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16. Abstract Emissions of nitrogen oxides, carbon monoxide, and unburned hydrocarbons were measured in a burner where liquid Jet A fuel was sprayed into the heated air stream and vaporized upstream of a perforated plate flameholder. The burner was tested at inlet air temperatures at 640, 800, and 833 K, an inlet pressure of $5.6 \times 10^5 \text{ N/m}^2$, a reference velocity of 25 m/sec, and equivalence ratios from lean blowout to 0.7. Nitrogen oxide levels of below 1.0 g NO_2/kg fuel were obtained at combustion efficiencies greater than 99 percent. The measured emission levels for the liquid fuel agreed well with previously reported premixed gaseous propane data and agreed with well stirred reactor predictions. Autoignition of the premixed fuel air mixture was a problem at inlet temperatures above 650 K with 104 msec premixing time.					
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EXHAUST EMISSIONS FROM A PREMIXING, PREVAPORIZING FLAME TUBE USING LIQUID JET A FUEL

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SUMMARY

Liquid Jet A fuel was injected into the inlet air stream upstream of a perforated plate flameholder. Emissions of nitrogen oxides, carbon monoxide, and unburned hydrocarbons were measured in the flame tube at inlet air temperatures of 600, 800, and 833 K, an inlet pressure 5.6×10^5 newtons per square meter, a reference velocity of 25 meters per second, and equivalence ratios from lean blowout to 0.7. Emission levels of nitrogen oxides were below 1.0 gram NO_2 per kilogram of fuel at combustion efficiencies of greater than 99 percent for the lean mixtures.

A single pressure atomizing nozzle was used spraying contraflow to the air flow. A uniform fuel air mixture was obtained at the flameholder. The measured emission levels for the liquid fuel agreed well with previously reported premixed gaseous propane data and agreed with well stirred reactor predictions.

Autoignition of the fuel air mixture occurred in the inlet duct at inlet air temperatures above 650 K when the residence time upstream of the flameholder was greater than 104 milliseconds. The mixer residence time was decreased to 24 milliseconds, where it was possible to take data at 800 and 833 K at equivalence ratios below 0.56 without autoignition.

INTRODUCTION

Emissions were measured in a flame tube combustor operating with premixed, prevaporized Jet A fuel. The results were compared with previous data taken with gaseous propane fuel and with well stirred reactor predictions.

The technique of premixing the fuel and air before burning at lean equivalence ratios has been shown to be effective in reducing nitrogen oxides (NO_x) emissions (refs. 1 to 3). Anderson (ref. 1) used prevaporized propane injected 2.6 meters upstream of a water-cooled perforated plate flameholder. Anderson showed that by leaning out the burning

zone an order of magnitude reduction in NO_x is achieved while still maintaining 99 percent combustion efficiency. Roffe and Ferri (ref. 2) used Jet A fuel with a flame cone flameholder and high velocity mixer-vaporizer and obtained similar results.

In this experiment the apparatus of Anderson was used to permit a direct comparison between the propane data and liquid Jet A data. The apparatus simulates the primary zone of a gas turbine combustor. The operating conditions were an inlet pressure of 5.6×10^5 newtons per square meter, a reference velocity of 25 meters per second, inlet air temperatures of 600, 800, and 833 K, and equivalence ratios from lean blowout to 0.7. The autoignition characteristics were investigated.

APPARATUS

The liquid Jet A fuel was sprayed through a simplex pressure atomizing nozzle directly into a preheated inlet air stream. The flame-tube apparatus is shown in figure 1. Fuel was injected, vaporized, and mixed with air upstream of a water-cooled combustion section. The water-cooled combustor was 10.25 centimeters in diameter, the same as the inlet duct, and 31 centimeters long. At the downstream end, quench water was sprayed into the gas stream to cool the exhaust to 370 K. This mixture of combustion products and water passed through a remotely operated back pressure valve for control of rig pressure.

With the 640 K inlet temperature, liquid fuel was injected at one of two locations: either 2.6 or 0.61 meter upstream of the flameholder. For the 800 and 833 K inlet temperature only the 0.61 meter location was used.

The liquid fuel was sprayed through a 60° hollow-cone simplex pressure atomizing nozzle. The nozzle was rated at 0.242 cubic meter per hour (64 gal/hr) at a pressure differential of 68.9 newtons per square centimeter (100 psid). The injector pressure differential was maintained between 10 and 20 newtons per square centimeter (14.7 and 29.4 psid) to prevent impingement of the fuel on the wall. To insure good atomization, the nozzle was faced upstream to give a contraflow injection resulting in a high relative velocity between the fuel and the inlet air. Upstream penetration of the jet was approximately 1 centimeter. There was no sign of carbon deposits when the tests were completed after 200 hours of intermittent operation.

