79-1321
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AIAA/SAE/ASME 15th JOINT PROPULSION CONFERENCE
June 18-20, 1979 / Las Vegas, Nevada

THE EFFECT OF FUEL SPRAYS ON EMISSIONS
FROM A GAS TURBINE COMBUSTOR

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Abstract

In this program, a research gas turbine combustor is used to study the influence of individual variables (in particular, fuel spray characteristics) on primary zone emissions. The unique combustor is operated under realistic conditions and allows for independent control of drop size, fuel-air ratio, air inlet temperature, pressure, reference velocity, and residence time. Also, it lends itself to theoretical modelling and to turbulence intensity measurements through use of laser velocimetry.

A uniform spray is created by the air-blast atomization of fuel injected through 37 needles. Unidirectional gas flow is obtained (with no large scale recirculation) which allows for straightforward determination of residence time and unambiguous interpretation of emissions results. Measurements of the following are presented: local concentrations of NO_x, CO and unburned hydrocarbons at various locations within the flow, local gas temperature, gas velocity and the turbulence intensity. Validity of the emissions data is tested using a comprehensive data analysis program to calculate the local fuel-air ratio and the sum of the mole fractions of the species present.

Results indicate that increasing the drop size, keeping residence time and all other parameters fixed, causes an increase in unburned hydrocarbons. Some unexpected trends in NO_x levels are discussed. Increasing the residence time, keeping drop size and other parameters fixed, results in sharp decreases in hydrocarbons and CO, and an increase in NO_x.

Introduction

It is known that characteristics of the fuel spray can have a significant effect on the emissions from gas turbine combustors[1,2]. In fact, it is believed that the drop size of the fuel and the spray density largely determine the type of combustion that occurs, i.e. whether the drops burn individually or significant evaporation of the entire spray occurs before combustion. However, it has been impossible to assess the way in which spray characteristics affect emissions because of the difficulties involved in changing one variable at a time in a spray.

For example, it is desirable to vary the drop size while keeping the residence time of fluid elements within the flame a constant. In an actual engine combustor with swirl and large scale recirculation, it is impossible to accurately measure and control the residence time. Emissions results

obtained for such combustors therefore depend largely on the physical geometry of the combustor, the spray geometry, flameholder geometry and the flow pattern.

For the present study, a unique gas turbine combustor has been designed which allows independent control over various combustion parameters[3]. The combustor also provides unidirectional gas flow and uniform spray properties. Residence time can be measured and controlled; the emissions results are geometry independent and can be interpreted unambiguously. To achieve these conditions, a uniform spray is formed by the air blast atomization of fuel injected through 37 separate needles. No flameholder is needed. Each of the following parameters can be varied, while holding all other parameters constant: (a) drop size, (b) fuel-air ratio, (c) residence time, (d) inlet air temperature, (e) pressure, and (f) reference velocity. By assessing the effects of these parameters, certain fundamental aspects concerning the nature of the combustion process can be determined.

Experimental Arrangement

In order to isolate and measure the effects of parameters (a) through (f) above, the research combustor shown schematically in Figs. 1 and 2 was used.
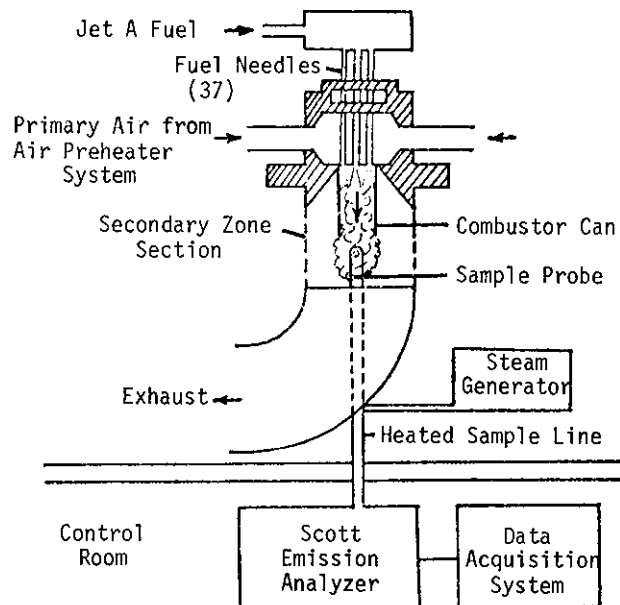

