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EFFECT OF EXHAUST GAS RECIRCULATION ON EMISSIONS FROM A FLAME-TUBE COMBUSTOR USING LIQUID JET A FUEL

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16. Abstract

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SUMMARY

The effects of uncooled exhaust gas recirculation as an inert diluent on emissions of oxides of nitrogen ($NO + NO_2$) and on combustion inefficiency were measured. Ratios of recirculated combustion products to inlet airflow were varied from 10 to 80 percent. Liquid Jet A fuel was used. The combustor pressure was maintained at 0.5 megapascal. The equivalence ratio was varied from 0.3 to 1.0. The inlet air temperature was varied from 590 to 800 K, and the reference velocity from 10 to 30 meters per second. Data were obtained with and without a flameholder.

Increasing the percent recirculation from 10 to 25 percent had the following effects: (1) the peak NO_x emission was decreased by 37 percent, from 8 to 5 grams of NO_2 per kilogram of fuel, at an inlet air temperature of 590 K and a reference velocity of 15 meters per second; (2) the combustion efficiency was increased, particularly at the higher equivalence ratios; (3) for a high combustor efficiency of greater than 99.5 percent, the range of operation of the combustor was nearly doubled in terms of equivalence ratio. Increasing the recirculation from 25 to 50 percent did not change the emissions significantly.

Cooling by heat loss appeared to be the major reason for the reduction in NO_x emissions by recirculation. Nonthermal effects such as increased mixing intensity, reduced residence time, and oxygen atom concentration reduction appeared to be present, but their role could not be quantitatively defined.

INTRODUCTION

Exhaust gas recirculation was used on a flame-tube combustor to determine its effect on exhaust emissions of oxides of nitrogen (NO_x), carbon monoxide, and unburned hydrocarbons.

The high combustor inlet air temperatures and pressures of advanced high-pressure-ratio engines increase the emissions of NO_x pollutants. Nitrogen oxide formation is strongly temperature and time dependent. Combustor designs which have been effective in reducing NO_x emissions involve lower primary zone flame temperatures and shorter primary zone residence times. A simple technique for reducing NO_x emissions is water injection into the primary zone. With this technique oxygen dilution occurs, and the flame temperature is reduced by the high latent and sensible heat capacity of the water diluent. Combustor tests (refs. 1 and 2) have demonstrated the decrease in NO_x emissions effected by water injection. However, water injection presents problems in practical applications. The added weight and storage volume, demineralization to prevent turbine deposits, and antifreeze protection must all be considered. Using exhaust combustion products for combustor primary zone dilution will avoid the cycle penalties of water injection.

External recirculation has reduced levels of nitrogen oxides in boilers and automotive Rankine cycle combustors (refs. 3 to 5). A recirculation ratio of 50 percent of the inlet airflow has reduced smoke formation and lowered flame luminosity with an improvement in combustion efficiency (refs. 6 and 7). The results of references 3 to 7 were obtained with external, cooled recirculation gas formed by exhaust products ducted back to the inlet and mixed with the inlet air.

In a gas turbine no heat is removed from the exhaust stream. The purpose of this experiment was to determine whether a significant reduction in nitrogen oxides occurs because of the decrease in oxygen concentration and the decreased primary zone residence time with minimal heat removal from the exhaust stream. The reduction in oxygen concentration reduces the oxygen atom concentration, which is the major contributor to the NO_x production reactions. The oxygen atom overshoot discussed in reference 8, which results in radical concentrations above thermal equilibrium levels, should be diminished. The residence time in the primary zone is shortened because of the increased mass flow rate with recirculation.

The experiments described in this report were performed in a simple flame-tube combustor. For measurements of the recirculation rates, external recirculation was used, where the exhaust products were ducted back into the air inlet. Thus, oxygen dilution was completed by mixing the inlet air and recirculated gases before additional fuel was injected. Fuel droplet evaporation was rapid because of the elevated temperature of the mixture. Tests were performed with and without a flame stabilizer cone. The exhaust gases were recirculated by an ejector nozzle driven by the inlet combustion air. The recirculation ratio R, the ratio of recirculated combustion products to inlet airflow, was varied from 10 to 80 percent by changing the ejector nozzle size. Reference velocity was varied from 10 to 30 meters per second, and the inlet air temperature was varied from 590 to 800 K. The combustor pressure was held constant at 0.5 megapascal. Liquid Jet A fuel was used, and the equivalence ratio varied from 0.3 to 1.0.

SYMBOLS

EI	emission index, g/kg fuel
FARR	ratio of gas sample fuel-air ratio to metered fuel-air ratio
f/a	combustor fuel-air ratio, metered fuel flow/airflow
$(f/a)_M$	fuel-air ratio of air and recirculated products at mixed station M
L	length of combustion zone
$\dot{m}_{air}$	mass flow rate of inlet air
R	recirculation, percent (eq. (2))
T_F	equilibrium flame temperature corrected for heat losses
T_M	temperature of air and recirculated exhaust products at station M
$T_{M,eq}$	equilibrium temperature calculated from T_3 and $(f/a)_M$
T_3	inlet air temperature
T_3'	inlet air temperature corrected for heat loss (eq. (6))
t	residence time
U_{ref}	reference velocity based on T_3, combustor pressure, and inlet airflow

Subscripts:

C	conditions in combustor
CO	carbon monoxide
eq	conditions at chemical equilibrium
M	conditions of mixed air and recirculated products at station M
NO_x	nitrogen oxides
R	condition in recirculation loop
UHC	unburned hydrocarbons

APPARATUS AND PROCEDURE

The test apparatus, shown in figures 1 and 2, was constructed of 10.2-centimeter-inside-diameter pipe. Inlet air was supplied at 1 megapascal and was indirectly heated to an inlet temperature T_3 of 590 to 800 K. The air passed through a control valve and then through a converging nozzle, which acted as an ejector by pumping the exhaust gases into the inlet stream. Three different nozzles, with inside diameters of 2.03, 2.54, and 3.20 centimeters, were used to vary the percent recirculation. The air and recirculated products traveled around two 90° bends for a length of 137 centimeters for complete mixing before introduction of additional fuel.

The simple combustor had a 28-centimeter-long pipe from the fuel injector to the exit tee. The combustor was operated with and without a 5.9-centimeter-diameter, 120°-cone flameholder providing 33 percent blockage. The exhaust flow divided at a tee, a portion going to a water quench and back pressure valve before exhausting to the atmosphere and the remainder forming the recirculation stream.

The liquid Jet A fuel was sprayed through a 60° simplex pressure-atomizing nozzle into the mixed stream. The nozzle was rated at 0.09 cubic meter per hour (24 gal/hr) at a pressure differential of 0.69 megapascal (100 psi).

The walls were water cooled by immersion in a water bath to prevent burnout of the combustor. Figure 2 shows the water bath with supplemental cooling for complete protection of the rig. A partition was placed between the flanges to reduce the cooling to protect only the hot region downstream of the fuel nozzle and the recirculation loop; see the broken line in figure 1.

The temperature of the mixed gases T_M and the inlet air temperature T_3 were measured with Chromel-Alumel thermocouples. The combustor pressure was measured upstream of the fuel injector.

