NASA Technical Paper 1463

Effect of Primary-Zone Equivalence Ratio on Pollutant Formation

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MAY 1979

NASA

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National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1979

SUMMARY

Tests were conducted to determine the effect of primary-zone equivalence ratio on the formation of smoke and other gaseous pollutants in an experimental can combustor. Of special interest was the amount of smoke produced during fuel-rich combustion in the primary zone. Several fuel-injection techniques were explored in an attempt to reduce fuel-rich combustion smoke levels. Two of the four fuel-injection configurations studied produced smoke levels below a smoke number of 20 at a primary-zone equivalence ratio of about 1.7. Increasing the combustor pressure drop from 4 percent to 10 percent decreased smoke levels such that, at a primary-zone equivalence ratio of 2.0, the smoke numbers were less than 20. These tests were conducted at an inlet-air temperature of 477 K and pressure of 0.34 megapascal. Smoke formation was augmented by increasing the inlet-air pressure to 0.69 megapascal; smoke formation was reduced by increasing the inlet-air temperature to 589 K. The primary-zone equivalence ratio was varied from 0.8 to 2.0. The higher equivalence ratios resulted in high levels of hydrocarbons and carbon monoxide and low levels of oxides of nitrogen. The exact levels of these pollutants varied significantly with the fuel-injection configuration used.

INTRODUCTION

As part of a continuing effort at the Lewis Research Center to reduce exhaust emissions produced by aircraft engines, an investigation was conducted to determine the effect of primary-zone equivalence ratio on the formation of gaseous pollutants. Special emphasis was placed on reducing the smoke produced during fuel-rich combustion in the primary zone. A number of fuel-injection techniques were investigated in an attempt to minimize smoke formation.

Two current trends in the development of advanced gas-turbine engines are compounding the problems faced by combustion engineers attempting to develop low-pollutant engines. The first trend is the development of energy-efficient turbofan engines. These engines characteristically use increased compressor pressure ratios and turbine inlet temperatures to improve the overall thermodynamic cycle efficiency. The resulting increased pressures and temperatures within the combustor enhance the formation of oxides of nitrogen (NO_x). Oxides of nitrogen are formed during any combustion process involving air. Altering gas-turbine combustors to substantially reduce these emissions is, perhaps, the most difficult task combustion engineers face.

The second trend is an increased emphasis on the use of domestic energy resources as the supply of imported liquid petroleum becomes more expensive and less certain. This trend may result in the use of synthetic liquid fuels (synfuels) derived from coal, oil shale, and tar sands as the fuel source for commercial and military aircraft engines (ref. 1). Liquid synfuels, however, may contain significant quantities of fuel-bound nitrogen, depending on the amount of refining they undergo. Fuel-bound nitrogen will increase the oxides-of-nitrogen levels produced by the combustor.

The Lewis Research Center is actively involved in examining several techniques to reduce oxides-of-nitrogen formation (refs. 2 to 4). Yet the continuing trends toward energy-efficient engines and the use of liquid synfuels may severely limit the effectiveness of these techniques. One proposed solution to these problems is to use combustion systems designed for fuel-rich combustion in the primary zone followed by carefully tailored combustion in the secondary zone. The secondary zone must operate at a flame temperature high enough for complete oxidation of carbon monoxide (CO) but low enough to prevent oxides-of-nitrogen formation. A major drawback to this technique is the formation of large quantities of visible smoke during fuel-rich combustion (ref. 5). Using liquid synfuels makes this smoke formation even worse because of their generally lower volatility and lower hydrogen content (refs. 6 and 7). For smoke-free, fuel-rich combustion, new levels of homogeneous fuel distribution will have to be reached.

This report describes the effect of primary-zone equivalence ratio on the formation of smoke and other gaseous pollutants in a 10-centimeter-diameter can combustor. This combustor was designed with a convectively cooled, fuel-rich primary zone. ASTM Jet-A fuel was used and the operating conditions were inlet-air pressures from 0.34 to 0.69 megapascal, inlet-air temperatures from 477 to 589 K, and primary-zone equivalence ratios from 0.8 to 2.0.

APPARATUS AND PROCEDURE

Test Facility

The tests in this study were conducted in a connected-duct test facility. This facility was able to supply air to the combustor at a flow rate of 0.7 kilogram per second at pressures to 0.7 megapascal. The inlet air was heated to 477 and 589 K in a nonvitiating preheater. In these tests the hot exhaust gases from the combustor were cooled in a water-spray section before entering the facility exhaust ducting. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. Airflow rates were measured by a square-edged orifice installed according to ASME specifications. Fuel flow rates were measured by two turbine flowmeters with frequency-to-voltage converters for readout and recording. The fuel used was ASTM Jet-A.

A schematic drawing of the test facility, showing the airflow passage through the inlet plenum into the research combustor, is shown in figure 1. Inlet-air pressures and temperatures were measured at the plenum exit. A single, six-point, water-cooled gas sample probe was located at the combustor exit. The exhaust gases collected were passed through steam-heated lines to the gas analysis console.