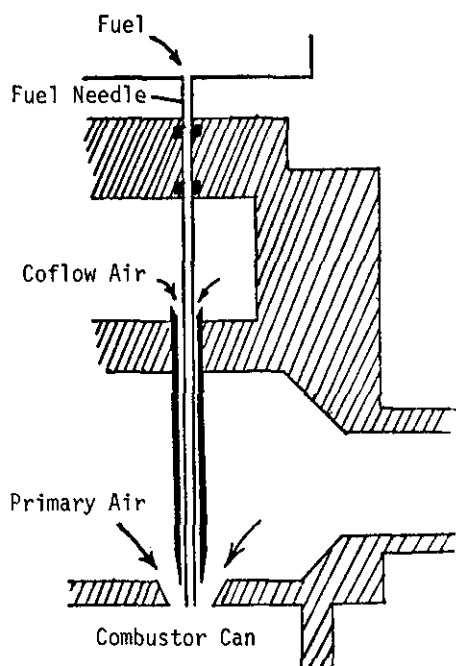Figure 1. Research Model Gas Turbine Combustor

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Figure 2. Details of the Fuel Needle Geometry

For the present study, only the primary zone was of interest, therefore no secondary air was introduced. The fuel drop generator consists of thirty seven fuel needles, each of 0.025 cm diameter, mounted at one end of the cylindrical combustor can, which has a radius of 5.4 cm. Jet A, a kerosene based fuel, is used. Surrounding each fuel needle is a concentric coflow tube, through which a small amount of room temperature air is passed. The coflow air prevents the fuel from boiling or coking in the fuel needles when high temperature primary air is used. Surrounding each fuel needle-coflow air tube is a 0.32 cm diameter nozzle through which primary air is introduced. The primary air atomizes the fuel by air blast atomization.

Drop size in the resulting spray is controlled by varying the primary air velocity at the nozzles. Sauter mean diameter was measured under non-combustion conditions using direct photography[3], and was found to correlate with the ratio of Weber number to Reynolds number, in accordance with the theory of Nukiyama[4], as shown in Fig. 3. Theory predicts a Sauter mean diameter d_o of:

$$d_o = 585 \frac{\sqrt{\sigma/\rho_\ell}}{(u_a - u_\ell)} + 597 \frac{u_\ell^{0.45}}{\sigma \rho_\ell} \left(1000 \frac{V_\ell}{V_a}\right)^{1.5} \quad (1)$$

where σ, ρ_ℓ, V_ℓ and u_ℓ are the surface tension, density, flow rate and velocity of the fuel, and V_a and u_a are the flow rate and velocity of the gas, respectively. Sauter mean diameter was varied between 10 μm and 58 μm, primary air inlet temperature was varied between 350°K and 800°K by using an air preheater; and air mass flow was varied from .09 to .13 kg/sec. Emissions data has been obtained at inlet air temperatures of 800°K, however all data reported in this paper is for an inlet air temperature of 360° ± 40°K, and for a combustor pressure of one atmosphere. No flameholder was needed since local recirculation near the fuel jets provided adequate flame stability for equivalence ratios between 0.5 and 1.5. The visible flame extended approximately 45 cm.

A water cooled gas sampling probe was used to extract samples at various locations within the flame. Four 0.05 cm orifices were located on the cylindrical side wall of the probe, 0.2 cm from the tip. This orifice geometry provided rapid quenching of the reactions in the sample flow. The orifices were choked, resulting in pressure quenching. The sample also was thermally quenched in the water cooled probe. An inner steam jacket surrounded the sample line in the probe and maintained a sample temperature of 422°K. Emissions results indicated that reducing the sample temperature below 400°K caused undesirable hydrocarbon condensation in the probe.

A second sampling probe was used which had a single 0.1 cm orifice at the probe tip, in an arrangement similar to a pitot probe. With this probe, the measured UHC and CO values were nearly the same as the values measured with the first probe. However, the NO_x levels measured with the second probe were somewhat larger than those measured with the first probe. Because the orifice of the second probe was not choked, less effective quenching of the NO_x reactions may have resulted in the second probe.

