AIAA JOURNAL
Vol. 35, No. 11, November 1997

Stability and Emissions of Lean, Turbulent, Premixed Flames with Very Lean Coflow

J. C. Hermanson*
Worcester Polytechnic Institute, Worcester, Massachusetts 01609
and
M. B. Colket† and J. J. Sangiovanni‡
United Technologies Research Center, East Hartford, Connecticut 06108

The potential for improving lean stability and reducing NO_x emissions of combustion systems by employing an ultralean, partially premixed fuel injection strategy was examined experimentally. The test configuration was a coannular combustor configuration at atmospheric pressure with a simulated natural gas fuel. The core flow consisted of fuel premixed with air; the coflow was either fuel premixed with air, sufficiently lean to be below the flammability limit, or air only. The flame was stabilized on axisymmetric, bluff body flameholders sting-mounted along the centerline of the combustor. Mounting the flameholder from the inlet end of the combustor resulted in a more stable flame under lean conditions than was the case for the flameholder mounted from above the combustor exit. When either flameholder was located sufficiently far downstream from the core flow nozzle tip, an enhancement of lean stability was achieved by increasing the fuel content of the coflow stream. This change in stability can be accounted for by defining an effective equivalence ratio at the flameholder location that takes into account the presence of coflow fuel and the core/coflow mixing. The addition of fuel to the coflow resulted in up to a factor of 4 lower levels of total NO_x compared with the case with fuel in the core flow only. This decrease in NO_x was accompanied by a drop in peak temperature. The total exhaust NO_x concentration was comparable for all configurations when run close to their corresponding lean limits. These results suggest that changing the distribution of injected fuel can have a beneficial impact on the lean-limit stability and emissions characteristics of turbulent, premixed combustion systems.

Introduction

THE requirements for low emissions and concerns about flame stability have motivated numerous studies of a wide variety of model and practical combustion systems. In particular, the use of lean, premixed gaseous fuels or prevaporized liquid fuels has been seen to result in a significant decrease in exhaust emissions compared with the direct injection of gas-phase or liquid fuels.[1] However, significant practical problems have to be overcome to realize this potential reduction in NO_x levels. One practical difficulty lies in achieving perfect premixing. Perhaps more seriously, the possibility of fuel autoignition at high combustor inlet temperatures and pressures may pose a serious obstacle to the practicality of premixed combustion in some applications. The use of a very lean, i.e., incombustible coflowing mixture with a core combusting jet might allow the injection of significant amounts of fuel into a combustor while at the same time precluding autoignition. In addition, the use of a very lean coflowing stream may have a beneficial effect on the stability of a central fuel jet.[2]

Although NO_x production in premixed and partially premixed configurations has been studied previously,[3–8] much remains to be understood about the emissions of complex, turbulent, hydrocarbon flames with nonuniform fuel/air mixtures. Sun et al.[4] studied the combustion of a rich mixture of methane and air injected through a central tube. While maintaining a fixed overall equivalence ratio for the combustor, they found that by decreasing the core burner tube equivalence ratio they could reduce the amount of NO_x formed by nearly 20%. They also reported the existence of an optimum fuel tube equivalence ratio for the minimization of NO_x emissions. Turns et al.[6] mixed various amounts of inert diluent or air with the fuel. They found the effects of dilution and premixing to be strongly dependent on fuel type, with partial premixing leading to an increase in NO_x for sooty fuels, e.g., propane and ethylene, but a corresponding decrease for nonluminous flames (such as CO or hydrogen). The difference was attributed to flame radiation effects on flame temperature. Driscoll et al.[7] demonstrated a reduction in NO_x emissions by roughly a factor of 4 by increasing the amount of partial premixing in hydrogen/air flames. They attributed the decrease in NO_x emissions to a decrease in flame length and a reduction in the associated residence time due to the partial premixing. Negeshi[8] reported that changing the flow rate and composition of a pilot flame in a coaxial burner also could impact the NO_x emissions.

These studies generally used variations in the premixed state of the system by changing the stoichiometry and/or diluent level of a core flame in a combustor, often stabilized with the aid of a pilot flame. There have been relatively few emissions measurements performed for premixed combustion systems with a coflowing stream containing additional fuel. In one such study, Karim et al.[2] found that the presence of a small amount of fuel premixed in the surrounding stream greatly enhanced the flame stability. Their configuration consisted of a diffusion fuel jet injected with a coflow containing added fuel. The current work examines how the presence of a premixed fuel/air coflowing stream, itself sufficiently lean to be below the flammability limit, influences the lean stability limit, exhaust emissions, and temperature rise of a lean, premixed combustor.

Experimental Facility

Experiments were performed at atmospheric pressure using the axisymmetric, coannular combustor shown in Fig. 1. The core nozzle (19.6-mm diameter) was supplied with gaseous fuel premixed with air. The coflow (45-mm outer diameter) consisted either of fuel premixed with air or of air only. All air and fuel flow rates were metered using calibrated choked orifices with an estimated accuracy of ±3%. The mixture equivalence ratios were determined from the measured air and fuel flow rates and were thus accurate to within 6%. Shear layer mixing of the two streams commenced downstream of the core nozzle lip. The combustion zone was enclosed by a circular quartz chimney 180 or 270 mm in length. Upstream turbulence management was accomplished by several stations of perforated plate

Received Oct. 24, 1996; revision received June 27, 1997; accepted for publication July 14, 1997.

*Associate Professor, Mechanical Engineering Department. Senior Member AIAA.

†Principal Research Scientist, Advanced Propulsion and Thermofluid Systems. Member AIAA.

‡Manager, Thermochemical Components.

