EXTINCTION OF COUNTERFLOW DIFFUSION FLAMES
WITH FINE-WATER DROPLETS

A.K. Lazzarini, R.H. Krauss, and H.K. Chelliah
University of Virginia

G.T. Linteris
National Institute of Standards and Technology

BACKGROUND

Basic investigations aimed at better understanding the fire suppression mechanism of water dates back to the 1950s[1], while more recent studies have focused on water mist systems [2-7]. Although there is a consensus in the literature on the fundamental fire suppression mechanism of water, no detailed quantitative information on the various physical, thermal, and chemical effects of water **mist** were available until recent modeling capabilities were developed.

The recent detailed modeling efforts were primarily carried out in two configurations, counter-flow [4,5] and co-flow [7]. The fonner flow configuration provides a convenient approach to understanding the interactions of fine-water droplets with flames, including tlame extinction conditions. For example, investigations by Lentati and Chelliah [4] have shown that dilution of the air stream (or displacement of oxygen) with saturated water vapor alone reduces the flame extinction condition (characterized here by the flow strain rate) of a methane-air nonpremixed tlame by about 12%. Experimental results presented here support such predictions. The further addition of water, in the form of fine droplets, causes significant thermal cooling of the tlame front because of the relatively large latent heat of vaporization of water. Addition of 3% of water by mass in the form of $20 \, \mu m$ monodisperse droplets (the optimum size for this flow configuration) was shown to reduce the extinction strain rate by an additional 55% [4]. By selectively excluding the source terms contributing to the gas-phase and the condensed phase conservation equations, the importance of thermal effects associated with water mist was clearly demonstrated [5]. The chemical (e.g., shifting of the water-gas equilibrium reaction and enhanced three-body recombination effects) and other physical (e.g., modification of transport coefficients) effects associated with fine-water droplets were shown to have a minor effect.

NONMONOTONIC EFFECT OF DROPLET SIZE

For a given mass fraction of water in condensed phase, predictions with monodisperse droplets have shown an increase in the flame extinction strain rate when droplet sizes are either below or above $20 \, \mu m$, indicating a nonmonotonic effect on flame suppression as a function of droplet size [4]. This optimal size may not be general and can depend on the flow field around the fire. Another significant finding in these initial counterflow numerical studies was that. on a mass basis, $20 \, \mu m$ water droplets are equally as effective in suppressing counterflow flames as the chemical suppressant Halon 1301 [5]. Experimental results reported here are part of an effort to verify these modeling results and assist development of super effective condensed-phase fire suppressants to replace Halon 1301.

EXPERIMENTAL METHOD

COUNTERFLOW BURNER

In experiments, a steady, planar, nonpreinixed flame established within the mixing layer of a counterflow of methane and air was employed. Figure 1 shows a schematic of the experimental

setup of the counterflow burner, in which the fuel and air nozzles shown are made from Pyrex glass. The typical separation distance between the two nozzles was between **10-12** mm.

