

Pollution Measurements of a Swirl-Can Combustor

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Pollutant levels of oxides of nitrogen, unburned hydrocarbons, and carbon monoxide were measured for an experimental annular swirl-can combustor. The combustor was 42 in. diam., incorporated 120 modules and was specifically designed for elevated exit temperature performance. Test conditions included combustor inlet temperatures of 600°, 900°, and 1050°F, inlet pressures of 5–6 atm, reference velocities of 69–120 fps and fuel-air ratios of 0.014–0.0695. Tests were also conducted at a simulated engine idle condition. Results demonstrated that swirl-can combustors produce oxides of nitrogen levels substantially lower than conventional combustor designs. These reductions are attributed to reduced dwell times resulting from short combustor length, quick mixing of combustion gases with diluent air, and to uniform fuel distributions resulting from the swirl-can approach. Radial staging of fuel at idle conditions resulted in substantial increases in combustion efficiencies and corresponding reductions in pollutant levels.

Introduction

THIS paper presents measured combustor exhaust pollutant levels of oxides of nitrogen, unburned hydrocarbons, and carbon monoxide, describes factors controlling their formation, and demonstrates reductions in oxides of nitrogen attainable with a swirl-can combustor.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons and carbon monoxide during idle and taxi, and oxides of nitrogen and smoke during takeoff and landing. Oxides of nitrogen are also considered to be the most predominant emission products formed during altitude cruise.

Altering gas turbine combustor designs to make substantial reductions in oxides of nitrogen will be an extremely difficult task.¹ Oxides of nitrogen are formed during any combustion process involving air. The amount formed is reaction rate controlled and is a function of flame temperature, dwell time of the combustion gases at high temperatures, concentrations of nitrogen and oxygen present, and, to a somewhat lesser extent, the combustor pressure. Flame temperatures increase as the combustor inlet temperature increases and as the primary zone fuel-air ratio approaches stoichiometric values. Dwell time is affected by combustor primary zone length and reference velocity. Trends in combustor operating conditions indicate a steady increase in inlet temperature due to increasing compressor pressure ratios.²

Past studies of swirl-can combustors,^{2,3} have indicated that this combustor type offers several inherent advantages for reducing oxides of nitrogen. These advantages include:

1) Short combustor lengths with accompanying short recirculation zones are realized for burning and mixing. Thus dwell time is reduced.

2) Quick mixing of burning gases and diluent air occurs inasmuch as swirl-can combustors pass nearly all of the air flow through the primary combustion zone and large interfacial mixing areas exist between combustion gases and airflow around the swirl cans.

3) Premixing of fuel and air occurs upstream of the burning zone and produces a more uniform mixture of fuel and air thereby reducing localized intense burning. This effect is reinforced by the large number of fuel entry positions.

The swirl-can combustor used in these tests was designed for operation up to stoichiometric fuel-air ratios. Most of the pollution data were obtained during the testing to stoichiometric conditions. Some data were also obtained parametrically to illustrate the effects of reference velocity and inlet air temperature upon formation of oxides of nitrogen. Data previously reported⁴ are also included at a simulated engine idle condition to illustrate how pollutant levels of unburned hydrocarbons and carbon monoxide can be successfully minimized by fuel staging. Pollutant concentrations of nitric oxide (NO), oxides of nitrogen (NO + NO₂), unburned hydrocarbons and carbon monoxide are presented for the following spans of test conditions: combustor inlet air temperature, 600°, 900°, and 1050°F; inlet pressure, 5–6 atm; fuel-air ratio, 0.014–0.0695; and reference velocity, 69–120 fps.

Apparatus and Procedure

Test Facility

Tests were conducted in a connected-duct component test facility at the Lewis Research Center. The details of the test facility and instrumentation are contained in Appendices A and B of Ref. 5.

