EFFECTS OF PREVAPORIZED FUEL ON EXHAUST EMISSIONS OF AN EXPERIMENTAL GAS TURBINE COMBUSTOR

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ABSTRACT

Effect of fuel vaporization on the exhaust emission levels of oxides of nitrogen (NO_x), carbon monoxide, total hydrocarbons, and smoke number were obtained in an experimental turbojet combustor segment. Two fuel injector types were used in which liquid ASTM A-1 jet fuel and vapor propane fuel were independently controlled to simulate varying degrees of vaporization. Tests were conducted over a range of inlet-air temperatures from 478 to 700 K (860 to 1260° R), pressures from 4 to 20 atmospheres, and combustor reference velocities from 15.3 to 27.4 m/sec (50 to 90 ft/sec). Converting from liquid to complete vapor fuel resulted in NO_x reductions as much as 22 percent and smoke number reductions up to 51 percent.

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SUMMARY

Effects of fuel vaporization on the exhaust emission levels of an experimental combustor segment were determined. Test conditions were inlet-air temperatures from 478 to 700 K (860 to 1260° R), pressures from 4 to 20 atmospheres, combustor reference velocities from 15.3 to 27.4 m/sec (50 to 90 ft/sec) and vaporization percentages from 0 to 100. The degree of vaporization was simulated by varying the ratio of liquid ASTM A-1 jet fuel and vapor propane fuel introduced into the combustor through dual concentric fuel injectors. Two different dual fuel injector designs were investigated. In the first configuration the liquid fuel was introduced through a simplex nozzle located at the center of the assembly and vapor fuel was injected through a series of 8 evenly-spaced holes located on a diameter concentric with the simplex orifice. The second configuration was a commercial duplex nozzle with liquid fuel supplied through a small center orifice and vapor fuel supplied through a larger annular ring.

Exhaust emission levels comparisons between all liquid fuel and all vapor fuel operation are presented. Results with all vapor fuel using the first fuel nozzle injector indicate that:

(1) The oxides of nitrogen emission index level was reduced up to 22 percent at high inlet-air temperatures.

(2) At conditions corresponding to engine idle both the carbon monoxide and total hydrocarbons emission index levels were reduced 36 percent.

(3) At the most severe smoking condition (20 atmospheres pressure) the smoke number was reduced 51 percent.

(4) Similar reduction in emission levels were observed with the second fuel nozzle geometry as the proportion of vapor propane was varied from 0 to 100 percent.

Although substantial reductions in exhaust emission levels were experienced, the decrease was not as large as anticipated - probably because of inadequate control of the primary zone equivalence ratio.

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Careful control of the mixing process will also be required to obtain more substantial emission reductions with vaporized fuel.

INTRODUCTION

An experimental investigation was undertaken at the NASA Lewis Research Center to determine the effect of substituting vapor fuel for liquid fuel on the emission level of an experimental gas turbine combustor. The turbojet combustor emission products that are of primary concern for hydrocarbon fuels are the oxides of nitrogen (NO_x), carbon monoxide (CO), total hydrocarbons (THC), and smoke number (Ref. 1). The relative level of these emission products depends on many factors including the fuel preparation, distribution, mixing, and recirculation patterns within the reaction zone. The combustion characteristics are effected by the inlet combustor operating conditions which are dependent on the engine compressor pressure ratio, power output, flight speed, and altitude.

In a turbojet combustor the formation of CO, THC, and smoke number are the result of incomplete reaction; the formation of NO_x is primarily dependent on the flame temperature and residence time. At idle and low power output (low combustor inlet-air temperature and pressure) the CO and THC are highest due to low combustion efficiency. At high power output (high combustor inlet-air temperature and pressure) the NO_x and smoke number levels increase and become the predominating pollutants. At high power output combustion depends primarily on the mixing process between fuel and air rather than on chemical kinetic limitations (Ref. 2). Thus, techniques which improve mixing should reduce emissions of CO and THC by enhancing complete reaction between fuel and air. The oxides of nitrogen can be reduced by providing a lean uniform primary zone equivalence ratio. One technique to obtain a more uniform equivalence ratio is to prevaporize the fuel to eliminate hot zones which are associated with localized liquid droplet burning.

In order to determine effects of fuel vaporization on performance, a segment of an experimental combustor was operated at inlet temperature levels to 700 K (1260° R) and pressures to 20 atmospheres. The combustor operates with intense primary zone mixing with most of the air introduced by swirlers concentric with the fuel nozzles as described in reference 3. Vaporized propane was used to simulate vaporized liquid jet fuel. Propane was chosen since it is relatively easy to handle and burning characteristics are similar to the majority of the constituents of jet fuel. Two different fuel nozzles were used in which liquid ASTM A-1 jet fuel and vapor propane fuels were independently controlled to simulate varying degrees of vaporization. Data were obtained for the effects of fuel vaporization on the ex-

haust emission levels of oxides of nitrogen, carbon monoxide, total hydrocarbons, and smoke number. A more detailed description of the subject research effort is described in reference 4.

APPARATUS AND PROCEDURE

Test Facility and Instrumentation

The test combustor was mounted in the closed-duct facility described previously in reference 3 and shown in figure 1. Tests were conducted up to pressure levels of 20 atmospheres. Combustion air drawn from the laboratory high pressure supply system was indirectly heated up to 700 K (1260° R) in a counter-flow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold by-passed air. Airflow through the heat exchanger and by-pass flow system and the total pressure of the combustor inlet air-flow were regulated by remote controlled valves.

Combustor instrumentation stations are also shown in figure 1. The inlet-air temperature was measured at station A with eight chromel-alumel thermocouples. Inlet-total pressures were measured at the same station by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential pressure strain gage transducers that were balanced by wall static pressure taps located at the top and bottom of the duct. Combustor outlet temperatures, pressure, and smoke sample were obtained with a traversing exhaust probe mounted at station C. The probe consisted of 12 elements: five aspirating platinum-platinum-13 percent rhodium total-temperature thermocouples, five total-pressure probes, and two wedge-shaped static pressure probes. A portion of the aspirated exhaust was by-passed for use as a smoke sample indication. At station D a four-point air-cooled probe was located to provide the exhaust emission gas sample. Station D was located 0.914 m (36 in.) downstream of the combustor exhaust in a circular pipe with a diameter of 0.508 m (20 in.).

Test Hardware

Combustor. - The combustor used in this investigation was similar to Combustor Model Number 3 of reference 3 with the faceplate slightly modified to accomodate different fuel nozzle injectors. A schematic of the combustor is shown in figure 2. The combustor liner was composed of a series of panels which are independently supported from the outer wall as shown in figure 2(a). The combustor has an inlet snout area which was 40 percent of the combustor inlet area.