Gas samples were taken at the three stations shown in figure 1. A traversing gas-sampling probe, at station C, was used to determine the change in reaction length with varying recirculation rates. The recirculation gas-sampling probe, at station R, was 53 centimeters downstream of the exhaust tee and 13 centimeters upstream of the ejector. The mixed gas-sampling probe, at station M, was upstream of the fuel injection point. The water-cooled stainless-steel gas-sampling probes were 0.63 centimeter in outside diameter and had a center sampling tube 0.159 centimeter in diameter. Stainless-steel tubing 0.95 centimeter in diameter connected the gas-sampling probes with the exhaust gas analyzers. Condensation of unburned hydrocarbons was prevented by steam tracing and then electrically heating the sample lines to maintain the sample gas temperature between 410 and 450 K. The sample line was approximately 18 meters long.

Gas analysis equipment included a flame ionization detector for measuring unburned hydrocarbons, nondispersive infrared analyzers for measuring concentrations of carbon monoxide (CO) and carbon dioxide (CO_2), and a chemiluminescent instrument for measuring total NO_x concentration.

Calibration of the instruments with standard calibration gases was performed at the beginning of each day's testing and whenever a range change was made.

Inlet air humidity was measured and was essentially zero for all tests. Measurements of CO, CO_2, and NO_x were made after water vapor was removed from the sample. The concentrations of all constituents were corrected for the amount of water present in the combustion products at the particular equivalence ratio. The NO_x concentration (ppm) is presented on the wet basis.

ANALYSIS

The calculation of combustion inefficiency from gas analysis is presented in this section. Also, several aspects of recirculation are discussed, including the calculation of the percent recirculation and the calculation of a corrected inlet air temperature to account for heat loss.

Combustion Inefficiency

The combustion inefficiency is computed from the carbon monoxide and unburned hydrocarbon measurements by the equation

$$\text{percent inefficiency} = 0.1\ EI_{UHC} + 0.0234(EI_{CO} - EI_{CO,eq}) \qquad (1)$$

where EI_{UHC} is the emission index of unburned hydrocarbons, in grams per kilogram of fuel; EI_{CO} is the emission index of carbon monoxide; and $EI_{CO,eq}$ is the calculated chemical equilibrium carbon monoxide emission index. Only the combustion inefficiency is reported rather than the carbon monoxide and unburned hydrocarbon measurements.

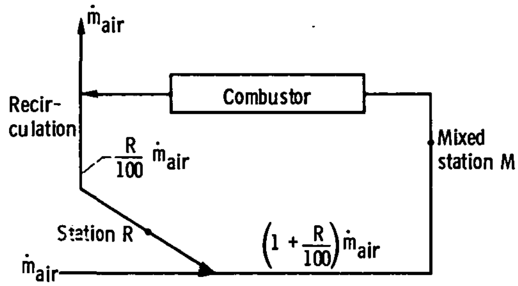
Recirculation

The percent recirculation R is defined in this report as

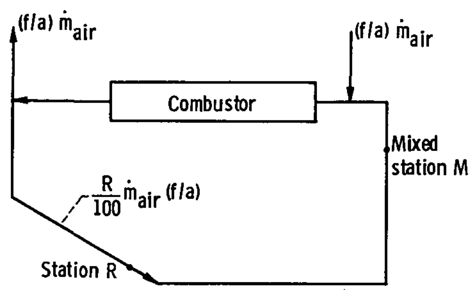
$$R = \frac{\text{weight flow of recirculation}}{\text{weight flow of inlet air}} \times 100 \qquad (2)$$

Recirculation has been previously defined on the basis of stoichiometric airflow (refs. 6 and 7), airflow and fuel flow (ref. 3), and total combustion flow (ref. 4). The different values can easily be related given the overall fuel-air ratio.

External recirculation was used in this experiment so that the quantity of recirculated gas could be measured and the gas could be mixed with the inlet air before entering the combustor. The recirculation ratio was determined from gas analysis measurements of the mixed stream, at station M.



(a) Airflow schematic showing mass flow rates of air.



(b) Fuel flow schematic showing mass flow rates of fuel.

From sketches (a) and (b), the ratio of fuel flow to mixed airflow at station M is

$$\left(\frac{f}{a}\right)_M = \frac{\frac{R}{100}\,\dot{m}_{air}\,\frac{f}{a}}{\left(1+\frac{R}{100}\right)\dot{m}_{air}} = \frac{\frac{R}{100}\,\frac{f}{a}}{1+\frac{R}{100}} \tag{3}$$

where f/a is the metered fuel-air ratio.

From measurement of CO, CO_2, and unburned hydrocarbon concentration, the fuel-air ratio of the mixed stream $(f/a)_M$ is calculated. Let FARR be the ratio of $(f/a)_M$ to the metered fuel-air ratio f/a. Then from equation (3),

$$\text{FARR} = \frac{\frac{R}{100}}{1+\frac{R}{100}} \tag{4}$$

Solving for R gives

$$R = \frac{\text{FARR}}{1-\text{FARR}} \times 100 \tag{5}$$

Equation (5) was used to calculate the percent recirculation.

Correction for Heat Loss From Recirculation Loop

The apparatus required cooling, which resulted in heat losses of from 5 to 20 percent of the heat released in combustion. The magnitude of the heat loss depended on the fuel-air ratio, percent recirculation, reference velocity, and inlet air temperature. The heat loss could be computed by comparison of the measured mixture temperature T_M with the computed equilibrium temperature $T_{M,eq}$ at the measured fuel-air ratio $(f/a)_M$ and the inlet air temperature T_3.

An adiabatic recirculation cycle was determined by computing a corrected inlet temperature to account for heat losses. The corrected inlet temperature T'_3 was calculated from

$$T'_3 = T_3 - (T_{M,eq} - T_M) \tag{6}$$

The flame temperature is reduced by heat losses. A corrected flame temperature T_F can be calculated from T'_3 and the combustor fuel-air ratio by assuming an adiabatic combustor. The data are presented in terms of T_F.

RESULTS AND DISCUSSION

As exhaust gas was recirculated, the oxygen concentration decreased, the residence time in the combustor decreased, the mixing intensity increased, and the fuel vaporization rate increased. In this experiment the reference velocity and the inlet air temperature were varied in addition to the equivalence ratio and the percent recirculation so that the effect of residence time and the effect of reduced flame temperature could be separated out. The latter resulted from heat losses from the recirculation loop. The recirculation was varied from 10 to 80 percent. No data were obtained at zero percent recirculation, but the data at 10 percent recirculation were representative of combustors without external recirculation. The equivalence ratio was obtained by dividing the fuel-air ratio by the stoichiometric fuel-air ratio (0.068 for Jet A fuel). The reference velocity was computed from the inlet air mass flow, the inlet air temperature, the combustor pressure, and the maximum cross-sectional area of the combustor.

The emission data presented are for the recirculation gas-sampling station R (fig. 1). Combustion was incomplete at the traversing-probe station C at the end of the combustor, with combustion inefficiencies ranging from 5.5 to 12 percent. Only limited data were obtained with the traversing probe. The ratio of gas analysis fuel-air ratio to metered fuel-air ratio FARR ranged from 0.9 to 1.5 on the centerline at station C, which indicated that the fuel-air distribution within the combustor was not homogeneous.