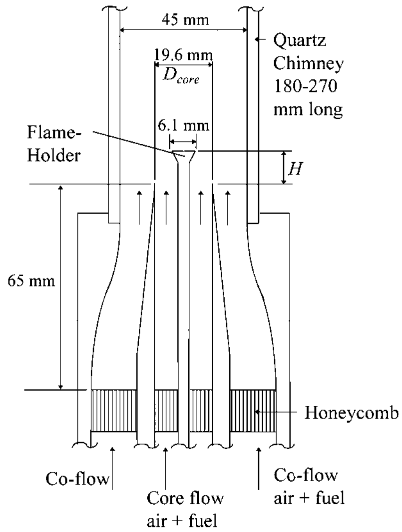

Fig. 1 Schematic diagram of combustor.

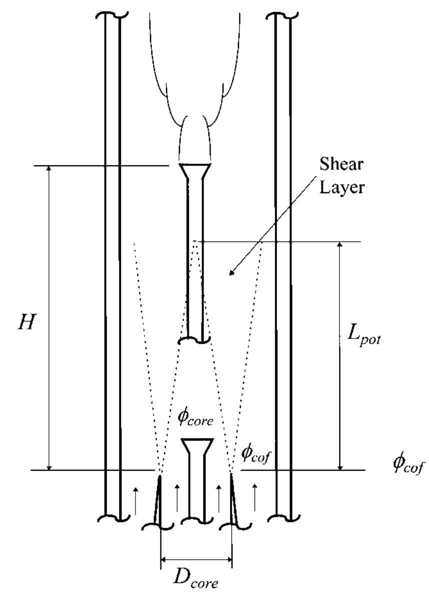

Fig. 2 Close-up of mixing geometry.

(not shown) and a section of honeycomb, followed by a 1.8:1 contraction in the coflow stream (the core stream was not contracted). The length of the contraction section was 65 mm. The cold gas velocity in the core flow, U_{core}, was varied over a range of 10–20 m/s. For all cases reported here, the core flow velocity exceeded that of the coflow by the ratio $U_{\text{core}}/U_{\text{cof}} = 4.1$.

Experiments were conducted using a natural gas simulant consisting of 93% methane and 7% ethane. All inlet air and fuel/air mixtures were unheated. The flame was stabilized on a bluff-body flameholder mounted on a sting placed on the centerline of the core stream. Either of two bluff-body flame stabilizers was employed in this work: an inverted, truncated cone [90 deg vertex angle, sting-mounted from below the combustor inlet (bottom-mounted) as shown in Fig. 1] or a flat disk mounted from beyond the combustor exit (top-mounted). In both cases, the flameholder diameter was 6.1 mm. The downstream position of the flameholders, H/D_{core}, was adjustable, allowing placement of the flameholder at any desired station relative to the potential core region of the core flow (shown schematically in Fig. 2). In cases where the flameholder was situated within the potential core, i.e., $H < L_{\text{pot}}$, the fuel/air mixture at the flameholder was essentially that of the core nozzle flow. For flameholder locations downstream of the end of the potential core ($H > L_{\text{pot}}$), the mixing of core and coflow streams led to a fuel/air stoichiometry in the vicinity of the flameholder in between the values of the core and coflow streams. The length of the potential core was estimated from determination of the lean blowoff limit to be approximately 2.9 diameters downstream of the core nozzle exit, i.e., $L_{\text{pot}}/D_{\text{core}} \approx 2.9$.

The luminous flame region was recorded on videotape, allowing determination of the combustion lean stability limits by visual observation. Gas sampling was performed by a water-cooled stainless steel sampling probe with the coolant maintained at a temperature exceeding 100°C to preclude water condensation. Water vapor was subsequently removed by a cold trap before the sample gas entered the emissions analyzers. The sampled gas was analyzed for NO_x (NO and total NO_x), CO, CO_2, O_2, and unburned hydrocarbons using standard chemiluminescent, nondispersive infrared, paramagnetic, and flame ionization detection instruments, respectively. The repeatability of emissions measurements performed during combustor operation was typically 6% or better. The concentration of NO_x in all cases exceeded the measured amount of NO, and because of the overall lean conditions of the sample gas, there was no reason to expect a loss of NO during the conversion to NO_2 in the analyzer as has been observed under fuel-rich conditions.[9] Time-averaged temperatures were measured using a platinum/platinum-13% rhodium thermocouple assembly fabricated from 25-μm-diam wire and coated with silicon oxide. The sampling probe and thermocouple were located 7.7 core nozzle diameters (150.9 mm) downstream of the flameholder. The chimney length was selected in all cases to maintain a constant distance from the flameholder to the chimney exit for each flameholder position.

Results

Lean Stability Limits

Combustor lean stability limits employing both the top-mounted and bottom-mounted flameholders are shown in Fig. 3. For all cases shown here, the flameholders were mounted close to the core nozzle exit, well within the potential core at the location $H/D_{\text{core}} = 0.32$. As seen in Fig. 3, the addition of fuel to the coflow had no impact on the flame stability, confirming the absence of core flow/coflow mixing at the location of the flameholder in this case. A correlation for the stability limits of premixed flames can be expressed in terms of a Peclet number, $Pe \equiv U_{\text{BO}}D/v$, where U_{BO} is the blowout velocity, D the flameholder diameter, and v the cold kinematic viscosity.[10] The correlation shown in Fig. 3 was developed from arguments presented by Spalding[11] and Ballal and Lefebvre.[12] Spalding initially suggested a correlation of the form

$$U_{\text{BO}}D/a = \text{const}(S_L D/a)^n \tag{1}$$

where S_L is the laminar flame speed. The exponent has the value $n = 2$ for $Pe > 10^4$ and has the value $n = 1.5$ when $Pe < 10^4$. The change in the correlation exponent evidently reflects changes in the nature of the flame stabilization with different flow conditions. Specifically, changes in the hot wake structure impact the flame stability, as the flame will blow off when the time that the fresh gas is in contact with the hot recirculation zone becomes too short for ignition.[13] These changes can be characterized in terms of the flameholder Reynolds number $Re \equiv U_{\text{BO}}D/v$. Zukoski and Marble[14] reported a distinct change in flame stability at a Reynolds number in the neighborhood of 1×10^4, above which a fully developed turbulent wake exists. In the current investigation, the flameholder Reynolds numbers and Peclet numbers were, respectively, in the ranges $4 \times 10^3 \leq Re \leq 8 \times 10^3$ and $3.9 \times 10^3 \leq Pe \leq 7.9 \times 10^3$, indicating use of the lower value of the exponent in the correlation, $n = 1.5$.