The gas analysis console is a packaged unit consisting of four commercially available instruments and a smoke meter. The hydrocarbon content of the exhaust gas was measured with a Beckman Instruments model 402 hydrocarbon analyzer. This instrument uses a flame ionization detector. Oxides-of-nitrogen concentrations were measured with a Thermo Electron Corp. model 10A chemiluminescent analyzer. This instrument was used with a thermal reactor to reduce nitrogen dioxide in the sample system to nitric oxide. Both carbon monoxide and carbon dioxide were measured with Beckman Instrument model 315B. These instruments use nondispersive infrared detectors.

The smoke concentration was measured in accordance with SAE-recommended practice (ref. 8). Metered volumes of exhaust gas were passed through a filter paper, depositing the soot contained in the gas on the filter paper. The darkness of the stain on the paper, as determined optically, indicated the smoke number of the exhaust gases. After the smoke number was recorded at each equivalence ratio, sufficient time was allowed to completely purge the gas sample lines.

Liner temperatures were measured with 15 Chromel-Alumel thermocouples at various axial and circumferential locations on the combustor. Liner temperatures normally ranged from 1100 to 1300 K and were continuously monitored to prevent combustor damage. This was particularly important when the primary zone was operating at stoichiometric conditions.

Test Conditions

Combustor operating conditions for the test evaluating the four fuel-injection configurations were as follows:

Inlet-air pressure, MPa	0.34
Inlet-air temperature, K	477
Airflow rate, kg/sec	0.33
Fuel-air ratio	0.023 - 0.059
Nominal combustor pressure drop, percent	4

During tests in which the inlet-air temperature and pressure were increased to 589 K and 0.69 megapascal, respectively, the airflow rate was adjusted to maintain a constant pressure drop across the combustor. During tests in which the combustor pressure drop was increased to 10 percent, the inlet-air pressure and temperature were maintained at 0.34 megapascal and 477 K.

Research Combustor

A schematic drawing of the experimental can combustor used in this study is shown in figure 2. Designated the "rich-burn combustor," it was designed with a very short secondary (or burnout) zone so that the emissions measured by the gas analysis system would be largely a function of the primary-zone combustion process. The primary zone was convectively cooled and had six fuel-air entry ports.

Each fuel-air entry port was designed to meter the air and fuel so that the fuel-air ratio at each point of entry into the combustion zone would be the same. One of these fuel-air entry ports was the front headplate. The amount of air entering the headplate was determined from cold-airflow calibration. The headplate was designed to flow 14 percent of the total combustor airflow and to control the equivalence ratio of the fuel-air mixture entering at this point by injecting a precisely metered amount of fuel.

The five other fuel-air entry ports were a series of fuel-air chutes located circumferentially around the rich-burn combustor. A cross section of a fuel-air chute is shown in figure 2. Each fuel-air chute was designed to flow 5 percent of the total combustor airflow, or together 25 percent of the total airflow. A splash-groove fuel injector (ref. 9) was located in each chute. After water-flow calibrations to ensure that each splash-groove nozzle flowed approximately the same amount, the nozzles were joined together in a common manifold. The manifold was sized to provide an equal supply pressure to each nozzle. The fuel supply to this manifold was metered to control the equivalence ratio of the fuel-air mixture entering the primary zone from the fuel-air chutes.

Together the headplate and the fuel-air chutes were designed to flow 39 percent of the total combustor airflow. The remainder of the airflow passed between the fuel-air chutes and was used for either dilution of the combustion gases or film cooling. Figure 2(a) shows the air passage through the combustor.

Four variations in fuel injection were made, as detailed in figure 3. The first configuration used splash-groove fuel injectors in both the headplate and the fuel-air chutes. The splash-groove fuel injector in the headplate was mounted in a radial-flow air swirler. This configuration was used as a baseline and is depicted in figure 2. Reference 10 reports improved emissions with the use of splash-groove fuel injectors. The five splash-groove fuel injectors mounted in the fuel-air chutes were moved from their axial location in configuration 1 to a position farther upstream in configurations 2 to 4. This was done to improve the premixing of the fuel-air mixture and to increase the prevaporization of the fuel.

Configuration 2 used a simplex pressure-atomizing nozzle mounted in the radial-flow air swirler on the headplate. This headplate configuration had worked well in the study reported in reference 11, and the effect of the spray cone in distributing the fuel was of interest. Configuration 3 used an air-assist nozzle in place of the pressure atomizer in configuration 2. It was hoped that the finer droplets produced by the nozzle might be more readily entrained in the airflow and produce a better fuel-air distribution in the combustion zone. Configuration 4 used a pressure-atomizing nozzle and a axial-flow air swirler mounted in a premixing carburetor tube. This configuration was designed to premix and partially prevaporize the fuel entering the combustion zone from the headplate. Using the carburetor tube required a small amount of airflow to film cool the headplate. The reverse-flow film cooling scheme used was designed to flow less than 1 percent of the total combustor airflow. The fuel supplied to the carburetor tube was correspondingly increased so that the overall fuel-air ratio of the fuel-air mixture supplied by the headplate would equal that supplied by the fuel-air chutes. Figure 4 shows the rich-burn combustor with the configuration 4 headplate mounted in the test housing.