The FARR values at the recirculation gas-sampling station R ranged from 0.9 to 1.1. The emissions obtained were representative of those which would be obtained if the combustor were lengthened to permit adequate reaction times.

Effect of Recirculation at Constant Inlet Air Temperature and Reference Velocity

Combustor emissions of total oxides of nitrogen ($NO + NO_2$), carbon monoxide, carbon dioxide, and unburned hydrocarbons were measured at several levels of recirculation. The carbon monoxide and unburned hydrocarbon emissions are presented in terms of combustion inefficiency as described in the ANALYSIS section (see eq. (1)). The percent recirculation varied slightly with equivalence ratio, as shown in figure 3. In general, a particular inlet air nozzle produced a given quantity of recirculation.

Oxides of nitrogen. - The emission index of NO_x as a function of equivalence ratio is shown in figure 4. At 10 percent recirculation, the NO_x emission index peaked at an equivalence ratio of 0.6 at a value of 8 grams of NO_2 per kilogram of fuel. At the higher recirculation ratios the peaks occurred at an equivalence ratio of 0.8 at a value of 5 grams of NO_2 per kilogram of fuel. Thus, increasing the recirculation ratio from 10 to 25 percent reduced the peak NO_x by 37 percent. In addition, for equivalence ratios less than 0.63, increased recirculation resulted in at least a 40-percent reduction in NO_x. Above an equivalence ratio of 0.7, the recirculating exhaust products increased NO_x emission index slightly. The increase in the recirculation ratio from 10 to 25 percent produced a significant change in emissions, but the further increase from 25 to 50 percent had little effect on the emissions.

The NO_x levels from the well-stirred-reactor predictions using the computer program of reference 9 are shown in figure 4 for three residence times. The experimental residence times varied from 65 to 15 milliseconds as the recirculation ratio was increased from 10 to 50 percent. The large differences between the shapes of the predicted NO_x curves and the experimental curves resulted from the nonuniform fuel distribution within the combustor. The actual radial distribution of the fuel and the residence time distribution were not known. Stable flames were obtained below an equivalence ratio of 0.4 at a 590 K inlet air temperature, which indicated fuel-rich zones, whereas the premixed data of reference 10 produced blowout below an equivalence ratio of 0.55.

Combustion inefficiency. - The combustion efficiency was improved as the percent recirculation was increased, as shown in figure 5. At the higher equivalence ratios the efficiency was significantly improved. The equivalence ratio range for good combustion efficiency nearly doubled. With a recirculation of 10 percent, equivalence ratios from 0.38 to 0.64 could be prescribed while maintaining combustion efficiencies of 99.5 percent or higher. When the recirculation was increased to 25 percent or higher, the range of equivalence ratios for operation with efficiencies of 99.5 or higher was increased to between 0.38 and 0.85, a range almost double that for 10-percent recirculation. Increasing the percent recirculation preheated the inlet air mixture to improve fuel vaporization and increased the mixing intensity in the combustor. The instrumentation limited the minimum combustion inefficiency to 0.01 percent, as shown in figure 5, although some of these points may represent even lower inefficiencies.

Almost all of the improvement in combustion inefficiency was achieved by increasing the recirculation ratio from 10 to 25 percent, an effect similar to the NO_x emission results in figure 4.

Effect of Recirculation at Varying Inlet Temperature

The system was operated at three inlet air temperatures which would correspond to various values of flame temperature at a given equivalence ratio and simulate various amounts of heat removal.

Oxides of nitrogen. - Figure 6 presents the NO_x emission index data for 10- and 50-percent recirculation. For an inlet temperature increase of 200 K (from 590 to 790 K) the NO_x would be expected to be three to four times greater (ref. 11). The maximum increase for 10-percent recirculation and an equivalence ratio of 0.55 was 0.54 times greater for the 200 K inlet temperature increase (fig. 6(a)). For 50-percent recirculation (fig. 6(b)), the maximum increase was 0.6 times greater for the same equivalence ratio. One probable explanation for this reduced temperature sensitivity is that heat losses also increased with the inlet temperature increase, and the effective flame temperature change was relatively small.

Combustion inefficiency. - The combustion inefficiency was reduced with increasing temperature for 10-percent recirculation (fig. 7(a)). For 50-percent recirculation (fig. 7(b)), the combustion inefficiency changed slightly with temperature. The decrease in combustion inefficiency with increased temperature was small compared with the change with increased recirculation (fig. 5).

Correction for heat losses. - Although in this experiment a minimum amount of cooling was desired, some cooling was necessary to prevent burnout of the combustor and recirculation loop. The cooling loss varied from 5 to 20 percent of the heat of combustion depending on the equivalence ratio, the percent recirculation, and the reference velocity. Figure 8 shows the measured recirculation mixture temperature T_M and the corrected inlet air temperature T_3', calculated for adiabatic recirculation with the same mixture and flame temperatures (see ANALYSIS section, eq. (6)). The NO_x data of figure 4 are replotted in terms of concentration (ppm) as a function of equilibrium flame temperature T_F (based on T_3' and metered fuel-air ratio) in figure 9. Correcting the data for heat losses showed that the variation of NO_x with flame temperature was similar at the three levels of recirculation. The peak NO_x values were all near 170 ppm.

The effect of recirculation as a diluent in reducing the oxygen atom concentration and hence the nitrogen oxide level at a given calculated flame temperature appears to have been present, but the effect was not definitive. At the lower temperatures, say 1700 K, there was a reduction in NO_x with an increase in recirculation from 10 to 25 percent followed by an increase in NO_x when the percent recirculation was increased from 25 to 50 percent. At higher temperatures, above 2000 K, the values of the NO_x at 25- and 50-percent recirculation were above those for 10-percent recirculation. The shift in the peak NO_x with recirculation was probably due to the changes in fuel distribution at the higher mixture temperatures and higher velocities which occurred with increased recirculation. At temperatures below these maximums, the experimental curves were approximately parallel to the well-stirred-reactor curves for data below 1900 K after the corrections were applied for heat loss.

The peaks in the experimental curves were probably the result of the local fuel-air ratio going through an equivalence ratio of 1. The flame temperatures had been calculated at the metered fuel-air ratios by assuming the combustor was homogeneous. The well-stirred-reactor predictions are plotted only for lean equivalence ratios. At equivalence ratios above stoichiometric the predicted values of NO_x would decrease.

Although oxygen atom dilution and possibly other effects may have been present, cooling was apparently the major effect of recirculation. The data of reference 4 for the lean primary configuration (referred to as configuration B in ref. 4) and the rich primary configuration (referred to as configuration E) are plotted against the calculated equilibrium flame temperature in figure 10. The combustion products were cooled to the inlet air temperature before they were recirculated back to the combustor, which resulted in a lowering of the maximum flame temperature. There was a distinct decrease of NO_x with increasing recirculation, principally caused by the lowering of the flame temperature. There were other effects also, particularly for the lean primary combustor. With increased recirculation there was a decrease in residence time in the combustor, and with the higher mass flows, an increase in mixing intensity also affecting combustor emissions. A small effect of oxygen atom dilution may also have been present.