Figure 2 shows the water-cooled flameholder used in these tests. For durability reasons during flashback conditions, a water-cooled flameholder was used for all reported results. The flameholder was constructed of 0.63-centimeter-thick stainless steel plates. There were 61 holes 0.63 centimeter in diameter which resulted in an open area of 25 percent of inlet duct cross-sectional area. The total pressure drop across the burner was approximately 4.5 percent of the upstream total pressure.

A single Chromel-Alumel thermocouple was inserted 2 centimeters into the flow at

a location 12.7 centimeters upstream of the flameholder to measure the mixed temperature T_{35} of the fuel and air. The inlet air temperature T_3 was measured 3 meters upstream of the flameholder before injection of the fuel.

A single-point gas-sample probe was used. The probe could be traversed axially, radially, and circumferentially. Samples were taken on the centerline and within 1 centimeter of the wall. The water-cooled stainless-steel gas-sampling probe had a 0.63 centimeter outside diameter with a center sampling tube having a 0.159-centimeter diameter. Stainless-steel tubing (0.95 cm diam) connected the gas sample probe with the exhaust gas analyzers. To prevent condensation of unburned hydrocarbons this sample line was electrically heated to maintain the sample gas temperature between 410 and 450 K. The sample line was approximately 18 meters long.

Gas analysis equipment included a Model 402 Beckman flame ionization detector for measuring unburned hydrocarbons, Model 315B Beckman nondispersive infrared analyzers for measuring concentrations of carbon monoxide and carbon dioxide, and a Model 10A Thermo-Electron chemiluminescent instrument for total NO_x concentration.

Calibrating 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 with an EG & G Model 137 Vapor Mate II humidity meter with a Model S3 sensor. 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. Inlet air humidity was essentially zero for all tests.

RESULTS AND DISCUSSION

Emission levels of nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC) were measured from a premixing, prevaporizing combustor. The liquid Jet A data are compared to previously reported premixed gaseous propane data and to well stirred reactor predictions. The problem of autoignition is discussed.

Uniformity of Mixture and Emissions

For the contraflow fuel injection the mixture equivalence ratio based on the gas analysis carbon balance was very uniform across the combustor behind the flameholder and varied by at most ± 10 percent from the equivalence ratio based on the metered fuel and airflow rates. The emissions measured near the wall agreed with the values measured on the centerline.

Nitrogen Oxides Emissions

The NO_x emission levels from the Jet A combustor are shown in figure 3. Shown for comparison is a well stirred reactor (WSR) prediction using the model of Boccio, Weilerstein, and Edelman (ref. 4) and the premixed, prevaporized propane data of reference 1. It should be noted that the inlet temperatures used in reference 1 were of the propane/air mixture, while those of the present study are for the inlet air only with the fuel being at ambient temperature. An air inlet temperature of 640 K is comparable to a mixture temperature of 600 K, while an air temperature of 833 K is comparable to a mixture temperature of 800 K at an equivalence ratio of 0.5.

The NO_x results exhibit nearly exponential dependence on the equivalence ratio (flame temperature) characteristic of premixed flames at lean equivalence ratios. The data shown are for a hot gas residence time of 2 milliseconds; the residence time is computed from the mass flow rate, the equilibrium flame temperature, the cross-sectional area of the duct, and the distance of the probe from the perforated plate.

Two fuel-injection locations were used. With the 640 K inlet temperature, fuel was injected 2.6 meters upstream of the flameholder. However, with the 800 and 833 K inlet temperatures, this location resulted in autoignition upstream of the flameholder. Therefore, it was necessary to reduce the residence time of the injected fuel by moving the fuel nozzle closer to the flameholder. A location 0.61 meter upstream of the flameholder was chosen to allow enough time for droplet vaporization. To confirm if this permitted adequate residence time for fuel vaporization and fuel-air mixing additional data were taken at a 640 K inlet temperature at this new fuel injection location. It is apparent from figure 3 that the data taken at the 2.6-meter location agrees well with that at the 0.61 meter location. Both sets of data agreed well with the vaporized propane results and the WSR predictions. These comparisons indicate that mixing and vaporization are probably quite good in the present study for both fuel-injection locations.

The minimum level of NO_x emissions was 0.62 gram NO_2 per kilogram fuel at an equivalence ratio of 0.55 at 640 K. The combustion efficiency at this point was 99 percent. However, below an equivalence ratio of 0.55 blowout would occur and no data could be recorded.

At an inlet air temperature of 800 K, the minimum level of NO_x was 0.3 gram NO_2 per kilogram fuel at an equivalence ratio of 0.4. The combustion efficiency was 99 percent for this condition which was at an equivalence ratio slightly greater than lean blowout.

All of the well-mixed data correlate well as a function of the flame temperature as shown in figure 4. For the data shown, the combustor efficiency was greater than 99 percent and the combustor residence time was 2 milliseconds. Anderson (ref. 5) also obtained a good correlation of NO_x as a function of flame temperature for propane with hydrogen injection.

