The Applicability of Jet-Shear-Layer Mixing and Effervescent Atomization for Low-NO_x Combustors

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An investigation has been conducted to develop appropriate technologies for a low-NO_x, liquid-fueled combustor. The combustor incorporates an effervescent atomizer used to inject fuel into a premixing duct. Only a fraction of the combustion air is used in the premixing process. This fuel-rich mixture is introduced into the remaining combustion air by a rapid jet-shear-layer mixing process involving radial fuel–air jets impinging on axial air jets in the primary combustion zone. Computational modeling was used as a tool to facilitate a parametric analysis appropriate to the design of an optimum low-NO_x combustor. A number of combustor configurations were studied to assess the key combustor technologies and to validate the three-dimensional modeling code. The results from the experimental testing and computational analysis indicate a low-NO_x potential for the jet-shear-layer combustor. Key features found to affect NO_x emissions are the primary combustion zone fuel–air ratio, the number of axial and radial jets, the aspect ratio and radial location of the axial air jets, and the radial jet inlet hole diameter. Each of these key parameters exhibits a low-NO_x point from which an optimized combustor was developed. Also demonstrated was the feasibility of utilizing an effervescent atomizer for combustor application. Further developments in the jet-shear-layer mixing scheme and effervescent atomizer design promise even lower NO_x with high combustion efficiency.

Introduction

Recent concerns on the destruction of the ozone layer brought on by pollutants have led to the development of low emission aircraft combustor concepts. One ozone-depleting pollutant created during the combustion process is oxides of nitrogen ($NO_x = NO + NO_2$). NO_x is a catalyst to the destruction of ozone. The formation of NO_x has been shown to be an exponential function of flame temperature. The temperature sensitivity of NO_x production is due to the fact that the reactions primarily involve atomic oxygen, which does not appear in large quantities at low temperatures. The chemical rate reactions are also sensitive to temperature. Therefore, the key to any successful low-NO_x combustor is to provide sufficient time and temperature for complete combustion but not enough time and temperature for high-NO_x emission levels. This has been accomplished by producing a nearly homogeneous fuel–air mixture and burning well away from stoichiometric conditions (lean or rich combustion).

Many combustor schemes have been designed and tested to reduce NO_x emissions. One scheme is Lean Direct Injection (LDI). The idea behind the LDI combustor is to provide a suitable fuel atomizer that will produce exceptionally small droplets. Current atomizers produce droplets that are too large for low-NO_x applications. Small droplet production is essential since large drops burn stoichiometrically via a diffusion-type mechanism and create local hot regions in the flow field. In the LDI concept, fuel droplets are injected into the primary combustion zone in such a way as to provide complete mixing, vaporization and burning. If this is not accomplished fully, some degree of fuel and air nonuniformity will occur and give rise to local hot regions (Lyons, 1981).

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The present test program examines the effectiveness of an LDI combustor concept incorporating jet-shear-layer mixing for reducing NO_x emissions. A jet-shear-layer (JSL) mixing scheme, involving axial air jets impinging directly on radial fuel–air jets near the dome inside a flametube combustor, was shown by Abdul-Aziz and Andrews (1991), Abdul-Aziz et al. (1983), Abdul-Hussain and Andrews (1987, 1992), Abdul-Hussain et al. (1988a, b), Al-Dabbagh and Andrews (1981), and Al-Dabbagh et al. (1985) to provide rapid mixing with good combustion stability and low NO_x. They have demonstrated in one atmosphere the effectiveness of the JSL mixing scheme in combustor design. Water flow visualization tests were performed on axial and radial jet impingement showing mixing was 90 percent complete within five axial hole diameters and the jet spreading rate increasing to 90 deg as compared to 10 deg without radial jet interaction. The work done used both gaseous and liquid fuels. The use of liquid fuels has been shown to produce higher NO_x as compared to using gaseous fuels (Abdul-Aziz et al., 1987a, b; Abdul-Hussain and Andrews, 1989, 1990).

The goal of this study is to investigate whether the demonstrated low-NO_x potential of the JSL combustor when burning gaseous fuels is still present for liquid fuels. Two key features were added to the JSL combustor concept: a fuel–air premixing region and an effervescent atomizer. Premixing of all the fuel with some of the air prior to combustion permits greater fuel–air uniformity within the combustor and allows some degree of fuel droplet vaporization to take place (Anderson, 1973, 1975; Roffe and Ferri, 1975, 1976; Roffe, 1976). This fuel-rich, unignitable premixing region avoids the flashback problems encountered in some lean premixed combustor concepts.