Effect of Recirculation at Varying Reference Velocity

As the percent recirculation was increased, the residence time in the combustor decreased. The residence time t of the combusting gas was calculated by

$$t = \frac{T_3}{U_{ref}T_F}\left(\frac{L_c}{1 + \frac{R}{100}} + \frac{L_R}{\frac{R}{100}}\right) \tag{7}$$

where L_c was 28 centimeters and L_R was 53 centimeters. The residence time includes the recirculation loop because the emissions data are reported for the recirculation gas-sampling station R. This station was assumed to be representative of a combustor with residence time necessary to result in complete combustion. As stated earlier, the combustion inefficiency at the combustor exit measured with the traversing probe was always more than 5 percent.

The residence time is inversely proportional to the reference velocity U_{ref} and the ratio of the flame temperature T_F to the inlet air temperature T_3. The time decreased from about 65 to 15 milliseconds as the recirculation ratio was increased from 10 to 50 percent.

The effect of residence time was investigated by varying the combustor reference velocity from 10 to 30 meters per second (fig. 11). There was only a small difference in the emission index of NO_x as the reference velocity was varied from 10 to 30 meters per second. The maximum equivalence ratio obtained at 30 meters per second was 0.6 because of fuel flow limitations. There was a slight decrease in NO_x at 30 meters per second, but the variation was less than expected. Data at 25- and 50-percent recirculation, not presented, showed no change in NO_x with reference velocity. The combustion inefficiency data, not presented, did not vary as the reference velocity was changed.

Emissions Without a Flameholder

Emissions were measured without a flameholder present. After initial ignition, the mixed gas temperature was high enough to maintain combustion. The burner operated stably. Without the flameholder pressure drop, approximately 0.5 percent of the total pressure at the 15-meter-per-second reference velocity, the ejector nozzles produced higher recirculation rates. Supplemental cooling (fig. 2) was added to the mixing leg of the rig. Figure 12 shows good agreement of NO_x levels with and without the flameholder at 50-percent recirculation. Even though the gas in the recirculation zone behind the flameholder had a much longer residence time, which produced higher NO_x values, the overall mean residence time was the same with and without the flameholder at the same reference velocity and percent recirculation. With 80-percent recirculation the NO_x level was about half the value for 50-percent recirculation at lean equivalence ratios. Removal of the supplemental cooling resulted in some increase in the NO_x levels.

The combustion inefficiency is shown in figure 13 without the flameholder present. The range of equivalence ratios for efficient operation was narrow compared with that for operation with the flameholder present. This was attributed to the decrease in mixing intensity and the absence of the hot internal recirculation zone behind the flameholder.

All other data presented were taken with the flameholder in place without supplemental cooling.

Effect of Quenching Air Jets on Oxides of Nitrogen

The air ejector can be considered a quenching jet for the recirculating combustion gases. If quenching is rapid, no nitrogen oxides will be produced. If the quenching is slow, the addition of the air (an oxygen-rich stream) can produce more nitrogen oxides when the combustion gases are at temperatures above 2000 K.

If quenching is rapid, only dilution occurs, and the emission index of nitrogen oxides based on the equivalent fuel present in the gas stream determined from a carbon balance is unchanged. With dilution the emission index at the recirculation gas-sampling station R would be identical to the index at the mixed stream gas-sampling station M. Figure 14 shows the NO_x emission index before and after dilution for two ejector nozzles. For the larger nozzle the NO_x was 50 to 100 percent greater after dilution than before dilution. For the smaller nozzle no increase in NO_x occurred. The increase in NO_x with, for example, secondary air injection in a gas turbine combustor can be significant.

The correction to the data of this experiment for the NO_x produced in the quench step was small. Even though the NO_x was doubled, for the larger nozzle only 10-percent recirculation was present, so the net rise in the emission index due to the quenching step was 10 percent. It was difficult to predict whether the NO_x which was recirculated would be additive to the NO_x produced in the combustor, that is, whether the emission level would be changed compared with that where the recirculated gas contains no NO_x. If the emissions were additive, the NO_x at the recirculated gas-sampling station R would be the sum of what is produced plus what was recirculated:

$$(\text{kg } NO_x)_R = \underset{\text{in combustor}}{\text{kg } NO_x \text{ produced}} + \underset{\text{from mixed station M}}{\text{kg } NO_x \text{ entering combustor}} \tag{8}$$

or

$$\text{EI produced} = EI_R + \frac{R}{100}(EI_R - EI_M) \tag{9}$$

For the higher percent recirculations, EI_R was equal to EI_M, so the emission index produced would be that at station R. For the lower percent recirculations, R is small, so that even if the emission index doubled, the correction would be less than 10 percent.

SUMMARY OF RESULTS

The effects of nearly adiabatic recirculation of an inert diluent on combustor emissions were investigated. Emission levels of nitrogen oxides (NO_x), carbon monoxide, and unburned hydrocarbons were measured for recirculation rates of 10 to 80 percent of the inlet airflow. The unburned hydrocarbon and carbon monoxide emissions were reported as combustion inefficiency. Liquid Jet A fuel was used. The combustor pressure was maintained constant at 0.5 megapascal. The equivalence ratio was varied from 0.3 to 1.0, the inlet air temperature from 590 to 800 K, and the combustor reference velocity from 10 to 30 meters per second. Data were obtained with and without a flameholder present.

When the exhaust gas was recirculated, the oxygen concentration was decreased, the residence time in the combustor decreased, the mixing intensity increased, and the fuel vaporization rate increased.

Increasing the recirculation from 10 to 25 percent showed a significant reduction in emissions, but further increases from 25 to 50 percent had little effect. The increase in recirculation from 10 to 25 percent resulted in at least a 40-percent reduction in NO_x emission index for equivalence ratios less than 0.63 and reduced the peak value by 37 percent. Above an equivalence ratio of 0.7, the recirculating exhaust products increased the NO_x emission index. The combustion efficiency was increased as the percent recirculation increased, particularly at the higher equivalence ratios. The equivalence ratio range nearly doubled for combustion efficiencies greater than 99.5 percent.

The flame-tube combustor with recirculation showed a reduced dependence of inlet air temperature on NO_x emissions as compared with a well-stirred-reactor program. A 200 K rise in inlet air temperature increased the NO_x emission index by 60 percent rather than the predicted 300 to 400 percent, principally as a result of increased heat loss with increased inlet temperature.

Recirculation reduced the dependence of residence time on NO_x emissions. A threefold decrease in combustor reference velocity changed the NO_x emission index insignificantly.

The flame-tube combustor with recirculation could operate stably without a flameholder; NO_x emissions were comparable to those in flameholder runs, but combustion inefficiency increased without a flameholder.

The cooling by heat loss appeared to be the major reason for the reduction in NO_x emissions by recirculation. Nonthermal effects such as increased mixing intensity, reduced residence time, and oxygen atom concentration reduction appeared to be present, but their role could not be quantitatively defined.