Good mixing and complete vaporization are necessary for low emissions of nitrogen oxides. Several fuel injector configurations had been tested before a uniform fuel-air distribution was obtained. Among these were the simplex nozzle spraying both contraflow, pointing upstream to spray against the airflow, and coflow, pointing downstream to spray with the airflow. Figure 5 is a comparison of the NO_x emissions for these two methods with the nozzle located at 2.6 meters upstream of the flameholder. The coflow injection resulted in NO_x levels three times higher than the contraflow case. The coflow injection decreased the relative velocity between the fuel and air and produced large droplets. Incomplete mixing produced locally rich zones entering the combustor. Blowout occurred at an equivalence ratio of 0.49 compared with 0.55 for contraflow. All reported data were taken with contraflow injection except that shown on figure 5 for coflow injection.

Carbon Monoxide Emissions

The carbon monoxide emission levels are shown in figure 6. The equilibrium CO levels at 640 and 833 K are also shown. With a 2-millisecond residence time, the CO emission levels approached equilibrium for equivalence ratios greater than 0.55.

Unburned Hydrocarbons Emissions

The unburned hydrocarbon emission index at an inlet temperature of 640 K was below 1.0 gram HC per kilogram fuel at the 2-millisecond residence time for all conditions except near blowout.

At the 800 and 833 K inlet temperatures the unburned hydrocarbons emission index became greater than 1 at an equivalence ratio of 0.43 and increased rapidly until blowout at an equivalence ratio of 0.37.

Combustion Inefficiency

The combustion inefficiency as determined from the gas analysis measurements at an 833 K inlet temperature is shown in figure 7. The combustion inefficiency drops rapidly for an equivalence ratio greater than 0.5. At an equivalence ratio of 0.4 (1750 K equilibrium flame temperature) the inefficiency is 1 percent. Combustor blowout occurred at an equivalence ratio of 0.37. At a 640 K inlet air temperature, the combustion inefficiency was less than 1 percent until just before blowout at an equivalence ratio of 0.55.

Axial Concentration Profiles of Nitrogen Oxides

Axial profiles of gas concentrations were determined at low equivalence ratios. The nitrogen oxide and combustion inefficiency profiles are shown in figure 8. The initial production of nitrogen oxides is highly nonlinear with most of the NO_x appearing within the first 2 milliseconds of reaction time. Some of the nonlinearity can be accounted for because the time is not linear with distance. Initial reactions take place at temperatures much lower than the assumed equilibrium flame temperature. The most likely explanation for the higher initial NO_x production, however, is that radical overshoot occurs in the recirculation zones. As the time increases the production rate decreases and becomes low at the lean equivalence ratios. The NO_x levels at 2 milliseconds are still two orders magnitude below equilibrium levels.

The combustion inefficiency profiles of figure 8 show that the hydrocarbon and carbon monoxide oxidation rate is relatively rapid. The reaction is 99 percent complete after a 2-millisecond residence time. In contrast, NO_x formation is still far from equilibrium after 2 milliseconds.

Autoignition and Flashback

At an inlet temperature of 640 K and a 5.6×10^5 newton per square centimeter pressure, the flashback of flame upstream of the flameholder occurred on ignition because of the rapid pressure rise in the combustor. However, stable conditions could be achieved by lighting off at an initial pressure of 3×10^5 newtons per square meter. Then the pressure was gradually raised to the 5.6×10^5 newtons per square centimeter desired operating conditions.

At the 2.6-meter upstream injector location, combustion occurred between the fuel injection point and the flameholder at an inlet temperature of 800 K. To establish whether upstream burning was caused by autoignition or flashback after ignition, the fuel flow was started without the ignitor energized. The temperature rise upstream of the flameholder was significant and is shown in figure 9. The ideal temperature curve shown represents the mixture temperature that would have resulted when the ambient-temperature fuel was vaporized by the hot air and the unburned mixture came to an equilibrium temperature. These results show that auto-oxidation reactions were occurring which raised the mixture temperature to the autoignition point. Auto-oxidation reactions were found to begin at 650 K when the fuel residence time was 104 milliseconds. The temperature rise which took place between the injector and the flameholder was also a function of equivalence ratio as shown in figure 10. The autoignition temperature for Jet A is given as 515 K in reference 6, but these data were taken for long residence times (3 min) and rich mixtures. As the residence time is reduced the igni-

tion temperature increases.

When the time in the vaporizer mixer was reduced to 24 milliseconds, a stable flame could be obtained at 800 K for an equivalence ratio between 0.37 and 0.56 without burning upstream of the flameholder. Above an equivalence ratio of 0.56 autoignition would again occur in the vaporizer with T_{35} (fig. 1) exceeding 1200 K.

CONCLUSIONS

Exhaust emissions of nitrogen oxides, carbon monoxide, and unburned hydrocarbons were measured from a premixing prevaporizing flame tube burning Jet A fuel. The combustor operating conditions were a reference velocity of 25 meters per second, inlet air pressure of 5.6×10^5 newtons per square centimeter, and inlet air temperatures of 640, 800, and 833 K.