The heated sample gas flowed at a rate of 0.20 cm^3/sec to a Scott Emissions Analyzer System, consisting of a Scott 125 chemiluminescence analyzer for NO_x and NO measurement, a Scott 116 flame ionization detector for analysis of unburned hydrocarbons, Beckman 315 infrared detectors for CO and CO_2 analysis and a Beckman 741 oxygen detector.

In order to independently vary drop size, equivalence ratio and residence time, the probe location was varied using a motor driven traversing mechanism. For example, to increase drop size from 10 μm to 50 μm, it was necessary to decrease the primary air flow rate from .13 to .09 kg/sec, according to Eq. (1). To keep residence time fixed at 4.3 msec, the probe location z_o had to be decreased from 20.3 cm to 13.6 cm. Since the flow was unidirectional, residence time (t_{res}) was deduced from the axial temperature surveys T(z) described in the next section, using:
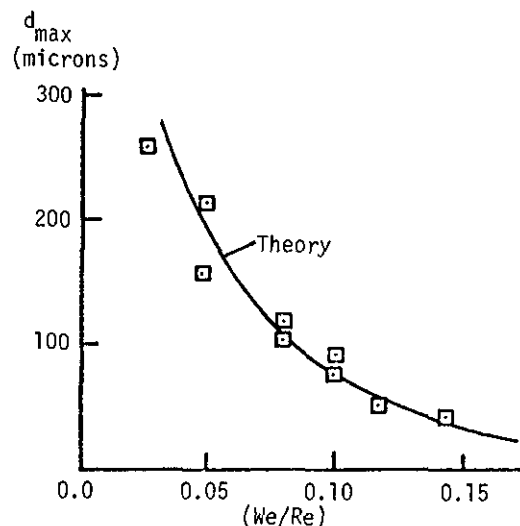

Figure 3. Measured Drop Size Compared to Theory of Nukiyama-Tanasawa

$$t_{res} = \int_0^{z_o} u_a^{-1} \, dz = \frac{A}{\dot{m}} \frac{p}{R} \int_0^{z_o} T^{-1} \, dz \qquad (2)$$

where u_a is the mean axial velocity averaged over the combustor cross sectional area A, p is one atmosphere, $\dot{m}$ is the total mass flow and R is the gas constant.

Results: Temperatures, Velocities, Turbulence Levels

To better understand the emissions data collected in the flame, measurements of the local flow conditions were made. These measurements were also used as input to a theoretical model developed for this program[5]. Gas temperature on the combustor axis was measured using a Pt-Rh thermocouple; results are shown in Figs. 4 and 5. The radiation loss correction factor applied[6] changed the raw thermocouple data by less than 5%.

A laser velocimeter (LV) system was used to measure mean velocity and turbulence levels in the combustor, both with and without combustion. The LV system consists of a 15 mwatt He-Ne laser, two acousto-optic frequency shifters and optics arranged in the forward scattering fringe mode. Alumina particles were introduced into the plenum chamber using a fluidized bed. Velocity data was recorded using 50 MHz line driver amplifiers, a digital counter and an Alpha 16 minicomputer.

Typical mean velocity profiles obtained in the combustor can at the axial location Z = 10 cm are shown in Fig. 6. Solid symbols represent LV data taken in the flame for an equivalence ratio of 0.9 and Sauter mean diameter of 26 microns. Velocities measured under combustion conditions are approximately 2.5 times larger than cold flow velocities measured for the same air mass flow. LV data obtained in the cold flow was compared with pitot
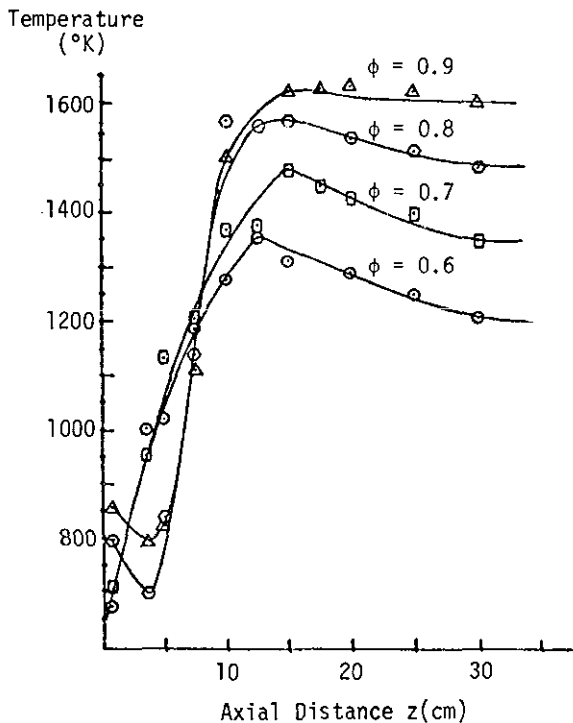