Equating the air ejector to a quench jet showed that inadequate quench rates could produce significant increases in nitrogen oxides by reaction of the exhaust gases with the inlet air.

Lewis Research Center,
National Aeronautics and Space Administration,
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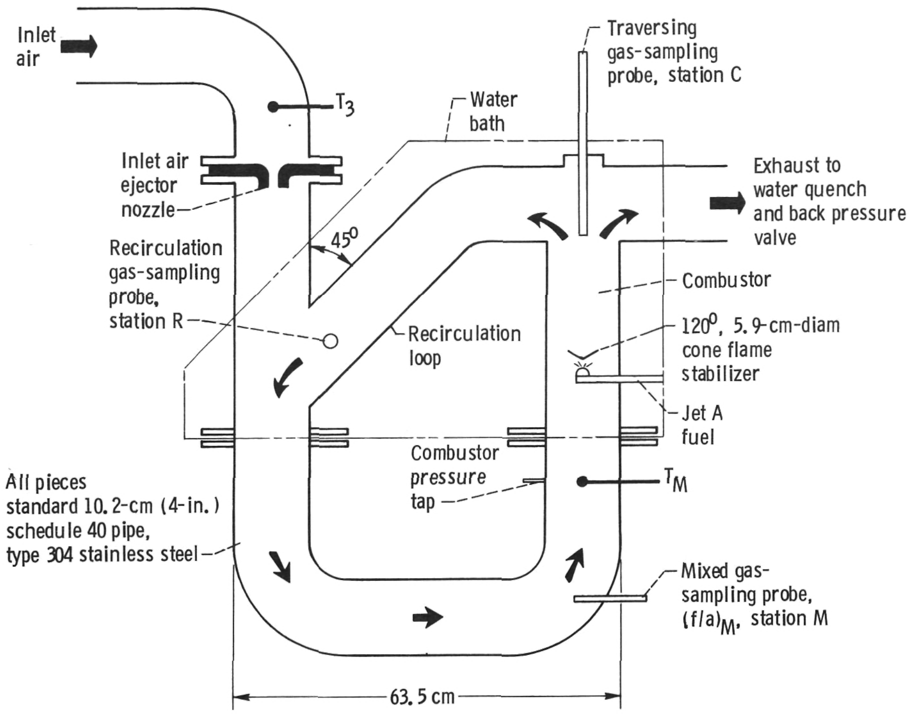


Figure 1. - Sketch of recirculation test rig.

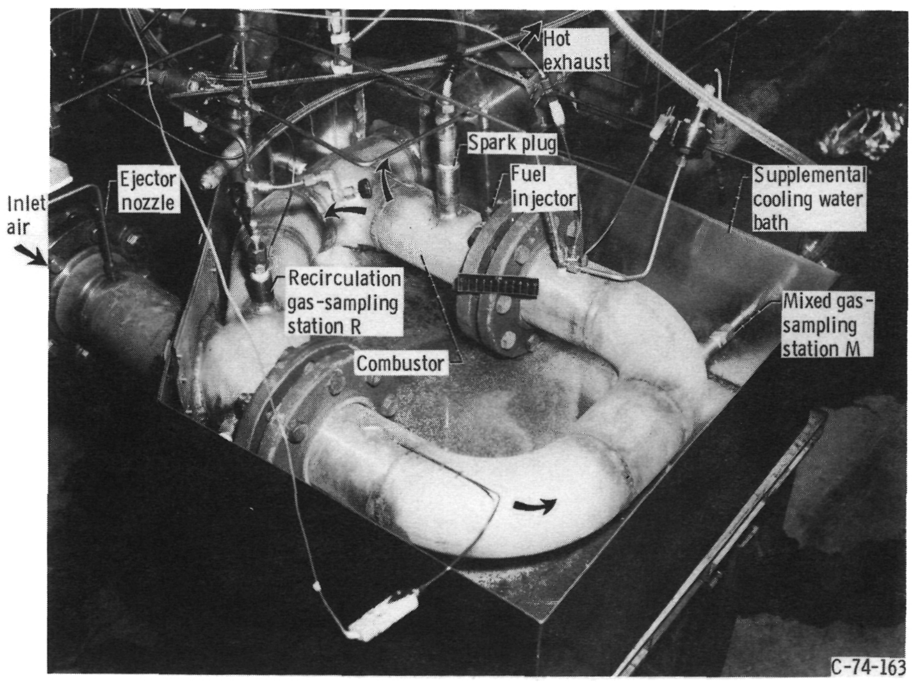


Figure 2. - Overall view of recirculation rig showing instrumentation and supplemental cooling water bath.

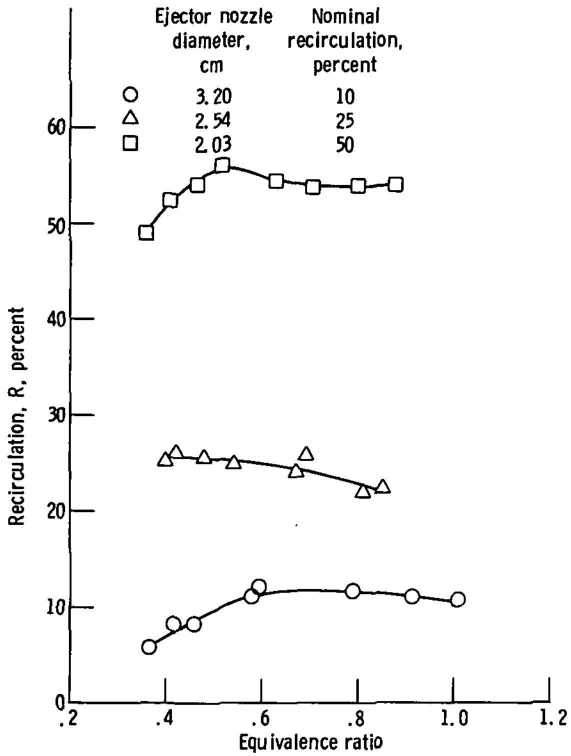


Figure 3. - Variation of percent recirculation with equivalence ratio. Inlet air temperature, 590 K; reference velocity, 15 meters per second.

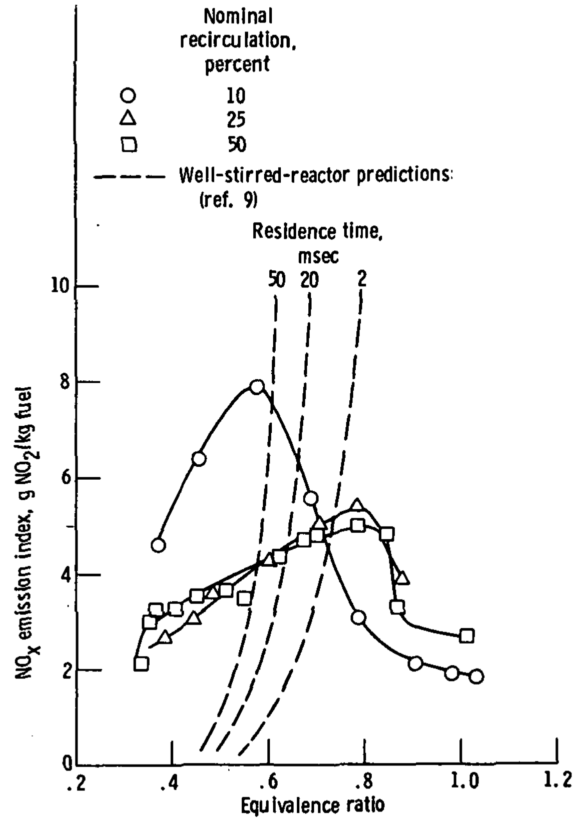


Figure 4. - Effect of recirculation on NO_x emission index. Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.

