AIAA 81-0327R

Fuel/Air Nonuniformity—Effect on Nitric Oxide Emissions

Valerie J. Lyons*
NASA Lewis Research Center, Cleveland, Ohio

An analytical and experimental study was performed to determine the effect of inlet fuel/air profile nonuniformity on NO_x emissions. The theoretical NO_x levels were verified in a flametube rig at inlet air temperatures of 600, 700, and 800 K, 0.3 MPa rig pressure, 25 m/s reference velocity, overall equivalence ratio of 0.6, and residence time near 0.002 s. The theory predicts an increase in NO_x emissions for increased fuel/air nonuniformity for average equivalence ratios less than 0.7, while for average equivalence ratios near stoichiometric, increasing the nonuniformity will decrease NO_x emissions. The results of this report can be used to predict the degree of uniformity of fuel/air profiles necessary to achieve NO_x emissions goals for actual engines that use lean, premixed, prevaporized combustion systems.

Introduction

THE purpose of this report is to present the results of an analytical and experimental study to determine the effect of the degree of nonuniformity in the incoming fuel/air profile on NO_x emissions.

Due to rising fuel and maintenance costs and regulations governing exhaust emissions from gas turbine engines,[1] interest has arisen in advancing combustor technology. Several studies[2-5] have explored ways of advancing combustor technology to meet these demands. A promising concept for reducing engine emissions and obtaining superior performance and high durability is lean premixed prevaporized (LPP) combustion. A number of flametube studies[6-11] have demonstrated that an order of magnitude reduction in NO_x levels can be attained while achieving 99% combustion efficiency in an LPP environment.

This LPP combustion concept formed the basis of a NASA Advanced Low Emission Combustor Program.[12] The purpose of this program is to evolve lean, premixed, prevaporized combustion technology into a practical aircraft gas turbine combustion system that exhibits superior performance, high durability, fuel flexibility, and environmentally acceptable pollutant emissions over the entire flight envelope. Although the LPP concept shows great promise for reducing NO_x emissions, several practical problems are associated with its application. These problems include blowout, altitude relight, autoignition, flashback, and achieving satisfactory premixing and prevaporization.

In applying lean premixed-prevaporized combustion to actual gas turbine engines, it may not be possible to uniformly premix the fuel and inlet air. Using any fuel injection system with discrete injection points will produce relatively fuel-rich and fuel-lean zones that may still be present when combustion occurs. A fully premixed system would be equivalent to a uniform fuel/air inlet profile. Any lack of mixing would produce nonuniform fuel/air inlet profiles. An analytical study of the effect of nonuniformity on NO_x emissions has been previously undertaken.[13] A slightly different presentation of the theory of NO_x production in a nonuniform fuel/air mixture will be presented here. Also, experimental data were taken to verify the theory.

In order to define what degree of premixing may be required in an LPP system to produce acceptably low NO_x emissions, several nonuniform, but fully vaporized, fuel/air inlet profiles were studied. The incoming fuel/air profiles were made nonuniform across the flametube rig by varying the amount of fuel to different zones of a multipoint fuel injector. The spatial fuel distribution and exhaust emissions were determined from measurements taken from a radially traversing probe downstream of a water-cooled perforated plate flameholder. for each of the inlet air temperatures of 600, 700, and 800 K, six fuel/air profiles were studied. Data were obtained in a flametube rig at a reference velocity of 25 m/s and rig pressure of 0.3 MPa. Jet A fuel was used.

Theoretical Calculations

In a flametube rig, the fuel/air distribution can be shown by a plot of local equivalence ratio [(fuel/air) local/(fuel/air) stoichiometric] ϕ_ℓ vs pipe radius r. If axial symmetry and uniform air density are assumed and a constant air velocity profile exists, the average equivalence ratio for a ϕ_ℓ vs r profile is

$$\bar{\phi}=\int_0^{r_{\max}} \phi_\ell r\mathrm{d}r \Big/ \int_0^{r_{\max}} r\mathrm{d}r \tag{1}$$

where $r_{\max}$ is half the pipe inner diameter.

The degree of nonuniformity of the profile can be described by a nonuniformity parameter

$$S=\left(\int_0^{r_{\max}} (\phi_\ell-\bar{\phi})^2 r\mathrm{d}r \Big/ \int_0^{r_{\max}} r\mathrm{d}r\right)^{1/2} \tag{2}$$

Basically, this nonuniformity parameter s is the standard deviation from the mean of the local equivalence ratio distribution. (Note that this s parameter is different from the s parameter used by Mikus, Heywood, and Hicks; in their similar study in Ref. 13, s was the standard deviation divided by the mean equivalence ratio.)