RESULTS

Exhaust emissions were measured for four fuel-injection configurations operating over a wide range of primary-zone equivalence ratios. The sample accuracy of these measurements changed as a function of the fuel-injection configuration. Sample accuracy was determined by comparing the calculated fuel-air ratio from gas sampling with the actual metered fuel-air ratio. On the average, fuel-injection configuration 1 gave calculated fuel-air ratios 25 percent higher than the metered fuel-air ratios. Configurations 2 to 4 gave calculated fuel-air ratios only 15 percent higher than their metered ratios. Fifteen percent is quantitatively acceptable, as the gas sample ports were not receiving some of the film-cooling air. The emission indexes (EI's) used to compare the exhaust emissions of the fuel-injection configurations were those computed by using the fuel-air ratio calculated from the gas sample content. This emission index provides a better indication of the combustor emissions, as it is the EI that, theoretically, would have been recorded by using both the calculated and metered fuel-air ratios had the gas sampling and the exhaust-gas mixing been improved. Therefore, even though the gas sampling is not very satisfactory, the results are valid and perhaps indicative of the mixing performance of the fuel-injection configuration. The test results with the four fuel-injection configurations are presented and discussed in the following sections.

Hydrocarbon Emissions

Unburned-hydrocarbon emissions as a function of primary-zone equivalence ratio for the four fuel-injection configurations are shown in figure 5. In general, the hydrocarbon levels produced by all the fuel-injection configurations decreased from an equivalence ratio of 0.8 to a minimum at an equivalence ratio of about 1.4. From this point on, hydrocarbon emissions increased sharply. At equivalence ratios of 1.8 or less, the hydrocarbon emissions produced by all configurations were relatively low. As a hydrocarbon emission index of 10 grams per kilogram of fuel represents 1 percent in combustion inefficiency (assuming all the hydrocarbon emissions are of the form CH_2), configurations 1 to 4 exhibited about 0.9, 0.6, 0.56, and 1.2 percent inefficiency, respectively, at an equivalence ratio of 2.0. But at an equivalence ratio of 1.8 the highest percentage was only 0.18. Configuration 3, which used an air-assist fuel nozzle in the headplate, produced the lowest overall hydrocarbon emissions. Configuration 4 produced on an average, the highest hydrocarbon emissions. The low hydrocarbon emissions of configuration 3 were probably due to the fine atomization of the fuel by the air-assist nozzle. The high hydrocarbon emissions of configuration 4 were probably due to fuel droplets centrifuging out on the carburetor tube wall.

Carbon Monoxide Emissions

Carbon monoxide emissions as a function of primary-zone equivalence ratio for the four fuel-injection configurations are presented in figure 6. As might be expected, because of the short combustor secondary zone, large quantities of carbon monoxide were produced at the higher primary-zone equivalence ratios. At an equivalence ratio of 0.8, carbon monoxide emission indices of 7 grams per kilogram of fuel were typical. At an equivalence ratio of 2.0, carbon monoxide emission indices were as high as

400 grams per kilogram of fuel. Since a carbon monoxide emission index of 42.5 grams per kilogram of fuel represents 1 percent combustion inefficiency, the higher primary-zone equivalence ratios resulted in combustion inefficiencies of about 9 percent. Actually at the highest equivalence ratios, equilibrium carbon monoxide, produced as a result of the high exhaust-gas temperatures, can be responsible for a significant amount of the total carbon monoxide emitted. Nevertheless, at the lower equivalence ratios, the combustion process was quite inefficient. For example, at an equivalence ratio of 1.0, all fuel-injection configurations exhibited about 1 percent inefficiency due to carbon monoxide. At an equivalence ratio of 1.2 the inefficiency was increased to 1.5 to 2.0 percent.

All the fuel-injection configurations displayed similar trends. Configuration 1, however, produced consistently higher carbon monoxide levels at primary-zone equivalence ratios from 0.8 to 1.8. For example, at an equivalence ratio of 1.0, configuration 1 had a carbon monoxide emission index of 30 grams per kilogram of fuel, but configurations 2 to 4 had indices of 16, 19, and 18, respectively. Configurations 2 and 3 produced the lowest carbon monoxide emission levels for most of the primary-zone equivalence ratios examined. But in general, none of the fuel-injection configurations exhibited minimal carbon monoxide emissions over the full range of equivalence ratios investigated.

Oxides of Nitrogen

Oxides-of-nitrogen emissions as a function of primary-zone equivalence ratio for the four fuel-injection configurations are shown in figure 7. Oxides-of-nitrogen emissions for all configurations were at a maximum near primary-zone equivalence ratios of 0.8 to 1.0, with emission indexes of about 5.5 grams per kilogram of fuel. Increasing the equivalence ratio resulted in gradually lower levels of oxides of nitrogen, with minimum recorded emission indices at ratios of 1.8 to 2.0. For configurations 1 to 4 the minimum recorded emission indices were 2.4, 1.6, 2.3, and 2.4, respectively. Configuration 2 produced the lowest oxides-of-nitrogen levels at equivalence ratios from 1.2 to 2.0. For the same range of equivalence ratios the other configurations displayed almost equal emissions levels. At lower primary-zone equivalence ratios the amount of oxides of nitrogen produced varied greatly from one configuration to the other.