Combustor Design

The test combustor, shown in Figs. 1 and 2, is an annular design 20.25 in. long from the diffuser inlet to the combustor

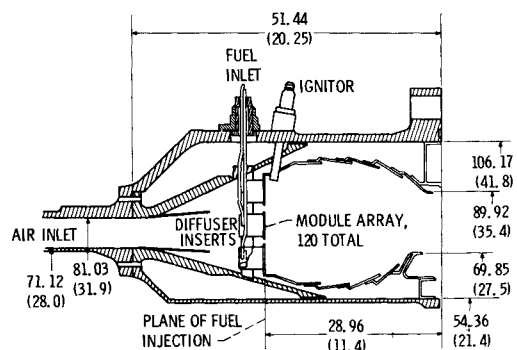


Fig. 1 Full annular model of high-temperature combustor [dimensions in centimeters (in.)].

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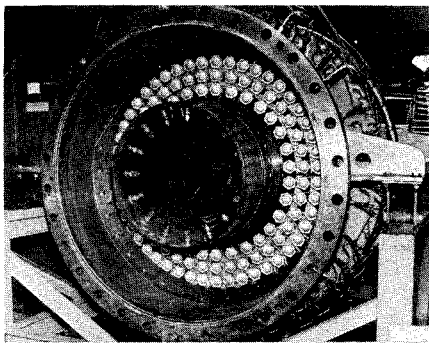


Fig. 2 Annular swirlcan-modular combustor.

exit plane, and is 42 in. diam. The combustor is a swirl-can design and incorporates several unique features including a combustor module array. The array consists of 120 modules, positioned on three circumferential rows, which distribute combustion uniformly across the combustor annulus. All of the combustor airflow, exclusive of liner coolant flow passes through the array thus providing an abundance of air for all stages of the combustion process, as well as providing the capability for quick mixing of hot gases and diluent air. The only airflow introduced downstream of the array is liner cooling air which accounted for 4%–7% of the total airflow. Performance of a prior model of this combustor over an extended exit temperature span has been described previously.³

Combustor Modules

A typical combustor module is shown schematically in Fig. 3. Each module consists of three components; a carburetor, swirler, and flame stabilizer. In operation, the modules perform several functions. Each module premixes fuel with air, swirls the mixture, stabilizes combustion in its wake, and provides large interfacial mixing areas between the bypass air through the array and combustion gases in the module wake. Several flame stabilizer designs have been employed. Three of the designs are shown in Fig. 3.

Test Conditions

All tests were conducted with ASTM-A1 liquid fuel. The fuel had an average hydrogen-carbon ratio of 0.161 and a lower heating value of 18,600 Btu/lb.

Tests were conducted over a range of fuel-air ratios of 0.005 to 0.0695. For combustor exit average temperatures below 2300°F, a 5-point radial traverse temperature and pressure rake was used to evaluate combustor performance, and all flow conditions of interest could be investigated. A choked nozzle was used to measure combustor performance for higher exit temperatures. Reference velocities were limited by the choked nozzle and with a

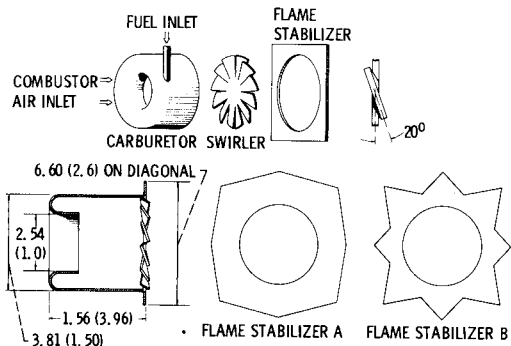


Fig. 3 Combustor module details [dimensions in centimeters (in.)].

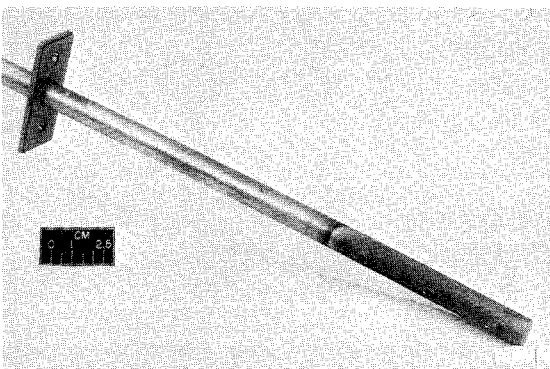


Fig. 4 Three-point gas sampling probe with water-cooled jacket.