The main portion of the airflow entering the snout passed through air swirlers. A small portion, approximately 6 percent of the total flow was used to film cool the sides of the combustor. The combustor liner walls were film cooled by means of continuous slots. The dilution air was admitted by means of external scoops. The mass flow distribution in the combustor, also shown in figure 2(a), was calculated by means of a computer program for the analysis of annular combustors as described in reference 5. No attempt was made to alter the airflow distribution pattern in this study.

Fuel nozzle injectors. - Two different fuel nozzle injectors were used in this investigation and are shown in figure 2(b). Configuration Number 1 consisted of two separate passages in which liquid fuel was injected through a simplex nozzle located in the center of the assembly and vapor fuel was injected through a series of 8 evenly-spaced 0.94 mm (0.037 in.) diameter holes (60° included angle) located on a 1.75 cm (0.69 in.) diameter concentric with the simplex orifice. Configuration Number 2 was a commercial duplex nozzle with liquid fuel in the smaller center orifice and vapor fuel in the larger annular ring.

Gas Sample Technique

Gas samples. - The exhaust gas sample is withdrawn through the four point air-cooled stationary probe shown in figure 3. The gas sample probe was located downstream of the traversing probe and in the center of the exhaust gas stream at station D as shown in figure 1. The gas sample at approximately 2 atmospheres pressure was passed through an electrically heated sampling line at a temperature of approximately 423 K (760° R) to the gas analyzer. To prevent contamination in the sample line, a nitrogen purge was used prior to and during combustor ignition.

Gas sample analysis. - The exhaust gas was analyzed for oxides of nitrogen, carbon monoxide, and total hydrocarbons. Carbon dioxide was also included to determine and cross-check the fuel-air ratio of the sample. The gas analysis equipment is shown in figure 4 and is in accord with the recommendations set forth in reference 6. Oxides of nitrogen were analyzed by a chemiluminescent meter. The meter included a converter for reducing NO_2 to NO which was measured. Measurement with and without the converter allows determination of both NO and NO_2 content; however, in this study only the total oxides of nitrogen are reported. The CO and CO_2 instruments were of the non-dispersive infra-red type. The total hydrocarbon content was determined by a flame ionization detector in which a portion of the sample gas was passed through a hydrogen flame. Concentrations of the oxides of nitrogen, carbon monoxide, and total hydrocarbons are reported on a wet basis. The oxides of nitrogen emission index is expressed as

grams of NO_2 per kilogram of fuel and the total hydrocarbons as grams of CH_2 per kilograms of fuel.

Since practical considerations limited exhaust gas sampling to only four positions across the exhaust duct, attempts were made to verify that the gas sampling was representative of the average concentration 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 value of fuel and air flow rates. All of the data presented in this report, for which both values of fuel-air were available, produced gas sample fuel-air ratios within plus or minus 15 percent of metered values.

Smoke sample. - The exhaust smoke sample was withdrawn through the moveable exhaust probe which traverses the combustor exit at station C as shown in figure 1. The sample line was heated by means of stream tracing and the smoke number was determined with the smoke meter shown in figure 5. The sample was analyzed in accord with SAE Aerospace Recommended Practice as discussed in reference 7. The gas flow rate at standard conditions was 2.36×10^{-4} m³/sec (0.50 ft³/min.), and four samples were obtained at each test condition for a time duration of 12, 22, 36 and 72 seconds, respectively. From a plot of smoke number against weight of gas samples per square centimeter of filter area, the smoke number at 1.623 grams of gas/cm² of filter (0.023 lbs of gas/in² of filter) was determined.

Combustor Test Conditions

The combustor was operated at the test conditions shown in table I. Data for three fuel-air ratio values of 0.008, 0.010, and 0.014 are presented using liquid ASTM A-1 jet fuel, vapor fuel, and combinations of 25 percent liquid-75 percent vapor, 50 percent liquid-50 percent vapor, and 75 percent liquid-25 percent vapor fuel were obtained for each fuel nozzle injector. Not all conditions could be obtained due to fuel flow limitations of the injectors.

Fuel Selection

Propane was used to simulate vaporized jet fuel since it is easier to vaporize and handle than liquid jet fuel; and, the combustion properties are similar to distillate jet fuels. Comparison of the selected properties of ASTM A-1 jet fuel are listed in table II. As shown in table II the lower heating value, flammability limits, flame velocity, and flame temperature of propane compare favorably with ASTM A-1 jet liquid fuel. The slight difference in combustion characteristics which might occur would probably not be encountered in this program. That is, the test conditions were pri-

marily at high inlet-air temperatures and pressures where combustion is limited by the mixing process rather than chemical kinetics. Experimental data in which the proportions of iso-paraffins, cyclo-paraffins, and normal-paraffins were varied over a wide range in vaporized jet fuel did not produce any appreciable difference in the NO_x, NO, and CO emissions as shown in reference 8.

The difference in the percent of hydrogen between the two fuels could possibly have an effect on the smoke number. In reference 8 it was shown that for a constant pressure that both the percentage of hydrogen in the fuel and the inlet-air temperature can effect the smoke number. Smoke emissions were shown to decrease as the hydrogen content increased for inlet-air temperatures up to 700 K (1260° R); however, at higher inlet-air temperatures the effect of fuel type was minor. Although ASTM A-1 jet fuels can constitute a wide variety of hydrocarbon types the largest proportion is usually of the n-paraffin type. In reference 2 it is shown that n-paraffins containing 2 or more carbon atoms have somewhat similar smoking criteria. Therefore, considering the percentage of hydrocarbon in the fuel, the inlet-air temperature, and the hydrocarbon type it would be expected that the smoke number might be less with propane fuel as compared to vaporized ASTM A-1 jet fuel at lower inlet-air temperatures. At inlet-air temperature levels of 700 K (1260° R) or more the two fuels would be expected to be similar.

RESULTS AND DISCUSSION

Effects of the percent of fuel vaporization on exhaust emission index levels of oxides of nitrogen, carbon monoxide, total hydrocarbons, and smoke number are presented. Combustion efficiency data are not presented since levels were of the order of 100 percent at all test conditions. To establish trends of fuel vaporization effects independent of injector geometry data from two different types of fuel nozzle injectors are included. Additional details are presented in reference 4.

Effect of Fuel Vaporization on NO_x Emission

Effects of fuel vaporization on NO_x emission for a fuel-air ratio value of 0.014 are presented in figures 6, 7, and 8 for variations in inlet-air temperature, inlet-pressure, and combustor reference velocity, respectively.

