THE BEHAVIOR OF SUB 10 μm WATER MIST DROPS IN PROPANE/AIR CO-FLOW NON-PREMIXED "CUP BURNER" FLAMES

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INTRODUCTION

Since the Montreal protocol banned the production of halon compounds, the focus of fire-suppression research has been on potential alternative agents. There is renewed interest in the use of water as a suppression agent, because it is readily available, environmentally friendly, and has a high heat capacity. There is high interest in very fine water mists (i.e., drops less than 10 μm in diameter). Smaller drops are potentially easier to deliver, particularly around obstructions, and may be more effective than the much larger drops that are currently in use in some fire-suppression systems.

Water functions as a physical suppression agent. Physical suppression occurs through two primary mechanisms—oxygen displacement and reaction zone cooling. Oxygen displacement is essentially a dilution effect, where the presence of water mist reduces the concentration of oxygen available to sustain the flame. Reaction zone cooling is a thermal mechanism, where the high heat capacity and heat of vaporization of water are heat sinks that reduce the flame temperature. The thermal conductivity of the low molecular weight water vapor also contributes to a smaller degree to reaction zone cooling. The characteristics of the water mist and the nature of the fire scenario determine which of these mechanisms is more important [1].

Unlike gaseous agents, condensed-phase agents are affected by drop/particle properties and transport issues. Cup burner agent behavior is often the basis for agent concentration guidance in the design of fire suppression systems, at least for gaseous agents. No reported studies have addressed the effectiveness of water mist in cup burner flames. This study examines the effectiveness of sub 10 μm diameter water drops and drop behavior for suppressing propane cup burner flames. Extinction concentrations were measured for nitrogen and for water mist, and these values were compared to determine the relative effectiveness of the water mist. Imaging of the flame and the surrounding mist-laden flow field was done to obtain qualitative information about the interaction of the mist with the flame.

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BACKGROUND

THE CUP BURNER

The use of the cup burner as an experimental tool in fire suppression research is well documented, and the widely employed apparatus is described in detail in the literature [2-12]. A cup burner flame is a non-premixed flame consisting of a cup or tube that either holds liquid fuel or delivers a low-velocity gas jet, with a surrounding laminar co-flow of air that contains the suppression agent of interest. The cup burner platform exhibits characteristics similar to real fires, including the initial separation of fuel and oxidizer, flame flickering, and regions of varying strain rates [2]. The cup burner flame was found to be more difficult to extinguish than full-scale fires for the same fuel using Halon 1301 and Halon 1211. This suggests that cup burner experiments provide extinction concentrations, with an inherent safety factor, for suppression agents that can be used to determine design concentrations in real fire suppression systems [3]. The cup burner has become a laboratory-scale platform for ranking the relative effectiveness of suppression agents and for determining the required extinction concentrations for these agents in real fire scenarios.

Some cup burner studies have investigated the suppression behavior and effectiveness of solid and condensed-phase particles [4-6]. These agents are considered more relevant to water mist than inert gas agents, because the suppression behavior of particles is dependent on particle size and shape. Hamins found that sodium bicarbonate powder (particles less than 10 μm), which acts through both physical and chemical suppression mechanisms, was on a mass basis three times more effective than Halon 1301 and five times more effective than N_2 [4]. Linteris et al. studied the effects of various metallic compounds on cup burner flames [5,6]. For very low volume fractions, these agents were found to be more effective than Halon 1301, but were still not as effective as expected based on the results of earlier studies in premixed flames. It was concluded that the loss in effectiveness of these organometallic agents was likely due to the formation of condensed-phase particles that were able to survive the flame.

WATER MIST

Quantification of suppression effectiveness is a necessary step toward understanding the behavior of water mists and their interaction with combustion systems. Sheinson et al. developed a model based on a large database of cup burner extinction data that predicts the mole fraction of a particular suppression agent required to extinguish a pool fire consisting of an organic liquid fuel surrounded by air [7]. The physical-action component of the model, which incorporates the sensible enthalpy of the suppression agent, is based on a reduction of the adiabatic flame temperature below the minimum required to sustain the flame. Based on this model, an n-heptane cup burner flame is expected to require mole fractions in the oxidizer stream of 16 % liquid water (10.6 % by mass) or 25 % water vapor (17 % by mass). These predicted extinction concentrations do not include the effects of water mist parameters (e.g., drop size) or transport considerations.