600°F inlet air temperature varied from 100 fps at an exit temperature of 1700°F to 69 fps at an exit temperature of 3700°F. Reference velocities for higher inlet air temperatures were proportionately affected. The test facility had a maximum pressure limitation of 6 atm.

Exhaust Gas Pollutant Sampling

Concentrations of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were obtained with an on-line system. All samples were drawn from one circumferential location and at three radial locations at the combustor exit through the water-cooled probe shown in Fig. 4.

Gas Sample System

Approximately 30 ft of 3/8-in. stainless steel line was used to transport the sample to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated to 310°F. Sample line pressure was maintained at 10 psig in order to supply sufficient pressure to the instruments.

The exhaust gas analysis system shown in Fig. 5 is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs were provided to the IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas was determined by a Beckman Instruments Model 402 total Hydrocarbon Analyzer. This instrument is of the flame ionization detector type.

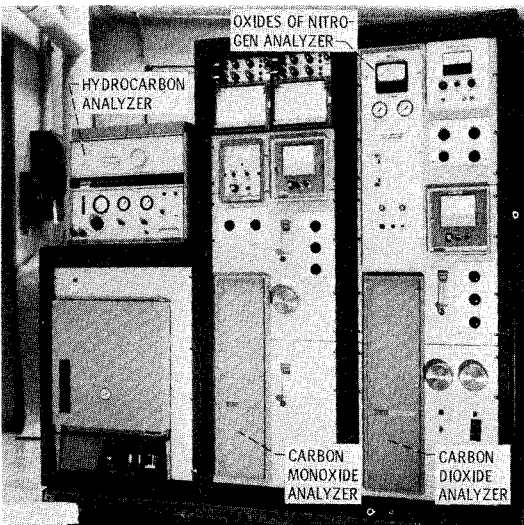


Fig. 5 Exhaust gas analysis system.

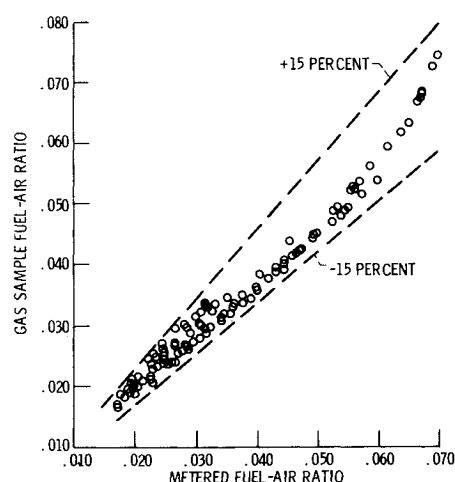


Fig. 6 Sample validity check.

Concentrations of oxides of nitrogen were determined by a Thermo Electron Corporation Model 10A Chemiluminescent analyzer. The instrument included a thermal convertor to reduce nitrogen dioxide to nitric oxide and was operated at 1290°F.

Both carbon monoxide and carbon dioxide analyzers were of the nondispersive infrared (NDIR) type (Beckman Instruments model 315B). The CO analyzer had four ranges: 0–100 ppm, 0–1000 ppm, 0–1% and 0–10%. This range of sensitivity was accomplished by using stacked cells of 0.25- and 13.5-in. length. The CO₂ analyzer had two ranges, 0–5% and 0–15% with a sample cell length of 0.125 in.

Analytical Procedure

All analyzers were checked for zero and span prior to tests. Since the analyzer console required only a few seconds for each instrument to switch from calibration to sample modes, it was possible to perform frequent checks to insure the calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included both inlet air humidity and water vapor from combustion. The equations used were obtained from Ref. 6.

