tions on Flow Through a Petal Nozzle," *Journal of the Institution of Engineers* (India), Vol. 70, March 1990, pp. 1–4.

[10]Anil, K. N., and Damodaran, K. A., "Mixing Characteristics of a Petal Nozzle with a Secondary Stream," *Proceedings of the 17th National Conference on Fluid Mechanics and Fluid Power*, Regional Engineering College, Warangal, India, 1990.

[11]Anil, K. N., and Damodaran, K. A., "Experimental Studies on Mixing Using a Petal Nozzle," *Journal of Propulsion and Power*, Vol. 10, No. 3, 1994, pp. 432–434.

[12]Anil, K. N., and Damodaran, K. A., "Isothermal Mixing of Two Axisymmetric Airstreams," *Proceedings of the First National Conference on Airbreathing Engines and Aerospace Propulsion*, National Aeronautical Lab., Bangalore, India, 1992, pp. 436–445.

[13]Greathouse, W. K., and Hollister, D. P., "Air-Flow and Thrust Characteristics of Several Cylindrical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0," NACA Lewis Flight Propulsion Lab., NACA RM E521L24, Cleveland, OH, March 1953.

[14]Joe, D., Jr., "Improved Methods of Characterizing Ejector Pumping Performance," *Journal of Propulsion and Power*, Vol. 7, No. 3, 1991, pp. 412–419.

Combustion of Microemulsion Sprays

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Nomenclature

D = drop diameter
L = flame length
S = mass concentration of surfactant
T = temperature
W = mass concentration of water
x = axial distance from the nozzle

Subscript
32 = Sauter mean

Introduction

IN the last two decades there has been considerable interest in using water-oil emulsions in spray combustors. Several studies on the combustion of drops and sprays of emulsions[1-3] in laboratory furnaces and in practical devices[4,5] have appeared in literature. A principal mechanism proposed to explain the effects of emulsification is the so-called microexplosion of drops attributed to the early vaporization of the internal-phase water leading to shattering of the parent oil drop. Some studies[2,3] suggest that microexplosion may not occur or may not be strong enough to explain the effects observed during spray combustion, particularly of the distillate oil. It has been shown that the internal-phase drop size is a critical parameter that could determine whether or not microexplosion occurs.[2] Most of these studies have been conducted with *macroemulsions* in which the internal-phase drop size is usually on the order of micrometers. On the other hand, the internal-phase droplet size in the so-called *microemulsions* is in the submicron range (100–600 Å) and microemulsions appear to be clear solutions,[6] and hence, the role of microexplosion is ques-

tionable in microemulsion flames. The studies by Naegeli and Moses[7] and Adiga[8] have shown that smoke emissions from a gas turbine combustor and a steam boiler were reduced when microemulsions were substituted for pure distillate fuels. However, the study by Naegeli and Moses showed that CO and NO emissions increased, but Adiga's study showed they decreased when microemulsions were used in place of pure fuels. The present study was conducted to compare the burning characteristics of air-assist atomized sprays of Jet-A fuel and its microemulsion with water (5% by mass) in a laboratory combustor where the conditions could be controlled much better than in practical combustors.

Experimental Apparatus and Procedure

An air-assist atomizer nozzle producing a solid spray with a cone angle of 20 deg with no swirl was used in this study. Since the density of emulsion varied with water content, the fuel rotameter was calibrated for each emulsion. The burner was mounted horizontally at the center of the exit section of an open-jet wind tunnel. The flames were confined mostly to the middle two-third section of the wind tunnel except for the tip regions of the flame. A steady airstream with a turbulence intensity of less than 5% was maintained in the test section.