We have studied water mist suppression of laboratory-scale gaseous fuel premixed flames and counterflow flames [13,14]. In these configurations, water mist was found to be a highly effective suppressant, in some cases more effective than Halon 1301. The suppression effectiveness, however, is dependent on the drop size, a consideration that makes water mists different from gas-phase agents.

Prior NRL research has shown that optical density measurements (ODM) can be used to quantify the mass concentration of water in an airflow-driven water mist [15]. The suppression effectiveness of water mist was studied using a propane Bunsen-type flame (1-cm ID tube) in a corral with the water loading determined from ODM. This study reported a liquid water mass fraction (due to the mist) of 7.5 % required to extinguish the flame, a loading that corresponds to an increase in the enthalpy of the air of 61.3 kJ per mole of O_2 or 0.52 kJ per liter of oxidizer (air plus agent). (This sensible enthalpy increase was incorrectly reported at the 2004 HOTWC as 0.52 kJ per liter of *air* [15].) The extinction concentration of N_2 in this configuration was not measured, making quantitative sensible enthalpy comparisons with the water mist results impossible.

Shilling et al. investigated cup burner flame extinction with fine water mist ($D_{v0.5}$ = 8.2 μm), both pure and doped with metal chloride species [16]. Flame extinction occurred for a pure water mist concentration of 174 g mist/m^3 air, as compared to the theoretical value of 149 g mist/m^3 air based on heat extraction calculations. The authors postulate that the lower observed suppression effectiveness is due to different transport rates to the flame for the drops compared to the air. Drop transport and drop evaporation behavior are investigated in the current work to determine their roles in the suppression process.

EXPERIMENTAL

MIST PRODUCTION

Two different piezoelectric-based ultrasonic misters were used to create water mist with drops less than 10 μm in diameter. Both mist generators were from the same manufacturer and were the same type; one had three piezoelectric heads and the other had a single head. The three-head unit was used for extinction measurements because it is capable of producing much larger quantities of mist, while the single-head unit was used for imaging studies because a lower mist density was required. The mist drop size and water concentration for this type of mist generator is dependent on time, water level above the mister, and water temperature. Water drops produced by this mist generator have an average diameter of 8 μm ± 1 μm under normal operating conditions [15]. An auxiliary water reservoir with a drain and a small pump were used to continuously circulate the water and maintain a constant water height and uniform water temperature.

CUP BURNER APPARATUS

The full experimental cup burner apparatus is shown in Figure 1. Starting at the bottom, the apparatus includes the mist generator (either singe-head or three-head), the water reservoir surrounding the mister, the entrainment tube, a section containing wire mesh

screens serving as flow straighteners, a section containing windows for ODM measurements, a section to anchor the cup burner, the chimney base, and the chimney. All of the outer enclosure pieces are made of 1/4"-thick clear acrylic, with the exception of the ODM windows, which consist of hollow plastic tubes with the ends cut at the Brewster angle and sections of a glass slide bonded to the ends to serve as windows.

The lower section of the apparatus is circular in cross-section. The upper chimney section has a square cross-section with an inside area approximately equal to the lower section. A square chimney was chosen to provide better optical access for imaging purposes. Dimensions of the chimney and lower section (top views) are shown in Figure 1 (left).
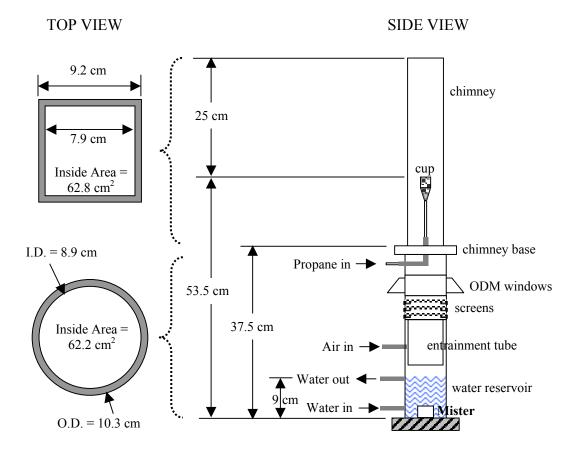

Figure 1. The experimental cup burner apparatus. Top views of the lower enclosure sections and the chimney (not to scale) are shown on the left.