The constant factor in the correlation cited in Eq. (1) can be expressed in terms of a shape factor C_S, which accounts for the geometry of the flameholder, and a blockage correction factor B_a (Ref. 12). Matching the correlations at the point $U_{\text{BO}}D/a = 10^4$ gives the required expression for blow off velocity for the current study as

$$U_{\text{BO}}D/a = 10[C_S(1 - B_a)]^{0.75}(S_L D/a)^{1.5} \tag{2}$$

There is some variation in the laminar flame speed S_L as reported in the literature. The correlation given by Eq. (2) was evaluated in this work using flame speed data for methane fuel reported by Van Maaren et al.[15] The blockage correction was not large, as the flameholder was always located downstream of the core nozzle exit.

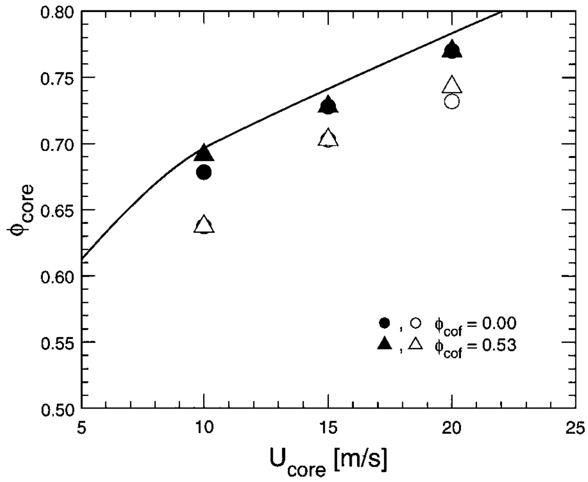

Fig. 3 Lean stability limits. Closed symbols, top-mounted flameholder; open symbols, bottom-mounted flameholder; and ——, correlation [Eq. (2)] based on laminar flame speed data by Van Maaren et al.[15]

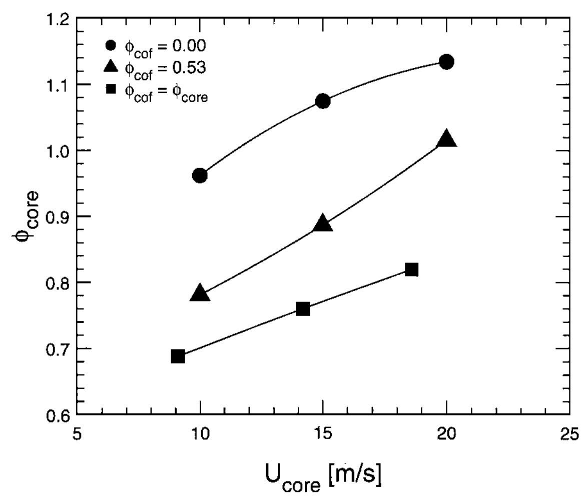

Fig. 4 Effect of coflow fuel on lean stability limit for top-mounted flameholder.

The lean stability limit for the top-mounted flameholder is in reasonable agreement with the correlation presented earlier, as seen in Fig. 3. A noticeably leaner stability limit was observed for the bottom-mounted flameholder at each flow condition. The difference in the experimentally determined stability limit substantially exceeds that due to the difference in the geometric shape factor between the value of $C_S = 1.6$ employed for the disk (and used in the correlation shown) and $C_S = 1.4$ for the 90-deg cone. The bulk of the observed difference is likely due to a combination of fuel/air mixture preheating due to heat conduction along the length of the sting and also sting boundary-layer effects, both of which are operative for the bottom-mounted flameholder only.

For cases where the flameholders were mounted farther downstream ($H/D_{\text{core}} > 2.9$) from the core flow nozzle tip, increasing the fuel content of the coflow stream resulted in a decrease in core equivalence ratio at lean blowout. Representative lean stability results for these cases are shown in Fig. 4, where the top-mounted flameholder was mounted at a downstream distance of $H/D_{\text{core}} = 6.4$. At a given cold gas inlet velocity, the core equivalence ratio at blowoff decreased substantially with the addition of fuel to the coflow air.

The results of the current work indicate that the coflow fuel was entrained into the core flow and played an important role in flame stabilization at the flameholder, even when the coflow mixture itself was well below the flammability limit. Note that the observed decrease in core equivalence ratio at lean blowoff generally did not imply a lower overall equivalence ratio for the system; the amount of fuel in the coflow stream actually resulted in a slight increase in overall equivalence ratio.