Two methods of determining an average theoretical value of NO_x were used. The first method required obtaining an experimental ϕ_ℓ distribution and then predicting a NO_x level for each measured ϕ_ℓ from the well-stirred reactor program described in Ref. 14. The second method does not need experimental data. Instead, it is assumed that Gaussian distribution of ϕ_ℓ exists that has the same $\bar{\phi}$ and s as the corresponding experimental results.

Once proved reliable, the Gaussian method can be used to predict NO_x levels without experimental data. All that would be needed would be an estimate of the average equivalence ratio $\bar{\phi}$ and degree of nonuniformity s for the combustion system and the average NO_x level could be predicted. For the Gaussian method, the well-stirred reactor program of Ref. 14

Presented as Paper 81-0327 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted Feb. 23, 1981; revision received Aug. 31, 1981.

*Aerospace Engineer. Member AIAA.

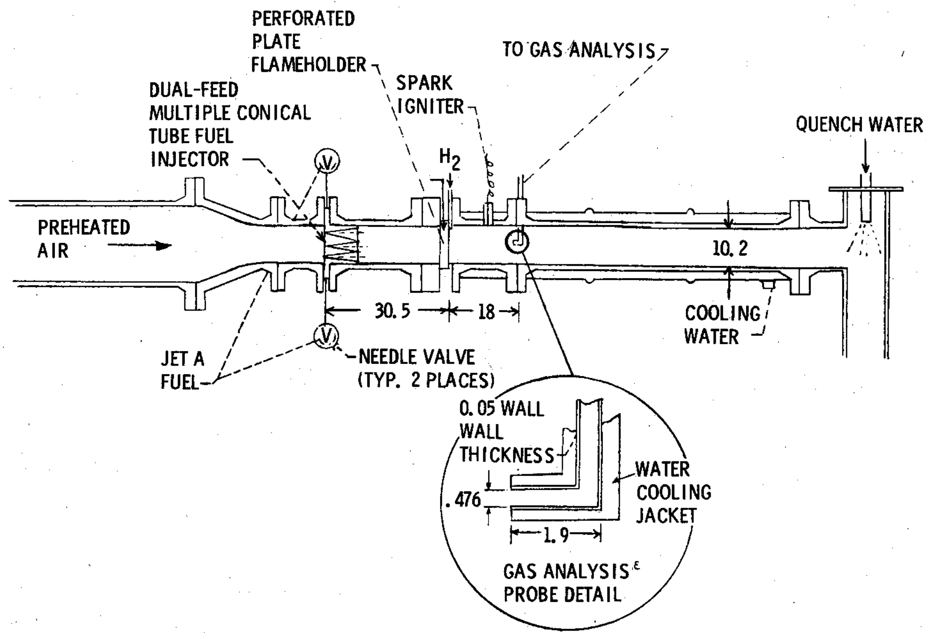

Fig. 1 Rig schematic (all dimensions in cm).

was used to predict local NO_x values for a set of ϕ at the given inlet air temperature and pressure and combustor residence time. These NO_x values were then weighted by a Gaussian distribution function

$$f(\phi_\ell) = \frac{1}{\sqrt{2\pi}s} \exp\left[\frac{-(\phi_\ell - \bar{\phi})^2}{2s^2}\right] \tag{3}$$

The predicted value of NO_x for the given nonuniform profile described by s and the Gaussian distribution is

$$NO_{x_{\text{Gaussian}}} = \int_{\bar{\phi}-2s}^{\bar{\phi}+2s} NO_x(\phi_\ell) f(\phi_\ell) \mathrm{d}\phi_\ell \Big/ \int_{\bar{\phi}-2s}^{\bar{\phi}+2s} f(\phi_\ell) \mathrm{d}\phi_\ell \tag{4}$$

where

$$\int_{\bar{\phi}-2s}^{\bar{\phi}+2s} f(\phi_\ell) \mathrm{d}\phi_\ell \tag{5}$$

is approximately unity.

The integrations used 24 values of ϕ_ℓ equally spaced between $\bar{\phi}-2s$ and $\bar{\phi}+2s$. The well-stirred reactor program predicted corresponding NO_x values for each of these 24 ϕ_ℓ. All integrals were performed numerically by using Simpson's rule together with Newton's ⅜ rule or a combination of these two rules.[15]

These theoretical NO_x values were then converted from ppm by volume to emission indices (EI) by the expressions discussed in Ref. 16 for comparison with the experimental data. In the conversion from ppm to EI, $\bar{\phi}$ was used as the equivalence ratio needed for the calculations.