The entrainment tube is a 1.7-mm thick hollow plastic tube that leaves clearances of approximately 2.5 cm and 0.65 cm above the water reservoir and inside the outer tube, respectively. Three wire mesh screens are used to straighten the flow through the tube as it approaches the burner, as shown in the diagram. The quartz cup is the same cup that was used in previous studies [7,9]. The bottom half of the cup is tapered into the stem, there is a 45-degree chamfer at the lip of the top, and the outlet diameter is 2.55 cm. The cup was packed with 3-mm glass beads up to a point approximately 2 mm below the top.

WATER CONCENTRATION MEASUREMENTS

The water mass concentration in the mist-laden airflow was measured using a previously reported ODM technique [15]. A distributed feedback (DFB) laser beam with a polarized output at 761 nm penetrates through the mist and is measured by a silicon photodiode. The ODM windows were designed to be at the Brewster angle to minimize reflection losses and maximize the detected signal. The windows were electrically heated with resistors to prevent mist condensation on the inside surfaces. Attenuation through the mist follows the Beer-Lambert-Bouguer law,

$$-\ln\left(\frac{I}{I_0}\right) = a \cdot l \cdot c \tag{1}$$

where I and I_0 are the measured signal intensities with and without the presence of water mist, respectively, a is the extinction coefficient (L/g-cm), l is the pathlength (cm) and c is the water concentration (g water/L air). With the measured extinction coefficient, the signal attenuation (left side of Equation 1) can be used to determine the water concentration in real time during subsequent experiments.

In general, attenuation results from both absorption and scattering. At this wavelength, there is no absorption; attenuation is only due to scattering. Optical density was observed to *linearly* increase with pathlength and there was no measurable depolarized signal, indicating that multiple scattering does not affect the ODM signal and the extinction coefficient of the water drops is constant [15]. The extinction coefficient is determined by measuring water loss in the reservoir over a known period of time with a known volumetric airflow rate.

EXTINCTION MEASUREMENTS

The fuel for these experiments was propane. The propane flow rate was 0.27 standard liters per minute (SLPM), which equates to an average velocity at the cup outlet of 0.9 cm/s. Extinction measurements were done for both nitrogen and water mist with the same total flow of 35 SLPM in the oxidizer stream. The total oxidizer flow of 35 SLPM in the square cross-section chimney corresponds to an average velocity of 10 cm/s and a velocity ratio of 11.3 (airflow:fuel). The experimental protocol, starting with an agent concentration well below what was expected for flame extinction, was to light the flame and allow a 30-second pre-burn before adding any additional suppression agent. Once the pre-burn was complete, the agent concentration was incrementally increased in small amounts, with a wait time of 10 seconds between increments to allow flow with the new agent concentration to reach the flame, until flame extinction was achieved.
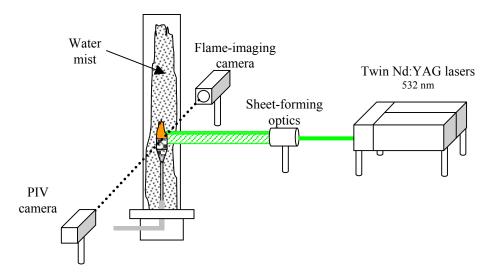
The propane and nitrogen gas streams were monitored through mass flow meters and controlled by needle valves. The airflow was both monitored and controlled by a mass flow controller. The nitrogen concentration was increased in small increments with the needle valve. The water concentration for the mist extinction measurements was controlled using the reservoir temperature. The water temperature in the reservoir slowly

increased due to the ultrasonic vibration of the mister. The slight increase in water reservoir temperature increased the water loading in the mist to the point of flame extinction.
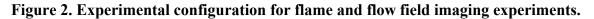
For all experiments, including the imaging studies described below, the oxidizer streams (including any additional N_2) were humidified to minimize premature mist evaporation in the airflow. Temperature and relative humidity measurements were taken during the experiments to determine the water vapor loading in the oxidizer stream. Three replicate measurements of the extinction concentration were measured for both nitrogen and water mist.

IMAGING OF THE FLAME AND SURROUNDING FLOW FIELD

Imaging techniques were used to simultaneously monitor both the flame and the surrounding flow field to assess the nature of the interactions between the water mist drops and the flame. The imaging configuration is shown in Figure 2. To image the flame and flow field simultaneously, it was necessary to use two separate cameras.

The flow field camera is a CCD camera integrated into a computer-controlled particle image velocimetry (PIV) system. Two frequency-doubled pulsed Nd:YAG lasers (532-nm output) were used to illuminate the area of interest. A combination of spherical and cylindrical lenses transformed the laser beam into a sheet of laser light to illuminate the sample volume in the flow field. Images were acquired using the scattering of the 532-nm laser light from water drops in the viewing area. The two laser pulses with known time difference illuminated the sample volume and two separate images of the flow field were acquired by the CCD camera. The velocity field was then determined by correlating the two images to calculate the distance each drop traveled during the time lapse.