The emission levels of all of the constituents were converted to an emission index parameter. Emission index values were computed from the measured quantities as proposed by the SAE Committee E-31.⁶ An alternate procedure based on metered fuel-air ratio was also employed. Using the later technique, emission index values for any constituent, X , can be calculated by the following expression:

$$EI_x = (M_x/M_a)[(1+f)/f](x) \times 10^{-3}$$

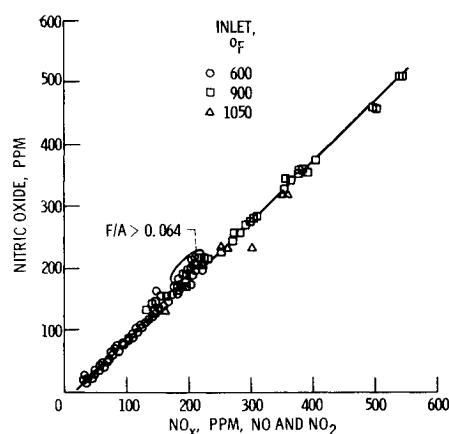
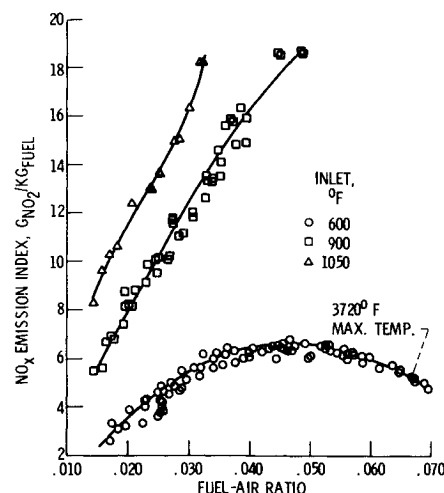
Fig. 7 NO and NO_x concentrations.

Fig. 8 Effects of combustor inlet temperature and fuel-air ratio on oxides of nitrogen formation. Combustor inlet pressure, 5–6 atm; airflow, 85–110 lb/sec.

where EI_x = emission index in grams of X /kg of fuel burned, M_x = molecular weight of X , M_a = molecular weight of air, f = metered fuel-air ratio, and (x) = measured concentration of x , ppm. Both procedures yielded identical results when the sample validity was good.

Since practical considerations limited exhaust gas sampling to only one circumferential location, attempts were made to verify that the gas sampling position was representative of pollutant levels at the combustor exit. Two fuel-air ratios were calculated. The first value was computed from measured quantities of carbon dioxide, carbon monoxide, and unburned hydrocarbons. The second fuel-air ratio was obtained from metered values of fuel and air. Fuel-air ratios obtained by both methods are shown in Fig. 6. All of the data presented in this paper, for which both values of fuel-air ratio were available, produced gas sample fuel-air ratios within + or – 15% of metered values.

Results and Discussion

Oxides of Nitrogen

Nitrogen oxides are formed during any combustion process involving air. These oxides, commonly referred to as NO_x, consist primarily of Nitric Oxide (NO) and significantly lesser amounts of Nitrogen Dioxide (NO₂). NO concentrations and NO_x concentrations expressed in ppm are shown in Fig. 7. Test conditions were inlet temperatures of 600°, 900°, and 1050°F, a reference velocity span of 69–120 fps, inlet pressures of 4–6 atm and a combustor exit temperature span of 1600°–3700°F. In spite of the wide variances in test conditions, nearly all of the data appear to fall along a straight line indicating that the formation rate of NO₂ is constant. Exceptions occur where the fuel-air ratios are 0.064 or higher. NO₂ concentrations are lower than expected in this range probably due to lack of available oxygen in the combustion zone.

By convention, succeeding figures present NO_x concentrations in terms NO₂ emission index values. NO emission index values can be obtained by using the curve on Fig. 7 and the ratio of molecular weights of NO₂ and NO.