Apparatus and Procedure

The facility used for this set of experiments consisted of a closed-duct system shown in Fig. 1. The incoming air was heated to the three given inlet temperatures of 600, 700, and 800 K by a nonvitiating preheater. Reference velocity was determined from the total airflow rate, the inlet total temperature and pressure, and the combustor cross-sectional flow area. The jet A fuel was injected through the fuel injector mounted 26 cm upstream of a water-cooled perforated plate flameholder. Combustion occurred downstream of the flameholder in a water-cooled section which was instrumented to sample the combustion products to determine gaseous emissions.

The experimental data were obtained in a flametube rig by sampling the exhaust emissions 18 cm downstream from the flameholder. The local equivalence ratios were determined from a carbon balance of the sample exhaust species.[16]

The experimental value of NO_x for a given fuel/air profile was found from

$$NO_{x_{\text{exp}}} = \int_0^{r_{\max}} NO_{x_\ell} r \mathrm{d}r \Big/ \int_0^{r_{\max}} r \mathrm{d}r \tag{6}$$

where NO_{x_ℓ} is the locally measured NO_x value taken at 1 cm increments across the flow. A curve fit was found through the data so that 24 NO_{x_ℓ} values could be used in the integration. The NO_x values are in ppm and after the integration, $NO_{x_{\text{exp}}}$ is converted from ppm to EI using $\bar{\phi}$ and the expressions of Ref. 16. For more details on the rig and gas sampling procedures, see Ref. 17.

The fuel injector shown in Fig. 2 consisted of 17 conical tubes, each with an upstream diameter of 1.3 cm and a half angle of 7 deg. The tubes were 10.2 cm long. Fuel was injected at the air inlet end of each tube through a 0.5 cm i.d. open-ended tube. Each fuel tube was 25.4 cm long. The five center fuel tubes were supplied through one control valve, and the outside ring of 12 tubes was supplied from a second control valve. A uniform fuel/air profile was produced by opening both valves fully. Various nonuniform profiles were produced by varying the amount of fuel flow to the two regions of the fuel injector by using these two valves. The overall equivalence ratio was determined from the fuel turbine flow meter reading and the airflow rate as determined by a differential pressure measurement across a calibrated orifice. The overall equivalence ratio was maintained while the fuel/air profiles were changed. This fuel injector was the same fuel injector used in Ref. 18. In that study, it was shown that complete vaporization of the fuel was achieved at the conditions used here.

Results and Discussion

Effect of Equivalence Ratio

NO_x production is a strong function of flame temperature,[18] which varies with fuel/air ratio or equivalence ratio. The results of the theoretical predictions of the average NO_x levels for uniform fuel/air profiles ($s=0$) and for progressively more nonuniform fuel/air profiles (increasing s) are seen in Fig. 3. The local NO_x values increase nearly exponentially with increasing ϕ_ℓ for low values of ϕ_ℓ. NO_x

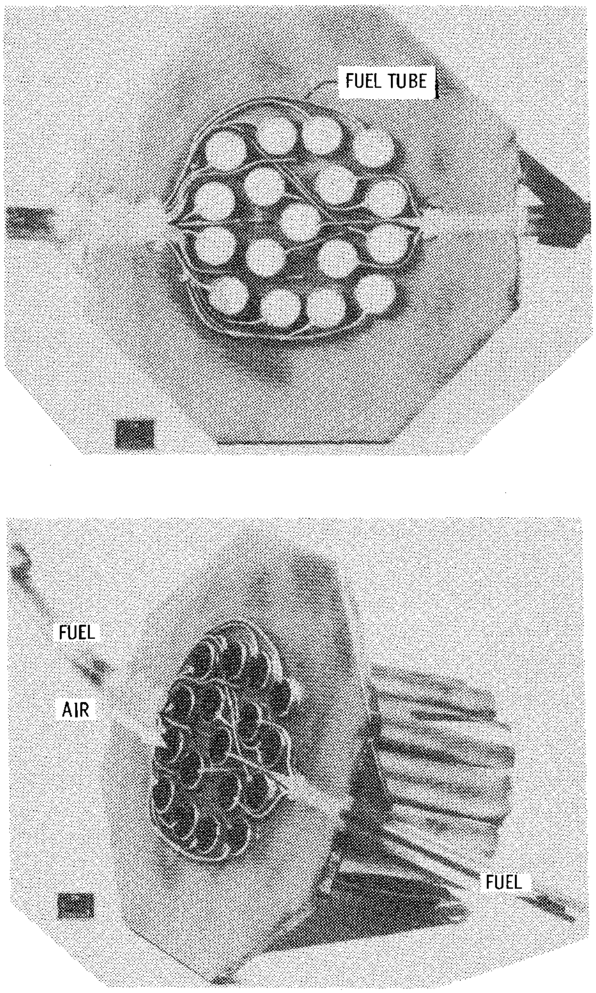

Fig. 2 Multiple conical tube injector.