For experiments involving water vapor and droplets, the metered dry air was saturated before it entered the vertical Pyrex air tube by passing it through a porous tube submerged in a water flask. Heating the water flask to about 1-5°C above the room temperature was found to facilitate saturation of air to >99% relative humidity. There was no detectable increase in air temperature above the room temperature because the long connecting tube allowed sufficient time to attain thermal equilibrium with the surroundings. The droplet atomizer was located at the bottom of the vertical Pyrex air nozzle such that the droplets were uniformly dispersed at the nozzle exit. This uniformity of droplet size distribution was characterized using the PDPA. The glass tube proved to be very **useful** in observing the droplet dispersion and condensation on the inner walls.
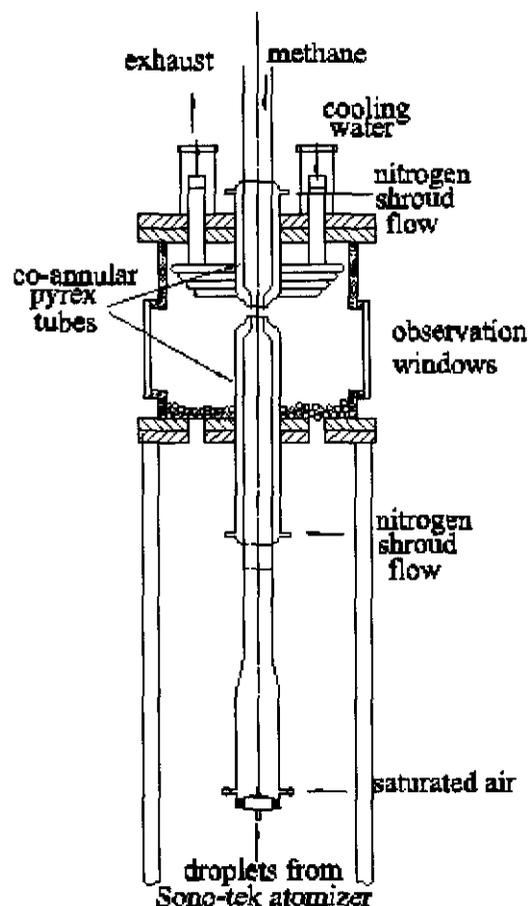

Figure 1. Counterflow burner configuration with the
Sono-Tek water droplet atmozier.

DROPLET GENERATION

Two types of droplet generators were used: (a) piezoelectrically excited fluid jet atomization system acquired from Fluid Jet Associates [8] and (**b**) ultrasonic fluid surface breakup system acquired from Sono-Tek. The first atomizer is capable of generating truly monodispersed droplets. By varying the plate orifice diameter, the size of monodisperse droplets can be varied,

hut because of the very narrow orifices used (e.g., 10 μm hole generating –20 μm droplets), it was susceptible to clogging and erosion problems. The second atomizer from Sono-Tek was found to be relatively simple to implement and was free of the operational problems of the Fluid Jet atomizer, but the droplets generated had a relatively wide size distribution. The median droplet size of the ultrasonic atomizer could be varied by selecting a different nozzle tip length and resonance frequency. **All** of the experimental tlame extinction data presented in this paper were obtained using this Sono-Tek atomizer.

The Sono-Tek droplet generation system consists of an ultrasonic nozzle and the Sono-Tek Broadband Ultrasonic Generator. A syringe pump (Instech Model 2000), fitted with a plastic Becton Dickinson 10cc syringe was used to feed water to the atomizer. For a fixed water mass flow rate, the air and fuel flows were increased until the flame extinguished. The flame was found to be very stable until the extinction point.

The method of calibrating the droplet mass flow rate is extremely important for data validation. The calibration was performed using a container 75 mm in diameter and 35 mm in height with a plastic lid that sealed tightly onto the end of the air nozzle. The damp cotton inside the container provided a tortuous path to trap the droplets and ensured that the air left the container still saturated (if the relative humidity of the air decreased as it passed through the container, the measured droplet flow rate would appear to vary in time and result in a water droplet mass flow rate higher than the actual value). The air escaped the container through holes that were punched at the top of the container. Before and after each flame extinction experiment, the air-side burner was lowered to where the calibration cup could be attached. Calibration was performed in the same manner for both pure water and water-NaOH cases.