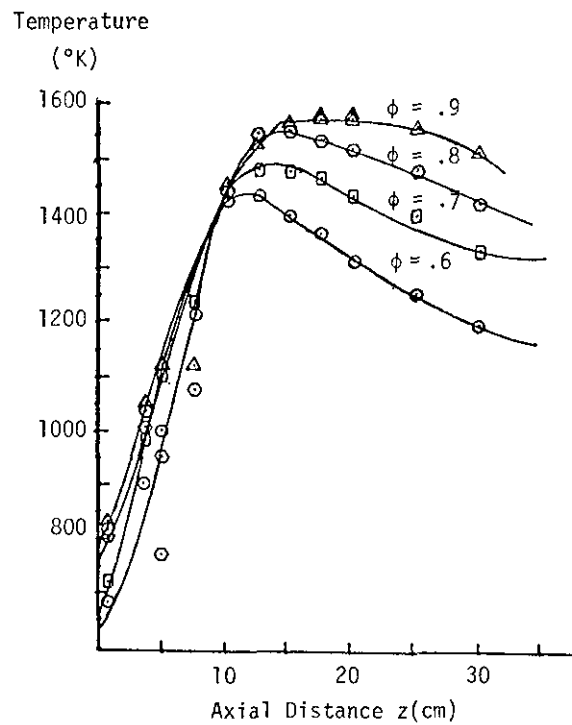Figure 5. Measured Flame Temperature for 58 μm Drop Size

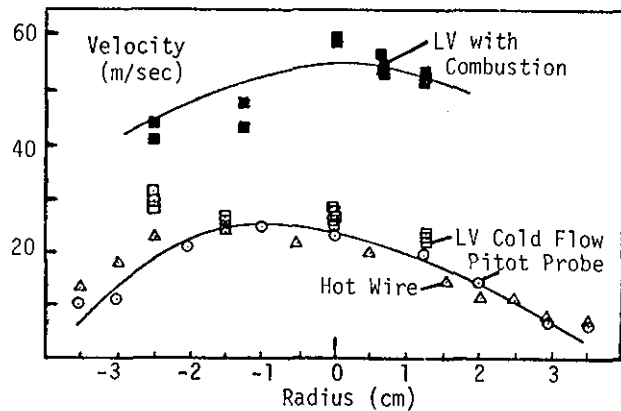Figure 6. Mean Axial Velocity

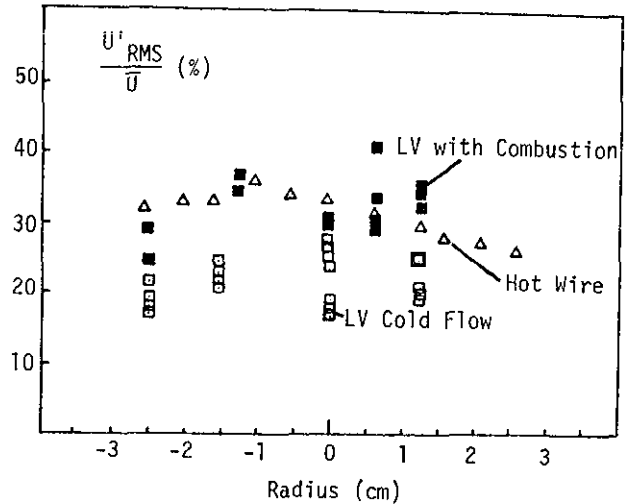Figure 4. Measured Flame Temperature for 10 μm Drop Size

Figure 7. Turbulence Levels

probe and hot wire velocity profiles. While the agreement in Fig. 6 between probes is reasonable, the LV results are believed to be the most accurate since velocity fluctuations exceeding 30% of the mean were observed. In highly turbulent flow, pitot probe readings tend to be erroneously low due to instantaneous probe misalignment with the flow.