Figure 2. Experimental configuration for flame and flow field imaging experiments.

The quality and utility of PIV images depend on many factors, including the size of the seed particles and the density of these particles in the flow field. In the current study, these parameters were not optimized to enhance the image quality. Rather, images were obtained and utilized for experimental flame configurations where the size and concentration of drops were dictated by realistic suppression scenarios.

The flame-imaging camera is an online video camera (black-and-white, 30 frames per second). A computer-controlled frame-grabber was used to acquire instantaneous snapshots coincident with the first of the two laser pulses. To improve the image quality and contrast, an OH bandpass filter was placed in front of the camera lens. A TTL trigger from the PIV system was used in conjunction with a digital delay/pulse generator to ensure that the flame-imaging camera and the PIV camera acquired simultaneous images.

Images were obtained for propane flames. The propane flow rate was 0.31 SLPM, which equates to an average velocity at the cup outlet of 1 cm/s. Water mist suppression behavior was investigated for three different oxidizer stream flow conditions corresponding to different levels of suppression. Relevant flow conditions are listed in Table 1. The total flow of 38 SLPM corresponds to an average velocity of 11 cm/s surrounding the cup and a velocity ratio of airflow to fuel of 11 for all three flow conditions. Flow rates were chosen to be consistent with documented gaseous fuel cup burner studies (i.e., ~ 40-SLPM airflow and 10:1 air-to-fuel velocity ratio) [4-6,8]. The oxidizer streams for flames A, B, and C all had the same water loading.

Table 1. Flow conditions for flame and flow field imaging studies.

Flame	Airflow rate (SLPM)	Additional N_2 flow rate (SLPM)	N_2 mass fraction (%)
A	38	0	0
B	35	3	7
C	32.5	5.5	13

RESULTS

Cup burner extinction results are given in Table 2. The propane flames were extinguished with 29 % nitrogen by volume (molar basis), which equates to 28 % by mass. For the same flame and flow conditions, an extinction concentration of 14 % by mass was measured for the water mist. The sensible enthalpy contributions of nitrogen and water mist based on the experimental values are shown in Table 2.

Table 2. Extinction concentrations and sensible enthalpy calculations for nitrogen and water mist suppressed propane cup burner flames.

Agent	Extinction concentration (by mass)	Sensible enthalpy 300 K → 1600 K (kJ/g)	Sensible enthalpy added per mole of O_2 (kJ)
N_2	28 %	1.5	87
H_2O	14 %	5.2 (*liquid*) 2.9 (*vapor*)	124 (*liquid*) 71 (*vapor*)

Sensible enthalpies are calculated based on two assumptions—the species are initially at room temperature (300 K) and the flame temperature is reduced to 1600 K at extinction [17]. Calculations are shown for liquid water (includes vaporization enthalpy and vapor sensible enthalpy) and vapor (vapor sensible enthalpy only). Sensible enthalpy calculations for all cases include the contribution of water vapor in the humidified airflow. The air (or air-nitrogen mixture) temperature was 23°C with a relative humidity of 65 %, which corresponds to 11 grams of water vapor per *kilogram* of air.

Representative images from each of the three flame conditions listed in Table 1 are shown in Figure 3. On the left are visual images acquired by the flame-imaging camera showing the flame front and mist scattering of the laser light sheet, with the dashed boxes in the center of each image showing the approximate field of view for the PIV camera. The field of view for the flame-imaging camera is 4.3 cm x 3.2 cm while the field of view for the PIV camera is 2.25 cm x 1.8 cm. The viewing area of the flame-imaging camera is 3.4 times larger than that of the PIV camera. As the two cameras are positioned on opposite sides of the reactor, the visual images have been horizontally inverted to create the same perspective as for the PIV camera. Also, negative images are shown to enhance image contrast; the luminous flame front appears as a dark line and the cup is visible as a dark region below the flame. No laser light scattering is observed in the light gray region to the right of the flame. This region is devoid of liquid drops. Drops in the flow field are indicated by the darker gray region farther to the right.