Effects of inlet air temperature and fuel-air ratio on NO_x formation are shown in Fig. 8. With 600°F inlet air, the emission index level increases from a value of about 3 at a fuel-air ratio of 0.018 to a peak value of 6.5 at a fuel-air ratio of 0.048 and then decreases and approaches a value of about 4.6 at a fuel-air ratio of 0.0695. The shape of the emission index curve is affected by many factors such as reaction rates, availability of free oxygen, and reaction zone temperatures. A simplified, qualitative model explaining formation rates in the three fuel-air ratio zones based

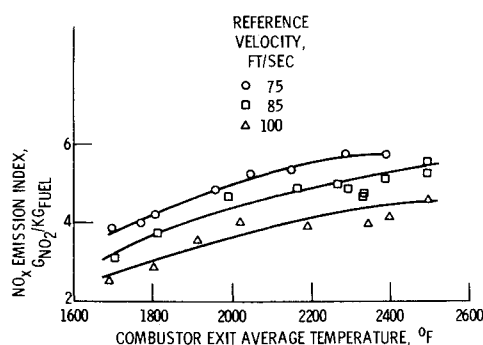


Fig. 9 Effects of combustor reference velocity on oxides of nitrogen formation. Combustor inlet air temperature, 600°F.

on combustion data and visual observations of swirl-can combustors in operation is as follows: At lower fuel-air ratios, combustion proceeds rapidly and is completed a short distance from the module array since the major portion of combustion air is supplied through the modules. Combustion is generally restricted to the module wakes. Bypass air through the array recirculates in the module wakes mixing with the combustion gases thus reducing flame temperatures and NO_x formation. As fuel-air ratio is increased, heat flux increases and flame is not restricted to the module wakes but propagates across the entire array. At this condition, highest reaction zone temperatures are probably attained and the rate at which NO_x is formed increases.

Further increases in fuel-air ratio cause additional effects to occur which cause the formation rate of NO_x to decrease. As fuel-air ratio is increased, more of the oxygen is used in combustion and becomes unavailable for NO_x formation. Also, the added fuel causes the fuel-air ratio in the vicinity of the modules to become overly rich thus reducing reaction zone temperatures and NO_x formation. Accompanying the decrease in reaction zone intensity is an elongation of the reaction zone along the combustor axis. Thus hot gases have less combustor length to traverse and their residence time in the combustor decreases. This condition appears to exist for fuel-air ratios between 0.048 to 0.0668. Within this span combustor exit

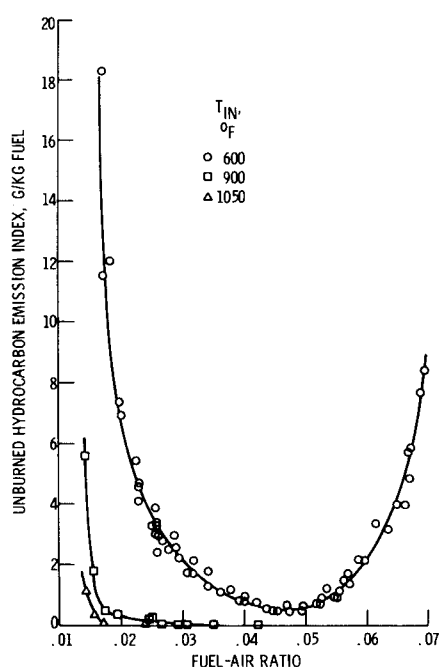


Fig. 10 Effects of combustor inlet air temperature and fuel-air ratio on unburned hydrocarbon formation. Combustor inlet pressure, 5-6 atm; airflow, 85-110 lb/sec.