The turbulence levels ($u'_{rms}/\bar{u}$) measured under combustion conditions were 30-35%, as shown in Fig. 7. This is only slightly higher than the corresponding turbulence levels which were measured with no combustion. Turbulence levels in the combustor are consistent with those typical of turbulent jets. It is therefore concluded that the combustion itself has only a secondary effect on the turbulence levels. The autocorrelation of velocity fluctuations also was measured, from which it was possible to deduce the eddy diffusivity, mean eddy lifetime and the Kolmogoroff length scale of the turbulence, as discussed elsewhere[7].

Results: Emissions Data

A comprehensive data analysis program was developed to perform the following tasks: a) the mean emissions index (g/kg fuel) was deduced from raw data, b) validity of the data was checked by computing the fuel-air ratio and comparing this value with the known input value, and c) the validity of the data was checked again by computing the sum of measured mole fractions and comparing this value with unity. Checking the emissions results in this manner proved especially useful. Initially, deviations between calculated and input fuel-air ratios were found, which led to the detection of a small air leak in the sample line. If one of the components of the emissions analyzer system should malfunction, the program immediately indicates that the sum of mole fractions is not unity; it also indicates which measurement is most likely in error.

Results of the emissions measurements are shown in Figs. 8-13. Each data point plotted represents the average of at least four measurements taken at the same run conditions. Data obtained with the first probe described previously is plotted using open symbols, data obtained with the second probe is plotted using closed symbols.
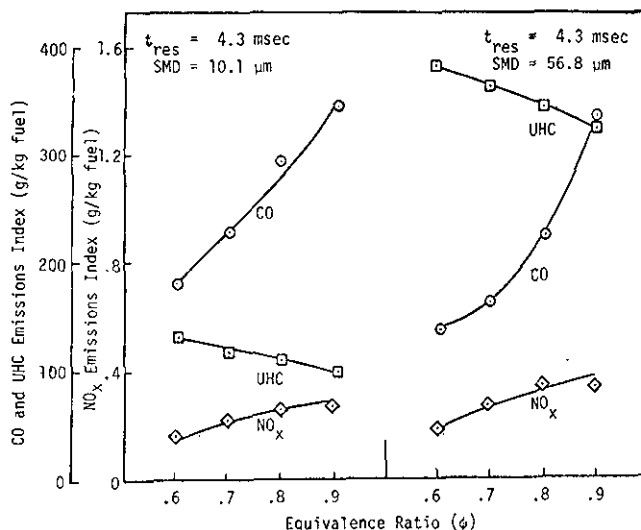
Each set of measurements was considered valid only if the sum of mole fractions deviated by less than 5% from unity. The computed fuel-air ratios were found to be consistently less than the measured input fuel-air ratio by 10-20 percent. It is suspected that the local fuel-air ratio on the combustor centerline is 10-20% less than the total fuel-air ratio, since the air flow rate on the centerline is maximum, as shown in Fig. 6.

Discussion

The first conclusion that can be drawn from the data is that the measured unburned hydrocarbon (UHC) levels within the flame are greater than theoretical levels predicted using the assumption of single droplet combustion, as seen in Figs. 12 and 13. To calculate the theoretical curve in Figs. 12 and 13, the measured drop size distribution was used as input to the theory of Sirignano[8], which is a modified version of conventional single droplet combustion theory that also includes convective heat transfer effects. The discrepancy noted between measurements and single droplet combustion theory shown in Figs. 12 and 13 indicates that a significant portion of the droplets (most probably the smallest droplets) do not burn with individual flames about each droplet.

Instead, it is believed that the smallest drops evaporate and burn in a manner similar to a gaseous turbulent diffusion flame, due to a lack of oxygen within the dense fuel spray. This conclusion also is consistent with the observation that the measured gas temperatures within the flame, shown in Figs. 4 and 5, are considerably less than the adiabatic flame temperature, which for Jet A fuel at $\phi = 0.9$ is approximately 2000°K. Correspondingly, the ratio of the axial velocity in the flame to the reference velocity should equal the ratio of the local flame temperature to the inlet air temperature, if the flow is truly unidirectional. From the data of Figs. 4, 5 and 6, these ratios are approximately the same. The hydrocarbon and temperature values of Figs. 4, 5, 12 and 13 are in general agreement with values reported by Onuma[9] in a spray combustion flame operated at air flow rates one thousand times less than in the present study. Data of Figs. 4 and 5 indicates that flame temperature increase as

