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Low NO_x Potential of Gas Turbine Engines

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LOW NO_x POTENTIAL OF GAS TURBINE ENGINES

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SUMMARY

The purpose of this paper is to correlate emission levels of gas turbine engines. The predictions of NO_x emissions are based on a review of the literature of previous low NO_x combustor programs and analytical chemical kinetic calculations. Concepts included in the literature review consisted of Lean-Premixed-Prevaporized (LPP), Rich Burn/Quick Quench/Lean Burn (RQL), and Direct Injection. The NO_x emissions were found to be an exponential function of adiabatic combustion temperature over a wide range of inlet temperatures, pressures and (lean) fuel-air ratios. A simple correlation of NO_x formation with time was not found. The LPP and Direct Injection (using gaseous fuels) concepts have the lowest NO_x emissions of the three concepts. The RQL data has higher values of NO_x than the LPP concept, probably due to the stoichiometric temperatures and NO_x production that occur during the quench step. Improvements in the quick quench step could reduce the NO_x emissions to the LPP levels. The low NO_x potential of LPP is offset by the operational disadvantages of its narrow stability limits and its susceptibility to autoignition/flashback. The Rich-Burn/Quick-Quench/Lean-Burn (RQL) and the Direct Injection concepts have the advantage of wider stability limits comparable to conventional combustors.

INTRODUCTION

The purpose of this paper is to correlate the nitrogen oxide (NO_x) levels of different, low emission combustor concepts.

Interest in the environment by scientists and the general public is increasing due to such things as the discovery of the antarctic ozone hole, hot summers and the greenhouse effect, and the increased smog in the cities. Thus there will be a continued and probably increased interest in the emissions from gas turbines.

The design of a low emission gas turbine combustor consists of a balance of providing enough time and sufficiently high temperatures to complete the hydrocarbon reactions (through flame product recirculation) and yet low enough time and temperatures so that the formation of NO_x is kept to a minimum. Since the formation rate of nitrogen oxides (NO_x) is an exponential function of temperature, NO_x occurs primarily at high power operation and will be particularly difficult to control as advanced engine cycles increase combustor inlet and exit temperatures. The emission levels of carbon monoxide and soot in present conventional engines are low at high power conditions, although they can be a problem at low power conditions such as idle. In the design of low NO_x combustors what is done to decrease NO_x usually increases CO or soot. However, due to other environmental considerations, the carbon monoxide, unburned hydrocarbons and soot must not have substantial increases.

Concepts that have experimentally demonstrated low emissions include the Lean-Premixed-Prevaporized (LPP), and the Rich Burn/Quick Quench/Lean Burn (RQL) combustors. The LPP was the first concept to appear to control NO_x in the early 70's. The concept is simple; provide a uniform mixture of fuel vapor and air that burns at low temperatures where NO_x is a minimum. The disadvantages of the LPP is that it has narrow stability limits and is subject to autoignition and flashback.

The RQL combustor was first designed to control the formation of NO_x from alternate fuels with large amounts of fuel-bound-nitrogen. In a rich burning primary zone the fuel bound nitrogen is not converted to NO_x . The RQL, although more complex than a LPP combustor, has the additional advantage of the stability of a conventional combustor and thus is being considered with the use of fuels with low amounts of fuel-bound nitrogen, such as current jet engine fuels. Besides the LPP and RQL concepts there has been also work reported on direct injection concepts. In the direct injection concept all the combustion air enters the front end, and the fuel is injected directly into the combustion zone.

The correlations and emission predictions for these low emission concepts are based on a review of the literature. The data has been reported in a variety of forms including parts per million, parts per million at 15 percent oxygen and emission index ($\text{g NO}_2/\text{kg fuel}$). In this report the data will be reported as emission index and correlated as a function of adiabatic combustion temperature. The data covers a range of inlet air temperatures, pressures and fuels. The analysis of low NO_x emissions concepts is based on using present high quality fuels that have low amounts of fuel-bound nitrogen fuels since it appears that for at least the next 20 years high quality fuels should be abundant.

RESULTS AND DISCUSSION

The NO_x emission data is presented as NO_2 emission index versus adiabatic combustion temperature. NO_x includes both the NO and NO_2 exhaust emissions. Even though the predominant species is NO (approximately 90 percent, ref. 1) the emission index is defined as NO_2 with the assumption that eventually all the NO will be oxidized to NO_2 in the atmosphere. Since the rate of NO_x formation is given as a differential equation in terms of concentration and adiabatic combustion temperature, the data from previous reports has been plotted as the log of NO_x concentration versus the adiabatic combustion temperature. In this report a normalized form of the concentration is used, that is the emission index. The emission index is defined as the amount of emittant in grams per kilogram of fuel. Emission index is a useful data format because the amount of emissions expelled into the atmosphere can be calculated directly from it, as can system parameters such as fuel flow and specific fuel consumption.

The data is presented by combustor type: first the LPP, then the Direct Injection and, finally the RQL.

LEAN-PREMIXED-PREVAPORIZED LOW NO_x DATA

Data from five sources are presented. The experimental configurations are presented in figure 1. The configurations from the first four references are quite similar with the fuel injected upstream of a perforated flame holder. The configuration from reference 5 is somewhat different in that the flame is not stabilized by a flameholder but by the hot flame tube wall that is externally heated by an independent flame. Table I summarizes the important physical characteristics and experimental conditions. The pressure drop across the flame holders were similar, in the 2- to 4-percent range of the upstream pressure at the experimental conditions. The fuels used were propane by Anderson (ref. 1) and Roffe and Venkataramani (ref. 2), externally vaporized Jet A by Semerjian and Vranos (ref. 3), liquid Jet A by Cooper (ref. 4), and hexane by Tang et. al. (ref. 5).

Constant Residence Time of 2 msec

In figure 2 the log of NO_x emission index is plotted as a function of adiabatic combustion temperature for a constant residence time of 2 msec. Data was taken at a residence time of 2 msec by Anderson (ref. 1), Roffe and Venkataramani (ref. 2) and Semerjian and Vranos (ref. 3). The data from each source correlates well with adiabatic flame temperature but the data between sources only agree to within a factor of five. The data from each source will be discussed individually, followed by a discussion of the differences between sources.