DROPLET SIZE DISTRIBUTION

The droplet size distribution in the vicinity of the Sono-Tek atomizer nozzle has been characterized by the manufacturer and is known to follow a log-normal distribution, with a median diameter of about 20 μm and a Sauter mean diameter (SMD) of about 30 μm. Based on the estimated settling velocities of different drop sizes, for typical flow velocities in the air tube, it was found that not all the drops were convected out of the air nozzle. For example, for air flow rate corresponding to a flow strain rate of about 285 s^{-1}, the estimated maximum drop size that could be carried in the air stream was about 75 μm, while for a strain rate of 160 s^{-1} the corresponding maximum drop size was about 55 μm. These estimates and the quality of the air-droplet flow leaving the air nozzle were verified using the PDPA. Figure 2a shows the measured drop size distribution for a high strain rate of 160 s^{-1}; Figure 2b shows a similar plot for a lower strain rate of 285 s^{-1}. The shift in maximum size of droplets is consistent with estimated values, while the general shape of the distribution still retains the lognormal shape.
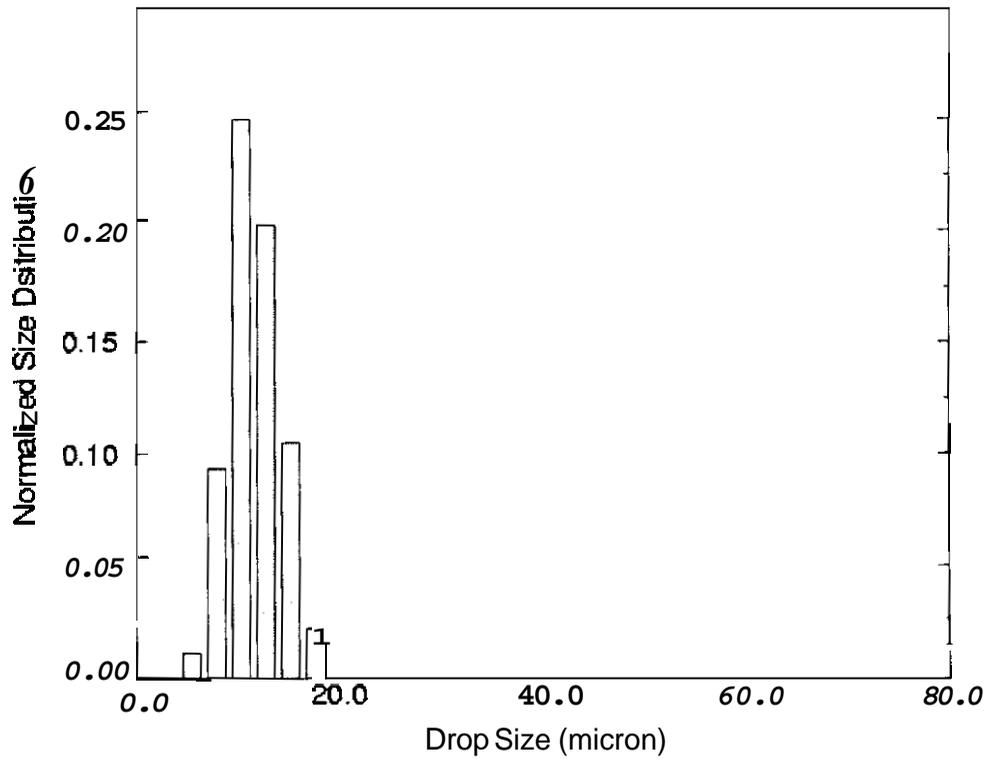
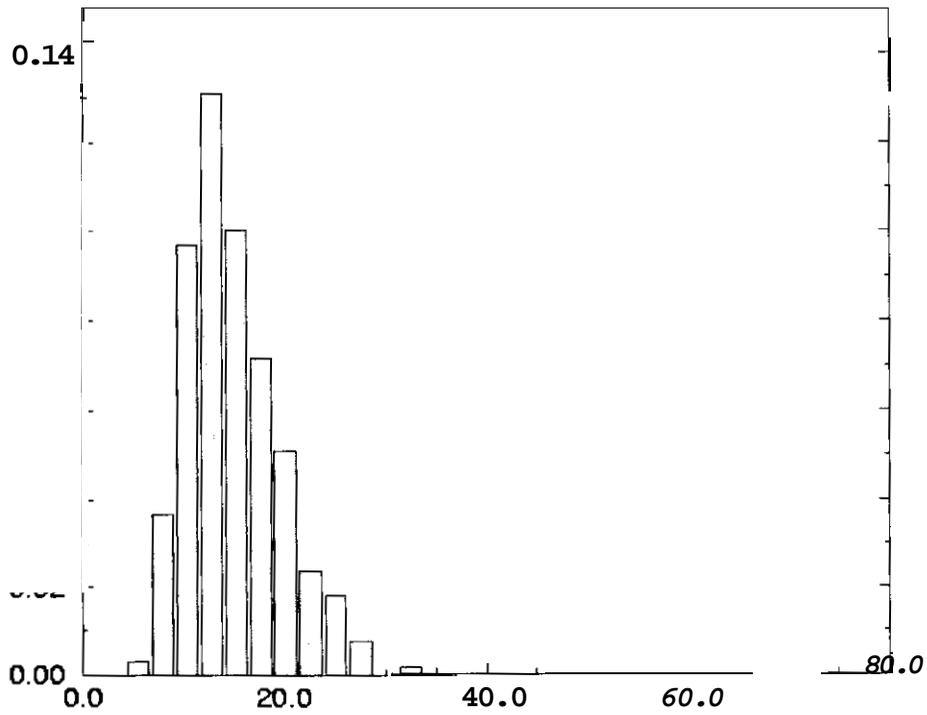Figure 2a. The normalized water droplet distribution at the nozzle exit for strain rate of $160\,\text{s}^{-1}$