Effect of inlet-air temperature. - In figure 6 the effects of inlet-air temperature on the NO_x emission index for various proportions of vapor fuel are presented for a constant inlet pressure of 10 atmospheres and a combustor reference velocity of 21.3 m/sec

(70 ft/sec). Test results using fuel nozzle injector #1 show that
as the inlet-air temperature is increased from 478 to 700 K (860 to
1260° R) the NO_x emission index increased from 5 to 22 for 0 percent
vapor fuel. The effect of vapor fuel on NO_x reduction is negligible
for an inlet-air temperature of 478 K (860° R). At the higher inlet-
air temperatures the reduction in NO_x that occurred as the propor-
tion of vapor fuel was increased became more significant. A 22 per-
cent decrease in NO_x at inlet-air temperatures of 589 and 700 K
(1060 and 1260° R) was obtained as the fraction of vapor was in-
creased from 0 to 100 percent. Using fuel nozzle injector #2 NO_x
reductions were similar in trend but smaller in magnitude. One
hundred percent vapor fuel flows were not attainable with fuel noz-
zle injector #2 due to fuel flow limitations.

Factors which effect the NO_x emission index include primary zone
equivalence ratio and dwell time which in turn can be effected by the
reaction zone volume, reference 9. An increase in NO_x with increas-
ing inlet-air temperature as shown in figure 6 would be expected
since the overall fuel-air ratio (primary zone equivalence ratio) and
combustor reference velocity (dwell time) remained constant. There-
fore, the flame temperature was primarily dependent on the inlet-air
temperature. The reduction of NO_x for a constant inlet-air temper-
ature, for variation in the degree of fuel vaporization, and for
variation in fuel nozzle geometry can be attributed to variation in
the effective primary zone equivalence ratio. The primary zone
equivalence ratio is determined by the proportioning of fuel and air.
At an operating overall fuel-air ratio of 0.014 the primary zone
equivalence ratio was calculated to be 0.75. However, the local
equivalence ratio determines the maximum flame temperature. If the
system is well mixed the minimum NO_x emission level would be estab-
lished; however, local stoichiometric regions could lead to higher
NO_x emission. In this combustor primary air is introduced through
air swirlers concentric with the fuel nozzles. In the case of fuel
nozzle injector #1 a rather coarse liquid spray was obtained which
could penetrate to the primary air stream. The vapor fuel was in-
jected directly into the air stream by means of 8 jets inclined 30°
into the air stream. With this configuration relatively intense
mixing is established. The higher NO_x emission with liquid fuel as
compared to vapor fuel is probably due to local stoichiometric burn-
ing associated with liquid fuel droplets. It is also quite possible
that even with vapor fuel locally rich zones are present due to the
fact that fuel and air do not mix instantaneously. Additional study
would be required to determine the minimum NO_x level with a premixed
system.

An additional reduction of approximately 20 percent in NO_x level
was obtained with fuel nozzle injector #2 as compared to injector #1.
This reduction in NO_x is attributed not to an improvement in mixing

but due to poorer mixing as a result of the fuel distribution. A finer spray was inherent with injector #2 which probably did not penetrate to the primary stream but remained within the center of the vortex causing a very rich local region. Lower flame temperatures are associated with rich mixtures so that a reduction in NO_x would be expected. A rich mixture is also very susceptible to smoke formation; whereas lean mixtures usually burn smoke free. Operation with fuel nozzle injector #2 produced a great deal of smoke indicating insufficient primary zone mixing.

Effect of inlet pressure. - In figure 7 the effects of inlet pressure on the NO_x emission for various proportions of vapor fuel are presented for a constant inlet-air temperature of 589 K (1060° R) and a combustor reference velocity of 21.3 m/sec (70 ft/sec). Results show that as the inlet pressure is increased from 4 to 20 atmospheres the NO_x emission index increased from 7.5 to 15 for 0 percent vapor fuel and fuel nozzle injector #1. A reduction in NO_x emission index of 36 percent was obtained by converting to 100 percent vapor at a pressure level of 20 atmospheres. The NO_x emission index was not obtained at higher inlet-air temperatures due to facility limitations. Results with fuel nozzle injector #2 indicate that there was no appreciable effect of pressure or degree of fuel vaporization. Normally it would be expected that an increase in the NO_x emission index would be observed as was the case with fuel nozzle injector #1. The fact that no increase in NO_x emission occurred with injector #2 can be attributed to a lower flame temperature as a result of poor primary zone mixing as evident by excessive smoke.

Effect of reference velocity. - In figure 8 the effects of combustor reference velocity on NO_x emission for various proportions of vapor fuel are presented with fuel nozzle injector #1 for a constant inlet-air temperature of 589 K (1060° R) and a pressure of 10 atmospheres. As the reference velocity increased from 15.3 to 27.4 m/sec (50 to 90 ft/sec) the NO_x emission index decreased 7 percent with fuel nozzle injector #1 for 0 percent vapor fuel. As the proportion of vapor fuel was increased to 100 percent a reduction in NO_x of about 16 percent was obtained at a reference velocity of 27.4 m/sec (90 ft/sec). A reduction in NO_x of approximately 53 percent over the same range of reference velocity was observed with injector #2. However, there was no appreciable effect due to vapor fuel injection. The reduction in NO_x with increased reference velocity was anticipated since increasing reference velocity reduces dwell time in the primary combustion zone.

Effect of Fuel Vaporization on CO Emission

Effects of fuel vaporization on CO emission for a fuel-air ratio of 0.014 are presented in figures 9, 10, and 11 for variation in

inlet-air temperature, inlet-pressure, and cumbustor reference velocity, respectively.

Effect of inlet-air temperature. - In figure 9 the effect of inlet-air temperature on the CO emissions for various proportions of vapor fuel are presented for a constant inlet pressure of 10 atmospheres and a combustor reference velocity of 21.3 m/sec (70 ft/sec). Two points are also included in figure 9 to indicate the CO emission index level for a simulated idle condition with an inlet-air temperature of 478 K (860° R), pressure of 4 atmospheres, reference velocity of 21.3 m/sec (70 ft/sec), and fuel-air ratio of 0.008. A somewhat lower combustion efficiency corresponding to approximately 95 percent was obtained at idle as compared to approximately 100 percent for the parametric study. Results indicate that as the percentage of vapor fuel is increased from 0 to 100 percent the CO emission index decreases from 110 to 70, corresponding to an improvement of 36 percent at idle conditions. Comparison of the CO emission index at idle with fuel nozzle injector #2 was not made due to operational difficulties.