The improvement in the lean stability of the flame due to the addition of coflow fuel can be characterized in terms of an effective equivalence ratio at the flameholder, which can be defined to take into account the mixing of the core and coflow streams. The effective equivalence ratio ϕ_{eff} can be expressed in terms of the stoichiometries of the coflow and core streams as follows:

$$\phi_{\text{eff}} = \alpha\phi_{\text{cof}} + (1-\alpha)\phi_{\text{core}} \tag{3}$$

where the parameter α is used to characterize the amount of mixing. The extreme values of the mixing parameter are $\alpha = 0$ for no core/coflow mixing, e.g., $H/D_{\text{core}} = 0.32$, and $\alpha = 0.52$ for the idealized case of complete core/coflow mixing ($H/D_{\text{core}} \gg 5$). The maximum possible value of α exceeds 0.5 due to the slightly higher volumetric flow rate (velocity × area) of the coflow relative to that of the core flow. One approach to determine α is to assume that, for fixed core/coflow velocities and fixed geometry, i.e., flameholder type and location (H/D_{core}), the effective equivalence ratio at lean blowoff can be taken to be a constant. In this case, only the distribution of the fuel changes, allowing differentiation of Eq. (3):

$$\mathrm{d}\phi_{\text{eff}}/\mathrm{d}\phi_{\text{cof}} = \alpha + (1-\alpha)(\mathrm{d}\phi_{\text{core}}/\mathrm{d}\phi_{\text{cof}}) = 0 \tag{4}$$

which allows solving for the mixing parameter, giving $\alpha = (1 - \mathrm{d}\phi_{\text{cof}}/\mathrm{d}\phi_{\text{core}})^{-1}$. The flame stability results do, in fact, indicate, for given velocities and a fixed flameholder position, a sufficiently linear decrease in core equivalence ratio with increasing coflow fuel to allow the determination of the degree of mixing and effective equivalence ratio at the flameholder using this method.

Calculated effective equivalence ratios at lean blowoff for both flameholders at several downstream locations are shown in Fig. 5. The bottom-mounted flameholder was not extended to the position $H/D_{\text{core}} = 6.4$. The curves shown were faired through the data for the close-mounted flameholders, i.e., at $H/D_{\text{core}} = 0.32$. The value of the mixing parameter for the bottom-mounted flameholder was $\alpha = 0.12$ at the location $H/D_{\text{core}} = 5.1$; the corresponding value for the top-mounted flameholder at the same location was $\alpha = 0.13$. As expected, the value of the mixing parameter increased with downstream distance, rising to a value of $\alpha = 0.27$ for the top-mounted flameholder at $H/D_{\text{core}} = 6.4$. For the case of the bottom-mounted flameholder, the effective equivalence ratio calculated for $H/D_{\text{core}} = 5.1$ agrees fairly well with the corresponding values for $H/D_{\text{core}} = 0.32$, suggesting that the effective equivalence ratio concept does characterize the impact of the mixing of the core and coflow streams upstream of the flameholder on the flame stability.

For the top-mounted flameholder, the effective equivalence ratios for the flameholder locations $H/D_{\text{core}} = 5.0$ and 6.4 increased somewhat from corresponding values for $H/D_{\text{core}} = 0.32$, that is, the flame became less stable. The amount of this change appeared to increase with increasing velocity. The degraded stability might be related to a fluid mechanical transition in the wake, which could occur at a lower Reynolds number for the downstream flameholder locations

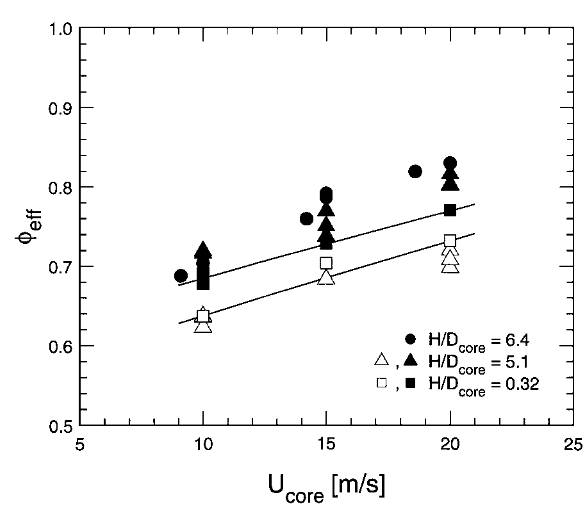

Fig. 5 Effective equivalence ratio at lean blowoff. Solid symbols, top-mounted flameholder and open symbols, bottom-mounted flameholder.

Table 1 Centerline species and temperatures[a]

Case	H/D_{core}	ϕ_{core}	ϕ_{cof}	ϕ_{eff}	ϕ_{oa}	UHC, ppm	CO_2, %	CO, ppm	O_2, %	NO_x, ppm	T, K
1	0.32	0.94	0.00	0.94	0.46	71	11.2	>2500	3	10.2	2098
2	5.1	0.94	0.00	0.83	0.46	1040	8.5	1200	6.7	10.68	1909
3	5.1	0.73	0.53	0.71	0.63	732	7.3	843	8.2	2.78	1835
						At lean blowoff					
4	0.32	0.66	0.00	0.66	0.31	4117	5.3	2088	10.8	1.44	1569
5	5.1	0.75	0.00	0.67	0.37	5402	3.7	>2500	13.4	2.09	1292
6	5.1	0.67	0.53	0.65	0.60	1029	7.8	981	8.3	2.53	1749

[a]All values reported on dry basis; NO_x corrected to 15% O_2.

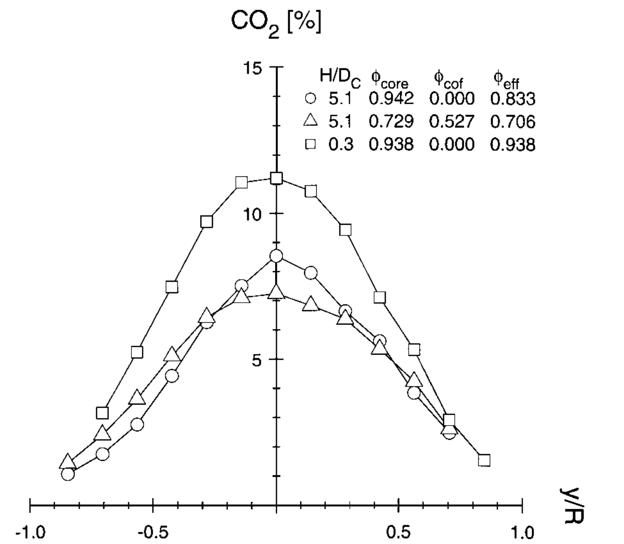

Fig. 6 CO_2 profiles. The location $y/R = 0$ corresponds to the combustor centerline.

than for the close-mounted flameholder ($H/D_{core} = 0.32$) due to turbulent mixing. This may be related to the observation by Zukoski and Marble[14] that the hot wake becomes unstable with increasing Reynolds numbers (up to about 1×10^4), leading to a shorter recirculation region and, consequently, a higher lean stability limit. By contrast, for the bottom-mounted flameholder, the flame appeared to become relatively slightly more stable with increasing downstream flameholder location (in terms of ϕ_{eff}) than the corresponding top-mounted flameholder cases. In this case, the presence of the support sting upstream of the flameholder cone, with its associated boundary layer, would complicate the wake transition effect suggested for the top-mounted flameholder, possibly resulting in a different stability trend.