The data of Anderson (ref. 1) correlates well, with the log of NO_x varying linearly with adiabatic combustion temperature up to 2100 K. There is a weaker dependence at higher temperatures because the mixture approaches stoichiometric and there is less oxygen available for NO_x production. At the 600-K inlet temperature this trend is apparent at a combustion temperature of 2100 K and at the 800-K inlet temperature the decreased dependence begins at 2300 K.

Roffe and Venkataramani (ref. 2) conducted a set of experiments to determine the pressure effect on the formation of NO_x. Roffe's NO_x data correlates very well with flame temperature. At an inlet air temperature of 800 K, pressure levels were varied from 10 to 30 atm and there was no effect on NO_x levels. At equilibrium this is to be expected since there is no volume change. Reaction rates are affected by pressure through an increased concentration. However, most of the reactions in the fuel decomposition and oxidation are weak functions of concentration and the overall effect appears to be small.

The Roffe and Venkataramani data at an inlet air temperature of 600 K and a pressure of 30 atm agreed with the 800-K data, but at 10 atm the 600-K data was about one-half the NO_x levels at a pressure of 30 atm. Roffe conjectures that the difference may be due to an unstable flame at the lower inlet temperature and pressure, thus delaying the start of the reactions and the amount of NO_x produced. The carbon monoxide and unburned hydrocarbon data did not show any difference in trends between the different test conditions.

The NO_x data of Semerjian and Vranos (ref. 3) at an inlet temperature of 750 K and a pressure of 1 atm approximately agrees with Roffe and

Venkataramani data at inlet conditions of a temperature of 600 K and a pressure of 10 atm.

In general there is about a 5-to-1 range between the high and low NO_x data at a residence of 2 msec. The lean-premixed-prevaporized combustion process seems simple in concept, and it is surprising that there is that much scatter. As mentioned above, the data of Roffe shows about a 2-to-1 variation, which he attributes to a difference in flame stability. Anderson in reference 1 also notes that his NO_x levels at certain conditions were about one-half of the values he had found in reference 6. Anderson conjectures that it might be the nature of this type of data to expect a 2-to-1 range of differences in the data. Another possibility to account for part of the difference is in the manner of sampling. For example, a single point measurement in the center of the duct as done by Anderson and Semerjian will be less sensitive to heat loss than a sample that is taken at multiple radial locations including locations near the wall. Further analysis and possibly more experimental work will be required to determine the differences.

Effect of Residence Time

Anderson and Semerjian obtained emissions data as a function of distance from the flameholder; thus the formation of NO_x as a function of residence time can be determined. The data of Cooper (ref. 4) and Tang et al. (ref. 5) taken with a residence time of approximately 8 msec can also be compared to the 2-msec residence time data. The data at various residence times is plotted in figure 3.

The data of Anderson is plotted for a residence time of 2 and 4 msec. At a combustion temperature of 1800 K, the 4-msec NO_x data is only slightly greater (15 percent) than the 2-msec data. However, at a combustion temperature of 2200 K, the 4-msec data is twice the 2-msec data, which is what one might expect from the kinetic rate equations. A possible explanation is that at low combustion temperatures a greater fraction of the NO_x is made up of prompt NO_x .

Semerjian's NO_x data is also shown at a residence time of 2 and 4 msec. The 4-msec residence time data was nearly identical to the NO_x data at a residence time of 2 msec at low combustion temperatures and only about 50 percent higher at the highest flame temperatures of 2250 K. This follows the same trend as Anderson's data, but the rate of increase with combustion flame temperature is not as great. It is possible that the heat loss of Semerjian was greater than that of Anderson and thus accounts for the different results.

The effect of residence time on NO_x levels is also unclear when the data of Cooper (ref. 4) and Tang et al. (ref. 5) is considered. With residence times of approximately 8 msec the NO_x levels fall within the range of the 2-msec data. Comparison of data taken by different experimenters to determine the effect of residence time does not seem possible because of the wide range of data differences between sources.

Note that the data from Cooper is the only source in this group of references that injected liquid Jet A. Cooper used a multiple source fuel injector that distributed the fuel uniformly in the duct. In a follow up effort by

Semerjian et al.(ref. 7), various pressure atomizer fuel nozzles were used to inject liquid Jet A. With a 30° cone angle nozzle the NO_x levels approach those obtained with prevaporized Jet A.

Constant Combustion Efficiency

Combustion efficiency and the emissions of carbon monoxide and unburned hydrocarbons must also be considered when determining the optimum combustor residence time. The tradeoff in combustor design for low emissions at high power is to provide sufficient time for carbon monoxide and unburned hydrocarbon reactions to go to completion and yet limit the time so that the NO_x reactions do not go to completion. A plot of the NO_x levels as a function of flame temperature at constant combustion efficiency of 99.7 percent was made for the data of Anderson and Semerjian and Vranos. This is shown in figure 4. The NO_x data at a residence time of 2 msec is also plotted for comparison. At low combustion temperatures the 2-msec data is at approximately 99.7-percent combustion efficiency. As the combustion temperature increases, the 2-msec NO_x data of Anderson increases substantially faster than the 99.7-percent data. Thus at higher flame temperatures a substantial reduction in NO_x can be made if the residence time is reduced below 2 msec. The 2-msec and 99.7-percent NO_x data of Semerjian are approximately equal up to a combustion temperature of 2000 K. Above a combustion temperature of 2000 K the NO_x levels are at a much lower level than the 2-msec data. However, the carbon monoxide level at the 2230-K combustion temperature was substantially below equilibrium, indicating heat loss affected the results.

DIRECT INJECTION LOW NO_x DATA

The direct injection concept is defined as a low NO_x concept in which the fuel is directly injected into the reaction zone. In the three direct injection references described in this report, all the combustion air enters the front end or dome region and there is no dilution zone. The three concepts are shown in figure 5.