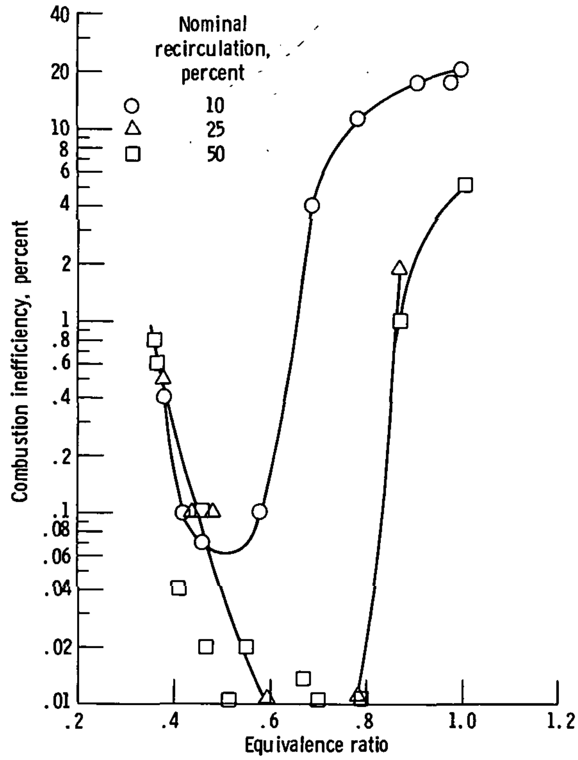
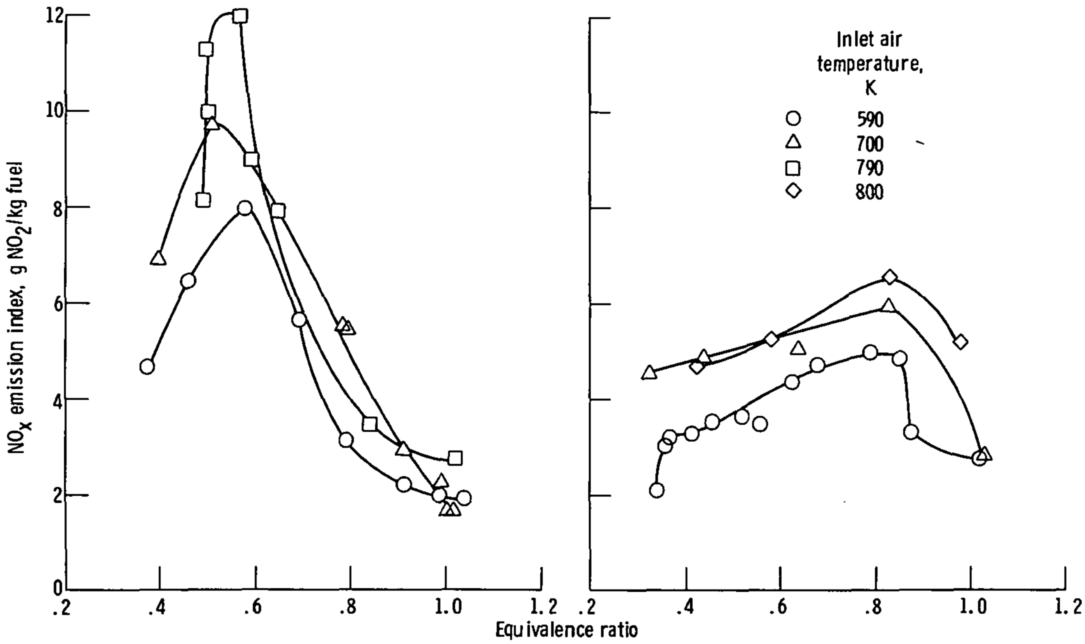


Figure 5. - Effect of recirculation rate on combustion inefficiency. Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.



(a) Nominal recirculation, 10 percent.

(b) Nominal recirculation, 50 percent.

Figure 6. - Effect of inlet air temperature on NO_x emission index. Pressure, 0.5 megapascal; reference velocity, 15 meters per second.