Calculation of the value of the mixing parameter for different flameholder locations also allowed the approximate determination of the point below which no significant core/coflow stream mixing occurred, i.e., $\alpha \approx 0$. This yielded the threshold value of $H/D_{core} \approx 2.9$ cited earlier.

Exhaust Emissions and Flame Temperatures

Quantitative measurements of emissions and time-averaged temperatures were performed for flames both with and without fuel in the coflow stream. For all cases reported here, the sampling probe and thermocouple were located 7.7 core nozzle diameters (150.9 mm) downstream of the flameholder. This location was sufficiently far downstream from the flameholder so that near the combustor centerline ($y/R \leq 0.5$, where y is the distance from the combustor centerline and R the radius of the chimney) in general less than 0.1% of the injected fuel was unburned, as determined from the measurement of the concentration of unburned hydrocarbons. For the cases near the lean blowoff limit, up to 0.6% of the fuel remained unburned at the probe sampling location for $y/R \leq 0.3$. The measurement of emissions and gas temperatures was only performed for the bottom-mounted flameholder.

Representative carbon dioxide concentration profiles are shown in Fig. 6. All emissions data in this work are reported on a dry basis (water vapor removed). The air velocities were the same in all cases shown in Fig. 6, with the only difference being the flameholder position and the fuel distribution, as indicated. The two cases without coflow fuel were run at approximately the same core flow equivalence ratio. For the case with coflow fuel at $H/D_{core} = 5.1$, sufficient fuel was added to the coflow stream to create an incombustible mixture with an equivalence ratio of $\phi_{cof} = 0.53$. At the same time, the core equivalence ratio decreased to roughly 0.05 above the point of lean blowoff.

The highest observed centerline carbon dioxide concentration was for the case of the close-mounted flameholder ($H/D_{core} = 0.32$). Because the flameholder in this case was mounted within the inner jet potential core (see Fig. 2), there was less dilution and turbulent mixing between the flameholder location and the sampling probe tip than for cases where the flameholder was mounted farther downstream. For this reason, mounting the flameholder farther downstream, e.g., $H/D_{core} = 5.1$, yielded a noticeably lower level of centerline CO_2, even for a similar equivalence ratio. For fixed overall equivalence ratios, the mass-averaged CO_2 level should be identical for these two cases. That this is not clear from the results shown in Fig. 6 was due to high levels of CO and unburned hydrocarbons (beyond the useful range of the analyzers) toward the periphery of the combustor, i.e., $y/R > 0.5$.

Rearranging the fuel distribution by premixing some of the fuel into the coflow instead of the core flow resulted in an additional decrease in centerline CO_2 concentration, even for a somewhat higher overall fuel/air ratio. The case with coflow is also seen to exhibit a slightly broader CO_2 profile than the case with core fuel only, with slightly higher amounts of CO_2 away from the combustor centerline. This broadening is consistent with the broader distribution of fuel. This systematic decrease in CO_2 concentration is also consistent with the corresponding decrease in the calculated effective equivalence ratio at the flameholder for each case.

A summary of representative centerline emissions and temperatures at the sampling probe location is presented in Table 1. The effective equivalence ratio was calculated for each case using Eq. (3); the overall equivalence ratio ϕ_{oa} was determined from the volume flow rates and equivalence ratio of the core and coflow streams. The first three cases (1–3) correspond to those presented in Fig. 6 discussed earlier. The second set of three cases (4–6) were run with equivalence ratios very near the lean-blowoff limit (within roughly 0.015) in all cases. The concentration of CO and, especially, the amount of unburned hydrocarbons increased significantly as the lean-blowoff limit was approached. The high level of CO measured for case 1 is consistent with the expected equilibrium value at that relatively high equivalence ratio. The CO levels for cases 3 and 4–6 are somewhat higher than those indicated for equilibrium. As these cases are all closer to lean blowoff than case 1, an elevated level of CO would be expected owing to the incomplete combustion.

The measured values of centerline CO_2 and O_2 concentration can be compared with the theoretical equilibrium value for a given equivalence ratio. Equilibrium calculations performed using the CHEMKIN (Ref. 16) and STANJAN (Ref. 17) codes for the equivalence ratio $\phi_{eff} = 0.94$ (case 1) gave values (on a dry basis) of CO_2 and O_2 concentration of 10.5 and 1.7%, respectively. The value of CO_2 is within 6% of the experimental value. The O_2 value agrees somewhat less favorably. The agreement is less satisfactory for cases 2 and 3, where the theoretical CO_2 values are on average 16% above the measured values. The reason for the discrepancy evidently lies in the increased dilution and mixing that accompanied the cases at $H/D_{core} = 5.1$, which would be expected to reduce the amount of CO_2 while at the same time leading to an increased residual O_2 concentration.