Figure 2b. The normalized water droplet distribution at the nozzle exit for strain rate of $285\,\text{s}^{-1}$.

EXPERIMENTAL EXTINCTION RESULTS

With the counterflow burner described above, flame extinction experiments were conducted by increasing the air and methane nozzle exit velocities such that the momentum of the two streams was balanced, i.e., $(\rho v^2)_{air} = (\rho v^2)CH_4$ where p is the density and v is the axial velocity. Knowing the nozzle separation distance, L, the flow strain rate is defined by the global formula $a = 4|v_{air}|/L$ [9]. For nonpremixed methane-air flames, the measured global flame extinction strain rate of $470 \, s^{-1}$ was obtained, while the measured local flow velocity using a laser Doppler velocimetry (LDV) system yielded a local flow strain rate of about $390 \, s^{-1}$. Both of these numbers were highly reproducible and consistent with previous experiments and modeling efforts [10]. The experimental **flame** extinction results presented in this paper are all based on the global strain rate formula, unless otherwise mentioned.

WATER VAPOR

The presence of condensed-phase water implies that the air stream *is* saturated with water vapor. At atmospheric pressure and room temperature of 300 **K,** the saturated water vapor mole fraction in air is 3.51% (or mass fraction Y_{vap}=0.0224). This saturated water vapor can have a significant effect on the flame extinction condition, mainly through the displacement of oxygen. Previously, detailed modeling efforts have indicated that the predicted local flame extinction strain rate can be reduced from $420 \, s^{-1}$ for a methane-air flame to $365 \, s^{-1}$ for methane and air saturated with water vapor (a reduction in extinction strain of 12%) [4]. Present experiments with saturated water vapor in the air stream have yielded a global extinction strain rate of $405 \, s^{-1}$ a reduction of 13% from $470 \, s^{-1}$), indicating an excellent agreement with the predictions.

PURE WATER DROPLETS

The ultrasonic atomizer described above with a median drop diameter of about $20 \, \mu m$ was employed to investigate interactions between water droplets and the nonpremixed laminar methane-air flame. With increasing droplet number density (or mass fraction of water droplets in the air stream), it is expected that the flame extinction will occur more easily, resulting in a lower extinction strain rate. Figure **3** indicates such a plot where the mass fraction of water in condensed phase (Y_o) is plotted as a function of the flame extinction strain rate. Note that the zero water droplet mass fraction corresponds to the case where the air stream is saturated with water vapor (i.e., Y_{vap}=0.024). In this figure, the symbols refer to experiments with the extinction strain rate determined from the global formula. Also shown in Figure 3 is the predicted variation of water droplet mass fraction as a function of global extinction strain rate, assuming $20 \, \mu m$ monodisperse droplets. Irrespective of the assumption of monodisperse drop size distribution in simulations, the predicted trend is seen to be in close agreement with the experiments.