The 35-mm color photographs exposed for 1 s were used to measure flame length. The drop size distribution in the near-nozzle regions of nonburning sprays was measured with a phase Doppler particle analyzer. Total thermal radiation emitted from the flame was measured using a water-cooled 150-deg view-angle thermopile radiometer with an absorptivity of 0.96. Temperature measurements were taken using a chromel-alumel (type K) thermocouple (bead diameter 0.3 mm) and were corrected to account for conduction and radiation losses from the bead following Fristrom and Westenberg.[9] An emissivity of 0.9 for the bead was used in the calculations.

The volumetric concentrations of O_2 (%), NO (ppm), and CO (%) were measured along the radial direction at a distance of two-thirds flame length from the atomizer. Gas samples were drawn from the flames through a water-cooled stainless steel tube (orifice diameter = 1 mm), were treated to remove particles and moisture, and were analyzed with chemiluminescent, nondispersive-infrared, and polarographic analyzers for NO, CO, and O_2 concentrations, respectively. Emulsions were prepared by adding the desired amount of surfactant (sodium dioctyle sulfosuccinate) to the mixture of water and Jet-A fuel and stirring the mixture until a clear solution was produced. The measurement uncertainties are quoted at 95% confidence level.

Results and Discussion

Microemulsions were clear transparent liquids when they were freshly prepared. When examined after storing them for 2 months at room temperature, the microemulsions with 5 and 10% (mass) of water still appeared as transparent liquids, whereas the microemulsions with 15 and 20% (mass) of water exhibited a slight milky appearance. This observation, which agrees with the study of Shah and Hamlin[6] suggests that a higher water content lowers the stability of microemulsions. In this study, flame structure was examined only for the microemulsion with a water content W of 5% and $S/W = 0.7$, where S and W are surfactant and water contents in the emulsion. The average values of the Sauter mean diameter D_{32} on a cross section located 38 mm from the nozzle in the nonburning Jet-A fuel and microemulsion sprays were 87 ± 13 and 90 ± 12 μm, respectively, and were not markedly different.

The pure Jet-A fuel flame was yellow and luminous over most of its length except over a small portion near the burner where some blue color was observed at the flame edges. No marked difference in the flame color was noticed between pure fuel and emulsion flames, although the luminosity of the

flame, particularly in the far-nozzle region, decreased when the microemulsion was used. The length and maximum width of the pure fuel flame were 61 ± 2 and 9.5 ± 0.5 cm, compared to 67 ± 2 and 11.8 ± 0.5 cm of the emulsion flame. Since the flowfields in both cases were essentially the same except for slight differences due to the initial momentum of the sprays, it is reasonable to assume the differences in flame dimensions are caused by the physico-chemical effects.

Figure 1 compares the temperature profiles in the flames of Jet-A fuel and microemulsion sprays. The flow rate of microemulsion was adjusted to keep the energy input rate the same as that in the pure fuel flame. It is noticed that in the near-nozzle region the temperature on the axis of the emulsion flame is lower than in the pure fuel flame and the situation is reversed in the downstream region. The lower temperature in the near-nozzle region of the emulsion flame may be attributed to the heat sink effect of water caused by the abstraction of sensible and latent heat of the additional water. The difference in the far-nozzle region temperature is caused by the different rates of radiation loss from the flame.

The radial temperature profiles in the far-nozzle region show a single peak on the flame axis in both pure fuel and microemulsion flames. The absence of a double hump structure suggests that the volumetrically distributed soot combustion, and not the homogeneous gas-phase interface combustion, is dominant in the far-nozzle region of both flames. Furthermore, the similarity of radial temperature profiles suggests that no dramatic shift in the dominant heat release mechanism occurs when microemulsion is used in place of pure fuel. The peak temperature is higher in the microemulsion flame which could be attributed to lower radiant losses in microemulsion flames. The slight asymmetry of the radial profiles about the axis is due to buoyancy effects because the atomizer was oriented horizontally.