The nitrogen oxide emission level was 0.6 gram NO_2 per kilogram fuel at an equivalence ratio of 0.55 and an inlet temperature of 640 K. The NO_x level at a 833 K inlet temperature was 0.3 gram NO_2 per kilogram fuel at an equivalence ratio of 0.4. These conditions were obtained with combustion efficiencies greater than 99 percent near the lean blowout point. Emission levels agreed well with predictions made with a well stirred reactor model with a 2-millisecond residence time. The NO_x emissions obtained from burning liquid Jet A fuel in this study compared well with previous resulting using gaseous propane fuel.

Autoignition was a problem at the higher inlet temperatures. Autoignition could be minimized by shortening the vaporizer residence time; however, it is necessary to allow enough time to completely vaporize the fuel to obtain low NO_x levels.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 28, 1976,
505-03.

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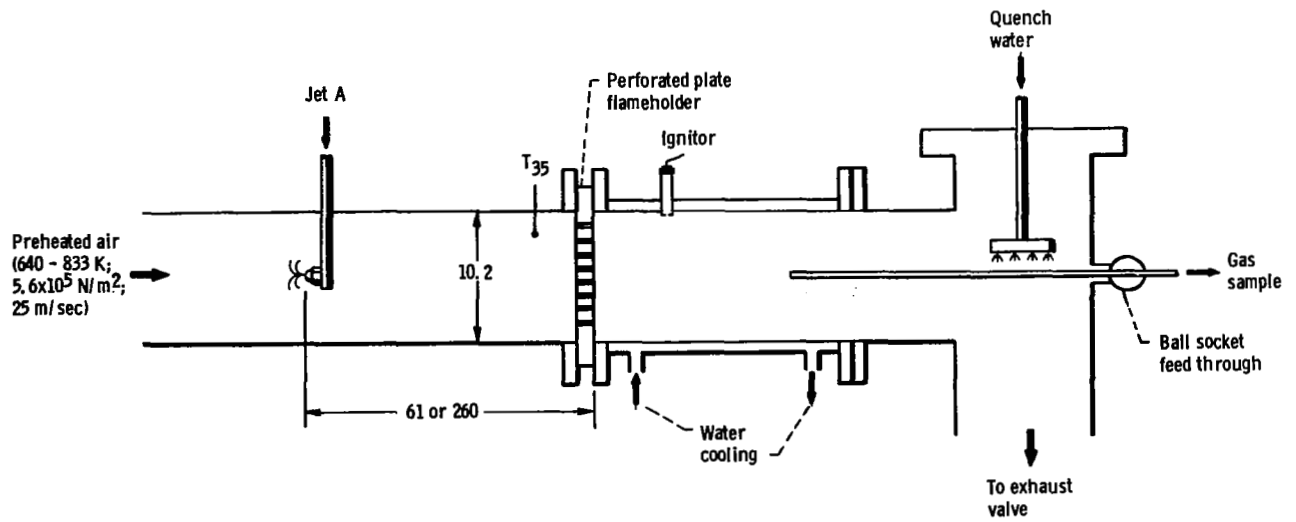


Figure 1. - Schematic of premixing-prevaporizing combustor. Dimensions are in centimeters.

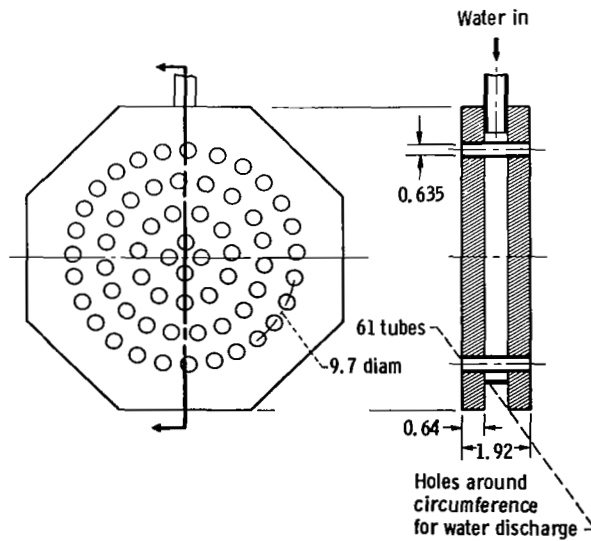


Figure 2. - Flameholder (dimensions in cm). Open area = 25 percent.