Although the experiments and predictions agree well for pure water vapor, with increasing droplet mass loading, the differences become rather large. In predictions, relaxation of the monodisperse size distribution approximation based on the measured distributions shown in Figure 2 is not expected to rectify this difference because $20 \, \mu m$ monodisperse droplets have been predicted to be the most effective. **As** discussed later in the numerical section, any broadening of the size distribution about $20 \, \mu m$ leads **to** a higher mass fraction of water in the condensed phase for the same flame extinction condition. Thus, differences seen in Figure 3 between experiments and
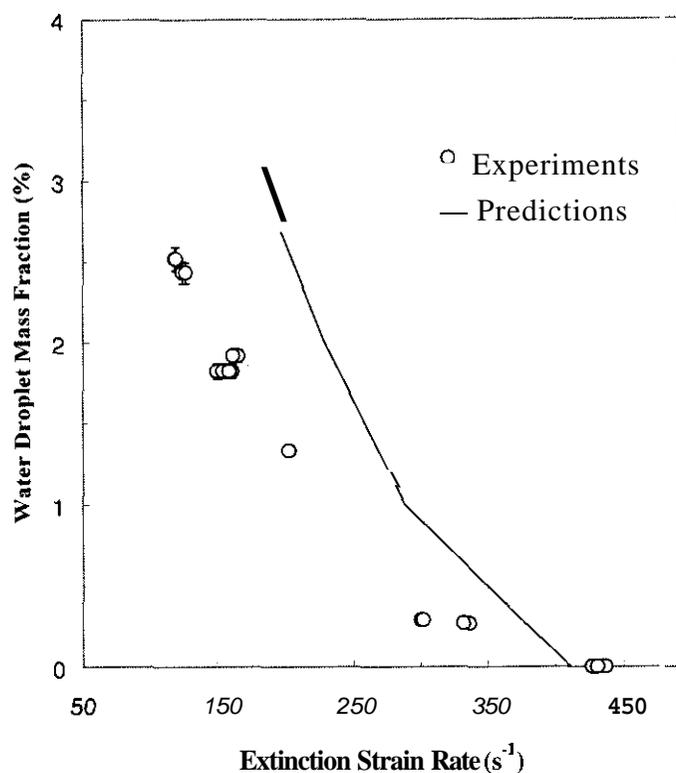
Figure *3.* Condensed phase water droplet mass fraction as a function extinction strain rate.

modeling are likely due to other causes. In experiments, calibration of the water droplet mass flow rate through gravimetric analysis can introduce errors: therefore, considerable care was taken to address uncertainties associated with the approach adopted.

WATER WITH NaOH

The primary mechanism of flame extinction by fine-water droplets is through the thermal cooling of the flame front leading to slower chemical reaction rates. For example, in a counterflow field of methane and air, the 20 μm droplets were shown to be most effective because most of the droplet mass is predicted to evaporate near the oxygen consumption or radical species production region [11]. This thermal effect of water droplets can be considerably enhanced by including a chemically active fire-suppressing compound in water. NaOH was selected as it is known to be the primary compound in the catalytic radical recombination path of sodium bicarbonate fire suppression [12]. Since the solubility of NaOH in cold water is about 30% of the total mass [13], a significant amount of NaOH can be released at the flame front, provided that the fine droplets consisting of water-NaOH are completely vaporized. Here, the same Sono-Tek atomizer with median drop size of 20 μm was used to deliver various solutions of water-NaOH in order to investigate their effect on suppressing counterflow methane-air flames.

Figure 4 shows a plot comparing the experimentally measured water-NaOH mass fraction as a function of the flame extinction strain rate. **As** before, the air flowing into the nozzle tube was saturated with pure water vapor. Because the NaOH vapor pressure is very small (< 1 mmHg at room temperature [13]), air saturated with pure water vapor is not expected to affect the evaporation of NaOH. The measured results indicate that with increasing NaOH mass fraction in water, the amount of water-NaOH mass fraction needed for flame extinction decreased significantly,