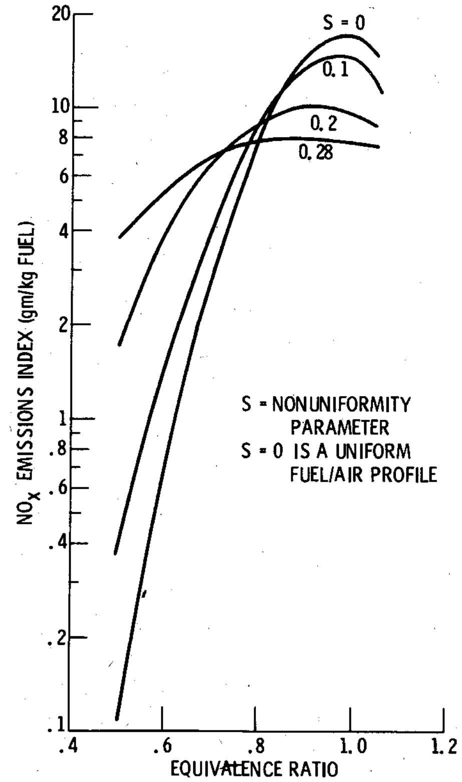

Fig. 3 Theoretical predictions of the effect of equivalence ratio and fuel/air nonuniformity on NO_x at an inlet air temperature of 600 K, pressure of 3 atm, and residence time of 0.002 s.

continues to increase until ϕ_ℓ approaches and exceeds stoichiometric (1.0) where the NO_x decreases with further increase in ϕ_ℓ. Consider now the effect of nonuniformity. For a given average equivalence ratio, say 0.6, a uniform profile ($s=0$) will have $\phi_\ell=0.6$ everywhere in the duct; thus, the local NO_x will everywhere correspond with that produced at $\phi_\ell=0.6$. As nonuniformity is introduced (s increased), regions with ϕ_ℓ greater than 0.6 and with ϕ_ℓ less than 0.6 will appear.

From Fig. 3, a uniform profile having $\phi=0.6$ would be expected to produce 0.75 g NO_2/kg fuel. A nonuniform profile, for example $s=0.1$, would produce 1.45 g NO_2/kg fuel. Thus, increasing s results in increasing average NO_x for this equivalence ratio.

For average equivalence ratios near stoichiometric, increased nonuniformity allows contributions from ϕ_ℓ greater than 1.0 and ϕ_ℓ less than 1.0, which will tend to produce less NO_x than the uniform, stoichiometric profile, again seen in Fig. 3. This figure shows that for average equivalence ratios less than 0.7, the trend is for increased NO_x levels with increased fuel/air nonuniformity. For average equivalence ratios near stoichiometric, the trend shows decreasing NO_x with increasing nonuniformity. From this figure, it is seen that the NO_x levels vary differently with s at each equivalence ratio.

Experimental Results

The six different fuel/air profiles studied at an inlet air temperature of 600 K are shown in Fig. 4. The average ϕ of 0.65 used in this experimental study is representative of the $\bar{\phi}$ expected in a lean, premixed-prevaporized combustor. A combustor operating at a lower $\bar{\phi}$ is less stable while a higher $\bar{\phi}$ will result in higher NO_x emissions. The corresponding NO_x and CO profiles which were measured are given in Figs. 5 and 6, respectively. Data were also taken at inlet air temperatures of 700 and 800 K and the results were similar. The degree of nonuniformity s of each fuel/air profile is shown in each figure.

In reviewing Fig. 5, note that at $s=0.024$ (the most uniform profile studied) the experimental NO_x value corresponds closely with the 1.5 g NO_2/kg fuel predicted in Fig. 3 at ϕ_ℓ of 0.65. The NO_x varies little across the duct. The profile with $s=0.090$ approaches stoichiometric at the 5 cm position (see Fig. 4); as expected, local NO_x is highest at 5 cm and values of 12 g/kg measured approach the predicted value of 17. Profiles in which ϕ_ℓ was greater than 1.0 near the center of the duct resulted in lower than stoichiometric NO_x values in this region. Again, this trend can be seen to be consistent with the predicted effects of ϕ on NO_x as shown in Fig. 3.