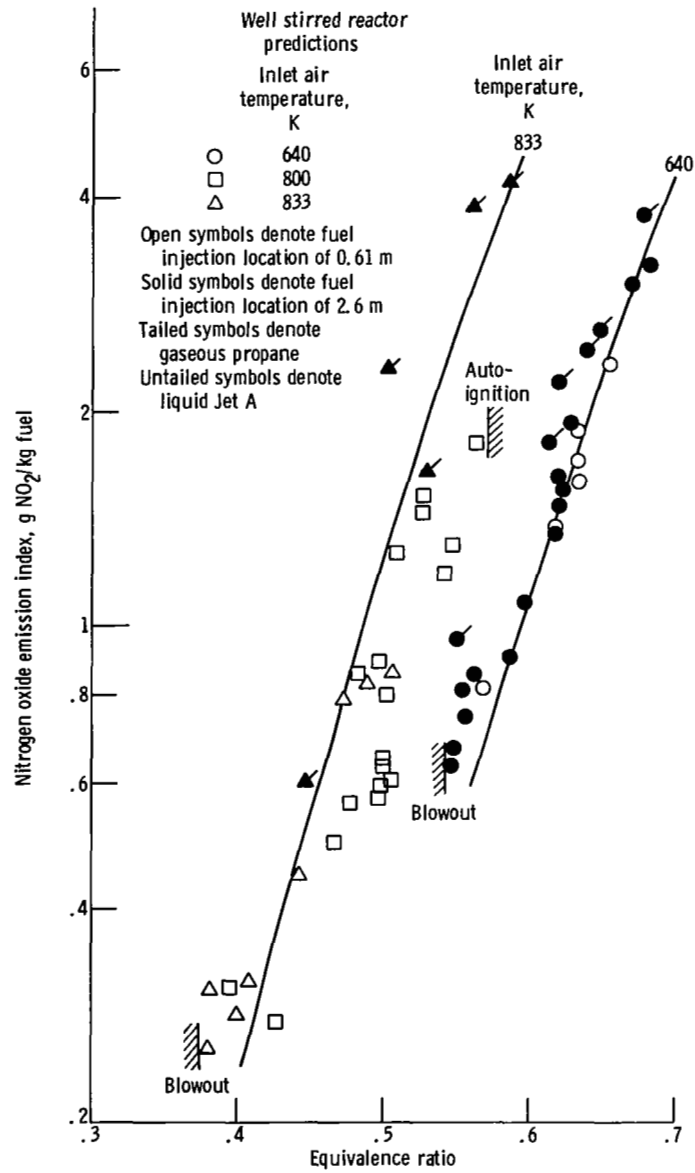


Figure 3. - Nitrogen oxide emissions for premixed systems. Inlet pressure, 5.6×10^5 newtons per square meter; reference velocity, 25 meters per second.

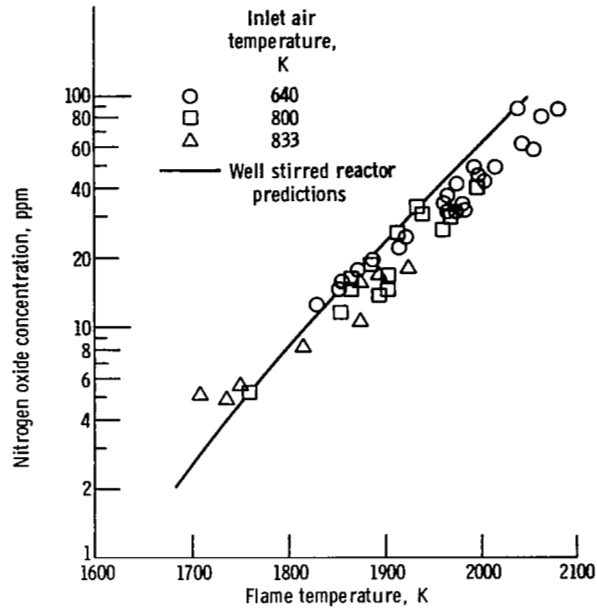


Figure 4. - Nitrogen oxide emissions as function of flame temperature.

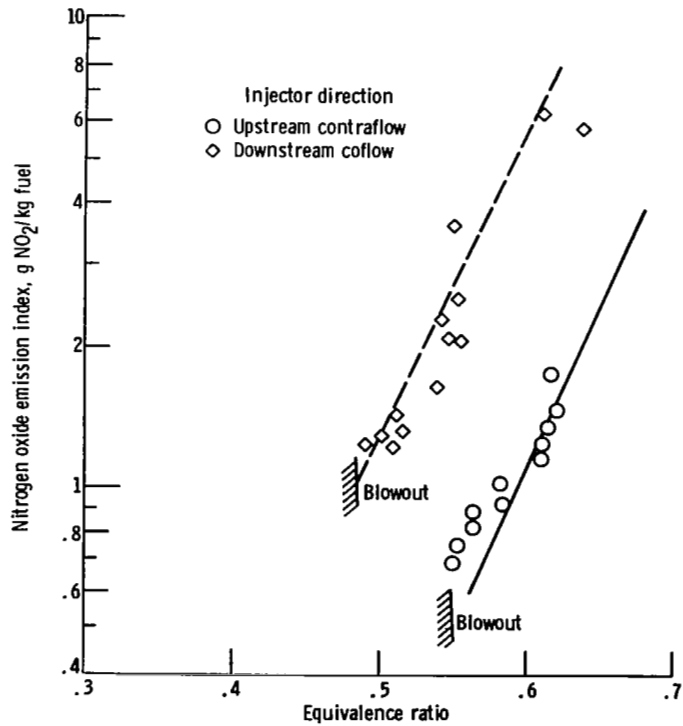


Figure 5. - Effect of fuel spray direction on nitrogen oxide fuel injector 2.6 meters upstream of flameholder. Inlet temperature, 640 K; inlet pressure, 5.6×10^5 newtons per square centimeter.