For the parametric variation of combustor inlet-parameters the results obtained using fuel nozzle injector #1 indicate that as the inlet-air temperature is increased from 478 to 700 K (860 to 1260° R) the CO emission index decreased from 60 to 8 for 0 percent vapor fuel. With 100 percent vapor fuel injection CO was decreased 33 percent at the most severe condition which corresponds to an inlet-air temperature of 478 K (860° R). Fuel nozzle injector #2 produced about the same level of CO. The effect of vapor fuel was more pronounced in reducing CO with fuel nozzle injector #2 than with fuel nozzle injector #1.

Higher CO emission index levels are evident at the lower inlet-air temperatures indicating incomplete combustion. The reduction in combustion efficiency could probably amount to a little over 1 percent since a loss in efficiency of 1 percent due to carbon monoxide for liquid ASTM A-1 jet fuel would result in a CO emission index level of 43. The inlet-air temperature of 478 K (860° R) is below the boiling point of the liquid fuel (final boiling point 532 K (956° R) and coupled with intense mixing the fuel vaporization and burning processes are probably delayed as compared to combustion with higher inlet-air temperature or 100 percent vapor fuel. As the inlet-air temperature is increased a sharp drop in CO is observed which reflects the improved reaction environment. The largest absolute gain using vapor fuel in CO reduction is at the lower inlet-air temperatures. At the higher inlet-air temperatures the CO levels are low so that large percentage gains do not amount to much of an actual decrease in absolute CO level.

Effect of inlet pressure. - The effect of inlet pressure on the

CO emission index for various proportions of vapor fuel are shown in figure 10 for the two fuel nozzle injectors for a constant inlet-air temperature level of 589 K (1060° R) and a combustor reference velocity of 21.3 m/sec (70 ft/sec). Results using fuel nozzle injector #1 indicate that as the pressure is increased from 4 to 20 atmospheres the CO emission index level decreased from 46 to 26 for 0 percent vapor fuel. One hundred percent vapor fuel further decreased the CO by approximately 28 percent at a pressure of 4 atmospheres. Using fuel nozzle injector #2 the CO emission index was further reduced from 32 to 12 at a pressure level of 4 atmospheres as the proportion of vapor was increased from 0 to 50 percent.

Effect of inlet velocity. - The effect of combustor reference velocity on CO emission index for various proportions of vapor fuel are shown in figure 11 for the two fuel nozzle injectors for a con-inlet-air temperature of 589 K (1060° R) and a pressure of 10 atmospheres. Results using fuel nozzle injector #1 indicate that as the reference velocity is increased from 15.3 to 27.4 m/sec (50 to 90 ft/sec) the CO emission index level increased from 25 to 39 for 0 percent vapor fuel. The effect of vapor fuel in proportions up to 50 percent did not significantly influence CO formation; however, 100 percent vapor fuel operation decreased the CO emission index approximately 27 percent at a reference velocity of 27.4 m/sec (90 ft/sec). The trends shown in figure 11 are consistent in that at the lower reference velocity the dwell time is increased and the CO emission reduced.

Effect of Fuel Vaporization on Total Hydrocarbon Emissions

The effect of fuel vaporization on the THC emission index for variation in inlet-air temperatures is shown in figure 12 for the two fuel nozzle injectors, for a pressure of 4 atmospheres and a reference velocity of 21.3 m/sec (70 ft/sec). Also included for fuel nozzle injector #1 is the THC emission level corresponding to an idle condition. As shown in figure 12 for the simulated idle condition the THC emission index is reduced from 21 to 13.5 (36 percent reduction) for injector #1 as combustion is converted from 0 to 100 percent vapor fuel. The level of unburned hydrocarbons decreases as the fuel-air ratio is increased for both fuel injectors for a constant inlet-air temperature of 589 K (1060° R). The THC emission index was near 1 for a fuel-air ratio of 0.014 over a range of vapor fuel flows from 0 to 100 percent. The THC emission index at higher inlet-air temperatures and pressures was so low (generally less than 1) that trends are ambiguous.

Effect of Fuel Vaporization on Smoke Number

Figure 13 presents the effect of inlet-air total pressure on the smoke number for various proportions of vapor fuel for a constant inlet-air temperature of 589 K (1060° R) and combustor reference velocity of 21.3 m/sec (70 ft/sec). The smoke number increased from 12 to 27 as the inlet pressure was increased from 4 to 20 atmospheres for fuel nozzle injector #1 with 0 percent vapor fuel. Operation with 100 percent vapor fuel decreased the smoke number 51 percent at the most severe condition of 20 atmospheres. Fuel nozzle injector #2 produced a very sharp increase in smoke number as the pressure was increased. Values over 80 were indicated at a pressure level of 20 atmospheres and 0 percent vapor fuel. One hundred percent vapor operation was not obtained with fuel nozzle injector #2; however, at a pressure of 10 atmospheres and 75 percent vapor a decrease in smoke number of 25 percent was obtained with injector #2 as compared to 66 percent with injector #1.

The difference in smoke number between the two fuel injectors are consistent with the prior emission index levels. For example, the NO_x emission index was lower with injector #2. This was attributed to lower flame temperature resulting from an over-rich condition in the primary zone. An over-rich primary would be susceptible to producing a smoking condition.

Effect of Fuel Injector Design

It has been shown that combustor exhaust emission were reduced as combustion was converted from liquid fuel to 100 percent vapor fuel. A reduction in emissions was observed with both of the fuel nozzle injectors. In general, it was necessary to convert to 100 percent vapor before any appreciable decrease in emission index was obtained. Even if 100 percent vapor fuel were available over the entire range of operating conditions larger reduction in the NO_x emission level would be desired.

The NO_x emission level is strongly dependent on the primary zone equivalence ratio. The primary zone equivalence ratio was predicted to be 0.75. It is possible that there may have been local pockets of fuel which burned at a higher temperature and caused the relatively high level of NO_x. Indications are that the primary zone equivalence ratio and volume would have to be further reduced in order to lower the NO_x emission. A further reduction in equivalence ratio could lead to instabilities at idle conditions which could result in increased CO and THC levels. Fuel staging or a variable geometry might possibly minimize these problems.

Fuel nozzle injector #2 was shown to operate with an overly rich primary zone because of the poor arrangement of the fuel admission ports and swirler combination. This arrangement is characteristic of the configuration that would result if vapor fuel were directly substituted for liquid fuel in a conventional combustor system. Obviously such an arrangement is unsatisfactory and would require alternate primary zone mixing methods.

The design, optimization, and development of the fuel nozzle injector and appropriate primary mixing zone presents a difficult task. Lowered flame temperature can be achieved by operating at lean equivalence ratios. However, careful control of the combustion process is required in order to prevent locally rich regions. Lowered flame temperature can also be achieved by operating with a rich equivalence ratio. However, excess smoke is produced which required additional dwell time in order to be consumed.