The Ultra Lean combustor concept of Anderson (ref. 8) was designed for an automotive gas turbine application. Since in this application the combustor inlet temperatures would be very high (approximately 1200 K), because of the regenerative cycle, this concept relied on the high inlet temperature for flame stabilization. There was no flameholder or swirl induced recirculation zones for flame stabilization. The fuel injector was the same type used in lean-premixed-prevaporized combustor flame tube experiments.

Two other concepts are shown, both developed at the University of Leeds (references 9 and 10). Both of these concepts relied on strong radial swirl for both fuel-air mixing and flame stabilization.

The NO_x emission index values for the direct injection combustors are plotted versus the adiabatic combustion temperature in figure 6. For comparison the lean-premixed-prevaporized NO_x data of Anderson and Semerjian and Vranos at a residence time of 2 msec is also plotted. The NO_x levels are

remarkably low for direct injection combustors and approach the values of lean-premixed-prevaporized NO_x data.

The data of Hussain et. al. (ref. 10) agrees very well with the LPP data. A linear fit of the data would almost exactly match the LPP data of Anderson. The combustion efficiency is 99.7 percent at a combustion temperature of 1640 K, and greater than 99.9 percent at temperatures greater than 1640 K. Data was taken as a function of length but only a small dependence on length or residence time was found. The authors believe that the reason for this is that the NO_x formed is primarily prompt NO_x that would not be a function of post-flame distance. Besides having NO_x levels expected of a LPP combustor, Hussain reports that its stability (in terms of lean blowout limit) is that of a conventional diffusion flame combustor.

The data of Alkabe et. al. (ref. 9) also contains low NO_x emissions. The NO_x level at a combustion temperature of 1600 K is about 4 times greater than Hussain et al., but at a combustion temperature of 1800 K the NO_x levels are approaching that of Hussain et al. The higher NO_x levels at lower flame temperatures may be the result of poorer fuel-air mixing. The combustion efficiency is greater than 99.9 percent for the NO_x values plotted. The residence time for this combustor is 16 msec. Alkabe also reports very good stability.

Note that the data described above is for propane; NO_x levels will increase for liquid fuel injection depending on the degree of atomization, vaporization and mixing that can be achieved; see the discussion of the Anderson data below. Also note that the pressure level is 1 atm. The authors predict a square root dependence of NO_x emissions on pressure level. However, it may be also possible to use the increased pressure and reaction rates to decrease the residence time and possibly have no net effect on NO_x .

The data from Anderson (ref. 8) using liquid diesel number 2 demonstrates the effect of atomization and vaporization and also the effect of fuel-bound nitrogen on NO_x levels. The fuel bound nitrogen levels add an emission index level of 0.4 to the NO_x levels. With lean combustion it assumed that all of the fuel bound nitrogen is converted to NO_x . If 0.4 were subtracted from the emission index the data of Anderson would approach that of the lean-premixed-prevaporized data.

The effect of liquid fuel atomization and vaporization is also seen in the data of Anderson. With a reference velocity of 32 m/sec the NO_x levels decreased as the inlet air temperature increased from 1100 to 1250 K. Anderson attributes this to faster vaporization at the higher inlet temperature and thus more closely approaching a premixed flame. The same effect is also seen by increasing the reference velocity. Since the fuel injector relies on the air velocity for atomization, the higher air velocity decreases the drop sizes and provides faster vaporization and a closer approximation of a premixed flame. The data of Anderson has no residence time effect. Residence times were varied over a 50-percent range without affecting the NO_x levels. An explanation for this is that the temperatures were low enough that thermal NO_x was not a major contributor and the NO_x was mainly from fuel-bound nitrogen and prompt NO_x .

RICH BURN-QUICK QUENCH-LEAN BURN LOW NO_x DATA

The rich burn-quick quench-lean burn (RQL) concept was conceived to control NO_x from fuels containing nitrogen. In a lean burn system nearly 100 percent of the fuel-bound nitrogen is converted into NO_x, whereas with rich burning very little of the fuel bound nitrogen is converted to NO_x. The rich burn zone can be thought of as a fuel preparation zone, followed by quick mixing with the remaining combustion air in the quick quench zone, and finally the process is completed in a lean burn zone at relatively low temperatures where thermal NO_x formation is kept to a minimum. For fuels not containing nitrogen the RQL offers the advantage of low NO_x formation and the stability of a rich front end.

Schematics of the four RQL experiments considered in this report are shown in figure 7. Note in the schematics that the experiments of Schultz (ref. 11) and Rosfjord (ref. 12) have no dilution downstream of the lean burn zone, whereas that of Novick and Troth (ref. 13) and Lew et al. (ref. 14) do have dilution downstream of the lean burn zone. Table II lists the test conditions used for the RQL references. Note that many fuels were evaluated in the references, including heavy fuels with large percentages of fuel-bound nitrogen, however the data used in this report is for light distillates without fuel-bound nitrogen. Also included is the work of Nguyen and Bittker (ref. 15) in which they computationally extended the range of the experimental data of Schultz.

The NO_x data from the RQL experiments is presented in figure 8 as emission index versus adiabatic combustion temperature in the lean zone. Also for comparison is the LPP data from Anderson and Semerjian and Vranos at a 2-msec residence time. The RQL references primarily concentrated their efforts in determining the rich zone equivalence ratio that minimized NO_x production. The rich zone equivalence ratio that minimized NO_x was generally in the range of 1.4 to 1.8. The data included in this report are at rich zone equivalence ratios that produced the minimum NO_x values.

As seen in figure 8, the NO_x levels for the RQL experiments are greater than the 2-msec residence time LPP data. The reason for the greater amount of NO_x could result from excess formation in the rich, quench or lean zones. There were no data taken in the intermediate zones to determine where the NO_x formation takes place.

The experiments of Schultz (ref. 11) and Rosfjord (ref. 12) were run without dilution downstream of the lean burn zone. Their NO_x levels were approximately the same although Schultz investigated much higher lean zone equivalence ratios and corresponding higher combustion temperature. Schultz had approximately a 12-msec residence time in the rich zone and a 2 msec residence time in the lean zone. Rosfjord had a 38-msec rich burn residence time and approximately a 11-msec lean burn residence time.