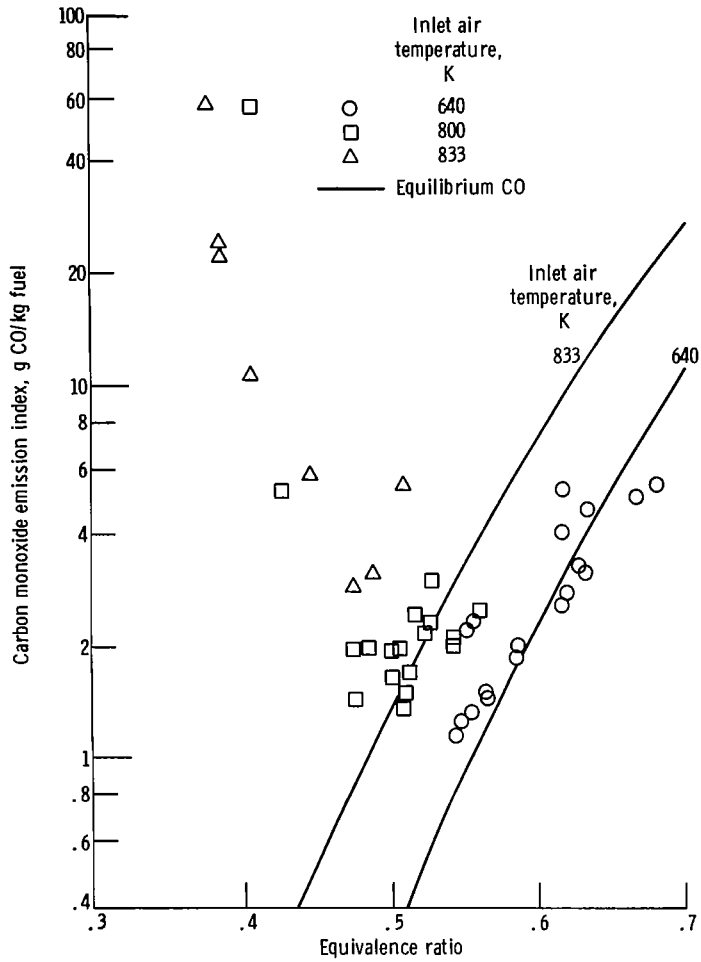


Figure 6. - Carbon monoxide emission index as function of equivalence ratio. Pressure, 5.6×10^5 newtons per square centimeter; residence time, 2 milliseconds.