Smoke

The amount of smoke produced by the four fuel-injection configurations as a function of primary-zone equivalence ratio is shown in figure 8. For all the configurations, increasing the primary-zone equivalence ratio augmented smoke formation. Up to an equivalence ratio of about 1.7, configurations 2 and 3 produced smoke levels below a smoke number of 20. At an equivalence ratio of 1.7, configuration 4 produced smoke levels only slightly higher, with smoke numbers of about 22. A smoke number of 20 is regarded as the visible threshold of smoke emissions for large gas-turbine engines. Maximum smoke numbers of 40 to 65 were recorded at a primary-zone equivalence ratio of 2.0.

Configuration 1 was the smokiest of all the configurations examined. This configuration produced a smoke number of 23 at an equivalence ratio of 1.2 and became steadily worse at the richer equivalence ratios. When smoke levels were below the visible threshold for configurations 2 to 4, configuration 1 emitted smoke numbers of about 50. The smoke production of configurations 2 to 4 increased sharply beyond equivalence ratios of 1.6 but never surpassed the smoke levels produced by configuration 1. Configuration 3 exhibited the lowest smoke levels.

Since smoke formation is a complex function of inlet-air pressure, inlet-air temperature, and the degree of fuel and air mixing in the combustion zone, a series of tests were conducted in which these conditions were parametrically varied. The effect of increased combustor pressure drop over a range of primary-zone equivalence ratios is shown in figure 9 for combustor configuration 2. As the combustor pressure drop was increased from 4 percent to 10 percent, significantly lower smoke levels were recorded. At the highest equivalence ratio of 2.0, the smoke number was reduced from 52 to 18. These lower smoke numbers can be attributed to two effects. First, the increased pressure drop improved the fuel-air mixing in the primary zone and thus resulted in more homogeneous combustion. Second, the increased pressure drop resulted in increased air velocity in the fuel-air chutes and thus improved the fuel atomization in these chutes. Reference 12 documents the effect that increased air velocity has on fuel atomization.

The effect of increased inlet-air temperature and pressure on smoke formation is shown in figure 10. At primary-zone equivalence ratios of 1.4 and below, the smoke levels were all so low as not to be significantly affected by changes in operating pressure or temperature. However, the smoke levels at the higher equivalence ratios were quite sensitive to pressure and temperature levels. For example, at an equivalence ratio of 1.8, the following smoke numbers were recorded: 59 for the increased inlet-air pressure condition, 12 for the increased inlet-air temperature condition, and 36 for the standard operating conditions of 0.34 megapascal and 477 K. In general, increasing the inlet-air pressure to 0.69 megapascal yielded higher smoke numbers and increasing the inlet-air temperature to 589 K yielded lower smoke numbers. Fuel-injection configuration 4 was used in these tests.

DISCUSSION OF EXHAUST EMISSION RESULTS

Examination of the exhaust emissions data led to the conclusion that low oxides-of-nitrogen emission indices can be produced concurrently with low smoke levels at high (fuel rich) primary-zone equivalence ratios. Unfortunately, in this study, high carbon monoxide levels were also produced, indicating inefficient combustion at the operating conditions used. If the combustor design were modified or the operating conditions were changed sufficiently to lower carbon monoxide levels, the oxides of nitrogen emissions might increase. Therefore, the results of this study do not conclusively prove that a combustor with a rich-burning primary zone will produce lower oxides-of-nitrogen emissions. The results do, however, point out the extreme importance of good mixing within the combustor and fine fuel atomization. The fuel-injection configuration that exhibited the worst gas sample accuracy - indicative of poor mixing in the combustor - also displayed the highest smoke levels. Increasing the combustor pressure drop - indicative of better mixing within the combustor - resulted in much lower smoke levels.

Present jet engine combustors operate at higher inlet-air temperatures and pressures than those the rich-burn combustor was tested at. Increased air pressure generally augments smoke formation; but for the rich-burn combustor, the smoke results (fig. 10) indicate that smoke levels at an equivalence ratio of 1.4 may not be significantly affected by higher pressures. To operate the primary zone at the equivalence ratios that resulted in minimum levels of oxides of nitrogen (1.8 to 2.0) would require that the decrease in smoke formation due to the higher inlet-air temperatures offset the increase in smoke formation due to the higher inlet-air pressures. If this did not occur, better mixing and fuel atomization would be required to keep smoke levels below the visible threshold.

SUMMARY OF RESULTS

In an investigation of the effect of primary-zone equivalence ratio on the formation of gaseous pollutants in an experimental can combustor, the following results were obtained:

1. The formation of gaseous pollutants was a strong function of both the fuel-injection configuration and the primary-zone equivalence ratio.

2. At a primary-zone equivalence ratio of about 1.7 the combustor produced smoke levels below a smoke number of 20 for two of the four fuel-injection configurations tested at an inlet-air temperature of 477 K and pressure of 0.34 megapascal.

3. Increasing the combustor pressure drop from 4 percent to 10 percent decreased the amount of smoke formed. At the higher pressure drop condition the primary zone could operate at an equivalence ratio of 2.0 and still produce smoke levels below a smoke number of 20.

4. Increasing the inlet-air pressure to 0.69 megapascal augmented smoke formation; increasing the inlet-air temperature to 589 K decreased smoke formation.