The data of Novick and Troth (ref. 13) and Lew et al. (ref. 14) were taken over a range of lean zone equivalence ratios (in addition to a range of rich burn equivalence ratios) with the amount of dilution varied so that the burner exit temperature remained constant. The NO_x level is seen to increase as the lean zone combustion temperature increases. The displacement of the curves between the two references may be due to assumptions that had to be

made to calculate the lean zone equivalence ratio for the experiment of Lew et al. since only nominal values were given in their report. The NO_x emission index after dilution is approximately the same for the two references.

Nguyen and Bittker (ref. 15) used a chemical kinetic computer program to study the effect of higher combustor inlet temperatures on NO_x formation. The model was made to match the RQL data of Schultz. In the model they assumed that the quench zone mixing was infinitely fast so that no NO_x was formed in the quench zone. The combustor inlet temperatures were varied with all other conditions kept constant. As the combustion flame temperature increases, as the result of increased inlet temperatures, the NO_x increased with approximately the same temperature dependence as the LPP data.

In general the lean zone adiabatic combustion temperature would be expected to correlate only the NO_x produced in the lean zone. The RQL contains two additional zones where NO_x may be formed, the rich and quench zones. However, the rich burn zone may not be a significant NO_x contributor, even though fuel is injected with a conventional fuel injector. According to Rosfjord, "Fuel is injected as a liquid and not as a fully-vaporized fuel-air mixture. Hence for any equivalence ratio there will be regions of near stoichiometric with the attendant production of high levels of NO_x . Therefore, an annihilation mechanism must be present to reduce these initial levels to the very low NO_x emission attained." The Nguyen and Bittker (ref. 15) calculations showed the NO_x from the rich zone was only about 10 percent of the total NO_x and that the greatest quantity of NO_x was produced downstream of the rich zone. However, the formation of NO_x in the quick quench zone could be a substantial contributor of NO_x depending upon the time spent at near stoichiometric mixture values. Downstream of the quench zone, the calculations of Nguyen and Bittker indicate that the thermal NO_x produced in the lean zone should be the same as that of a LPP combustor. However, it may be possible that the lean zone formation of NO_x would be inhibited by the partially and completely burned products from the rich zone.

The overall NO_x levels for the RQL experiments are low and met the EPA goals that were part of their programs. However, significant additional reductions in NO_x levels may be achievable. In particular, the higher levels of NO_x over the LPP levels are probably due to the time spent at near stoichiometric conditions in the quick quench step. The main focus of previous RQL studies was on reducing the NO_x levels caused by the fuel bound nitrogen. However, a substantial effort in optimizing the quick quench mixing zone was not conducted. It is likely that innovative quick quench mixing schemes can significantly reduce the overall RQL NO_x levels.

SUMMARY OR RESULTS

The predictions of NO_x emissions are based on a review of the literature of previous low NO_x combustor programs and analytical chemical kinetic calculations. Concepts included in the literature review consisted of Lean-Premixed-Prevaporized (LPP), Rich Burn/Quick Quench/Lean Burn (RQL), and Direct Injection. The NO_x emissions were found to be correlated for all concepts by the adiabatic combustion temperature over a wide range of inlet temperatures, pressures and (lean) fuel-air ratios. The NO_x emission index was found to be an exponential function of adiabatic flame temperature. No definite pressure effect was noticed. NO_x is also a function of time at the adiabatic

combustion temperature; however, a simple correlation of NO_x formation with time was not found.

The Lean-Premixed-Prevaporized (LPP) concept has the lowest NO_x emissions of the three concepts. The low NO_x potential of LPP is offset by the operational disadvantages of its narrow stability limits and its susceptibility to autoignition/flashback.

The Rich-Burn/Quick-Quench/Lean-Burn (RQL) concept has the advantage of good stability because of its rich zone, although variable geometry may be necessary. The RQL data has higher values of NO_x than the LPP concept. The higher NO_x emissions with the RQL is probably due to the stoichiometric temperatures and NO_x production that occur during the quench step. Chemical kinetics calculations show that only a small amount of NO_x is produced in the rich zone and the NO_x produced in the lean zone should be approximately the same as the LPP. Improvements in the quick quench step could reduce the NO_x emissions to the LPP levels.

The Direct Injection concept is defined as one in which the fuel is directly injected into the reaction zone. In the three Direct Injection references, all the combustion air enters the front end or dome region and there is no dilution zone. Nearly the same low levels of NO_x were produced using the Direct Injection concept as using the Lean-Premixed-Prevaporized concept. The direct Injection concept has the advantage of the stability of conventional combustors. Since the results were obtained primarily with gaseous fuels the challenge will be to produce the same low levels of NO_x with liquid fuels.

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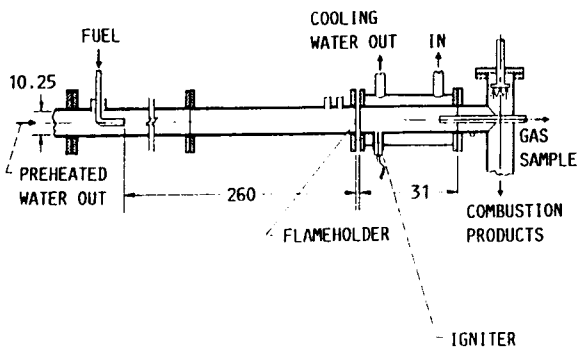
TABLE I. - LEAN-PREMIXED-PREVAPORIZED EXPERIMENTS

| Reference | T_{in} , K | P_{in} , atm | V_{ref} , m/sec | F.H. percent open | Fuel | Duct |
|-----------|-----------------|-------------------|----------------------|----------------------|-----------|---------------|
| Anderson | 600 | 5.5 | 25-30 | 25 | Propane | 10.25 cm diam |
| | 800 | 5.5 | 25-30 | 25 | Propane | 10.25 cm diam |
| Roffe | 600 | 10 | 25 | 22 | Propane | 7.9 cm diam |
| | 600 | 30 | 25 | 22 | Propane | 7.9 cm diam |
| | 800 | 10 | 25 | 22 | Propane | 7.9 cm diam |
| | 800 | 30 | 25 | 22 | Propane | 7.9 cm diam |
| Cooper | 600 | 3 | 35 | 25 | Jet A | 10.2 cm diam |
| | 700 | 3 | 35 | 25 | Jet A | 10.2 cm diam |
| Semerjian | 750 | 1 | 20 | 20 | Vap Jet A | 7.6 x 3.8 cm |
| Tang | 450 | 1 | 6-8 | -- | Hexane | 9.7 mm diam |