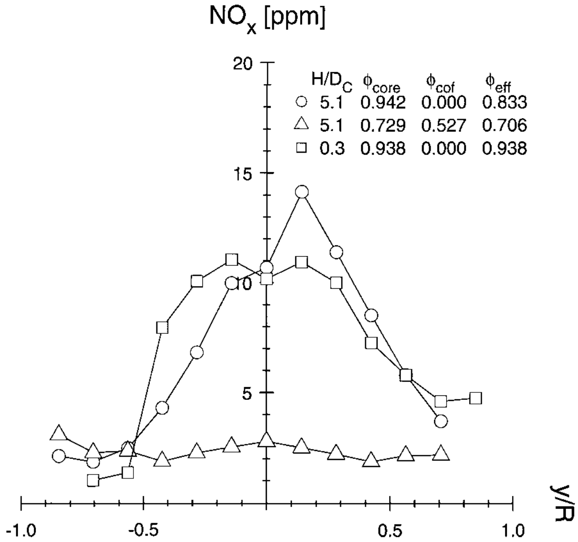

Fig. 7 Total NO_x profiles, corrected to 15% O_2.

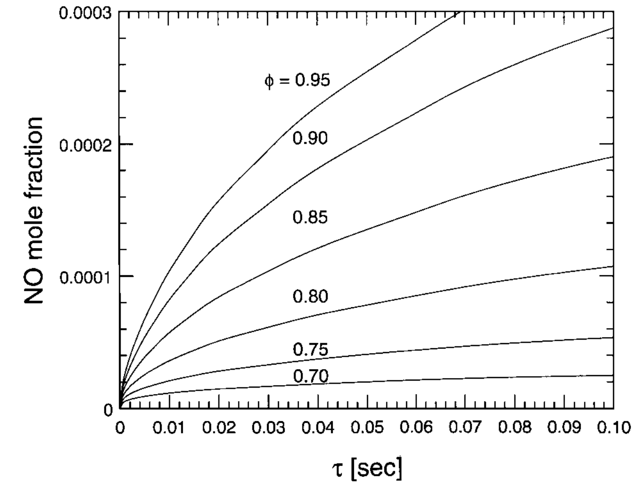

Fig. 8 Perfectly stirred reactor calculation of NO concentration, corrected to 15% O_2.

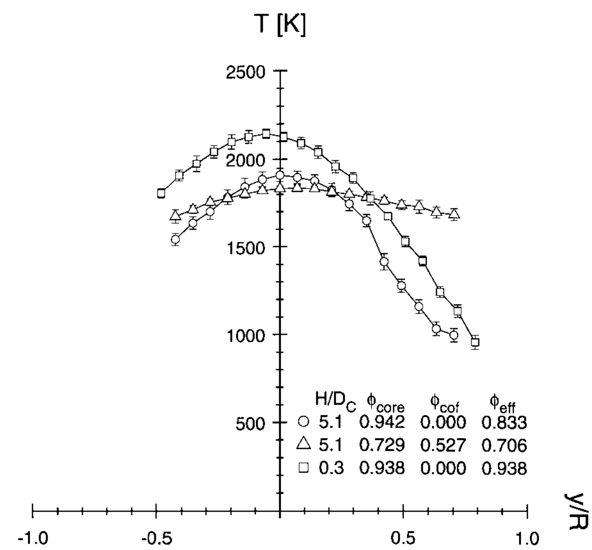

Fig. 9 Gas temperature profiles corresponding to the conditions of Figs. 6 and 7.

Typical measured NO_x profiles are shown in Fig. 7 for cases 1–3. All NO_x emissions data were corrected to 15% oxygen concentration on a dry basis. Nearly a factor of 4 decrease in peak total NO_x concentration on the combustor centerline was measured when fuel was in the coflow compared with the case with fuel in the core flow only at a fixed flameholder location. This decrease in NO_x concentration occurs in spite of the nearly 40% increase in the overall equivalence ratio brought about by the addition of coflow fuel. This reduction in NO_x level exceeds that observed by Driscoll et al.[7] for methane fuel. (They did, however, observe a comparable reduction in NO_x with hydrogen fuel.) In their case, air was diverted from the coaxial flow and premixed with the core jet, resulting in a leaner core jet but with the same total fuel and air flow. (They did not have any fuel in the coflow.) The NO_x behavior for diluted flames was also discussed by Turns et al.[6] They observed that the addition of an inert diluent or air to the fuel stream in a jet flame affected flame structure and NO_x production. The decrease in the amount of available fuel in the central jet, although keeping the mixing unchanged, gave a shortened flame length, accompanied by a decrease in NO_x for nonradiant flames. The combination of shorter residence times and lower temperatures yielded less NO_x. The current work appears to retain some of the benefits of fuel dilution, at least as regards NO_x production, while at the same time allowing the overall stoichiometry for the system to increase due to the presence of fuel in the coflowing stream. Also note that this decrease in NO_x emissions is consistent with the corresponding decrease in effective equivalence ratio.

The two cases without coflow fuel (1 and 2) exhibited similar centerline concentrations of total NO_x in spite of having different effective equivalence ratios. This was likely a consequence of the difference in residence time between the flameholder and sampling probe with the changing value of H/D_{core}. Thus, whereas case 1 ($H/D_{\mathrm{core}} = 0.32$) had a substantially higher equivalence ratio than its counterpart at $H/D_{\mathrm{core}} = 5.1$ (case 2), it also had a significantly shorter residence time for NO_x formation owing to the locally higher velocity.

The case with coflow fuel was in fact somewhat closer to lean blowoff than the cases without coflow fuel, as mentioned earlier. When the configurations represented in Fig. 7 were run near their respective lean-blowout limits (cases 4–6), the difference in NO_x levels largely disappeared (see Table 1). These much lower levels approached the lower detection limit of the NO_x analyzer.