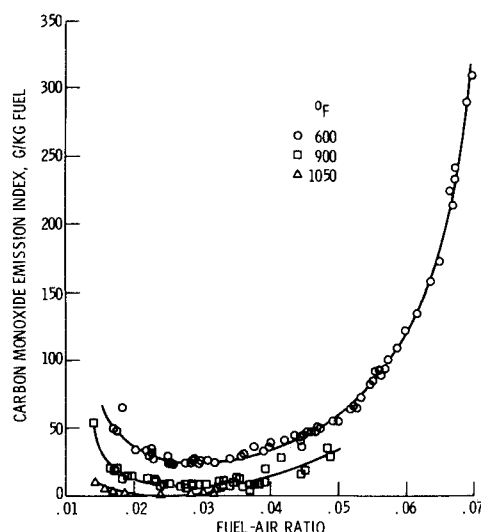


Fig. 11 Effects of combustor inlet air temperature and fuel-air ratio on carbon monoxide formation. Combustor inlet pressure, 5-6 atm; airflow, 85-110 lb/sec.

temperature continues to increase to a maximum value of 3720°F while emission index values decrease. Parts per million values level out and decrease also. Further increases in fuel-air ratio higher than 0.0668 indicate that additional oxygen is not available since exit temperatures decrease rather than increase.

The simplified model also suggests that performance parameters which increase reaction rates such as increased pressure and inlet temperature would also increase NO_x formation. Sufficient spans of pressure were not investigated due to facility limitations. However, increases in combustor inlet temperature to 900° and 1050°F, also shown in Fig. 8, significantly increased NO_x formation to 3 to 4 times values obtained with 600°F inlet air.

NO_x emission index values were reduced further by increasing combustor reference velocity. Figure 9 presents emission index data at 600°F inlet air temperature, a span of exit temperatures and three reference velocities. The decreases in emission index level with increasing reference velocities are probably due to reduced dwell time of hot gases within the combustor.

Unburned Hydrocarbons and Carbon Monoxide

Emission index values of unburned hydrocarbons and carbon monoxide plotted against fuel-air ratio for three combustor inlet temperatures are presented in Figs. 10 and 11, respectively. With 600°F inlet air temperature, both pollutant values were high at the lowest fuel-air ratios and produced a combustion inefficiency of approximately 3%. Pollutant values then decreased with increasing fuel-air ratio. However, both pollutant values again increased at the highest fuel-air ratios investigated probably because of a lack of available oxygen in the combustion zone. At a fuel-air ratio of 0.0695 unburned hydrocarbons produced

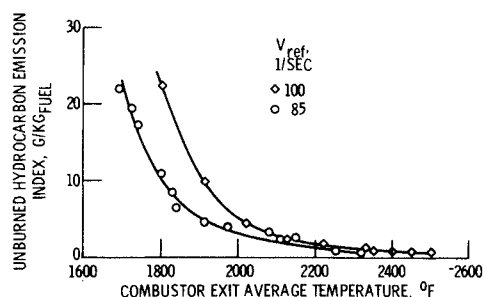


Fig. 12 Effects of combustor reference velocity on unburned hydrocarbon formation. Combustor inlet air temperature, 600°F.

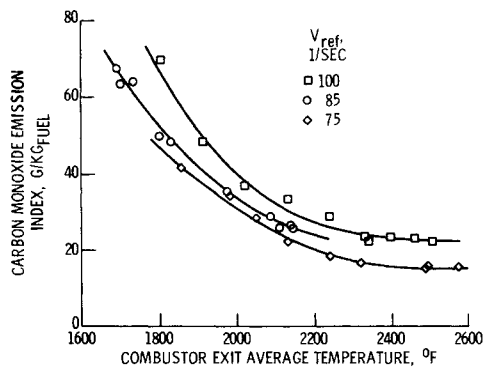


Fig. 13 Effects of combustor reference velocity on carbon monoxide formation. Combustor inlet air temperature, 600°F.

an inefficiency of approximately 1%. Carbon monoxide produced an inefficiency of approximately 7%. Both pollutant concentrations were substantially reduced at the higher inlet air temperatures.

The influence of reference velocity on unburned hydrocarbons and carbon monoxide are presented in Figs. 12 and 13, respectively. Unlike NO_x concentrations which were lowest at the highest reference velocity, unburned hydrocarbon and carbon monoxide concentrations increased with increasing reference velocity. The reduced concentrations of NO_x obtained by increasing reference velocity were compensated for by increases in the other pollutants. Thus, rather than increasing reference velocity (for NO_x reduction), methods of reducing dwell time of combustion gases such as reducing combustor length and facilitating quicker mixing would be preferable.