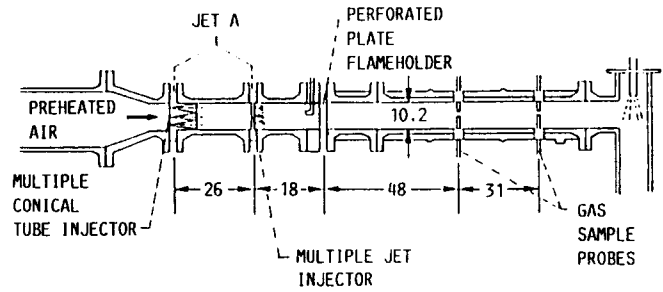
TABLE II. - RICH BURN-QUICK QUENCH-LEAN
BURN EXPERIMENTS

| Reference | T_{in} , K | P_{in} , atm | Fuel |
|-----------|-----------------|-------------------|-------------------|
| Novick | 634-670 | 11.1-11.3 | ERBS ^a |
| Lew | 588 | 14 | ERBS |
| Rosfjord | 589-644 | 10.2-12.2 | No. 2 Distillate |
| Schultz | 672 | 4.8 | Propane |
| Nguyen | 1000-1311 | 7.6 | Propane |

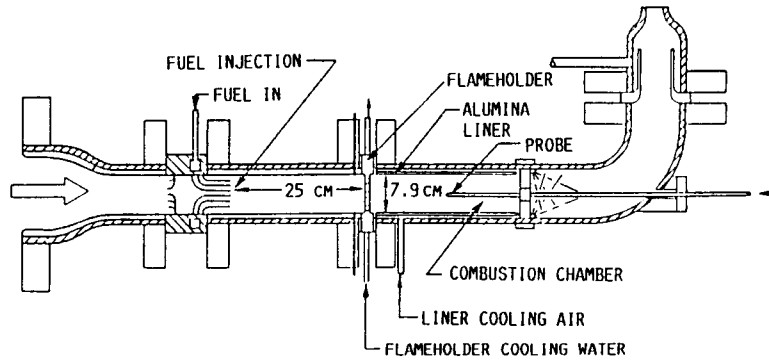
^aExperimental Referee Broad Specifications fuel



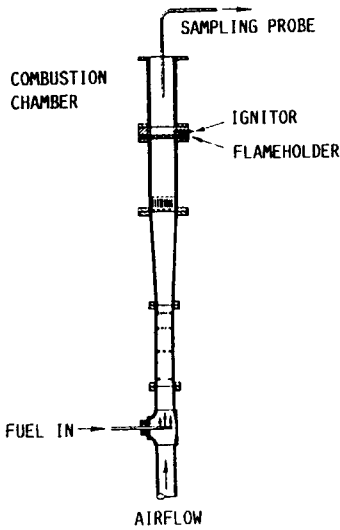
ANDERSON REF. 1



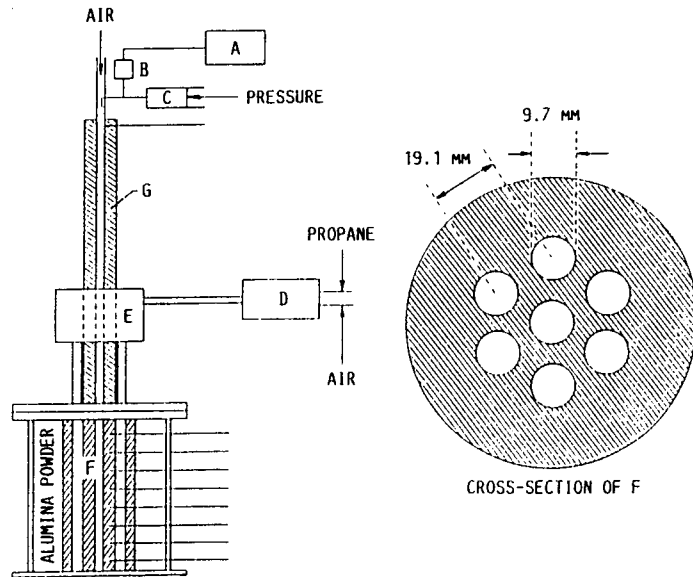
COOPER REF. 4



ROFFE REF. 2



SEMERJIAN REF. 3



A: FUNCTION GENERATOR AND COUNTER
B: VIBRATOR
C: FUEL RESERVOIR

D: MIXING CHAMBER
E: DISTRIBUTOR
F: COMBUSTION CHAMBER
G: REFRACTORY TUBE

TANG REF. 5

FIG. 1 LEAN-PREMIKED-PREVAPORIZED FLAME TUBE EXPERIMENTS.