The actual NO_x data may have differed from the predicted values due to the effects of diffusional mixing on the ϕ_ℓ profiles. The NO_x values measured for a given ϕ_ℓ profile may reflect the burning of a more sharply peaked ϕ_ℓ distribution farther upstream. Another factor affecting NO_x peaks is the radiant heat losses from the high-temperature regions (near $\phi_\ell=1.0$), causing lower local temperatures than expected and thus slightly lower NO_x.

The CO data presented in Fig. 6 shows that 2 cm from the walls, the CO levels reached a relative minimum for each profile. This position corresponds to the intersection of the ϕ_ℓ curves (near $\phi_\ell=0.650$) seen in Fig. 4. Any deviation from this optimum ϕ produces more CO. This same ϕ was seen to produce minimum CO in the experimental results of Refs. 19 and 20 for the same inlet conditions. For ϕ values less than 0.65, the low combustion efficiency produces more CO. For ϕ greater than 0.65, greater amounts of equilibrium CO are produced. Although some CO values shown in Fig. 6 are somewhat below equilibrium values (showing incomplete quenching in the probe), the relative values are still valid.

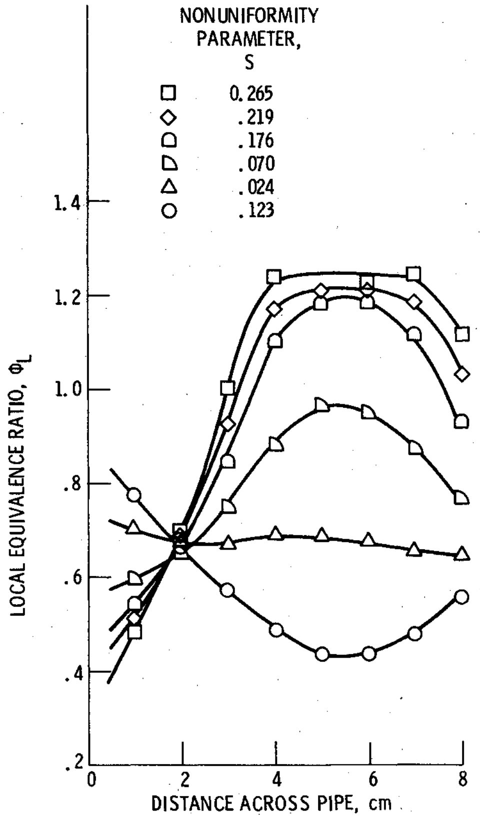

Fig. 4 Local equivalence ratio profiles (T_{INLET} = 600 K, pressure = 3 atm, average equivalence ratio = 0.65).

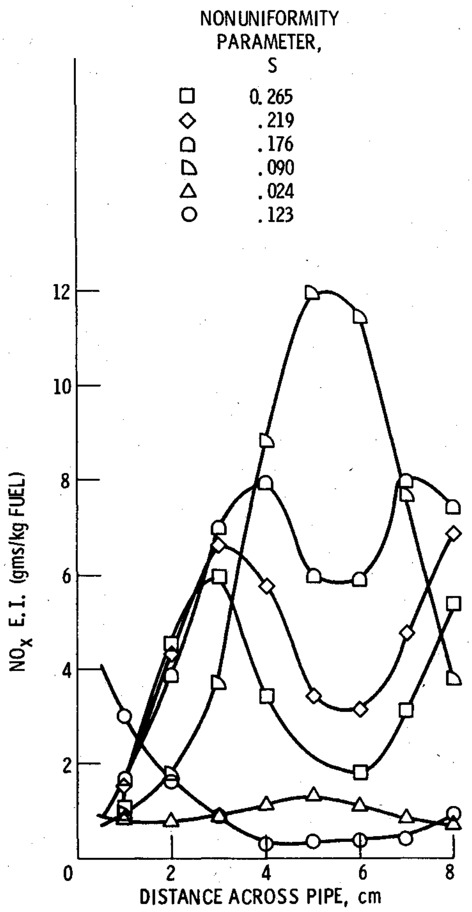

Fig. 5 Local NO_x emission index profiles (T_{INLET} = 600 K, pressure = 3 atm, average equivalence ratio = 0.65).