Numerical simulation of the NO_x concentration for the conditions of this investigation was performed using a PSR (perfectly stirred reactor) code[18] and the CHEMKIN II routines. Computations were performed using the GRI-Mech version 2.11 for methane/air chemistry. A plot of the calculated NO mole fraction, corrected to 15% oxygen, is shown in Fig. 8 for residence times τ ranging from 0–100 ms. Although the exact values of residence time on the centerline between the flameholder and the sampling probe are not known, limiting values can be inferred from the velocity of the core stream at the temperatures indicated in Table 1 and from the cold coflow velocity. This suggests a residence time ranging from 2.5 to 63 ms, respectively. The calculated results shown in Fig. 8 suggest, for this range of residence time, a drop in NO concentration of a factor of roughly 3–5 in going from an effective equivalence ratio of $\phi_{\mathrm{eff}} = 0.83$ to $\phi_{\mathrm{eff}} = 0.71$. This is in reasonable agreement with the observed experimental decrease of a factor of approximately 4. This analysis suggests that the drop in NO_x is consistent with the change in effective equivalence ratio for the cases with and without coflow fuel at $H/D_{\mathrm{core}} = 5.1$ (cases 2 and 3). These computations also suggest, for similar residence time, that the case at $H/D_{\mathrm{core}} = 0.32$ and $\phi_{\mathrm{eff}} = 0.94$ (case 1) would have a much higher level of NO_x production than the case at $H/D_{\mathrm{core}} = 5.1$ and $\phi_{\mathrm{eff}} = 0.83$ (case 2), as the effective equivalence ratio was a full 0.1 higher. The calculations shown in Fig. 8 suggest that this factor would be in the range of roughly 2–3. In fact, however, the residence time between the two cases could not be the same and was considerably shorter for case 1 ($H/D_{\mathrm{core}} = 0.32$) due to the relative lack of upstream mixing and accompanying momentum transport. This drop in residence time would imply a decrease in NO_x production amounting to roughly a factor of 2 for residence times on the order of 10 ms, effectively offsetting the increase in NO due to the higher fuel/air ratio.

The measured gas temperatures corresponding to the emissions measurements for the cases discussed earlier are shown in Fig. 9. All thermocouple data shown were corrected for radiation error, which typically amounted to less than 50 K for the peak temperatures. The noticeable drop in peak temperature (up to 250 K) between the profiles taken at $H/D_{core} = 0.32$ (case 1) and that at $H/D_{core} = 5.1$ (case 2) was a consequence of the more substantial amount of mixing between the core and coflow streams that had occurred at the probe location. In addition, the shorter residence time due to the higher velocity associated with the $H/D_{core} = 0.32$ case served to minimize the diffusion of energy, leading to a higher centerline temperature than for the case of $H/D_{core} = 5.0$. For the downstream flameholder location ($H/D_{core} = 5.1$), the introduction of fuel into the coflow resulted in a modest drop in the peak gas temperature of roughly 100 K. This drop is qualitatively consistent with the decrease in effective equivalence ratio at the flameholder brought about by the addition of fuel to the coflow stream. This modest decrease in flame temperature could, however, represent nearly an order of magnitude decrease in NO_x production due to the Zeldovich mechanism[19, 20] for temperatures in the vicinity of 2000 K. The addition of coflow fuel also resulted in a broadening of the temperature profile compared with the case with core fuel only. In fact, the relatively modest difference in NO_x level for the two cases with core fuel only, even though the measured gas temperature at the sampling probe location differed by nearly 200 K, suggests a large role for the flame-front generated NO_x chemistry, which is much less temperature dependent than the postflame (Zeldovich) mechanism.[5]

The centerline temperatures changed markedly for cases run near the lean-blowoff limit (cases 4–6, Table 1). Although the effective equivalence ratio was very similar for these cases (which is not unexpected, because the effective equivalence ratio is defined based on lean blowoff data), the measured temperatures vary considerably. The highest temperature was recorded for case 6, which had the highest overall fuel/air ratio. The somewhat lower fuel flow rate for case 4 led to a lower flame temperature than case 6. The lowest centerline temperature was recorded for case 6. In this case the mixing and dilution that accompanied this downstream location, in the absence of added fuel in the coflow, led to a relatively low flame temperature. This complicated behavior, for similar values of ϕ_{eff}, suggest that the effective equivalence ratio concept may be somewhat less useful in characterizing flame temperatures than in understanding flame stability changes brought about by mixing upstream of the flameholder combined with the addition of coflow fuel.

Summary

The potential to improve lean stability and to reduce exhaust emissions of combustion systems by employing a very lean, partially premixed fuel injection strategy was explored experimentally in a coannular combustor with a sting-mounted flameholder on the combustor centerline. For cases where the flameholder was located sufficiently far downstream of the core nozzle exit, increasing the fuel content of the coflow produced a decrease in core equivalence ratio at lean blowout but also generally resulted in a somewhat higher overall equivalence ratio. Mounting the flameholder sting at the inlet end of the combustor consistently resulted in a more stable flame under lean conditions, for a given flameholder location, than was the case when the flameholder sting was mounted from above the combustor exit. This shift in lean stability can be attributed to a decrease in velocity at the flameholder owing to the boundary layer on the sting, as well as preheating of the mixture upstream of the flameholder by heat transfer through the support sting.

For cases where the flameholders were situated more than three nozzle diameters downstream of the core flow nozzle tip, increasing the fuel content of the coflow stream resulted in a substantial decrease in core equivalence ratio at lean blowout. The stabilizing effects of the addition of fuel to the coflow can be characterized in terms of an effective equivalence ratio, which accounts for the mixing of the core and coflow streams upstream of the flameholder. The degree of this mixing was estimated from lean stability results for a given flameholder location and core and coflow inlet gas velocities. The effective equivalence ratio concept is successful in accounting for changes in flame stability over a range of velocities, flameholder locations, and core/coflow stoichiometries. Deviations from the expected fuel/air ratio at blowoff can be attributed to changes in the wake structure behind the flameholders with changing Reynolds number.