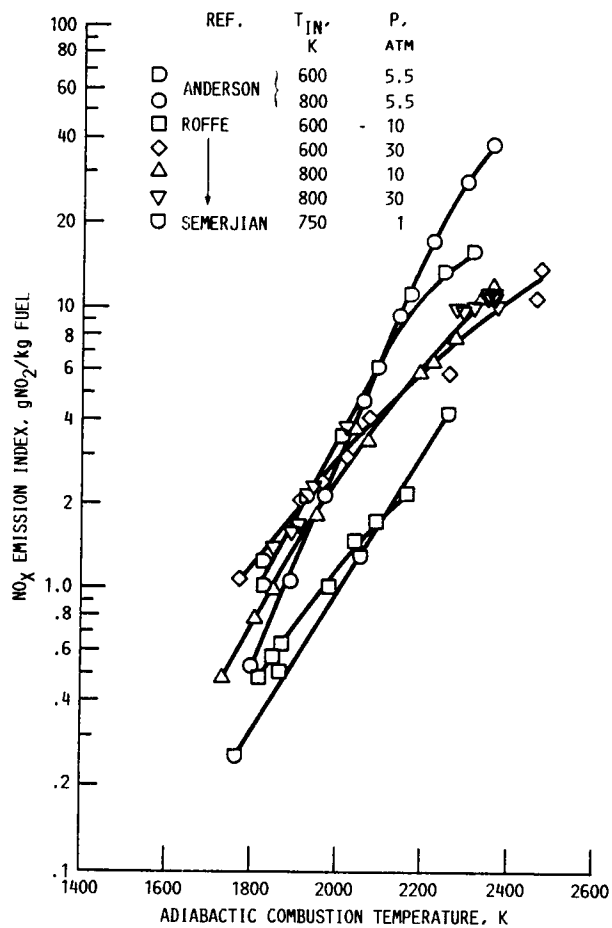


FIG. 2 LEAN-PREMIXED-PREVAPORIZED LOW NO_x DATA, CONSTANT RESIDENCE TIME OF 2MS.

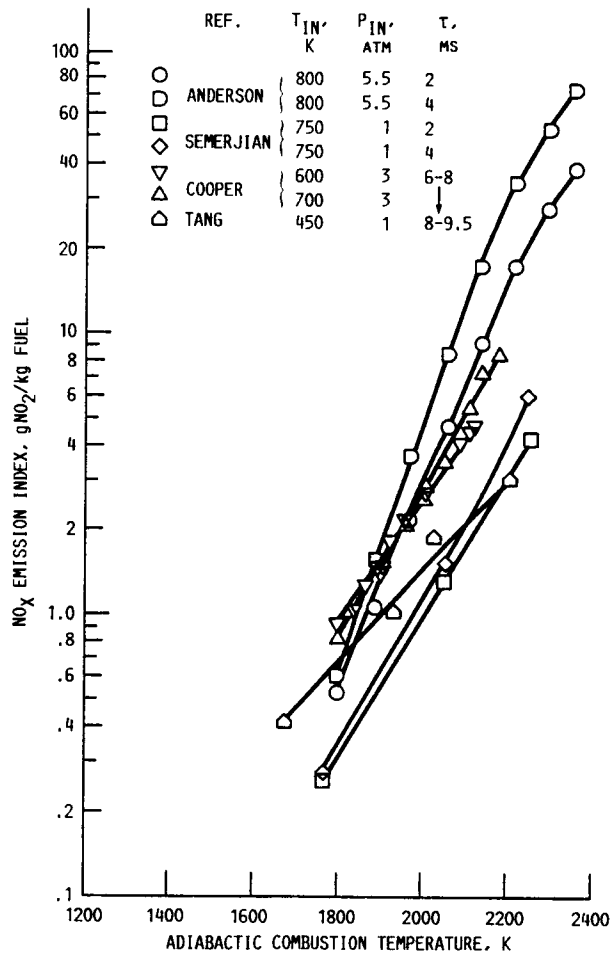


FIG. 3 LEAN-PREMIXED-PREVAPORIZED LOW NO_x DATA, VARIOUS RESIDENCE TIMES.

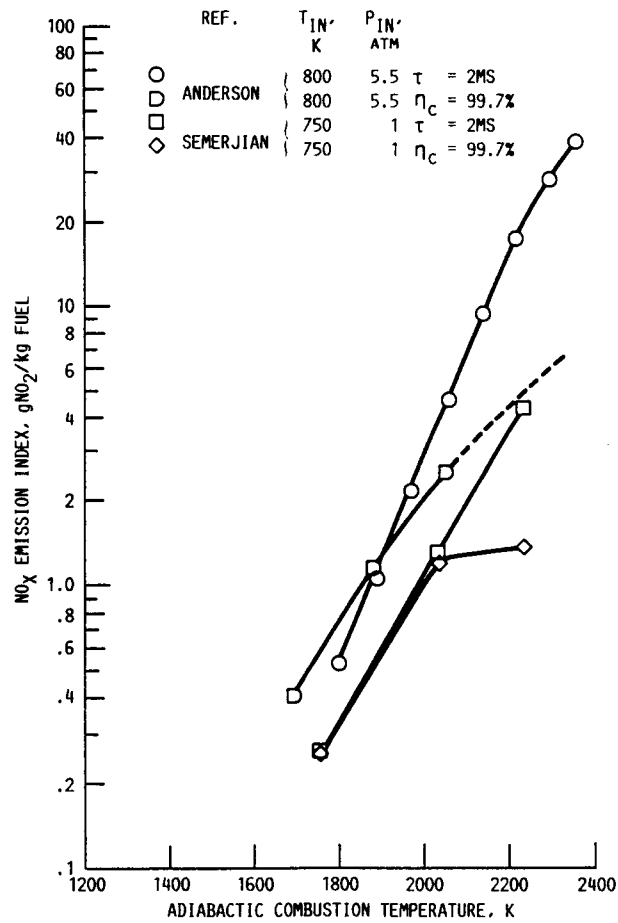


FIG. 4 LEAN-PREMIXED-PREVPORIZED LOW NO_x DATA, CONSTANT COMBUSTION EFFICIENCY.