SUMMARY OF RESULTS

The following results were obtained in a segment of an experimental combustor operating at the following test conditions: inlet-air temperatures, 478 to 700 K (860 to 1260° R), inlet-air pressures, 4 to 20 atmospheres; and combustor reference velocities, 15.3 to 27.4 m/sec (50 to 90 ft/sec). Two fuel injector types were used in which liquid ASTM A-1 jet fuel and vapor propane fuel were independently controlled to simulate varying degrees of vaporization. Specific results are presented for a dual fuel injector in which the liquid fuel was introduced through a simplex nozzle located in the center of the assembly and vapor fuel injected through a series of 8 evenly-spaced 0.94 mm (0.037 in.) diameter holes located on a diameter concentric with the simplex orifice. Increasing the proportion of vapor fuel injected into the combustor from 0 to 100 percent for a constant combustor reference velocity of 21.3 m/sec (70 ft/sec) indicated the following trends:

1. At an inlet total pressure of 10 atmospheres and fuel-air ratio of 0.014 the emission index for the oxides of nitrogen decreased 22 percent at inlet-air temperature levels of 589 and 700 K (1060 and 1260° R) but was not effected at an inlet-air temperature level of 478 K (860° R).

2. At an inlet-air temperature of 478 K (860° R), pressure of 4 atmospheres, and fuel-air ratio of 0.008 the emission index levels for carbon monoxide and total hydrocarbons were decreased 36 percent.

3. At an inlet-air temperature of 589 K (1060° R), pressure of 20 atmospheres, and fuel-air ratio of 0.010 the smoke number was decreased 51 percent.

4. Similar reductions in emission levels were observed with fuel nozzle configuration #2 as the proportion of vapor propane was increased.

5. Results indicate that changing the amount of vapor alone is insufficient to obtain major reductions in emission index levels. Design optimization of the primary zone equivalence ratio would also be required to achieve further improvement.

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TABLE I. - COMBUSTOR TEST CONDITIONS

Test condition	Inlet-pressure, atm	Inlet-temperature		Reference velocity*	
		K	^{O}R	m/sec	ft/sec
A	10	589	1060	21.3	70
B	10	478	860	21.3	70
C	10	700	1260	21.3	70
D	4	589	1060	21.3	70
E	20	589	1060	21.3	70
F	10	589	1060	15.2	50
G	10	589	1060	27.4	90

* The reference velocity is based on the total mass flow of air
through the maximum combustor housing cross-sectional area of
0.0464 m^2(72 in.^{2}).

TABLE II. - PHYSICAL AND CHEMICAL PROPERTIES OF TEST FUELS

	ASTM A-1 jet fuel	Propane*
Distillation		
Initial boiling point	334 K (800° R)	
Final boiling point	532 K (956° R)	231 K (416° R)
Lower heating value	43,000 joules/g (18,600 B/lb)	46,024 joules/g (19,927 B/lb)
Hydrogen-carbon ratio	0.160	0.220
Weight percent of hydrogen	14.3	18.2
Spontaneous ignition temperature	523 K (940° R)	778 K (1400° R)
Flammability limits		
Lean fuel-air ratio	0.035	0.034
Rich fuel-air ratio	0.27	0.19
Max. flame velocity	38 cm/sec	43 cm/sec
Flame temperature	2235 K	2252 K

* The propane fuel was a commercial grade about 90 to 92 percent pure. Impurities were primarily propylene (about 6 to 8 percent) and traces of ethylene and butane.

PREHEATER EXHAUST

EXHAUST GASES FROM FOUR J-47 COMBUSTOR CANS

AIRFLOW CONTROL VALVE

AIR ORIFICE

INDIRECT FIRED HEAT EXCHANGER

LABORATORY AIR SUPPLY

AIR BYPASS LINE

AUTOMATIC AIR-TEMPERATURE CONTROL VALVE

ATMOSPHERIC OR ALTITUDE EXHAUST

INLET DIFFUSER STATION A

STATIONARY GAS SAMPLING PROBE STATION D

EXHAUST CONTROL VALVE

NATURAL GAS

DIRECT FIRED HEAT EXCHANGER

CD-11036-28

WATER

PRESSURE SHELL

BELLMOUTH

DOME AIR DEFLECTOR

TEST COMBUSTOR

RADIOMETER STATION B

TRAVERSING TEMPERATURE, PRESSURE, AND SMOKE PROBE STATION C

Figure 1. - Test facility and auxiliary equipment.

COMBUSTOR CHANNEL SUPPORT TO OUTER HOUSING. TYPICAL SIX LOCATIONS ACROSS TOP AND BOTTOM.

DILUTION HOLES HAVE VANE DEFLECTORS EXTERNAL TO ENTRY

AIR SWIRLER

COMBUSTOR FACEPLATE

FUEL NOZZLES

AIR FLOW

30%
40%
30%

2.75%

80°

0.020 (0.785)

0.109 (4.3)   0.120 (4.8)

0.025 (1)

0.051 (2)

2.75%   2.75%

2.75%   2.75%

0.019 (0.78)

LINER WALL THERMOCOUPLE STATIONS 1, 2, AND 3

% AIR FLOW SPLITS
⊕ THERMOCOUPLE LOCATIONS

RADIOMETER LOCATION 0.05 M (2 IN.) FROM FACEPLATE IN-LINE WITH FUEL NOZZLES.

(a) COMBUSTOR LINER.

LIQUID A-1   VAPORIZED PROPANE

VAPORIZED PROPANE

8 ORIFICES EACH 0.00094 (0.037) DIAM

INLET-AIR SWIRLER

30°

0.175 (0.69)

LIQUID A-1

VAPOR

LIQUID

FUEL NOZZLE INJECTOR NO. 1

FUEL NOZZLE INJECTOR NO. 2

(b) FUEL NOZZLE INJECTORS.

Figure 2. - Schematic of combustor assembly. Combustor width 0.31 m (12 in.), length 0.32 m (12.5 in.), and maximum combustor housing height 0.15 m (6 in.).