i.e., almost a factor 5 for 18% NaOH by mass in water at the lowest strain rate considered. The concept of combining thermal and chemical effects could lead to a significant increase in fire suppression ability (Figure 4).
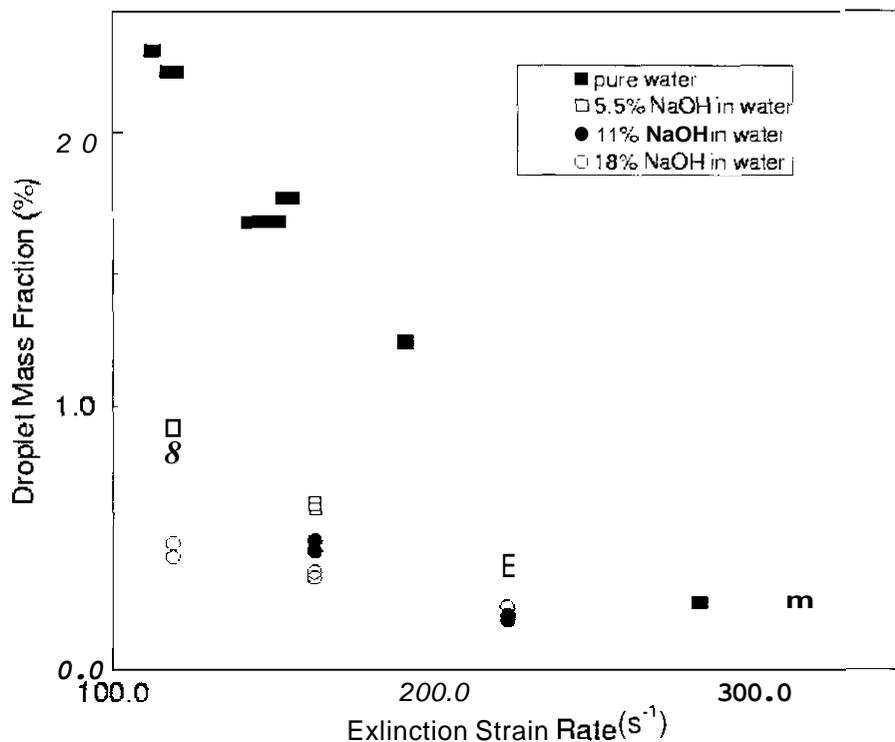

Figure 4. Comparison of the condensed phase droplet mass fraction as a function of extinction strain rate, for different mass loading of NaOH in water.

CONCLUSIONS

The main purpose of the present work was to provide experimental data to validate the recent numerical predictions on the effectiveness of fine-water droplets in extinguishing counterflow nonpremixed flames. On a mass basis, the predicted ability of fine water mist to suppress gaseous fires with similar or better effectiveness than Halon 1301 was verified. Although the original goal was to obtain results using monodisperse size fine droplets as assumed in previous theoretical investigations, this task became raiher challenging for many practical reasons. Instead, an ultrasonic water atomizer generating log-normal distribution of drop sizes, with median drop size of about 20 μm was employed. The actual droplet size distribution was expected to deviate from the prescribed distribution at the atomizer depending on the convective velocity in the air tube in the counterflow burner; this variation was characterized using a PDPA.

When the air stream was saturated with water vapor only, it was shown that the counterflow nonpremixcd flame extinction condition measurements agreed extremely well with the corresponding numerical predictions. With the addition of condensed phase water droplets. the trends agreed well; however, considerable differences do exist between the experiments and modeling. The observed differences have been shown to be mildly affected by the polydispersivity of the atomizer employed. This leads to the conclusion that other submodels in the numerical model, including radiative heat losses. need to be evaluated.

Addition of a chemically active fire-suppressing compound to water, namely NaOH, was shown to complement the thermal fire suppression mechanism of water. At the low end of the strain rates investigated ($-125\ s^{-1}$), 18% by mass of NaOH in the solution was shown to reduce the flame extinction strain rate by almost a factor of five. Although inclusion of NaOH may not be desired in many practical applications because of its corrosive effects, the concept of combining the thermal and chemical effects of these condensed phase agents may lead to the development of superior fire suppressants.

ACKNOWLEDGMENT

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