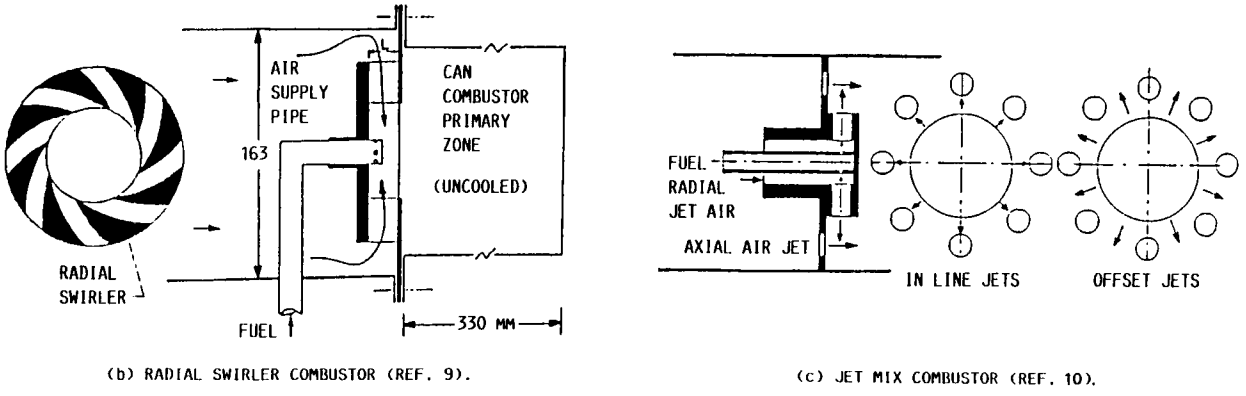
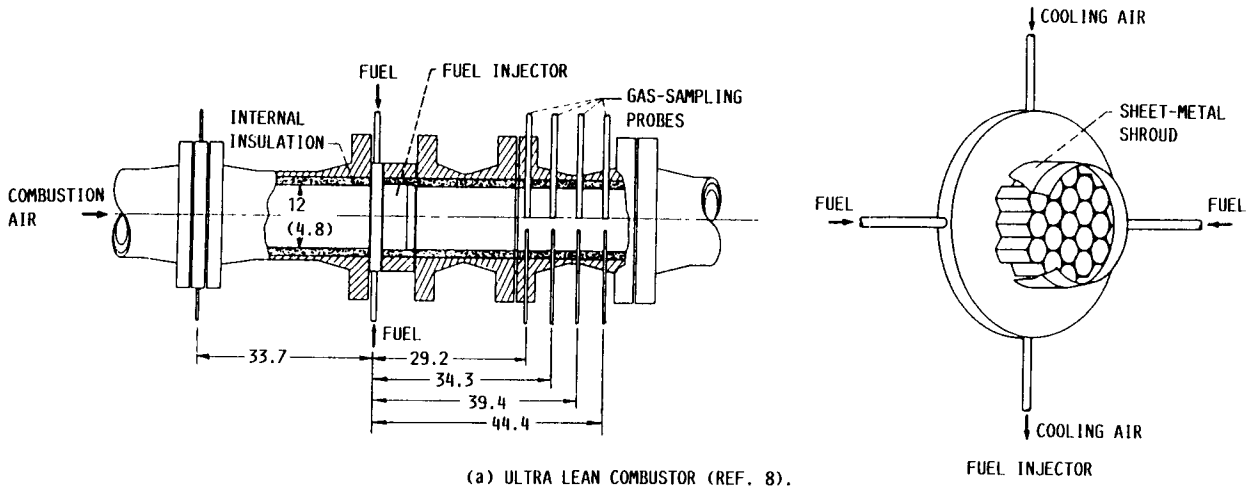


FIG. 5 DIRECT INJECTION LOW NO_x COMBUSTORS.

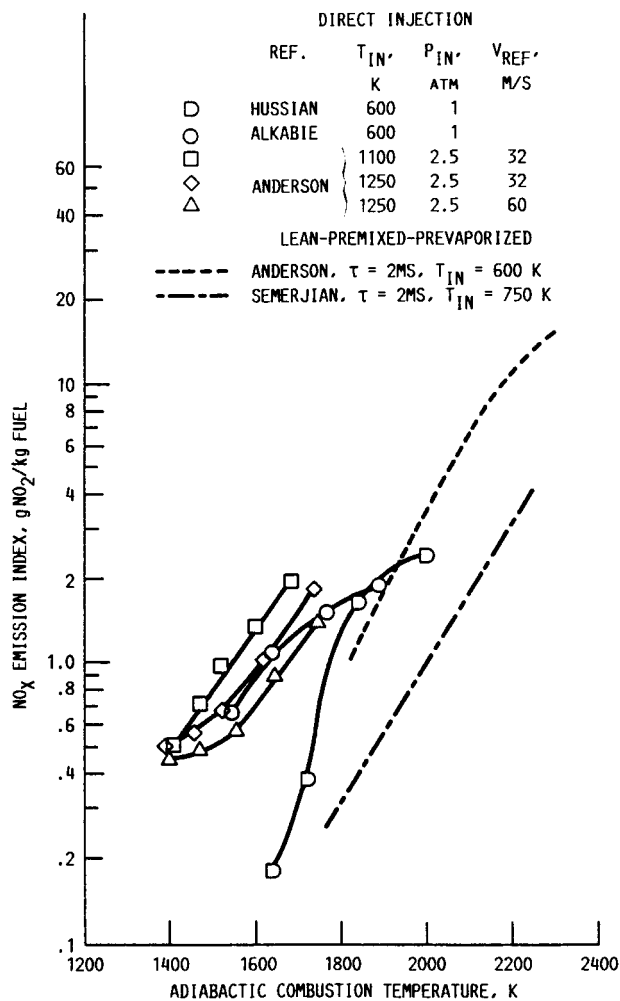
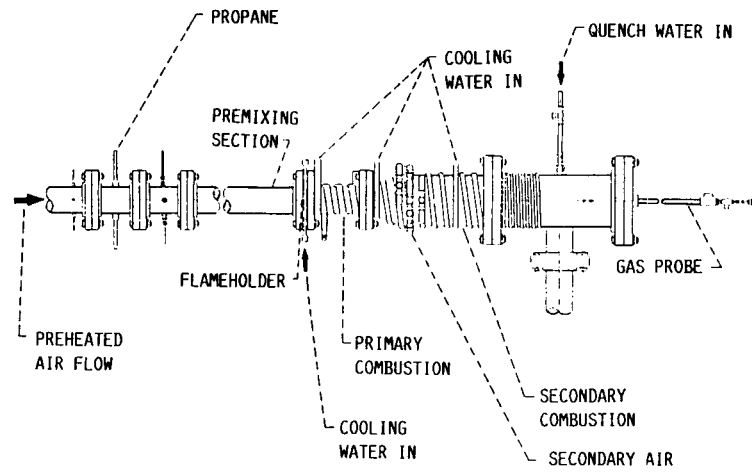
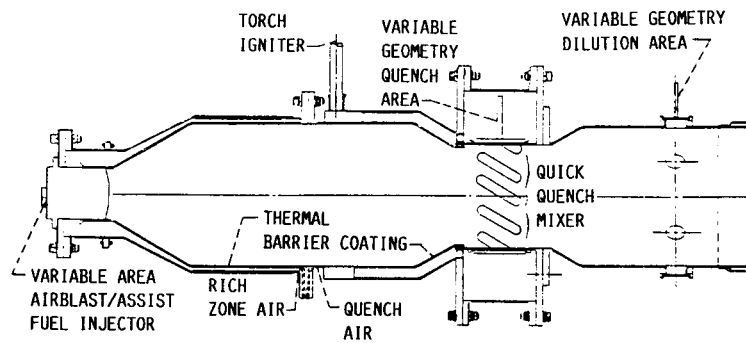