5. High levels of hydrocarbons and carbon monoxide and low levels of oxides of nitrogen were observed at the higher primary-zone equivalence ratios for all fuel-injection configurations tested. The primary-zone equivalence ratio was varied from 0.8 to 2.0.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1979,
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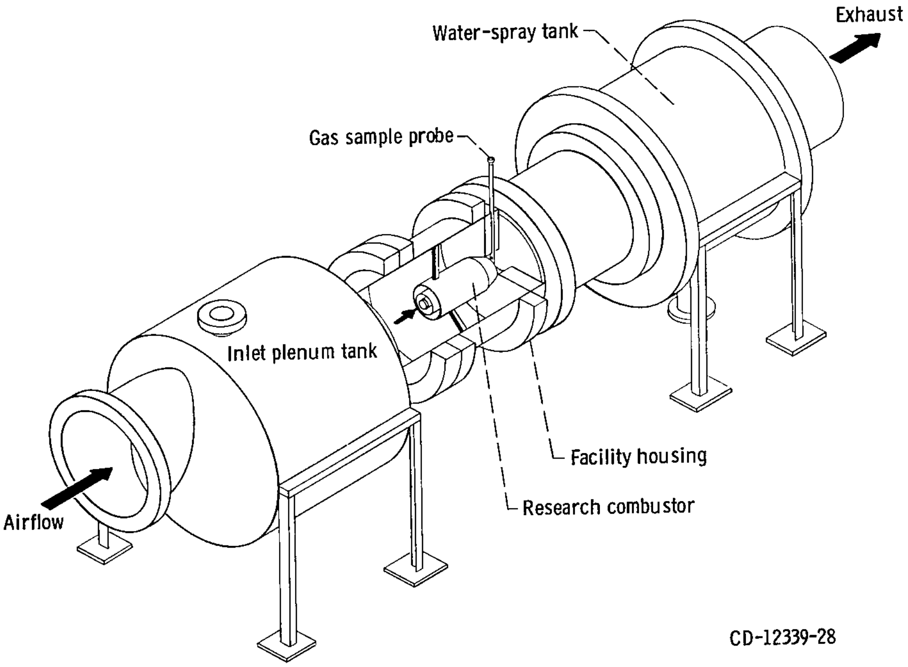
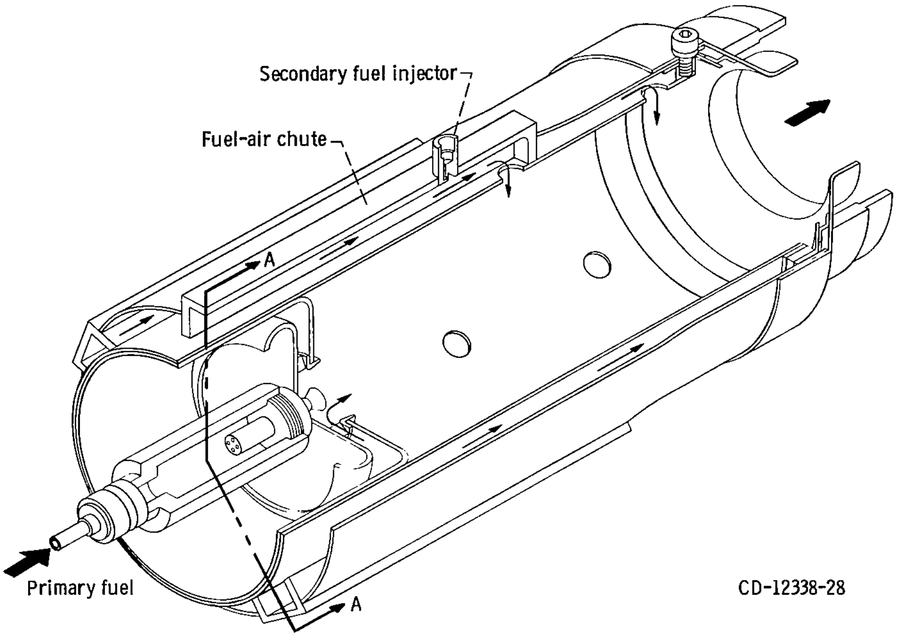
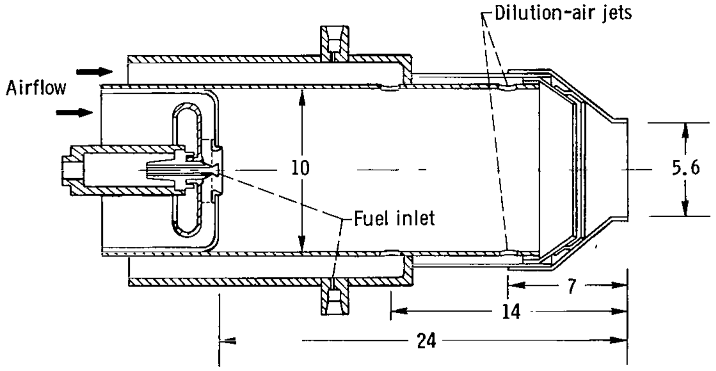


Figure 1. - Schematic drawing of test facility.