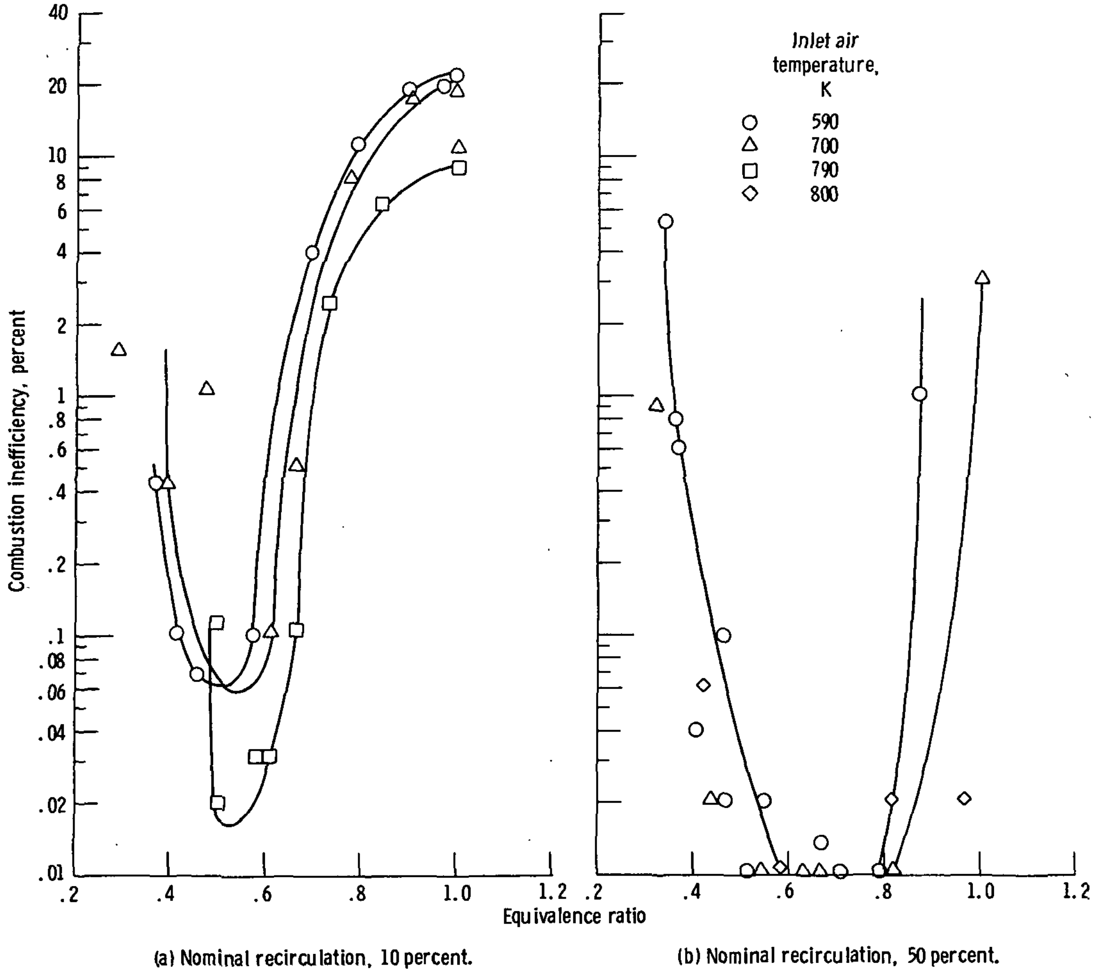


Figure 7. - Effect of inlet air temperature on combustion inefficiency. Pressure, 0.5 megapascal; reference velocity, 15 meters per second.

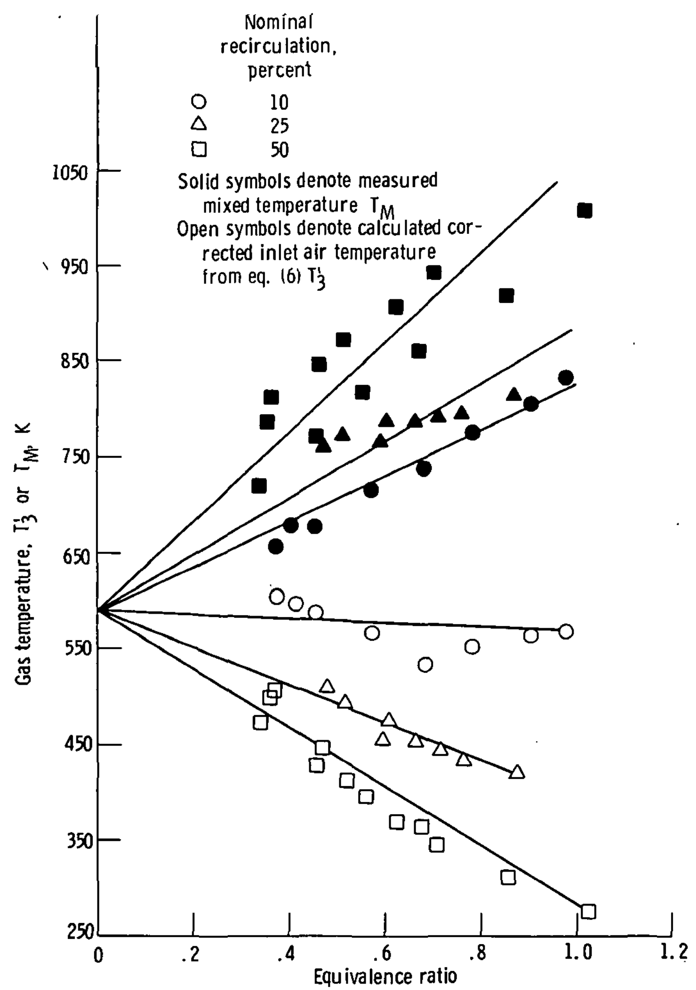


Figure 8. - Measured mixed temperature and corrected inlet air temperature calculated from equation (6). Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.

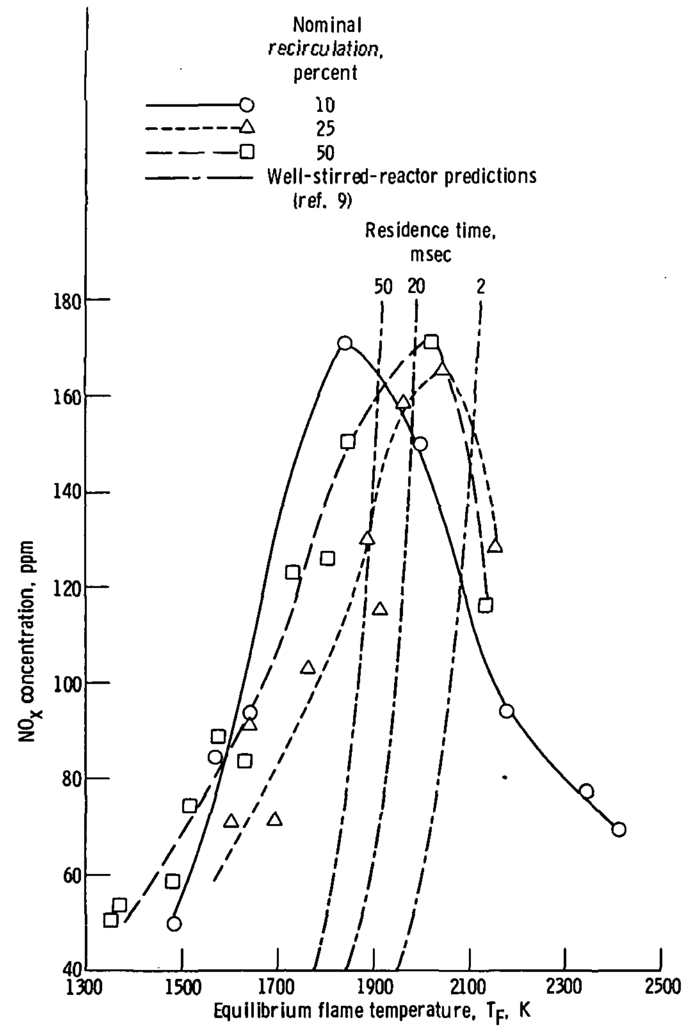
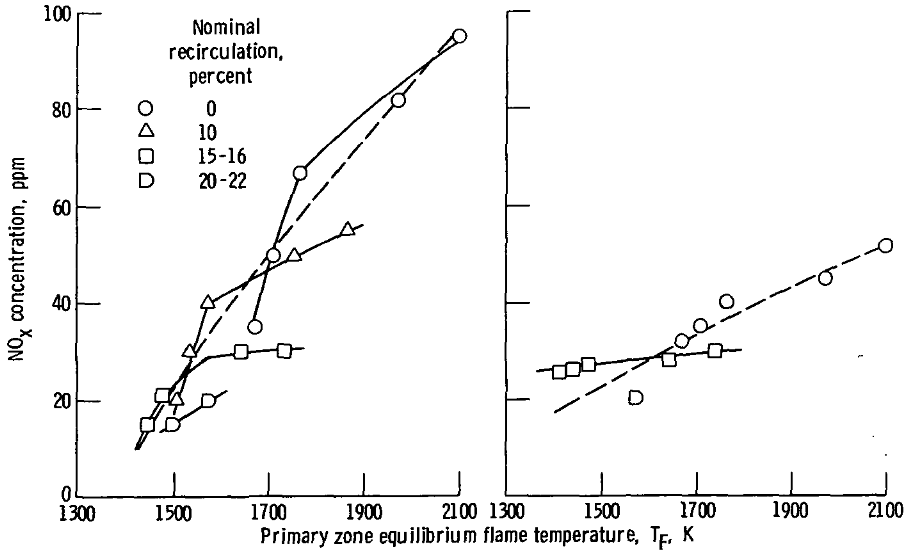


Figure 9. - Concentration of NO_x emissions as function of equilibrium flame temperature. Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.