The introduction of coflow fuel resulted in as much as a factor of 4 decrease in peak total NO_x concentration, even while the overall fuel/air ratio was increased nearly 40% by the addition of fuel to the coflow stream. This decrease in NO_x formation was accompanied by a decrease in the computed effective equivalence ratio. There was also a corresponding modest drop in peak gas temperature of roughly 100 K. The decreases in NO_x concentration and gas temperature were substantially less apparent, however, when cases with and without coflow fuel were run close to their corresponding lean limits.

Numerical calculation of the expected NO concentration for the conditions of this investigation was performed using a perfectly stirred reactor code. The indicated tradeoffs in equivalence ratio and residence time as they affect NO concentration levels are consistent with the results of the experiment. The NO_x emission and centerline combustion temperatures did not scale entirely consistently with the corresponding effective equivalence ratio, suggesting that the effective equivalence ratio concept may be somewhat less useful in characterizing emissions and temperature rise than in predicting the flame stability of lean, premixed flames with a very lean coflow.

Acknowledgments

Financial support for this research was provided by United Technologies Corporation. The authors acknowledge the assistance of T. A. McLeod and R. J. Sabala in conducting the experiments reported here, as well as helpful discussions and suggestions provided by L. J. Spadaccini, M. F. Zabielski, and B. A. Knight.

References

[1]Lefebvre, A. H., "Pollution Control in Continuous Combustion Engines," *Fifteenth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1974, pp. 1169–1180.

[2]Karim, G. A., Wierzba, I., Metwally, M., and Mohan, K., "The Combustion of a Fuel Jet in a Stream of Lean Gaseous Fuel-Air Mixtures," *Eighteenth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1981, pp. 977–991.

[3]Roffe, G., and Ferri, A., "Effect of Premixing Quality on Oxides of Nitrogen in Gas Turbine Combustors," NASA CR-2657 Feb. 1976.

[4]Sun, K., Lyle, K. H., Dutta, P., Frankel, S. H., and Gore, J. P., "A Computational and Experimental Study of Turbulent Partially Premixed Jet Flames," AIAA Paper 95-2683, July 1995.

[5]Røkke, N. A., Hustad, J. E., and Sønju, O. K., "A Study of Partially Premixed Unconfined Propane Flames," *Combustion and Flame*, Vol. 97, No. 1, 1994, pp. 88–106.

[6]Turns, S. R., Myhr, F. H., Bandaru, R. V., and Maund, E. R., "Oxides of Nitrogen Emissions from Turbulent Jet Flames: Part II—Fuel Dilution and Partial Premixing Effects," *Combustion and Flame*, Vol. 93, No. 3, 1993, pp. 255–269.

[7]Driscoll, J. F., Chen, R.-H., and Yoon, Y., "Nitric Oxide Levels of Turbulent Jet Diffusion Flames: Effects of Residence Time and Damkohler Number," *Combustion and Flame*, Vol. 88, No. 1, 1992, pp. 37–49.

[8]Negishi, N., "Lean Premixture Combustion on a Coaxial Burner," *Nineteenth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1982, pp. 441–447.

[9]Siewerts, R. M., "Hydrogen Interference in Chemiluminescent NO_x Analysis," *Combustion and Flame*, Vol. 25, No. 2, 1975, pp. 273–276.

[10]Putnam, A. A., and Jensen, R. A., "Application of Dimensionless Numbers to Flash-Back and Other Combustion Phenomena," *Third Symposium on Combustion, Flame, and Explosion Phenomea*, Combustion Inst., Pittsburgh, PA, 1949, pp. 89–98.

[11]Spalding, D. B., *Some Fundamentals of Combustion*, Butterworth, London, 1955, Chap. 5.

[12]Ballal, D. R., and Lefebvre, A. H., "Some Fundamental Aspects of Flame Stabilization," *Proceedings of the Fifth International Symposium on Airbreathing Engines* (Bangalore, India), National Aeronautical Lab., Bangalore, India, 1981, pp. 48-1–48-8 (A81-29051 12-07).

[13]Zukoski, E. E., and Marble, F. E., "Experiments Concerning the Mechanism of Flame Blowoff from Bluff Bodies," *Proceedings of the Gas Dynamics Symposium on Aerothermochemistry*, Northwestern Univ., Evanston, IL, 1955, pp. 205–210.

[14]Zukoski, E. E., and Marble, F. E., "The Role of Wake Transition in the Process of Flame Stabilization on Bluff Bodies," *Combustion Researches and Reviews*, 1955, AGARD, Butterworth, London, 1955, pp. 167–180.

[15]Van Maaren, A., Thung, D. S., and De Goey, L. P. H., "Measurement of Flame Temperature and Adiabatic Burning Velocity of Methane/Air Mixtures," *Combustion Science and Technology 96* (4–6), 1994, pp. 327–344.

[16]Kee, R. J., Rupley, R. M., and Miller, J. A., "CHEMKIN II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics," Sandia National Labs., Rept. SAND89-8009-UC-401, Livermore, CA, Sept. 1989.

[17]Reynolds, W. C., "STANJAN, Interactive Computer Programs for Chemical Equilibrium Analysis," Stanford Univ., Stanford, CA, Jan. 1981; also software by the author, Interactive Chemkin Driver for Stanjan-3, Version 3.8d, May 1988.

[18]Glarborg, P., Kee, R. J., Grcar, J. F., and Miller, J. A., "PSR: A Fortran Program for Modeling Well-Stirred Reactors," Sandia National Labs., Rept. SAND86-8209, Livermore, CA, Oct. 1988.

[19]Turns, S. R., and Myhr, F. H., "Oxides of Nitrogen Emissions from Turbulent Jet Flames: Part I—Fuel Effects and Flame Radiation," *Combustion and Flame*, Vol. 87, No. 3–4, 1991, pp. 319–335.

[20]Fenimore, C. P., "Formation of Nitric Oxide in Premixed Hydrocarbon Flames," *Thirteenth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1971, pp. 373–380.

K. Kailasanath
Associate Editor