Figure 2 compares the radial concentration profiles of O_2, CO, and NO in the far-nozzle region of pure fuel and microemulsion flames. The concentration of O_2 in the far-nozzle region is determined by the balance between the rate of entrainment of surrounding air and the rate of O_2 consumption by soot oxidation. The mutually counteracting effects of higher O_2 consumption rate and increased entrainment rate due to higher initial momentum flux of the emulsion probably account for the insignificant difference in the minimum concentration of O_2 between the two flames.
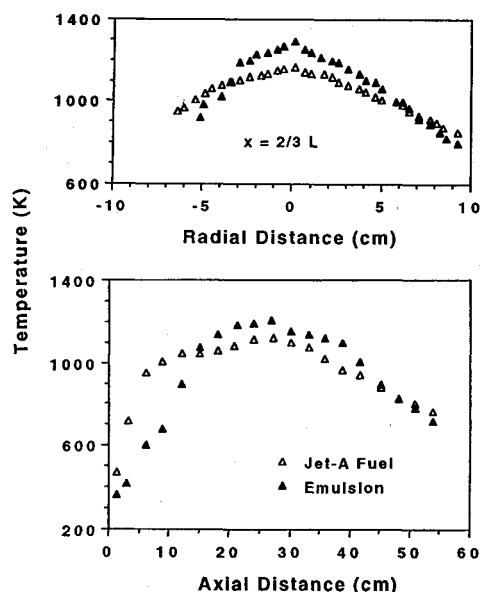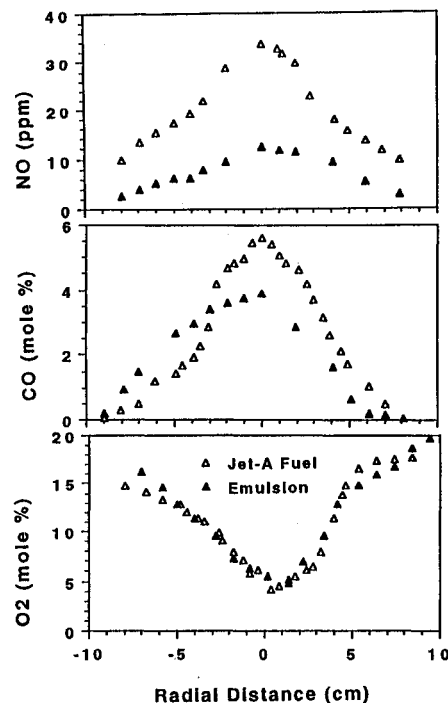

Fig. 2 Radial concentration profiles of O_2, CO, and NO in the burning Jet-A fuel and microemulsion sprays ($x = 2/3$ L; uncertainties: $O_2 = \pm 0.2\%$; CO $= \pm 0.3\%$; NO $= \pm 3$ ppm).

The radial concentration profiles of CO show trends inverse to the O_2 concentration profiles. The peak concentration of CO depends upon the amount of soot convected into the far-nozzle region and the local availability of O_2. The lower value in the microemulsion flame compared to that in the pure fuel flame indicates that the rate of particulate burning is smaller in the former.

The peak concentration of NO is lower in the microemulsion flame, which agrees with Adiga's[8] observation in a steam boiler burning number 2 diesel fuel-water microemulsion, but it is in contradiction with the results of Naegeli and Moses[7] in a gas turbine combustor burning microemulsions of jet fuels with water. The concentration of NO is determined by the local temperature, O_2 availability, and the concentrations of other species which affect the formation or destruction rate of NO. Over most of the flame, the temperature is higher in the microemulsion flame. The O_2 concentrations in those regions are not substantially different between the two flames. Thus, one would expect NO concentrations to be higher in microemulsion flames. However, other factors such as higher concentration of OH (due to additional water) and sulfur (in the surfactant), which strongly compete for O atoms, could reduce NO in the emulsion flame. At present, it is not possible to separate the quantitative contributions of these factors. The surfactant in the study of Naegeli and Moses contained a substantial amount of nitrogen (about 4% mass), and therefore could have resulted in higher values of NO in emulsion flames.