COOLING AIR OUT

SAMPLE GAS

4 ORIFICES, 0.30 CM (0.12 IN.) DIAM

N_2 PURGE

COOLING AIR IN
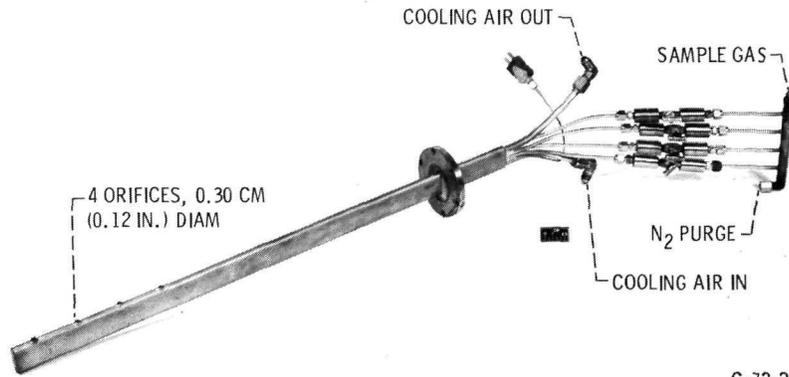
C-72-2492

Figure 3. - Stationary gas sampling probe.

THC CONTROL ANALYZER

RECORDERS

NO-NO_x CONTROL ANALYZER

CONTROL CLUSTER A (THC)

CONTROL CLUSTER C (NO-NO_x)

CONTROL CLUSTER B (CO)

CO_2 CONTROL ANALYZER

CO FILTER

OVEN

CO CONTROL ANALYZER

CONTROL CLUSTER D (CO_2)

BYPASS FLOW INDICATOR AND CONTROL

FILTERS: NO CO_2

NO_x CONVERTER SWITCH

NO PUMP SWITCH

C-71-3941
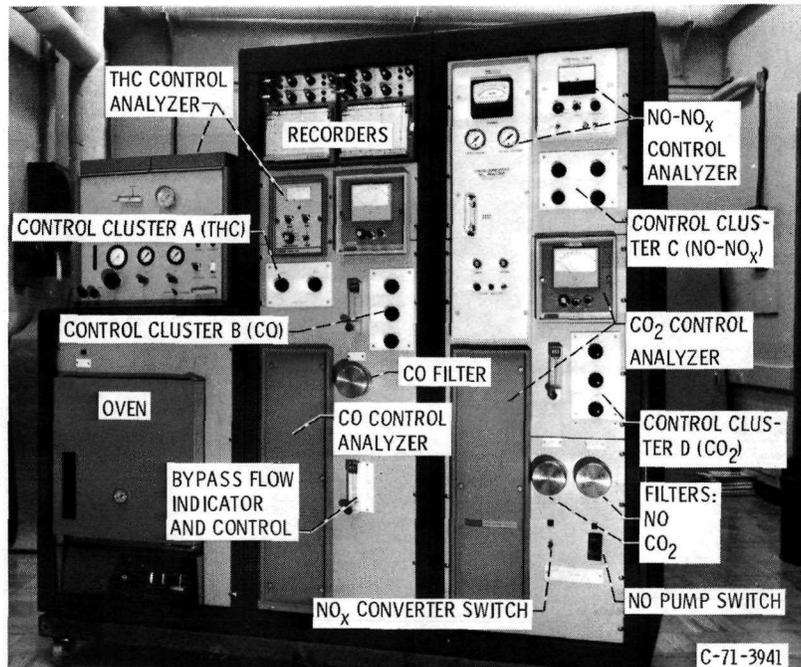
Figure 4. - Gas analysis equipment.
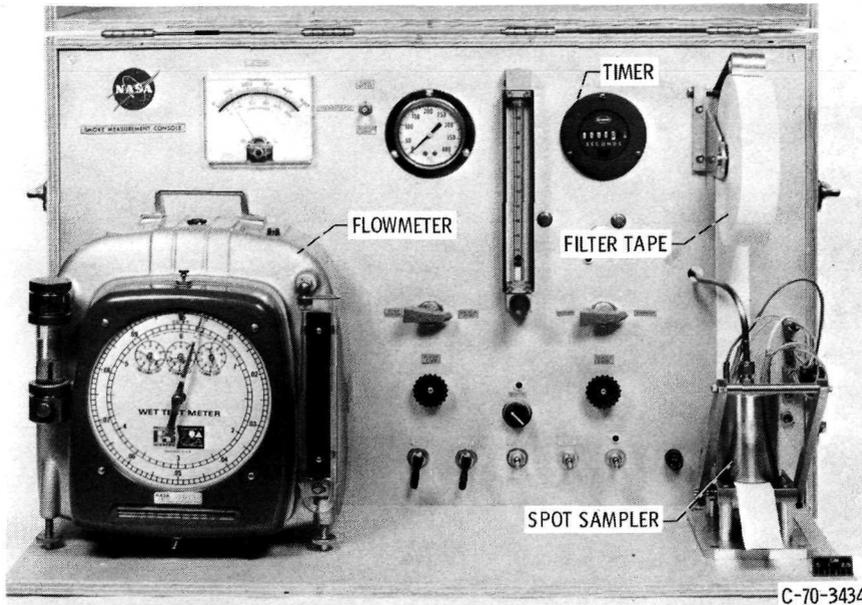
Figure 5. - Smoke meter.
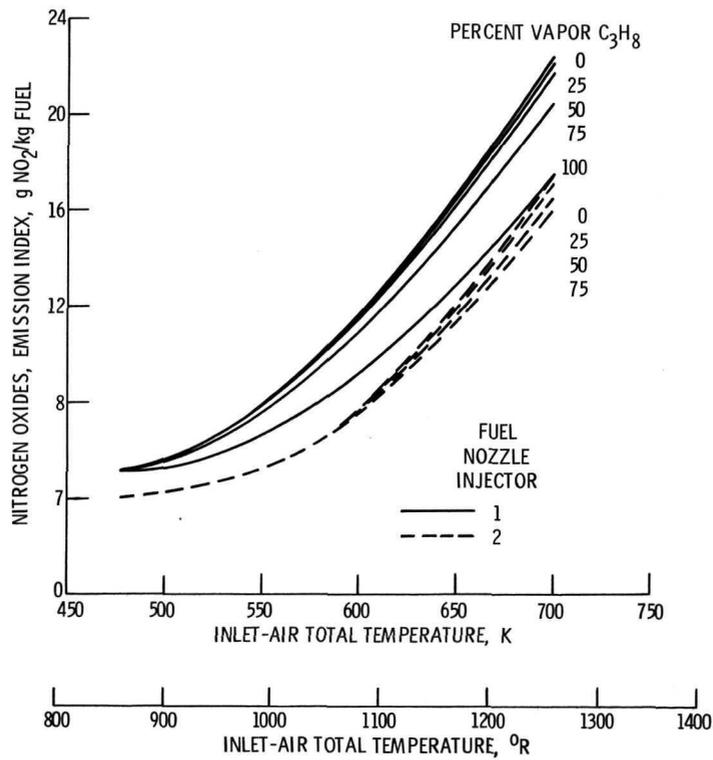
Figure 6. - Summary of the effect of combustor inlet-air temperature on NO_x emission index over a range of vaporized fuel proportions for a constant pressure of 10 atm, reference velocity of 21.3 m/sec (70 ft/sec), and fuel-air ratio of 0.014.
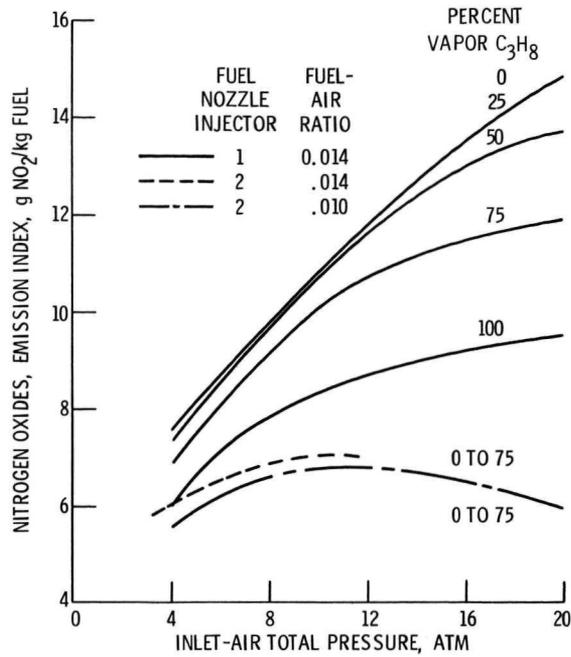
Figure 7. - Summary of the effect of combustor inlet-air pressure on NO$_x$ emission index over a range of vaporized fuel proportions for a constant inlet-air temperature of 589 K (1060° R), reference velocity of 21.3 m/sec (70 ft/sec).
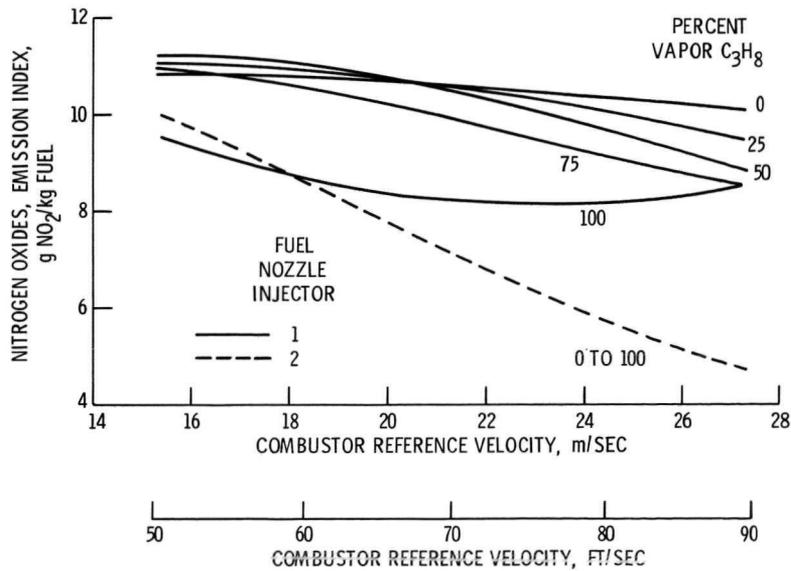