The velocity vector fields corresponding to each flame condition are shown on the right in Figure 3. The vector fields were obtained using the PIV software, which correlates two drop-scattering images. The PIV images are oriented such that the outer edge of the cup in each image is aligned to assist in determining the proximity of the drops to the cup for the different flame conditions. In the upper left corner of each PIV image is the vector scale, which is 1 m/s for all three images. The flow fields have a maximum velocity of 20 cm/s. This is a reasonable value since an *average* velocity of 11 cm/s assuming plug flow is calculated based on the total oxidizer flow.

Since all three flames shown in Figure 3 have the same total oxidizer flow rate (38 SLPM) and the water mist production efficiency was the same with the water reservoir at an approximately constant temperature, all three conditions had essentially the same water loading. Using the ODM technique described above, the water concentration was determined to be 4 % on a mass basis. The N_2 mass fractions were 0 %, 7 %, and 13 % for flames A, B, and C, respectively.

DISCUSSION

In order to interpret the significance of the measured water mist extinction concentration, it is necessary to first examine the extinction concentration measured for nitrogen. The value reported in this study is 28 % by mass (29 % molar). This amount of N_2 and the water vapor in the humidified oxidizer stream increases the oxidizer stream sensible enthalpy by 87 kJ per mole of O_2. This increase in sensible enthalpy equates to a *dry* (i.e., no humidity) nitrogen mass fraction of 30 % (30 % molar).
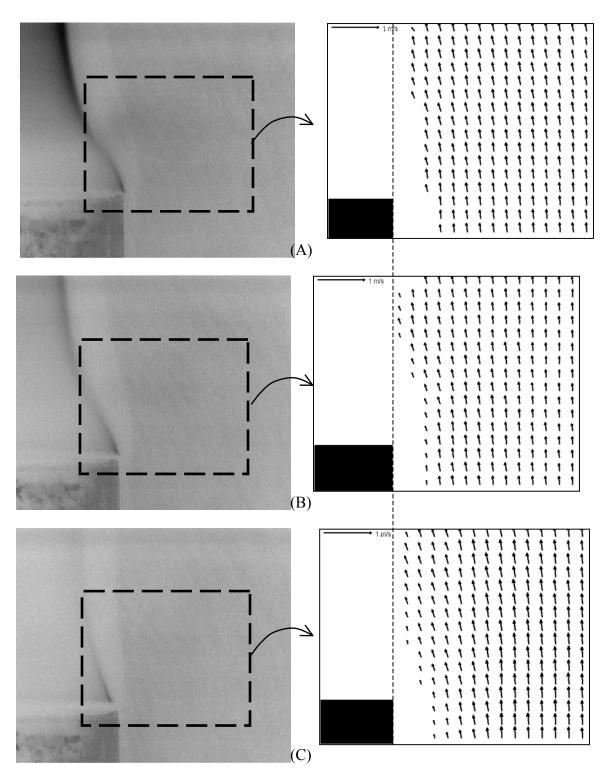
(A)

(B)

(C)

Figure 3. Visual images (left) and PIV vector fields (right) for each of the three propane flame conditions. The location of the edge of the cup is indicated in the lower left by the black rectangle. The vector scale (1 m/s) is shown in the upper left of each PIV image.

Sheinson et al. determined that 30 % nitrogen on a molar basis is required to extinguish an *n-heptane* cup burner flame [7,9]. Hamins et al. report that extinction concentrations for inert agents such as nitrogen are very similar between n-heptane and propane flames [8]. Cup burner studies for n-heptane and propane report molar extinction concentrations of 31 % to 33 % for dry nitrogen [8,12]. The extinction concentration measured in the present study (30 % molar for dry nitrogen) is consistent with the documented values.

Assuming that water mist acts as a thermal agent in the same manner as inert nitrogen gas, the sensible enthalpy increase of 87 kJ per mole of O_2 can be used to back out water mass fraction requirements to achieve flame extinction. Subtracting the contribution of water vapor in the humidified airflow, a mist-only mass fraction of 10 % would be required for liquid water and a mass fraction of 17 % would be required for water vapor. Since the measured extinction concentration is 14 %, water mist in this cup burner flame configuration is considered to have a suppression effectiveness that is approximately halfway between that of liquid water and water vapor. The measured water extinction mass concentration of 14 % can be carried forward to calculate sensible enthalpy increases per mole of O_2 of 124 kJ and 71 kJ for liquid water and water vapor, respectively.