To provide a minimal level of large, NO_x-producing fuel droplets, an effervescent fuel atomizer was used in the premixing region of the JSL combustor. In an effervescent atomizer, air bubbles are injected directly into the fuel upstream of the atomizer discharge orifice. Unlike some atomizers (e.g., air blast atomizers) only a small amount of air is needed for fuel atomization in an effervescent atomizer. It has been demonstrated (Roesler, 1988; Whitlow, 1990; Lefebvre, 1988) that these bubbles break up the fuel into ligaments, which are then ejected from the atomizer orifice at high velocities. The air bubbles explode upon exiting the orifice. These mechanisms all contribute to the production of small droplets (<20 μm Sauter mean diameter, SMD).

The simplicity and size of the JSL combustor make it an alternative to other low-NO_x combustors currently being developed. Therefore, for the present study it was hoped that successful, low-NO_x results could be achieved by incorporating an effervescent atomizer and partial premixing of the fuel and air into a JSL combustor using liquid fuels. To promote the highest degree of fuel-air mixing within the combustor a three-dimensional CFD code was used as a tool to facilitate a parametric analysis over a wide range of combustor operating conditions. This analysis led to an optimum configuration of a low-NO_x, JSL combustor. A number of combustor configurations were experimentally tested to demonstrate the low-NO_x potential of the liquid-fueled JSL combustor and to verify the CFD model.

Experimental

Various approaches to reducing NO_x were studied in some detail. Based on these reviews, an Allison T-56 combustor was modified to incorporate some key features of different experimental low-NO_x combustors. These key features include jet-shear-layer mixing in the primary zone, a premixed region upstream of the primary zone, and an effervescent atomizer.

The modified T-56 combustors are shown in Fig. 1. A summary of the JSL combustor configurations experimentally tested is listed in Tables 1 and 2. Airflow splits were calculated by using data obtained from measuring pressure drops (e.g., $\Delta P/P_3$ where P_3 is the combustor inlet pressure) across the combustor at various cold flow rates. Specific slots were blocked and pressure drops and flow rates were measured to determine the fraction of air going to each slot in the combustor. Most practical combustors have a cold flow pressure drop between 4 to 10 percent as compared to the 8 to 13 percent for the JSL combustor reported here. However, most of the combustor parameter changes were performed at 13 percent pressure drop so that their effect on emissions could be demonstrated. The combustors have a diameter of 0.138 m and an overall length of 0.432 m. The combustor liner length is 0.369 m. The combustor liner is a standard T-56 liner with all primary and dilution air holes on the liner blocked. Some cooling slots on the liner were still used to protect its structural integrity. The front dome sections of the T-56 combustors were removed and replaced by dome plates incorporating axial slots and a premixing duct from which radial jets eject a fuel and air mixture. All of the fuel and some of the air are premixed upstream of the primary combustion zone. Fuel is injected into the 38.1-mm-dia premixing duct via an effervescent atomizer, which can be moved axially to adjust the premixing length. The premixing duct is 0.102 m long.

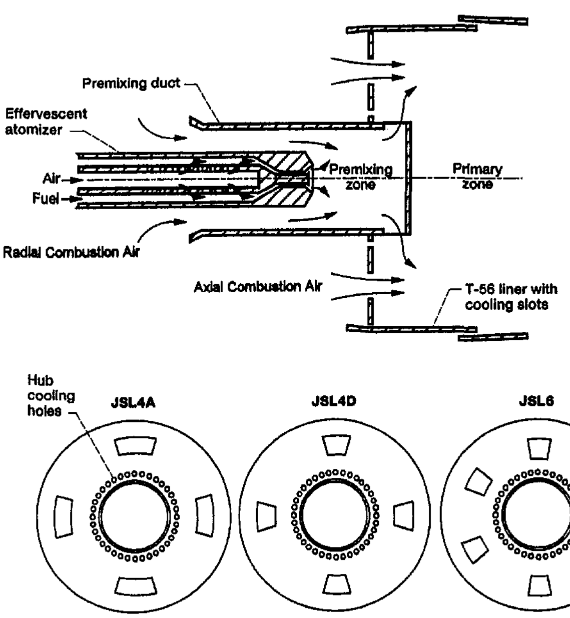

Fig. 1 Jet-shear-layer combustor configurations

Table 1 Airflow splits for JSL combustors

Air Slots	Combustor					
	JSL4A	JSL4B	JSL4C	JSL4D	JSL4E	JSL6
	Airflow splits, percentage of total airflow[a]					
Liner Cooling	50	40	25	25	25	25
Axial Combustion	32	39	48	48	47	48
Radial Combustion	14	16	20	20	22	20
Hub Cooling	4	5	7	7	6	7

[a]Nominal combustor airflow rate, 0.70 kg/s.