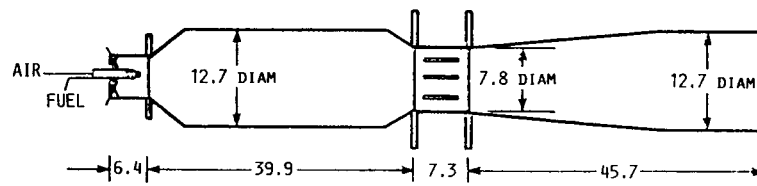
FIG. 6 DIRECT INJECTION LOW NO_x COMBUSTOR DATA AND COMPARISON WITH LEAN-PREMIXED-PREVAPORIZED DATA.



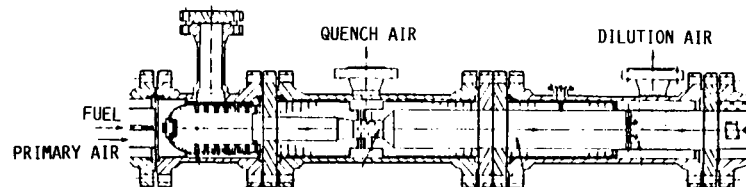
(a) SCHULTZ (REF. 11).



(b) NOVICK (REF. 13).



(c) ROSFJORD (REF. 12).



(d) LEW (REF. 14).

FIG. 7 RICH BURN-QUICK QUENCH-LEAN BURN COMBUSTORS.

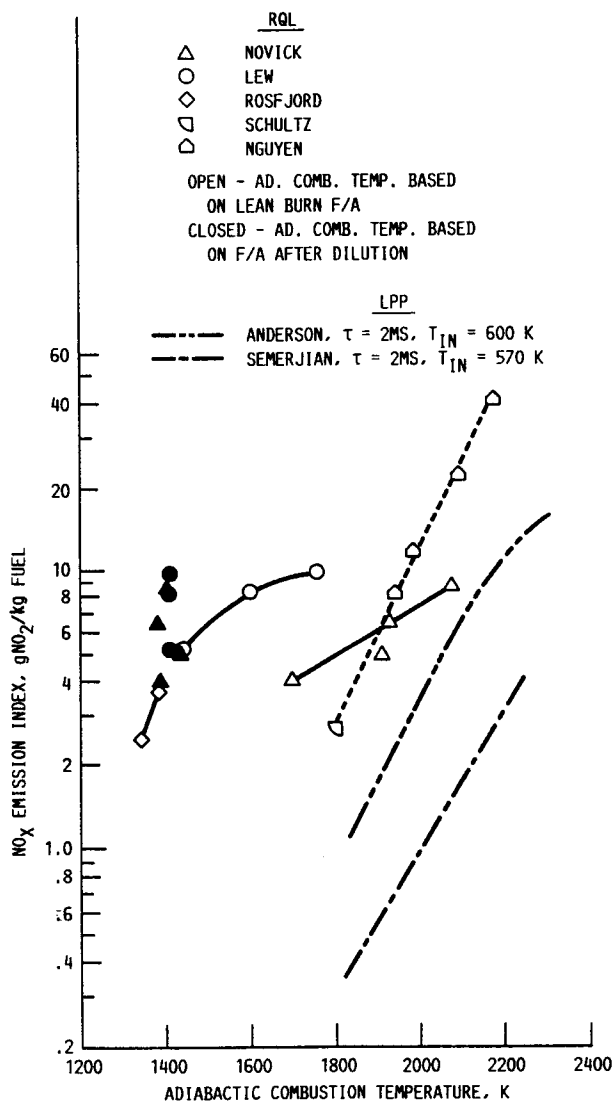


FIG. 8 RICH BURN-QUICK QUENCH-LEAN BURN LOW NO_x COMBUSTOR DATA AND COMPARISON WITH LEAN-PREMIXED DATA.

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| 16. Abstract The purpose of this paper is to correlate emission levels of gas turbine engines. The predictions of NO _x emissions are based on a review of the literature of previous low NO _x combustor programs and analytical chemical kinetic calculations. Concepts included in the literature review consisted of Lean-Premixed-Prevaporized (LPP), Rich Burn/Quick Quench/Lean Burn (RQL), and Direct Injection. The NO _x emissions were found to be an exponential function of adiabatic combustion temperature over a wide range of inlet temperatures, pressures and (lean) fuel-air ratios. A simple correlation of NO _x formation with time was not found. The LPP and Direct Injection (using gaseous fuels) concepts have the lowest NO _x emissions of the three concepts. The RQL data has higher values of NO _x than the LPP concept, probably due to the stoichiometric temperatures and NO _x production that occur during the quench step. Improvements in the quick quench step could reduce the NO _x emissions to the LPP levels. The low NO _x potential of LPP is offset by the operational disadvantages of its narrow stability limits and its susceptibility to autoignition/flashback. The Rich-Burn/Quick-Quench/Lean-Burn (RQL) and the Direct Injection concepts have the advantage of wider stability limits comparable to conventional combustors. | | | | | |
| 17. Key Words (Suggested by Author(s)) Low NO _x combustion Rich burn/Quick quench/Lean burn Lean Premixed Prevaporized | | | 18. Distribution Statement Unclassified - Unlimited Subject Category 07 | | |
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