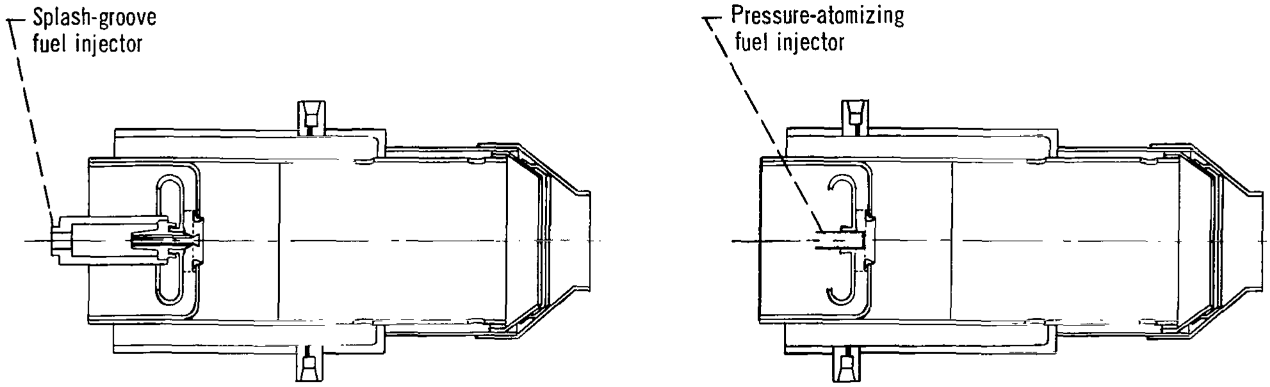


(a) Perspective view.



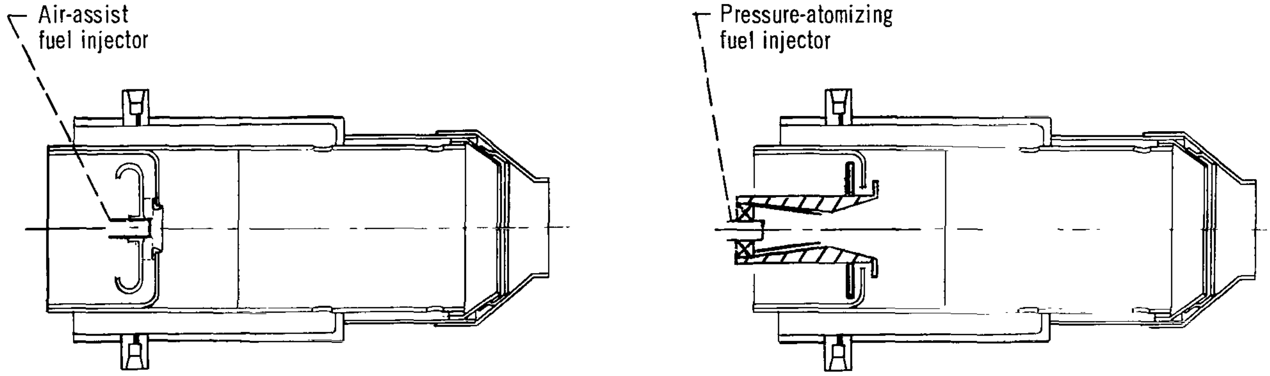
(b) Cross-section A-A. (Dimensions are in centimeters.)

Figure 2. - Schematic drawings of rich-burn can combustor.



(a) Configuration 1: headplate, radial-flow air swirler with splash-groove fuel nozzle; air chutes, splash-groove fuel nozzles approximately 3 centimeters upstream of injection into combustor.

(b) Configuration 2: headplate, radial-flow air swirler with simplex pressure-atomizing fuel nozzle; air chutes, splash-groove fuel nozzles approximately 13 centimeters upstream of injection into combustor.



(c) Configuration 3: headplate, radial-flow air swirler with air-assist fuel nozzle; air chutes, splash-groove fuel nozzles approximately 13 centimeters upstream of injection into combustor.

(d) Configuration 4: headplate, axial-flow air swirler in premixing carburetor tube; air chutes, splash-groove fuel nozzles approximately 13 centimeters upstream of injection into combustor.

Figure 3. - Rich-burn can combustor preparation configurations.