During the initial testing period, the central hub of the premixing duct that protrudes into the primary combustion zone partially ablated away. This was attributed to the central hub acting as a flameholder. To eliminate this problem, 36 2.54-mm-dia holes were drilled 10 deg apart around the outer perimeter of the hub (Fig. 1). These holes provide direct convective cooling to the hub. However, it should be noted that since the hub cooling jets are impinging on the radial jets, the radial jets will not be exactly 90 deg to the axial jets. Also, the radial jets may still have some residual axial velocity component stemming from the sharp 90 deg bend the premixed gas makes before exiting from the radial holes. This deviation from 90 deg will increase with larger radial location from the axial slots. This differs from past JSL flametube combustors tested by other researchers where the radial jet hole is longer to ensure a 90 deg impingement area.

The experimental combustor is configured in the test facility as shown in Fig. 2. The 0.635-m-long test section that houses the combustor tapers in diameter from 0.191 to 0.140 m. Flow straighteners are located upstream of the test section to smooth out the air flow. Downstream of the flow straighteners are two concentric diffusers used to expand the air to the 191-mm-dia test section inlet. Inlet temperature and pressure are monitored by a chromel/alumel thermocouple and a pressure tap, respectively, located in the test section housing. A traversing gas sampling probe, located directly downstream of the test section housing, is used to collect gaseous emissions. A description of

Table 2 Configurations for JSL combustors

Combustor	Axial Slot Centerline, r/R	Axial Slot Aspect Ratio, AR	Pairs of Axial/Radial Slots	Radial Hole Diameter, mm	$\Delta P/P_3$,%[a]
JSL4A	0.72	2.49	4	14.7	8
JSL4B	0.72	2.49	4	14.7	10
JSL4C	0.72	2.49	4	14.7	13
JSL4D	0.72	1.00	4	14.7	13
JSL4E	0.72	1.00	4	17.5	13
JSL6	0.72	1.00	6	12.3	13

[a]Cold flow pressure drop only.

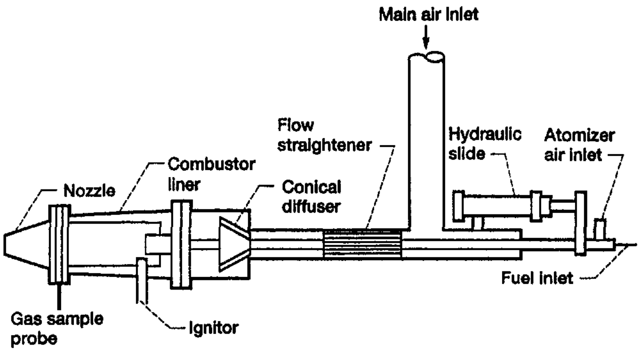

Fig. 2 Test section configuration

the gas sampling system is given elsewhere (Colantonio, 1993). This report also contains a full description of the methods employed in sampling and measuring NO_x, CO, CO_2 and unburned hydrocarbons. Essentially a single-point, water-cooled traversing probe was used to sample emissions on one radial axis of the combustor exit. A 4.76-mm-dia Iconel gas sampling collection tube was located 102 mm downstream of the combustor exit. Gas flows through an electrically heated sampling line maintained at 505 K up to the gas analyzers. The combustion exhaust gases exit the test section into a fixed-geometry converging nozzle, which governs back pressure at a given flow condition. The exhaust gases are then expelled to the atmosphere.

The effervescent atomizer used in this research program is shown in Fig. 1. Its geometry and flow characteristics are based on work done by Whitlow (1990). For the atomizer air–fuel ratio of 0.2 (by mass) used for this testing the Sauter mean diameter and drop size distribution parameter were experimentally determined to be 20 μm and 1.8, respectively. The atomizer consists of two concentric tubes, 25.4 mm and 12.7 mm in diameter. The inner tube supplies effervescent air to the annular gap region where fuel is flowing. Thirteen sets of 0.79-mm-dia holes, spaced 3.18 mm apart in the inner tube, are used to inject air bubbles into the fuel. The pintle gap width is 0.51 mm and produces a spray having an included angle of 90 deg. No variations in atomizer characteristics other than fuel and atomizer air flow rates were performed in this test program.

Computational

An advanced CFD package (CFD Research Corporation, 1990), REFLEQS (Reactive Flow Equation Solver), was used to model the primary combustion zone of the JSL combustor and incorporated the effects of liner cooling air. REFLEQS solves the full three-dimensional Navier–Stokes equations for fluid flow in a generalized coordinate system. For reactive flows, additional energy and species concentration equation are solved. The main features used in REFLEQS are the one-step instantaneous burning of propane (C_3H_8), a standard $k-\epsilon$ turbulence model, upwind differencing scheme, standard JANNAF thermodynamic properties and stoichiometric relations and a simple Zeldovich reaction scheme for calculating NO_x emissions. REFLEQS is a well-documented program and has been validated by many users. Over 30 validation cases have been performed and good-to-excellent agreement between benchmark data and predictions has been shown (Ratcliff and Smith, 1989; Smith et al., 1988).