Figure 8. Effect of Drop Size on Emissions for Fixed Residence Time of 4.3 msec
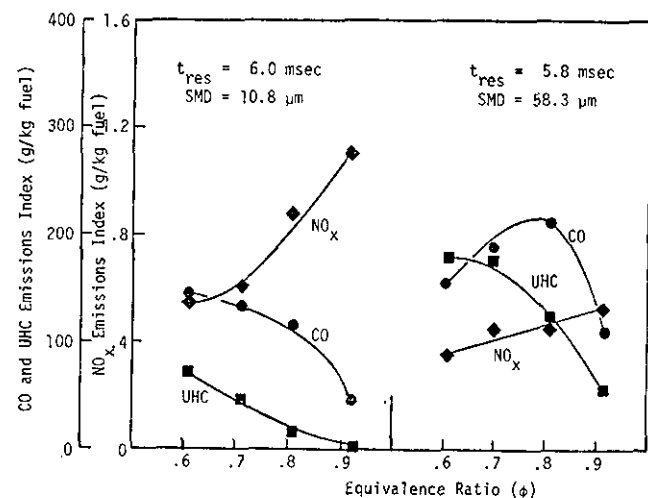

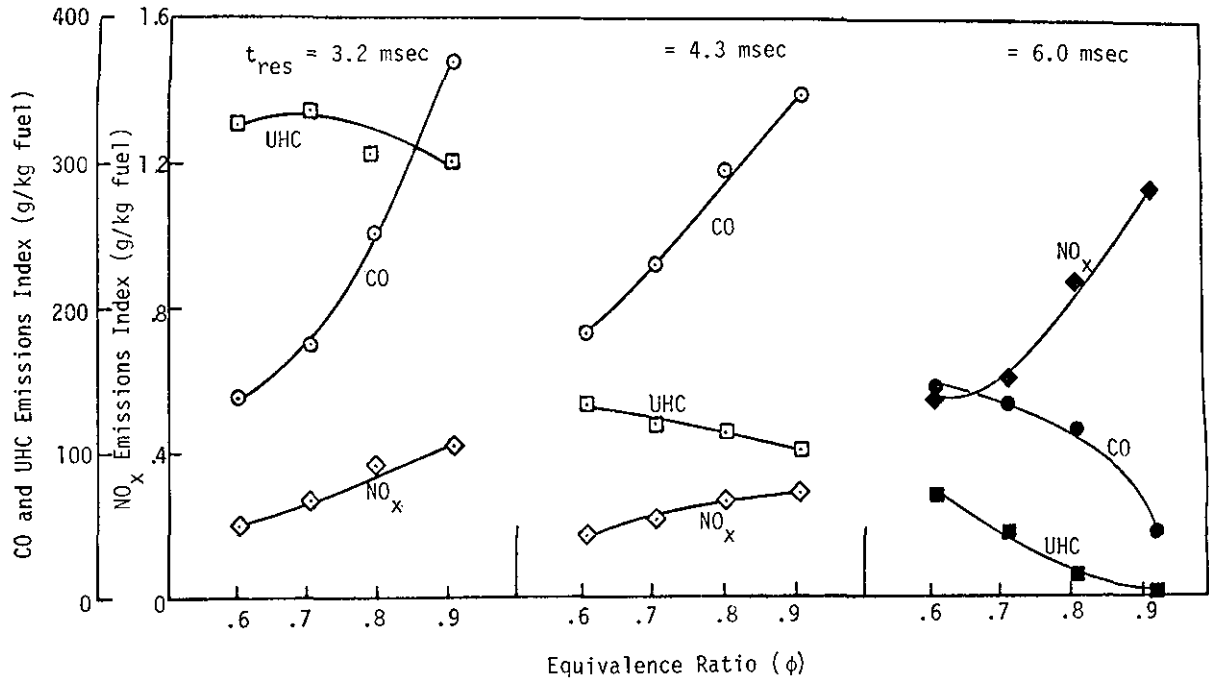Figure 9. Effect of Drop Size on Emissions for Fixed Residence Time of 6.0 msec