With the temperature, composition, and velocity data,[10] the emission index of NO was estimated as 1.5 ± 0.2 and 0.6 ± 0.2 g of NO per kg of fuel for the pure fuel and emulsion flames. The value of emission index in the pure fuel flame agrees well with the NO emission index in a gas turbine combustor burning kerosene type fuel reported by Anderson et al.[11]

The maximum radiation flux incident upon a radiometer placed at a distance of about two flame lengths from the flame axis and viewing the entire flame was 600 ± 20 W/m^2 for microemulsion flame compared to 850 ± 20 W/m^2 for the pure fuel flame. That indicates a lower soot concentration in the emulsion flame because soot is a major contributor to

Fig. 1 Temperature profiles in Jet-A fuel and microemulsion ($W = 0.05$, $S/W = 0.7$) burning sprays (uncertainty in temperature $= \pm 15$ K).

radiation. This observation is in conformity with the results of Naegeli and Moses.[7]

The presence of water affects the combustion characteristics of fuels in burning sprays in several ways. First, the heat abstraction by water prolongs the ignition delay and reduces the vaporization rate. Also, the reduction in the near-nozzle region temperature decreases the rates of liquid and vapor phase pyrolysis of fuel. Consequently, the soot formation rate would be lowered.

Since microexplosion effect is expected to be weak, the observed reductions in radiation emission in the microemulsion spray flame in the present study and in Refs. 7 and 8 suggest that the thermal and chemical effects of water are more dominant than the mechanical effects of microexplosion.

The emissions of CO and NO decreased when the microemulsion was substituted for pure fuel in the present study and the study by Adiga.[8] However, the opposite was observed in the study by Naegeli and Moses.[7] The fuels in the present study and the study by Naegeli and Moses are jet fuels, whereas the fuel in Adiga's study was a diesel fuel. The similarity of the present results and Adiga's results suggest that the microemulsion effects are not highly sensitive to fuel volatility. The surfactant in the present study and Adiga's study was the same, but different from the surfactant used by Naegeli and Moses. The surfactant in the study of Naegeli and Moses contained organically bound nitrogen, and hence, the increase in NO emission in emulsion flames was attributed to it. The surfactant in the present study and Adiga's study did not contain nitrogen, but it did contain sulfur, which partly accounts for the reductions in NO and CO emissions. However, the concentration of SO_x, which was not measured in these studies, could have increased. Hence, the composition of surfactant seems to exert a large influence in the flames of microemulsions.

References

[1]Gollahalli, S. R., "An Experimental Study of the Combustion of Unsupported Drops of Residual Oil Emulsions," *Combustion Science and Technology*, Vol. 19, No. 6, 1979, pp. 245–250.

[2]Maronne, N. J., Kennedy, I. M., and Dryer, F. L., "Internal Phase Size Effects on Combustion of Emulsions," *Combustion Science and Technology*, Vol. 33, No. 6, 1983, pp. 299–307.

[3]Gollahalli, S. R., Rasmussen, M. L., and Moussavi, S. J., "Combustion of Drops and Sprays of No. 2 Diesel Oil and Its Emulsion with Water," *Eighteenth Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, PA, 1980, pp. 349–360.

[4]Cook, D. H., and Law, C. K., "A Preliminary Study on the Utilization of Water-in-Oil Emulsions in Diesel Engines," *Combustion Science and Technology*, Vol. 18, No. 6, 1978, pp. 217–221.

[5]Zhang, Z., and Gollahalli, S. R., "Combustion of Kerosene-Water Emulsions in a Gas Turbine Combustor," *International Journal of Turbo and Jet Engines*, Vol. 5, No. 1, 1988, pp. 39–49.

[6]Shah, D. O., and Hamlin, R. M., "Structure of Water-in-Oil Microemulsions: Electrical, Birefringence, and Nuclear Magnetic Resonance Studies," *Science*, Vol. 171, Feb. 1971, pp. 483–485.