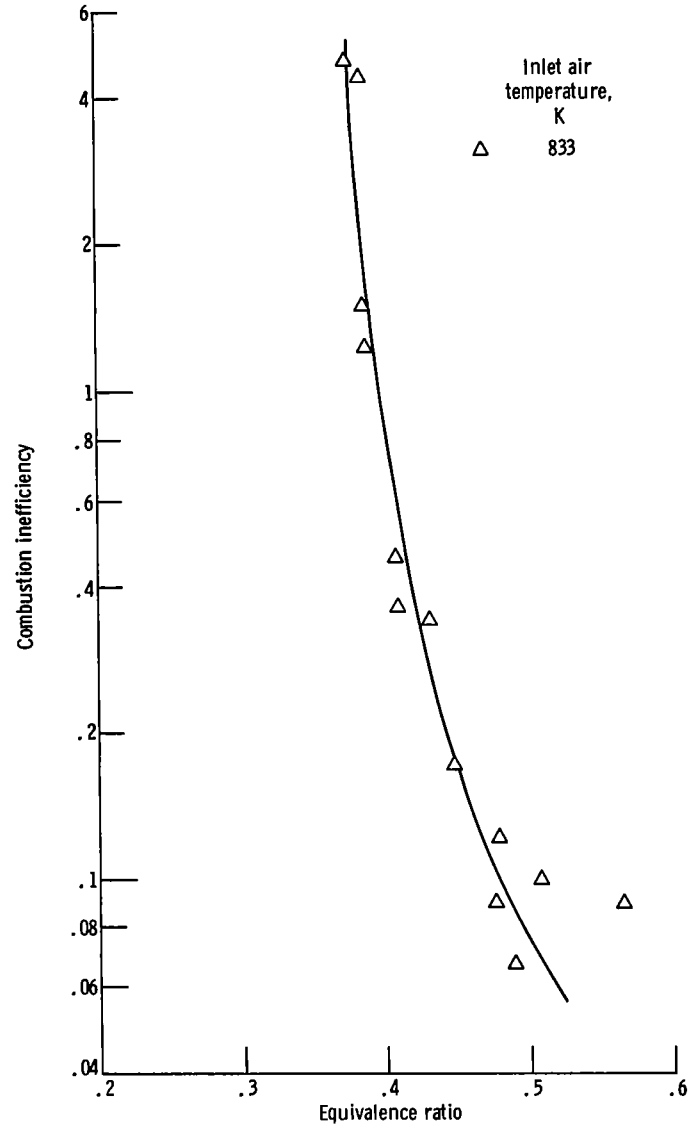
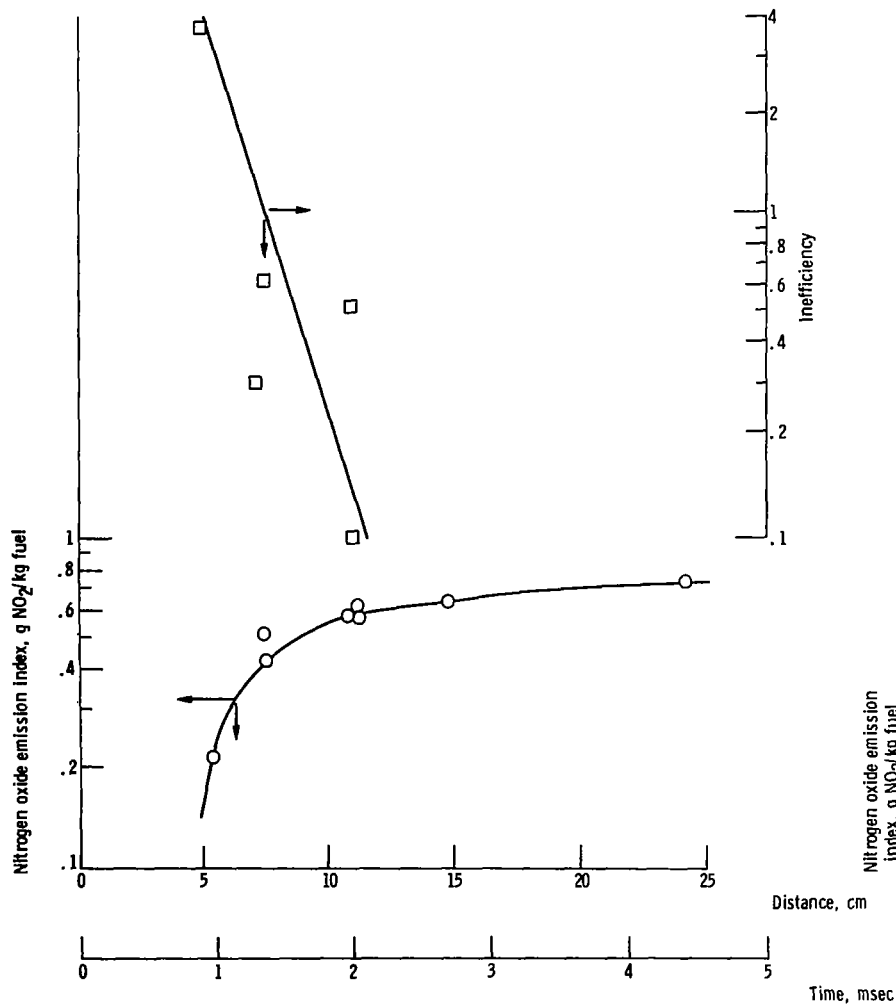
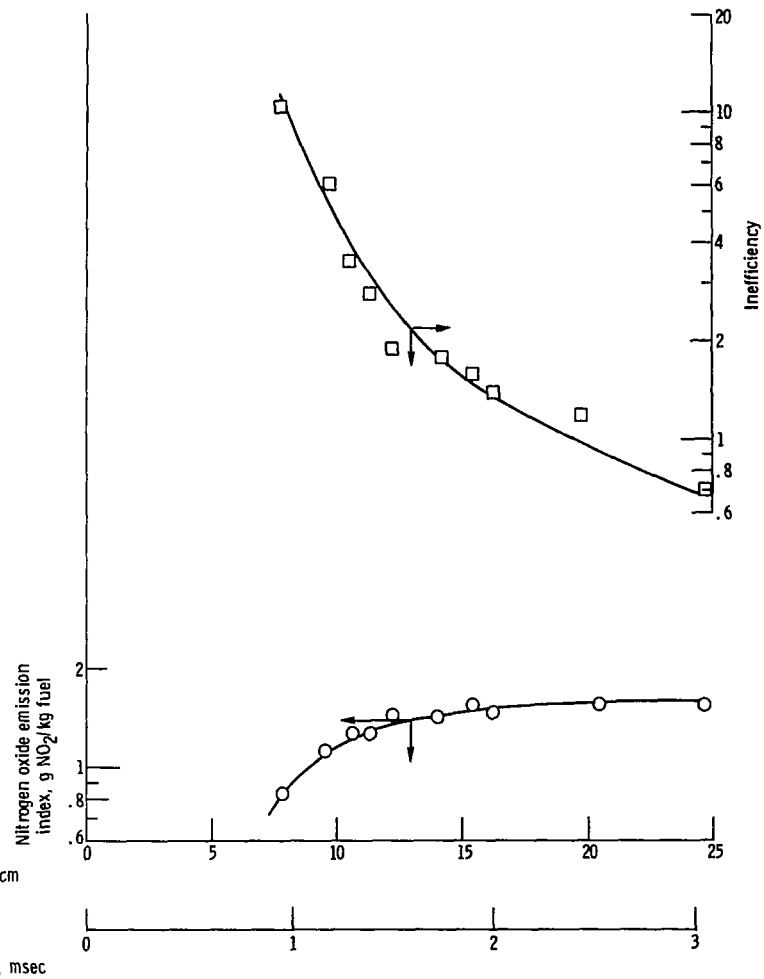