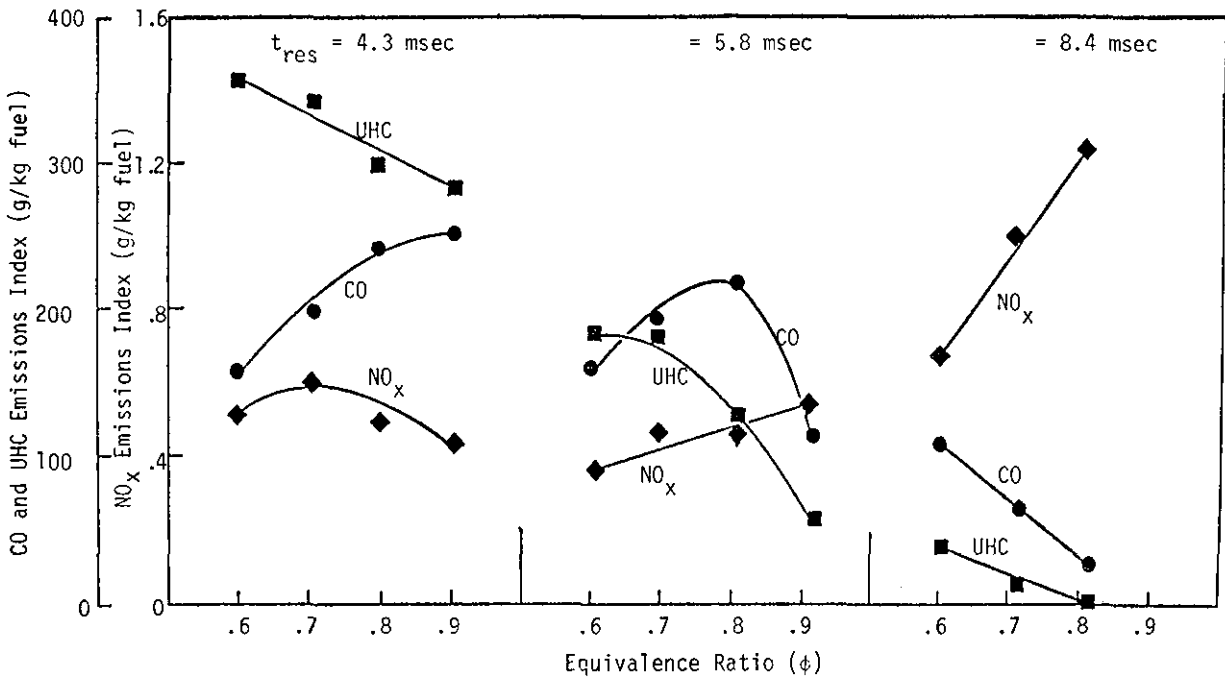Figure 10. Effect of Residence Time on Emissions for 10 μm Drops

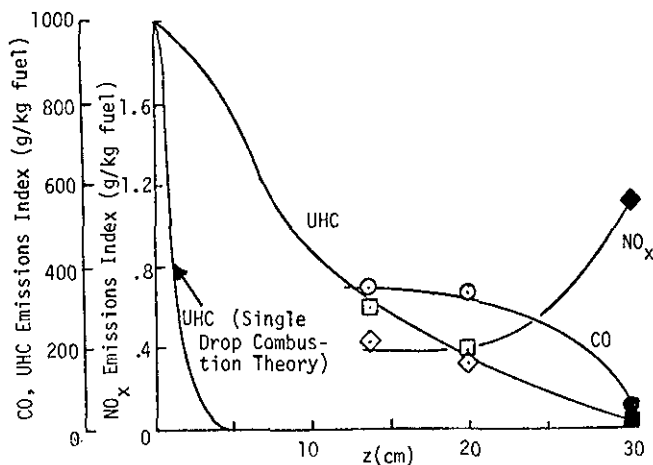Figure 11. Effect of Residence Time on Emissions for 58 μm Drops

Figure 12. Axial Variation of Emissions,
10 μm Drops, $\phi = .9$

Figure 13. Axial Variation of Emissions,
58 μm Drops, $\phi = .8$

equivalence ratio increases towards unity, but flame temperature does not change significantly as drop size increases from 10 to 58 μm.