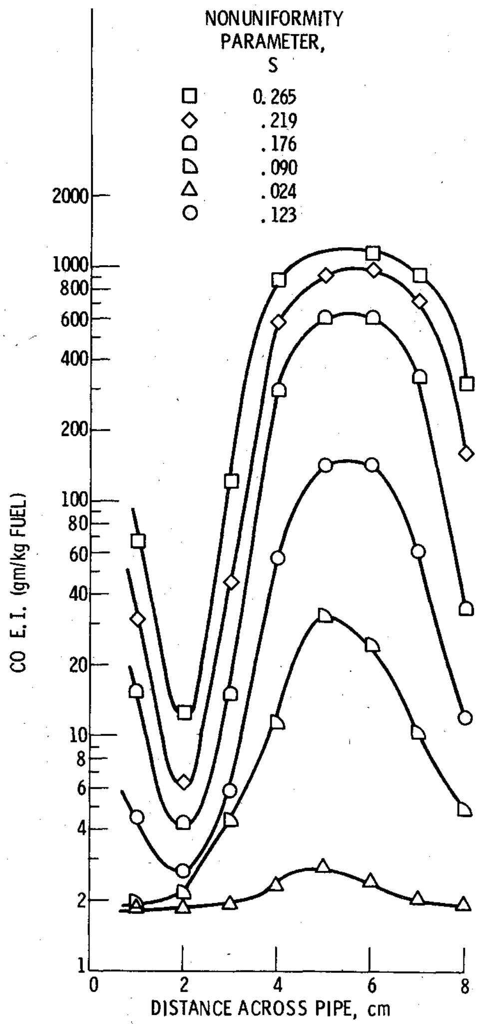

Fig. 6 Local CO emission index profiles (T_{INLET} = 600 K, pressure = 3 atm, average equivalence ratio = 0.65).

Figure 6 also shows that the lowest CO was produced for the most uniform profile. From this is seen that there is another benefit of attaining uniform fuel/air profiles: lower overall CO.

Theoretical Results

The next four figures present the theoretical predictions of NO_x along with the experimental results. Figures 7-9 present overall average NO_x values for each profile vs the values of the nonuniformity parameter s for each profile.

The Gaussian fuel/air profile assumption appears to be a good approximation of the local experimental data. In Figs. 7-9 average NO_x values are shown vs s for the well-stirred reactor prediction from the measured ϕ_ℓ profile and the Gaussian ϕ_ℓ profile along with the experimentally determined NO_x values for the three inlet air temperatures, 600, 700, and 800 K. The average experimental NO_x values are shown as data points in these figures along with their corresponding average equivalence ratios. Some of these average equivalence ratios are somewhat different from the others. One possible reason for this is that although the metered fuel-flow rate remained the same, the assumption of fuel/air profile symmetry may not be as accurate for some profiles as for others. Also, the measurements near the wall were weighted more highly than those in the center. Finer measurements taken near the wall may have produced more accurate values for $\bar{\phi}$. In drawing the curves for the theoretical predictions, average equivalence ratios near the majority of the experimental values were used and these average equivalence ratios are indicated in the figures.

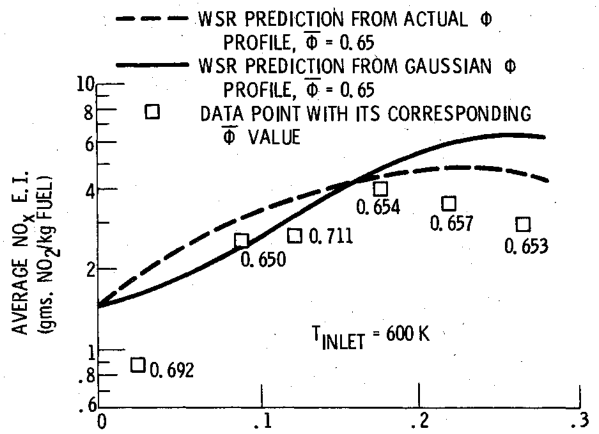

Fig. 7 Comparison of average NO_x values, experimentally determined, with theoretical predictions at inlet air conditions of 0.3 MPa and 600 K).

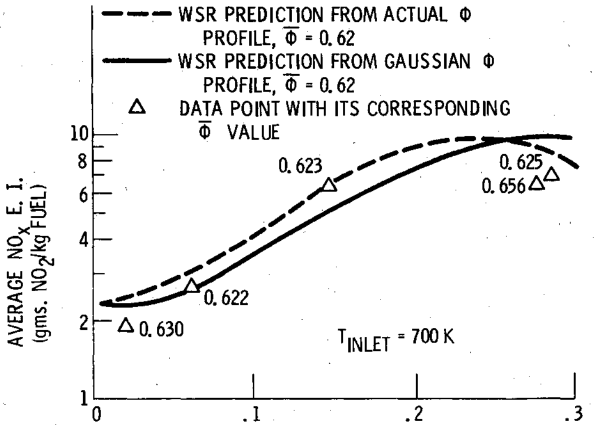

Fig. 8 Comparison of average NO_x values, experimentally determined, with theoretical predictions at inlet air conditions of 0.3 MPa and 700 K.