Figure 7. - Combustion inefficiency as function of equivalence ratio. Residence time, 2 milliseconds; pressure, 5.6×10^5 newtons per square centimeter.



(a) Inlet temperature, 800 K; equivalence ratio, 0.48.



(b) Inlet temperature, 640 K; equivalence ratio, 0.6.

Figure 8. - Gas concentration profiles.

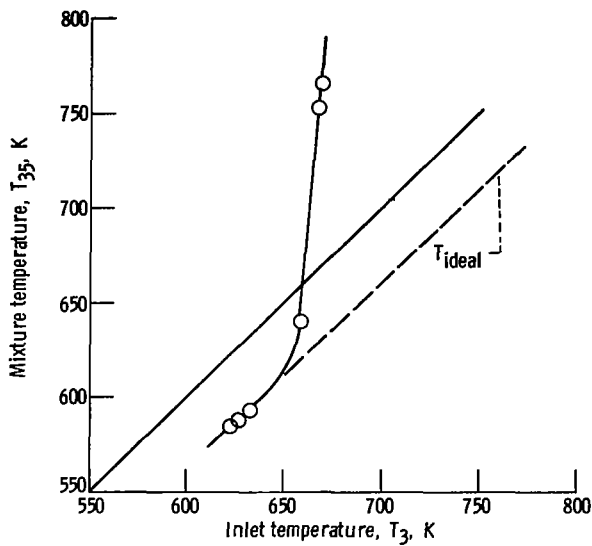


Figure 9. - Temperature rise in mixer at long vaporizer time. Inlet pressure, 5.6×10^5 newtons per square centimeter; reference velocity, 25 meters per second; equivalence ratio, 0.65; distance, 2.6 meters; vaporizer time, 104 milliseconds.

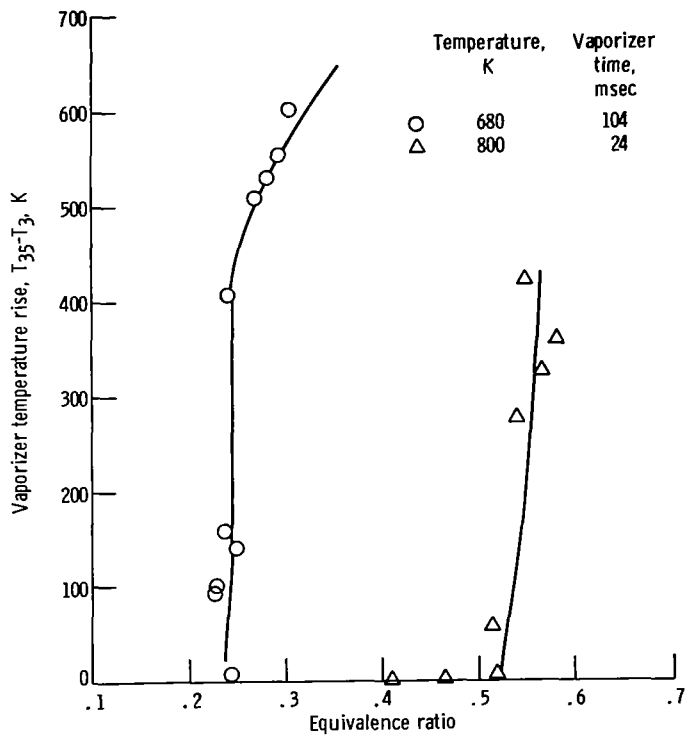


Figure 10. - Temperature rise in vaporizer mixer indicating autoignition reactions.



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