Figure 8. - Summary of the effect of combustor reference velocity on NO$_x$ emission index over a range of vaporized fuel proportions for a constant inlet-air temperature of 589 K (1060° R), a pressure of 10 atm, and a fuel-air ratio of 0.014.
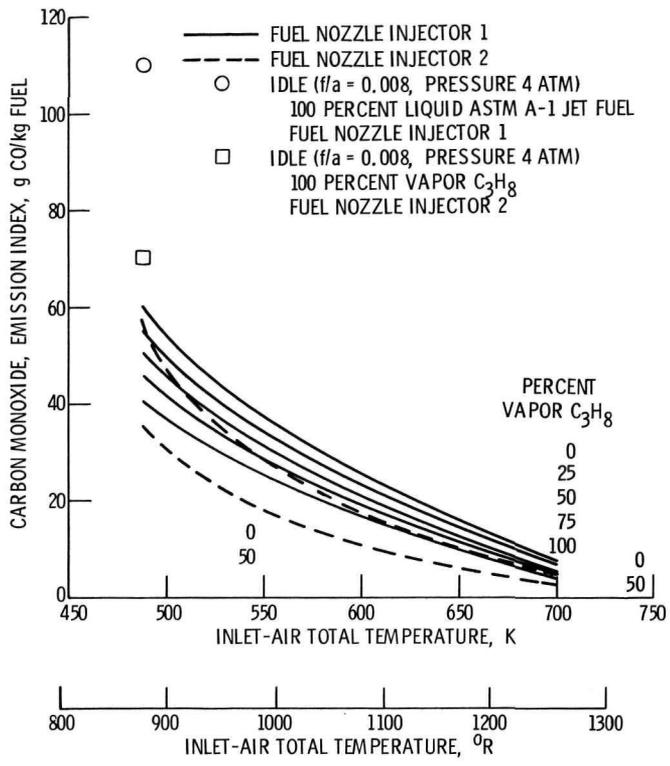
Figure 9. - Summary of the effect of combustor inlet-air temperature on CO emission index over a range of vaporized fuel percentages for a constant pressure of 10 atm, a reference velocity of 21.3 m/sec (70 ft/sec), and a fuel-air ratio of 0.014 except as noted.
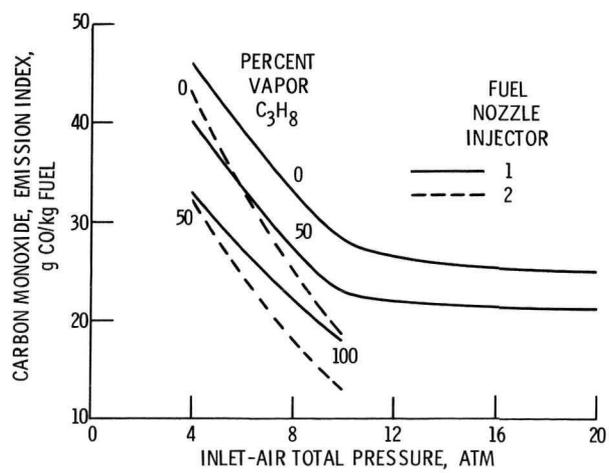
Figure 10. - Summary of the effect of combustor inlet-air pressure on CO emission index over a range of vaporized fuel proportions for a constant inlet-air temperature of 589 K (1060° R), a reference velocity of 21.3 m/sec (70 ft/sec), and a fuel-air ratio of 0.014.
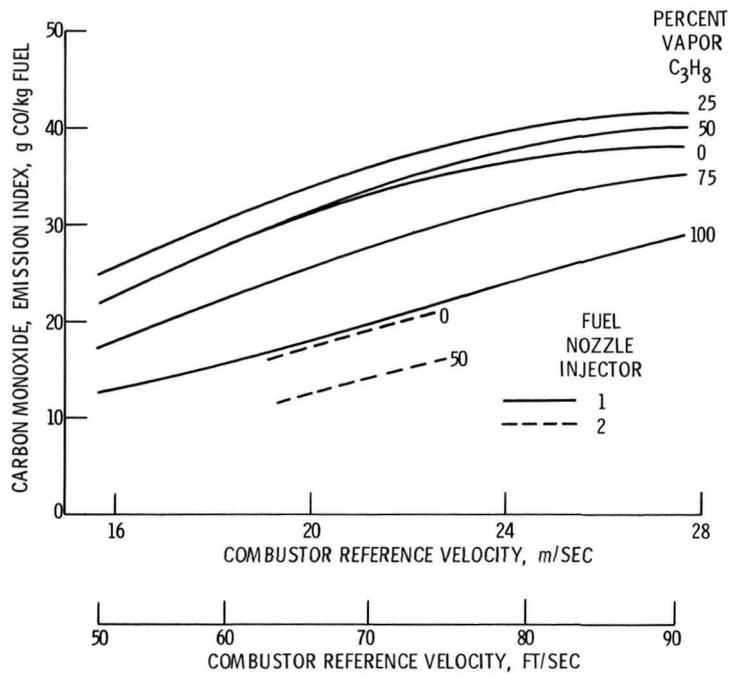
Figure 11. - Summary of the effect of combustor reference velocity on CO emission index over a range of vaporized fuel proportions for a constant inlet-air temperature of 589 K (1060^0 R), a pressure of 10 atm, and a fuel-air ratio of 0.014.