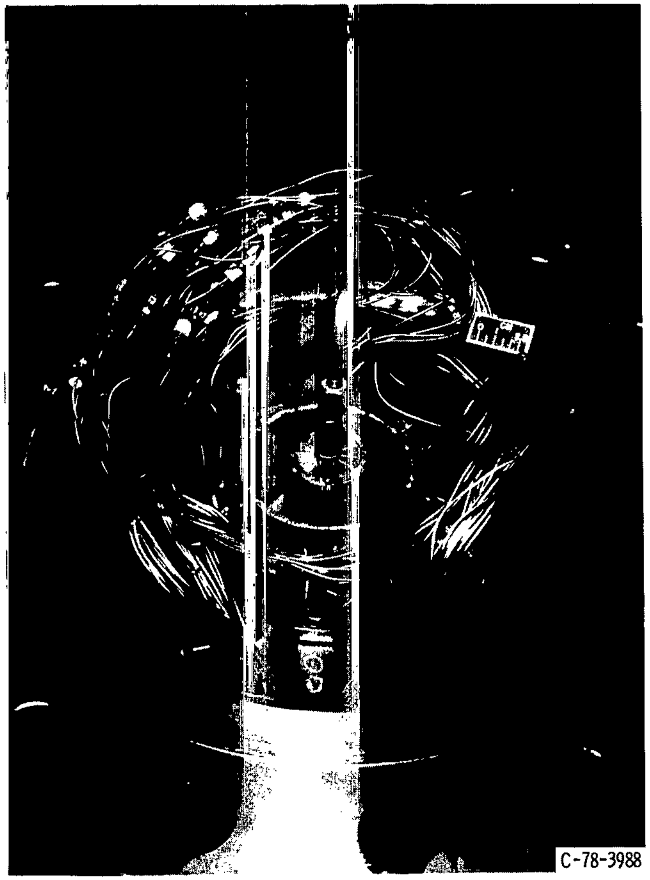


Figure 4. - Rich-burn can combustor installed in facility housing.

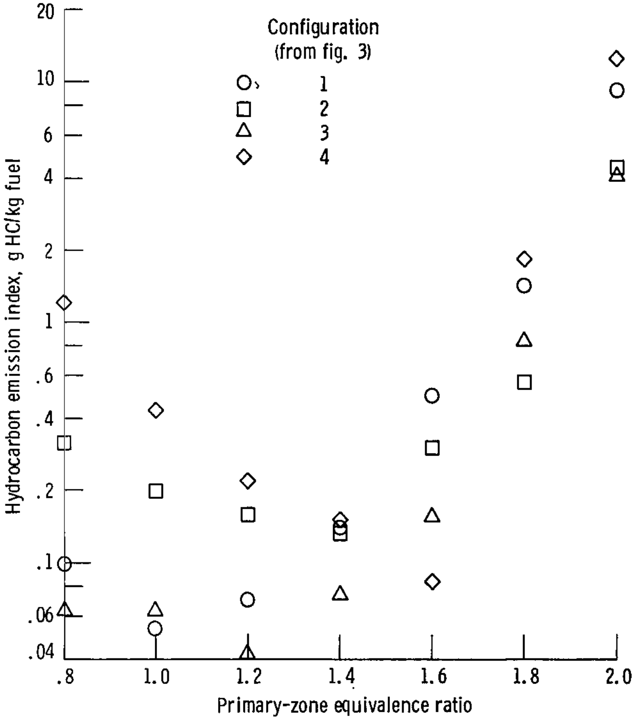


Figure 5. - Unburned-hydrocarbon emissions for four fuel-injection techniques. Inlet-air pressure, 0.34 MPa; inlet-air temperature, 477 K.

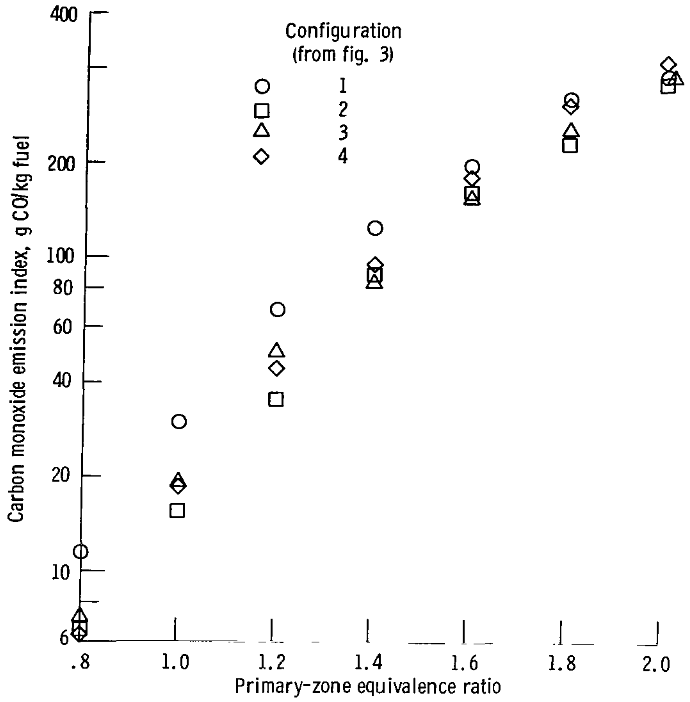


Figure 6. - Carbon monoxide emissions for four fuel-injection techniques. Inlet-air pressure, 0.34 MPa; inlet-air temperature, 477 K.

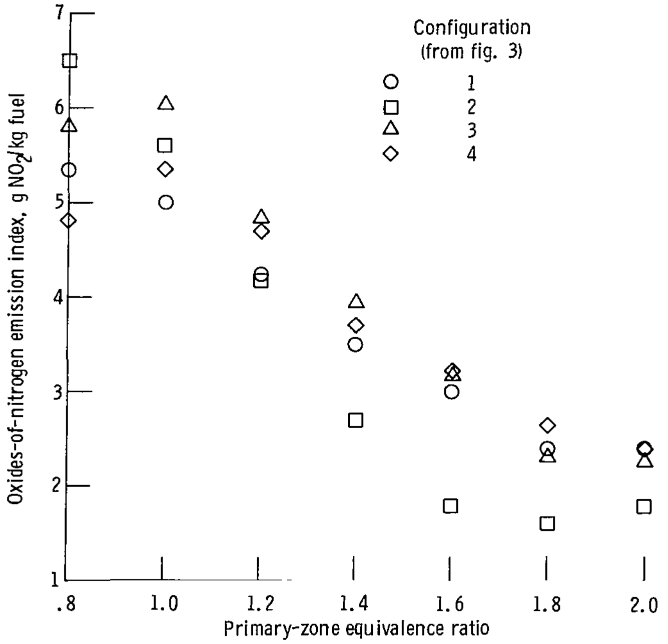


Figure 7. - Oxides-of-nitrogen emissions for four fuel-injection techniques. Inlet-air pressure, 0.34 MPa; inlet-air temperature, 477 K.