The effect of drop size on emissions is shown in Figs. 8 and 9. In Fig. 8, the Sauter mean diameter (SMD) is increased from 10 μm to 57 μm, keeping residence time fixed at 4.3 msec. In Fig. 9, SMD is increased similarly, but in this case residence time is fixed at 6.0 msec. Residence time was determined using Eq. (2). In Fig. 8, it is noted that as equivalence ratio (ϕ) increases, NO_x and CO increase and hydrocarbons decrease. This is consistent with the temperature data of Figs. 4 and 5, which indicates an increase in mean temperature with increasing ϕ. Furthermore, the levels of CO and NO_x are unaffected by drop size for the relatively short residence time of 4.3 msec in Fig. 9. This is consistent with the temperatures shown in Figs. 4 and 5 which also are not affected by drop size variations. The hydrocarbon levels in both Figs. 8 and 9 increase significantly as drop size increases. This cannot be explained by mean temperature changes, since mean temperatures of Figs. 4 and 5 are unaffected by drop size. Instead, it is proposed that drop evaporation and the local temperatures in the vicinity of the drops cause the observed trend. Since the evaporation time for 10 μm drops is 30 times less than that of the 58 μm drops, it is believed that the smaller droplets result in conditions closer to those of premixed combustion. With the larger drops, combustion is diffusion dominated, resulting in larger hydrocarbon levels.

One unexpected result that is noted in Fig. 9 is that the NO_x levels decrease as drop size increases from 10 to 58 μm. At first, this appears to contradict the above concept that decreasing drop size results in premixed combustion and less NO_x and hydrocarbon emissions. However, data by Nizami and Cernansky[10] indicates that while NO_x emissions display an overall increase with drop size, a local minimum in the NO_x emissions was observed for 50 μm drops. The NO_x data of Fig. 12 and data of Nizami are in general agreement. Reasons for a minimum in NO_x emissions for 50 μm drops are unclear, but may be attributable to the transition from premixed to single droplet combustion.
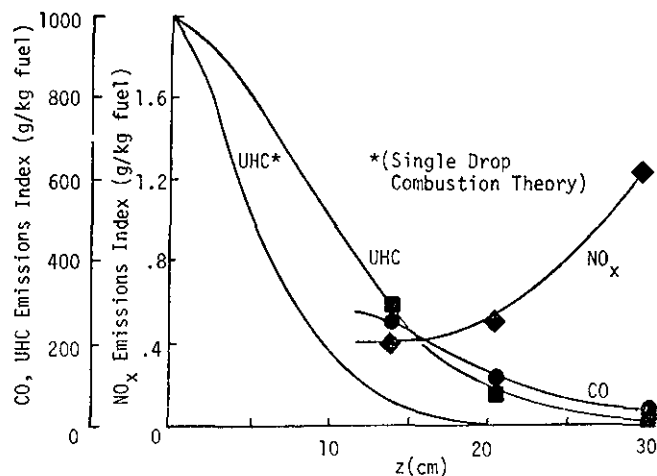
The effect of residence time on emissions is shown in Figs. 10 and 11. Drop size is held constant at 10 μm in Fig. 10; in Fig. 11 the drop size is 58 μm. For both drop sizes, the following trends are evident. As residence time increases, hydrocarbons decrease sharply. For residence times less than 6 msec, both NO_x and CO levels do not vary significantly. However, increasing the residence time above 6 msec causes a sharp increase in NO_x and a sharp decrease in CO. The trends observed are consistent with theory describing NO_x and CO kinetics. However it should be remembered that differences may occur between the present results and emissions predicted in premixed systems, due to heterogeneous combustion effects. For example, at short residence times it is expected that the smallest drops in a given drop size distribution will evaporate and burn either as a premixed flame or a gaseous diffusion flame, depending on the oxygen diffusion process. At increased residence times, the smallest drops no longer exist and the remaining drops may burn in a different manner, with individual flames surrounding each drop.

Much research is still needed to understand the complex effects of spray characteristics on emissions. Further work at elevated pressures and inlet temperatures is planned. If NO_x emissions do undergo a local minimum for certain drop sizes[10], as discussed above, then a better understanding of the transition from premixed combustion (i.e. small droplets) to diffusion limited combustion is needed. Laser velocimetry is ideal for such studies, as it allows a direct determination of the local turbulent diffusivity and the local drop size, from which the controlling parameter, the ratio of drop lifetime to eddy diffusion time, can be deduced[7]. Future work in this area also is planned.

Acknowledgments

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