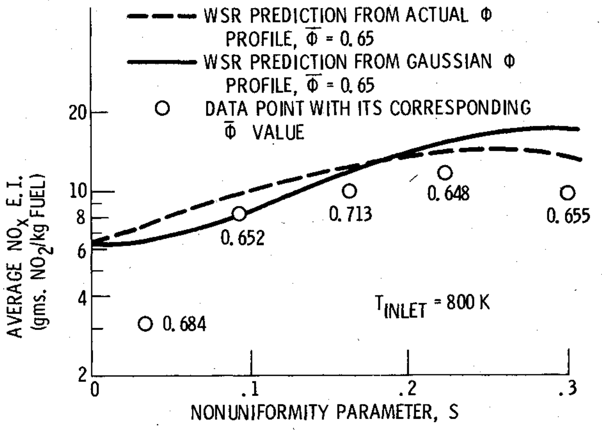

Fig. 9 Comparison of average NO_x values, experimentally determined, with theoretical predictions at inlet air conditions of 0.3 MPa and 800 K.

The two theoretical NO_x curves shown in Figs. 7-9 are the average NO_x values predicted by the well-stirred reactor program from the Gaussian ϕ_ℓ profile and from the actual ϕ_ℓ data profile. The data points shown are the average experimental NO_x values. Both curves approximate the data fairly well, justifying the use of the Gaussian ϕ_ℓ profile assumption.

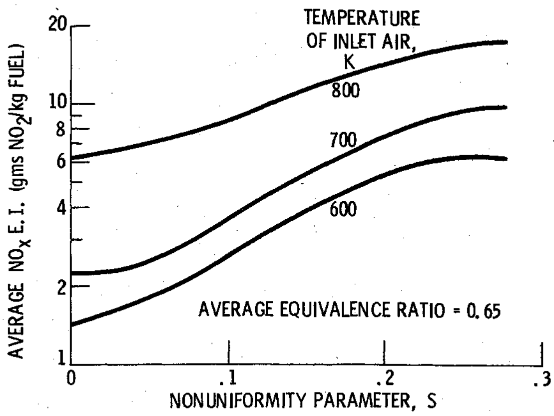

Fig. 10 Well-stirred-reactor program prediction of average NO_x values from Gaussian ϕ profiles at inlet air conditions of 0.3 MPa and 600, 700, and 800 K.

The Gaussian theoretical predictions for NO_x emissions at inlet air temperatures of 600, 700, and 800 K are shown in Fig. 10 for an average equivalence ratio of 0.65. The same trend of producing increased NO_x with increased nonuniformity is found at all three inlet air temperatures. This trend continues until an s value of approximately 0.2, at which point a larger amount of overstoichiometric burning occurs and less NO_x is produced.

Conclusion

The NO_x levels for nonuniform fuel/air profiles were successfully predicted by an analytical method and verified by experimental data. From the results of this study, greater understanding of lean premixed-prevaporized combustion has been achieved. The results show that it may be necessary for lean premixed-prevaporized combustors to have very uniform fuel/air distributions to achieve low NO_x emissions.

The results of this report can be used to estimate the degree of fuel/air nonuniformity required in the fuel preparation section of actual engines in order to meet NO_x standards. For example, if it were desirable to meet a NO_x goal of 3 g NO_2/kg fuel, Fig. 10 can be used to determine the degree of nonuniformity permitted for a primary zone equivalence ratio of 0.65. For inlet conditions of 600 K and 0.3 MPa, an s less than 0.08 would be needed to achieve this goal. At 700 K, 0.3 MPa, s less than 0.05 is required. This goal cannot be achieved at 800 K, 0.3 MPa, with a primary zone equivalence ratio of 0.65.

Summary of Results

The effect of fuel/air nonuniformity on NO_x emissions was analytically and experimentally investigated, with particular interest for lean, premixed-prevaporized combustion. The conditions studied were inlet air temperatures of 600, 700, and 800 K, pressure of 0.3 MPa, and inlet air velocity of 25 m/s. Jet A fuel was injected through a dual-zoned fuel injector and premixed with air so that six profiles of fuel/air mixtures were produced at each inlet air temperature. Gas sample measurements were taken downstream of a perforated-plate flameholder.

From this study, it was found that:

1) For average equivalence ratios less than 0.7 average NO_x emissions increased with increasing fuel/air nonuniformity.

2) For average equivalence ratios near stoichiometric, average NO_x emissions decreased with increasing fuel/air nonuniformity.

3) For any value of the nonuniformity parameter, NO_x emissions decreased with decreasing average equivalence ratio for average equivalence ratios less than 0.7.