Idle Tests

Since the combustor was designed for high exit temperature operation, it is not surprising that a falloff of combustion efficiency, with corresponding increases in pollutant levels, occurs at low fuel-air ratios. The extent of this problem can be seen from the top curve of Fig. 14. As the combustor exit temperature decreases, there is a notable rise in the unburned hydrocarbon emission index.

Effects of fuel scheduling can be seen from the bottom curve of Fig. 14. The number of fired modules was reduced from 120 to 104 by shutting off the fuel to one-half of the inner module row.

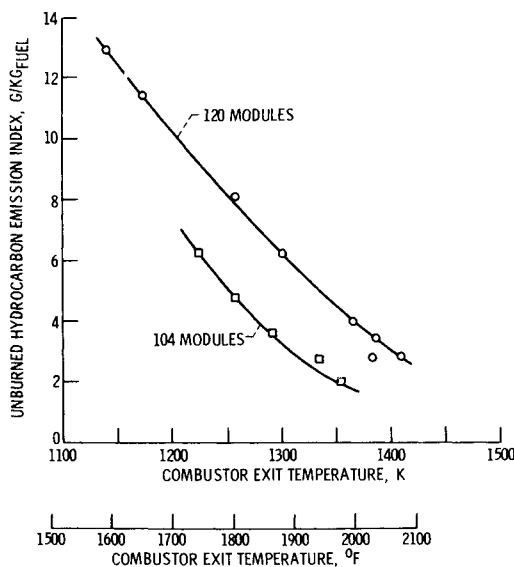


Fig. 14 Module number effect. Inlet air temperature, 589K (600°F); inlet air pressure, 6 atm; reference velocity, 26 m/sec (85 fps).

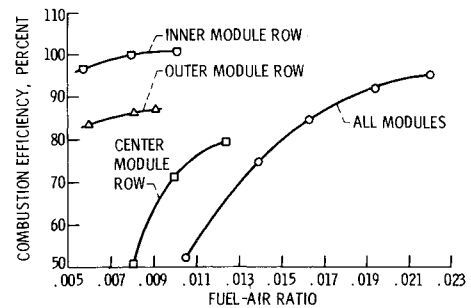


Fig. 15 Combustor efficiency during idle tests, inlet air temperature, 478 K (400°F); inlet air pressure, 4 atm; reference velocity, 26 m/sec (85 fps).

Emission index values were decreased from 30% to 60% for equivalent combustor exit temperatures with the greatest percentage decreases occurring at the highest combustor exit temperatures.

The combustor was tested at idle conditions with all of the modules supplied with fuel and also with each of the three module rows individually supplied with all the fuel. The test conditions were a combustor reference velocity of 26 m/sec (85 fps) and an inlet air temperature and pressure of 478 K (400°F) and 4 atm, respectively.

Combustion efficiency

Combustion efficiency results are presented in Fig. 15. Fuel-air ratios represent over-all values and represent all the air and fuel supplied to the combustor. With all the modules supplied with fuel, combustion efficiencies were low and blowout occurred at a fuel-air ratio of about 0.009. Supplying all the fuel to the center module row improved combustion efficiency somewhat but produced an efficiency of only 50% at a fuel-air ratio of 0.008. Supplying all the fuel to the outer module row increased combustion efficiency significantly. Supplying all the fuel to the inner module row raised the combustion efficiency to nearly 100%.

Effects of fuel scheduling were greatest for the inner module row, since this row contained the lowest number of modules, and thus each module was supplied with proportionately more fuel for a given over-all fuel-air ratio. The reason that scheduling fuel to the center module row produced only a small improvement in combustion efficiency was probably due to quenching resulting from the reduced blockage flame stabilizers that this row contained. The reduced blockage caused a proportionately larger amount of air to flow through the center of the array.