[7]Naegeli, D. W., and Moses, C. A., "Fuel Microemulsions for Jet Engine Smoke Reduction," American Society of Mechanical Engineers, Paper 82-GT-33, New York, 1982.

[8]Adiga, K. C., "Vaporization and Combustion Behavior of Water-in-Oil Microemulsions of Petroleum Distillates," *Emerging Energy Technology Symposium*, edited by S. R. Gollahalli, Energy Technology Conf. and Exhibition, Vol. PD-41, Houston, TX, 1992, pp. 9–14.

[9]Fristrom, R. M., and Westenberg, A. A., *Flame Structure*, McGraw-Hill, New York, 1965, pp. 150–152.

[10]Gollahalli, S. R., and Puri, R., "Flame Structure and Pollutant Emission of a Burning Spray with Injection of Diluents," *Journal of Energy Resources Technology, Transactions of the American Society of Mechanical Engineers*, Vol. 114, No. 3, 1992, pp. 209–215.

[11]Anderson, R. W., Patil, P. B., Chin, J., Nicholls, J. A., Mirsky, W., and Lyons, V., "The Effect of Drop Size on Emissions from the Primary Zone of a Gas Turbine Type Combustor," *Sixteenth Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, PA, 1976, pp. 265–275.

Pulsed Jets in Supersonic Crossflow

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Introduction

SINCE the late 1960s much interest has been focused on the subject of jet penetration in a supersonic crossflow. Now, however, the push for feasible schemes of efficient and practical gaseous fuel injection is much greater because of projects such as the National Aerospace Plane, which involve hypersonic travel.[1] The high Mach numbers such a plane could attain require that certain difficulties be overcome. One of these difficulties is the poor penetration of a transversely injected fuel in a SCRAMJET combustor. Progress in this area of research has been disappointing. Injection has been limited to heights that could cause a large thermal loading on combustor walls if combustion did occur.[2] For this reason, it is important to develop injection schemes that can provide fuel penetration to the combustor core. Once this objective is reached, the injection method may be further modified to improve the mixing characteristics of the fuel jet. Fuel injection struts or very high-pressure injection could place fuel within the combustor core, but the large shock losses associated with these methods make them undesirable.[3] The momentum flux ratio ($R = \rho_j v_j^2 / \rho_a v_a^2$) has been shown to correlate very well with injection height for the steady jet, however, attempting to increase the injectant penetration depth by increasing R through higher injection pressure is not practical since the effect of this overpressure produces a highly underexpanded jet. Underexpanded jets display a shock feature termed a "Mach disk" (normal shock), which was observed by Dowdy and Newton[4] and later discussed by Schetz and Billig[2] in their steady jet studies. The overall effect of the Mach disk is to reduce the dynamic pressure of the gaseous injectant to a fraction of its original value. This is detrimental since the dynamic pressure represents the energy available to produce turbulence and mixing in a supersonic flow.

A practical approach to this area of study is to investigate methods for increasing jet penetration without increasing R, thus strengthening the Mach disk. In this regard, unsteady injectants show promise. Previous studies of unsteady jets tend to focus on mixing characteristics. One of the first investigations of unsteady jet phenomena was conducted by Viets.[5] He developed a self-exciting, oscillating jet and injected helium into the injector flow to observe the mixing of the injectant with quiescent, ambient air. Viets found that the half-width spreading rate of the injectant exceeded that of a slot nozzle by a factor of 3. Similar studies of oscillating-type injection[6-10] have confirmed that mixing is greatly enhanced by the use of an unsteady jet. Studies have also been conducted using a pulsating injectant in still air[11,12] and in water,[13] but the objective of the investigation in every case was to determine the mixing characteristics of the pulsed jet. As noted earlier, supersonic airstreams have been used in con-