4) Inlet air temperatures between 600 and 800 K had no effect on the trends of the effect of nonuniformity on NO_x emissions.

5) Both the magnitude and trends of the experimental data agree with the analytical predictions of the average NO_x emissions for various degrees of nonuniformity, inlet air temperatures, and average equivalence ratios.

References

[1] Grobecker, A. J., Coronite, S. C., and Cannon, R. H. Jr., "Report of Findings: The Effects of Stratospheric Pollution by Aircraft," U. S. Dept. of Transportation, DOT-TST-75-50, Dec. 1974.

[2] Roberts, P. B., White, D. J., and Shekleton, J. R., "Advanced Low NO_x Combustors for Supersonic High-Altitude Aircraft Gas Turbines," Solar Division, International Harvester, San Diego, Calif., RDR-1814, Nov. 1975 (NASA CR-134889).

[3] Gleason, C. C., Rogers, D. W., and Bahr, D. W., "The Experimental Clean Combustor Program—Phase II," General Electric Co., Cincinnati, Ohio, Rept. R76AEG422, Aug. 1976 (NASA CR-134971).

[4] Roberts, R., Peduzzi, A., and Vitti, G. E., "The Experimental Clean Combustor Program—Phase II," Pratt and Whitney Aircraft, East Hartford, Conn., Rept PWA-5418, Nov. 1976 (NASA CR-134969).

[5] Dodds, W. J., Gleason, C. C., and Bahr, D. W., "Aircraft Gas Turbine Low-Power Emissions Reduction Technology Program," General Electric Co., Cincinnati, Ohio, Rept. R78AEG408, Oct. 1978 (NASA CR-135434).

[6] Anderson, D. N., "Effect of Premixing on Nitric Oxide Formation," NASA TM X-68220, 1973.

[7] Marek, C. J. and Papathakos, L. C., "Exhaust Emissions from a Premixing, Prevaporizing Flame Tube Using Jet A Fuel," NASA TM X-3383, 1976.

[8] Anderson, D. N., "Effects of Equivalence Ratio and Dwell Time on Exhaust Emissions from an Experimental Premixing, Prevaporizing Burner," NASA TM X-71592, 1974.

[9] Roffe, G. and Venkataramani, K. S., "Emission Measurements for a Lean Premixed Propane-Air System at Pressures up to 30 Atmospheres," General Applied Science Labs., Inc., Westbury, N. Y., Rept. GASL-TR-250, Aug. 1978 (NASA CR-159421).

[10] Roffe, G. and Venkataramani, K. S., "Experimental Study of the Effects of Flameholder Geometry on Emissions and Performance of Lean Premixed Combustors," General Applied Science Labs., Inc., Westbury, N. Y., Rept. GASL-TR-249, April 1978 (NASA CR-135424).

[11] Semerjian, H. G. and Ball, I. C., "Potential Reduction in NO_x Emissions with Premixed Combustors," Paper presented at The Combustion Institute, Central States Section, Spring Technical Meeting, Cleveland, Ohio, March 1977.

[12] Mularz, E. J., "Lean, Premixed, Prevaporized Combustion for Aircraft Gas Turbine Engines," NASA TM-79148, 1979.

[13] Mikus, T., Heywood, J. B., and Hicks, R. E., "Nitric Oxide Formation in Gas Turbine Engines: A Theoretical and Experimental Study," NASA CR-2977, 1978.

[14] Boccio, J. L., Weilerstein, G., and Edelman, R. B., "A Mathematical Model for Jet Engine Combustor Pollutant Emissions," General Applied Science Labs., Inc., Westbury, N. Y., Rept. GASL-TR-781, March 1973 (NASA CR-121208).

[15] "TSS Programmers Manual, Volume II," NASA Lewis Research Center, 1972.

[16] "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," SAE Aerospace Recommended Practice 1256, Oct. 1971.

[17] Lyons, V. J., "Effect of Fuel/Air Nonuniformity on Nitric Oxide Emissions," NASA TP-1798, 1981.

[18] Cooper, L. P., "Effect of Degree of Fuel Vaporization upon Emissions for a Premixed Partially Vaporized Combustion System," NASA TP-1282, 1980.

[19] Touchton, D. L. and Dibelius, N. R., "A Correlation of Nitrogen Oxides Emissions with Gas Turbine Operating Parameters," ASME Paper 76-GT-14, March 1976.

[20] Roffe, G. and Venkataramani, K. S., "Experimental Study of the Effect of Cycle Pressure on Lean Combustion Emissions," NASA CR-3032, 1978.