colorado School of Mines (CSM). We wish to acknowledge the invaluable help from the CCACS director, Frank Schowengerdt, and from the following graduate and undergraduate students: Francine Amon, Katie Squire, Erin Evans, Aragorn Earls, Jennifer Lawton, Sheli Babb, David Petrick, Tom Phare, and Richard Williams.

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