Unburned hydrocarbons and carbon monoxide

Emission index values for unburned hydrocarbons and carbon monoxide are shown in Figs. 16 and 17, respectively. Both pollutants followed inversely the same trends as combustion efficiency. A further indication of quenching of the center module

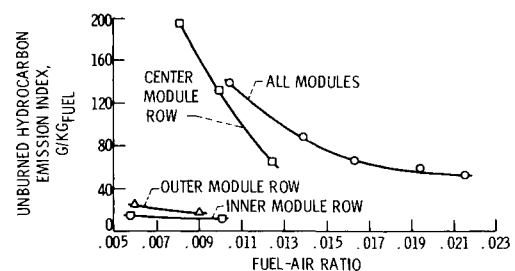


Fig. 16 Unburned hydrocarbon emissions during idle tests. Inlet air temperature, 478 K (400°F); inlet air pressure, 4 atm; reference velocity, 26 m/sec (85 fps).

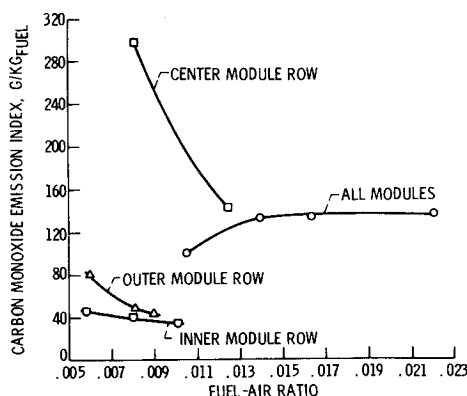


Fig. 17 Carbon monoxide emissions during idle tests. Inlet air temperature, 478 K (400°F); inlet air pressure, 4 atm; reference velocity, 26 m/sec (85 fps).

row is shown in Fig. 17, which shows carbon monoxide levels were higher for the center module row than when all the modules were supplied with fuel.

The lowest emission index values occurred with only the inner module row supplied with fuel. At a fuel-air ratio of 0.008 the emission index values were approximately 10 for hydrocarbons and 40 for carbon monoxide. Nitrogen dioxide emission index concentrations were low and did not exceed a value of 1.

Summary of Results

Pollutant concentrations of a full annulus swirl-can combustor were measured. These included concentrations of nitric oxide, total oxides of nitrogen, unburned hydrocarbons, and carbon monoxide. Test conditions were inlet air temperatures of 600°, 900°, and 1050°F, pressures of 5–6 atm, fuel-air ratios of 0.014–0.0695, and reference velocities of 69–120 fps. The following results were obtained.

1) With a 600°F inlet air temperature the maximum emission index value of oxides of nitrogen expressed as nitrogen dioxide was 6.5 and occurred at an intermediate fuel-air ratio of

0.048. Emission index values were lower for both higher and lower fuel-air ratios.

2) Increasing the combustor inlet air temperature to 900° and 1050°F increased nitrogen dioxide emission index values by factors of 3 to 4 at higher fuel air ratios.

3) A comparison of nitric oxide and oxides of nitrogen concentrations expressed in parts per million produced a straight line function indicating that the formation rate of nitrogen dioxide is constant in spite of wide variances in test conditions.

4) Increasing combustor reference velocity caused oxides of nitrogen concentrations to decrease by reducing dwell time of the hot combustor gases. However, these reductions were compensated for by increased concentrations of unburned hydrocarbons and carbon monoxide caused by the higher reference velocities.

5) Unburned hydrocarbons and carbon monoxide concentrations were reduced by increasing combustor fuel-air ratio and combustor inlet air temperature.

6) At simulated engine idle conditions, significant improvements in combustion efficiency and accompanying reductions in pollutant levels were realized by radial scheduling of fuel. Best results were obtained when all of the fuel was supplied to the inner module row. Combustion efficiencies near 100% were obtained. Unburned hydrocarbon and carbon monoxide emission index values were 10 and 40 g/kg, respectively.

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