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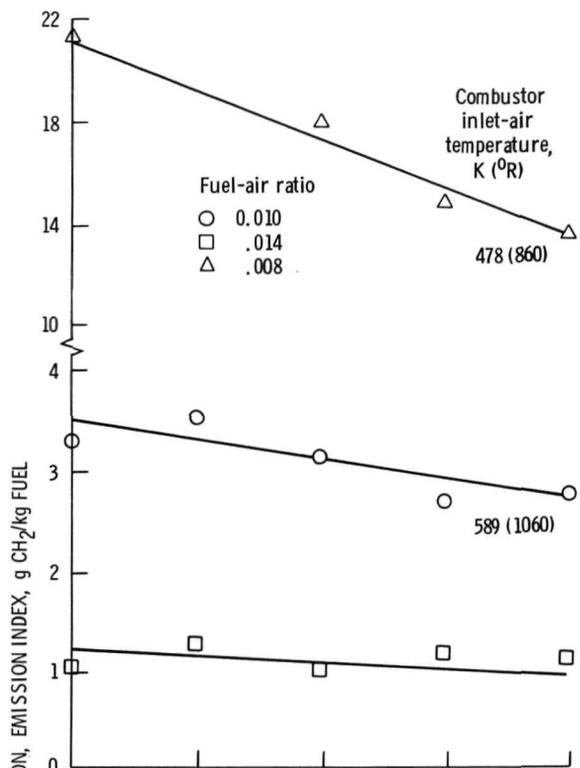
(a) FUEL NOZZLE INJECTOR 1.
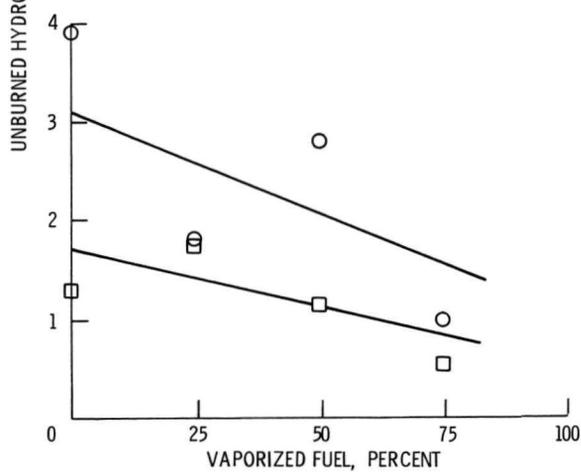
(b) FUEL NOZZLE INJECTOR 2.

Figure 12. - Effect of fuel vaporization on THC emission in-
dex for two temperature levels, a constant pressure of
4 atm, and a reference velocity of 21.3 m/sec (70 ft/sec).
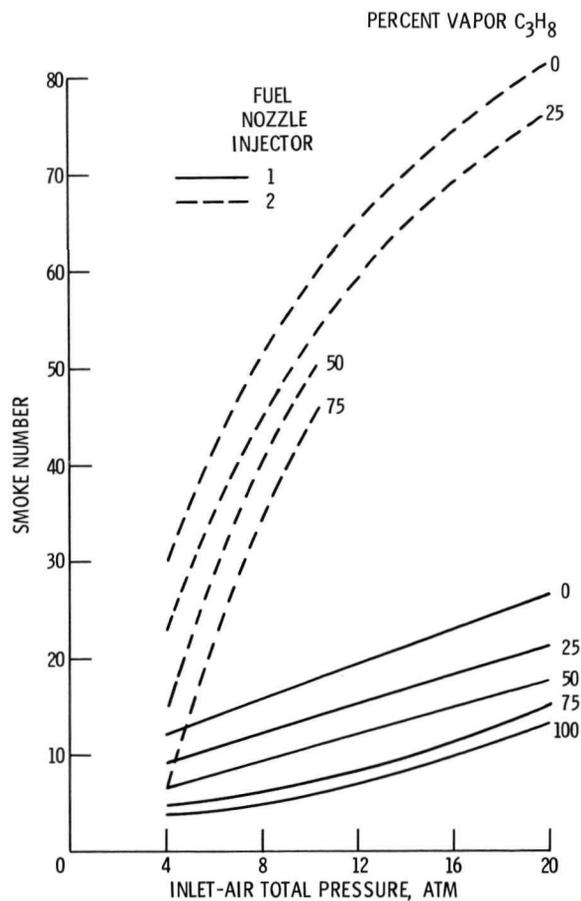
Figure 13. - Summary of the effect of combustor inlet-air
pressure on Smoke Number over a range of vaporized
fuel proportions for a constant inlet-air temperature of
589 K (1060° R), a reference velocity of 21.3 m/sec
(70 ft/sec), and a fuel-air ratio of 0.010.