(a) Configuration B, lean primary zone. (b) Configuration E, rich primary zone.

Figure 10. - Concentration of NO_x emissions as function of primary zone equilibrium flame temperature (ref. 4). Recirculated products cooled to inlet air temperature of 310 K; combustor pressure, 0.1 megapascal; reference velocity, 1.5 to 3.0 meters per second.

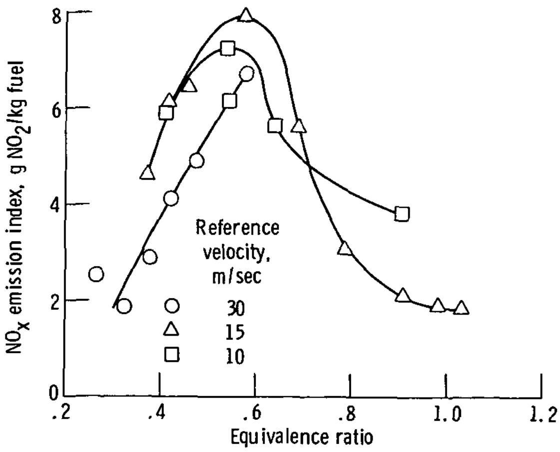


Figure 11. - Effect of reference velocity on NO_x emission index. Inlet air temperature, 590 K; pressure, 0.5 megapascal; nominal recirculation, 10 percent.

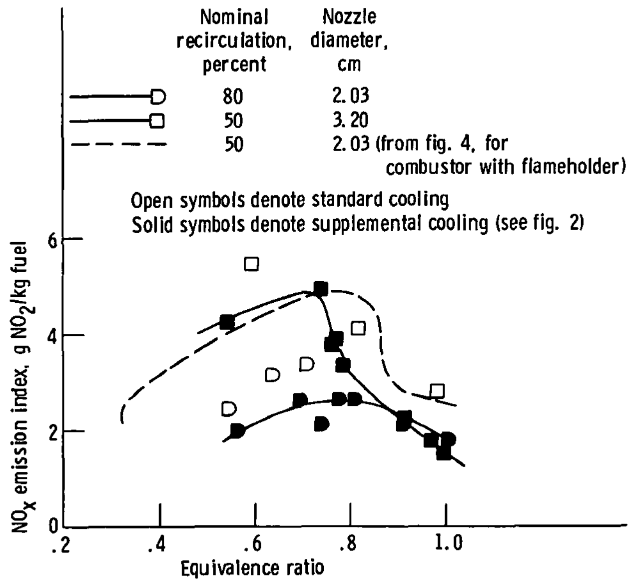


Figure 12. - Variation of NO_x emission index without flameholder present. Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.

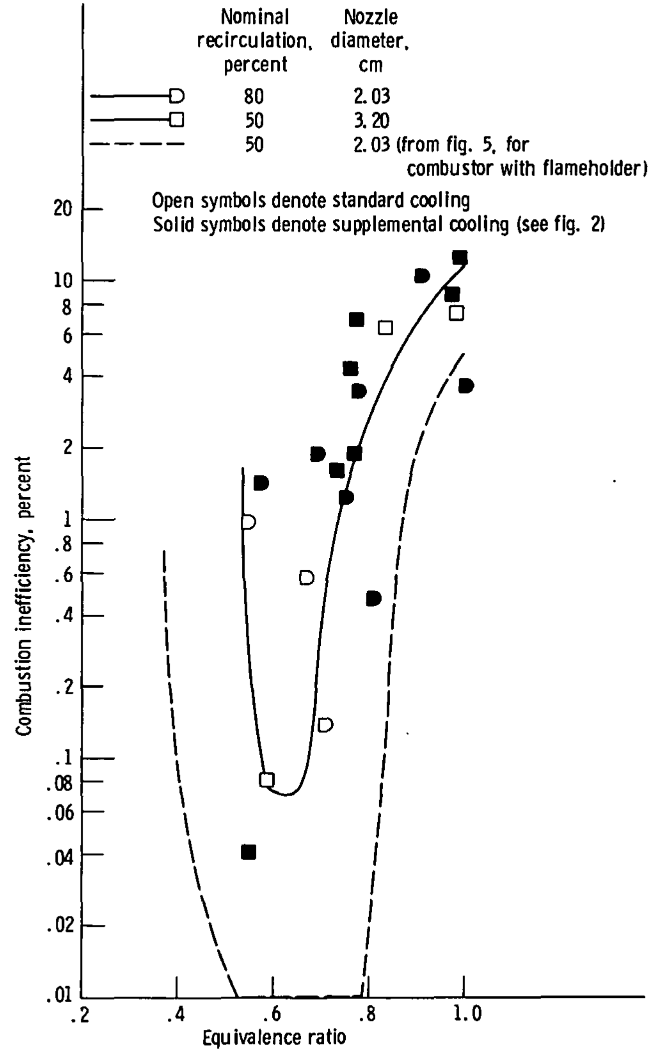


Figure 13. - Combustion inefficiency without flameholder present. Inlet air temperature, 590 K; pressure, 0.5 megapascal; reference velocity, 15 meters per second.

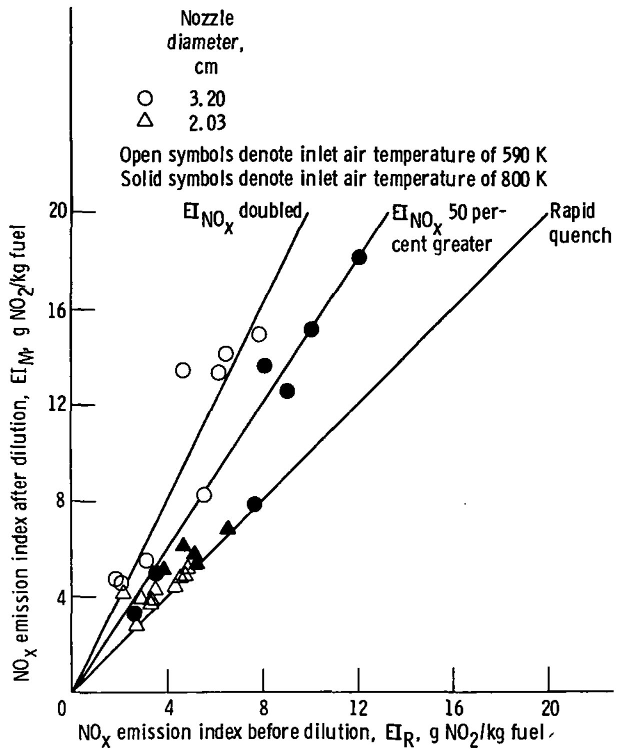


Figure 14. - Production of NO_x by quenching jet (ejector). Pressure, 0.5 megapascal; reference velocity, 15 meters per second.

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