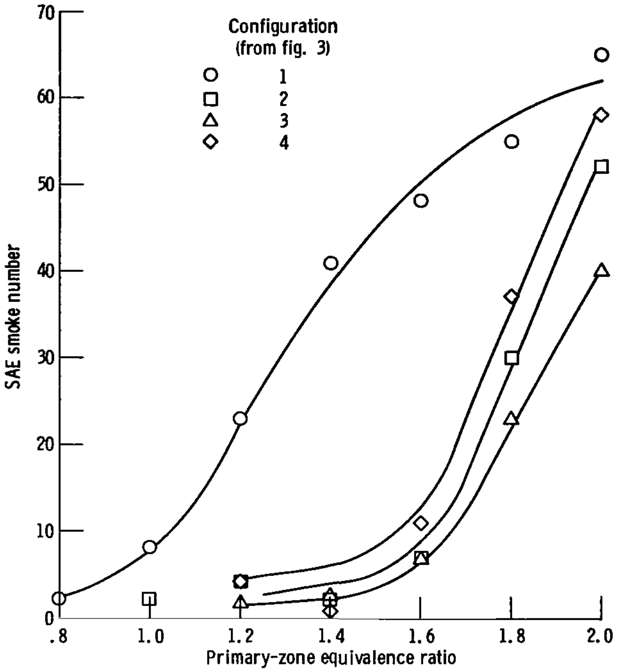


Figure 8. - Smoke formation for four fuel-injection techniques. Inlet-air pressure, 0.34 MPa; inlet-air temperature, 477 K.

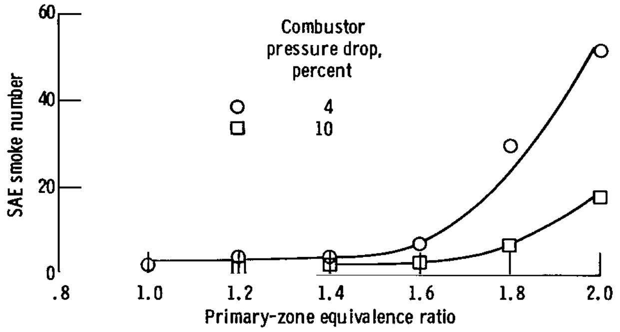


Figure 9. - Effect of increased combustor pressure drop on smoke formation for combustor configuration 2. Inlet-air pressure, 0.34 MPa; inlet-air temperature, 477 K.

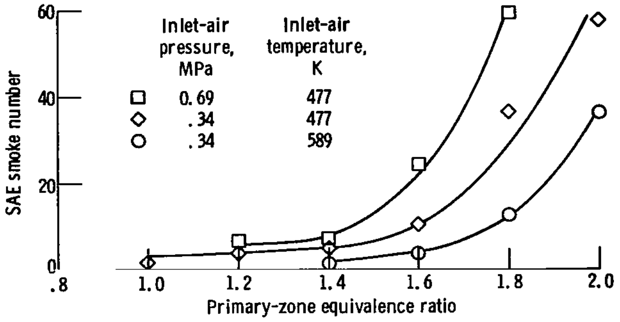


Figure 10. - Effect of increased inlet-air temperature and pressure on smoke formation for combustor configuration 4.

1. Report No.
NASA TP-1463

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
EFFECT OF PRIMARY-ZONE EQUIVALENCE RATIO ON POLLUTANT FORMATION

5. Report Date
May 1979

6. Performing Organization Code

7. Author(s)
Russell W. Claus

8. Performing Organization Report No.
E-9896

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
505-04

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Paper

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Tests were conducted to determine the effect of primary-zone equivalence ratio on the formation of smoke and other gaseous pollutants in an experimental can combustor. Several fuel-injection techniques were examined at primary-zone equivalence ratios from 0.8 to 2.0. The main emphasis was on reducing fuel-rich-combustion smoke levels. Two of the four fuel-injection configurations studied produced smoke levels below a smoke number of 20 at a primary-zone equivalence ratio of about 1.7. As the fuel mixing and atomization were improved by increasing the combustor pressure drop, smoke numbers below 20 were recorded at primary-zone equivalence ratios as high as 2.0. The gaseous emissions of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen were quite sensitive to the fuel-injection configuration as well as to the primary-zone equivalence ratio.

17. Key Words (Suggested by Author(s))
Fuel-rich combustion
Experimental combustors

18. Distribution Statement
Unclassified - unlimited
STAR Category 07

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
19

22. Price*
A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1979

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