For the full suppression potential of a liquid water drop to be realized, the drop must be vaporized in such a way that the cooling effect of this evaporation is experienced fully by the flame. The drop must be in sufficiently close proximity to the flame and spend sufficient time there, and the resulting water vapor and cooler air must thermally interact with the flame. If a drop that is near and moving toward a flame is so large that the evaporation time is greater than the residence time, it will survive the flame and the heat abstracted from the flame will be less because of partial evaporation. Likewise, if a drop is so small that it vaporizes far away from the flame and exchanges heat with the surrounding "bath" of water mist, less heat is abstracted from the flame. Based on the thermodynamic quantities and measured extinction concentrations, and assuming that the drops completely evaporate before entering the flame (valid based on the imaging data), only 31 % of the enthalpy of vaporization for this water mist is utilized in suppressing the flame.

The imaging results provide insight into the observed suppression effectiveness of the water mist. Visual images on the left in Figure 3 show three zones—the flame, the water mist, and the space between them that is devoid of water drops. For all three flame conditions, there is a region around the flame where there are no water drops and only air and water vapor exist. Although a quantitative comparison is difficult, it appears that the separation distance between the flame and the water drops shrinks as the images progress from the least suppressed flame (A) to the most suppressed flame (C). This is expected since the flame temperature decreases with the addition of a thermal suppressant (nitrogen).

The visual images suggest that the edge of the water mist zone follows an airflow streamline. The drop velocity vectors suggest that drops are not entrained into the flame. Their motion is primarily vertical. The drops are likely too large (8 μm) to exactly follow

the airflow. Water vapor resulting from drop vaporization near the flame would be expected to closely follow the airflow, although the flow field of the air was not measured. Future experiments will involve the use of PIV to image the airflow using smaller seed particles (0.3 μm) to determine the airflow behavior in this region.

The fact that the drop trajectories are essentially vertical throughout the flame region may help explain the observed suppression effectiveness of the water mist. It is clear that under the cup burner flow conditions liquid water drops do not make it to the flame front. This alone does not prevent the mist from achieving the maximum suppression potential of liquid water. The PIV data show that water drops are flowing past the flame zone with significant vertical velocity, which would reduce the residence time of the water mist and prevent the maximum amount of flame energy abstraction from taking place. This is an effect that results from the cup burner configuration (i.e., flame and flow geometry). It may not be as large a factor in other flame configurations such as the Bunsen flame in the corral [15]. Less directed vertical flow of the drops may be at least part of the reason why the water mist effectiveness reported at the 2004 HOTWC (corral study) is apparently higher than that reported in the current study. In the corral study, only 7.5 % water mass concentration was required for flame extinction as compared to the 14 % reported for the cup burner in the current study. Part of this difference is likely due to the type and size of the burners.

Although there is insufficient data from the corral study to make a definitive quantitative comparison, the effect of different burners was investigated. Experiments were conducted in the cup burner apparatus with nearly the same fuel volumetric flow rate, but with a 1.2-cm (ID) copper tube in place of the quartz cup. This tube is similar to the Bunsen burner used in the corral study. At a total flow (air plus nitrogen) of 20 SLPM, a nitrogen mass fraction of only 24 % was required for flame extinction with the copper tube compared to 28 % required for the cup. Although the total oxidizer flow rates are different in the two studies, the extinction value is not expected to be appreciably higher for the "tube burner" with a flow rate of 35 SLPM since the extinction concentration was essentially constant from 16 SLPM to 20 SLPM. It appears to be easier to achieve extinction for the tube burner flames than for the cup burner flames (at equal fuel flow rates).

Future work will include similar extinction measurements and imaging studies for both the cup burner and the corral flame configurations. The possibility of measuring the air flow field with tracer seed particles to examine entrainment into the flame will be investigated.

SUMMARY

The concentration of sub 10 μm water drops required to extinguish propane cup burner flames reported in this study (14 % by mass) is midway between the suppression potential of liquid water (10 %) and water vapor (17 %) based on the measured extinction concentration for nitrogen. Imaging studies show that in the cup burner flow field there is a drop-free zone between the flame and the bulk mist. Flame imaging and PIV studies show that drops essentially flow past the flame. The suppression effectiveness of this

water mist is less than what might be theoretically achieved but much greater than would be expected for water vapor alone. We conclude that in a typical cup burner flow field, water drops vaporize in the higher temperature region near the flame at a location that allows only part of the evaporative cooling to lower the flame temperature. The remaining temperature lowering effect is exchanged with the bulk mist and the maximum water mist cooling potential does not reach the flame.

ACKNOWLEDGEMENTS

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