Boundary conditions selected for REFLEQS are based on reviews of previous combustor modeling and testing and on data obtained from preliminary JSL combustor testing. A full description of the boundary conditions used can be found from Colantonio (1993). Although liquid Jet-A fuel was used in the experimental program, the chemical complexity of Jet-A combined with the unavailability of a fuel droplet vaporization and burning model in REFLEQS confined the present CFD work to a gaseous fuel, namely propane. Due to the incorporation of an effervescent atomizer and a premixing duct, the assumption of complete fuel vaporization was considered valid for a parametric study of the JSL combustor configuration. Combustor wall temperature boundaries were estimated from thermal indicating paint applied to the outside of the combustor and also from empirical relations for film-cooling combustor liners.

The NO_x model assumes NO_x reaction does not contribute to the overall heat release in the combustor and NO_x concentration itself is small compared to those of other species. Also, prompt NO is ignored in the model. This assumption allows NO_x reactions to be decoupled from the heat release reactions. NO_x is calculated as a passive scalar after the computation of the reacting flow field.

A simple Zeldovich reaction scheme was used to model NO_x formation. According to the mechanism, NO can be expressed by:

$$N_2 + O \rightarrow NO + N$$

$$O_2 + N \rightarrow NO + O$$

The first reaction is much slower than the second one and hence controls the rate of NO formation. If the concentration of NO is much smaller than the corresponding equilibrium value, the rate equation for NO can be written as:

$$\partial(NO)/\partial t = K(N_2)(O)$$

The rate coefficient, K, has been experimentally determined to be an exponential function of temperature. Approximating the concentrations of N_2 and O by the local equilibrium values, the rate equation is given by

$$\partial(NO)/\partial t = A\exp(-E/RT)(N_2)(O_2)^{1/2}$$

where A is an experimentally determined constant, E is the activation energy in joules per mole, R is the universal gas constant, and T is the gas temperature in degrees Kelvin. Due to the one-step instantaneous chemical kinetics model, REFLEQS does not take into account combustion inefficiency and chemical dissociation, both of which will lower the actual adiabatic flame temperature within the combustor and hence, over-estimate the NO_x emissions. Therefore, the NO_x model in REFLEQS was calibrated against experimental data shown in Fig. 3 over a wide range of fuel–air ratios by adjusting the A and E/R terms. Even with these simplifying assumptions REFLEQS provides

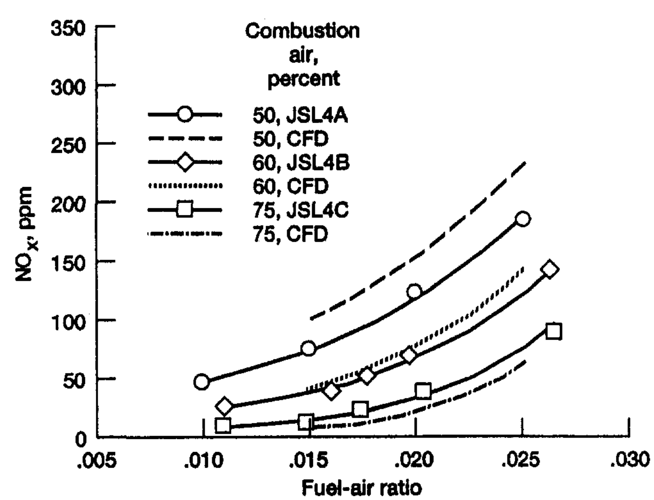

Fig. 3 Effects of fuel–air ratio and combustion air quantity on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

an unique means to optimize combustor parameters for low NO_x and substantiates the experimental results.

Results

In order to simulate an Allison T-56 combustor at cruise conditions the inlet combustor pressure, P_A, and inlet temperature, T_A, for both the experimental testing and computational analysis were 0.480 MPa and 551 K, respectively. The fuel–air ratios ranged from 0.012 to 0.025 for experimental testing and from 0.015 to 0.025 for CFD analysis. The nominal air flow rate was 0.70 kg/s. The nominal air flow rate for a T-56 combustor at cruise condition is 1.17 kg/s. However, this higher flow rate includes additional liner cooling, dilution, and secondary air not used in the present JSL combustor. Also, the air flow rate at a given inlet pressure is controlled by the fixed converging nozzle downstream of the combustor exit. The nominal air/fuel ratio (by mass) of the effervescent atomizer was 0.20. The premixing length was kept constant at 76.2 mm. In all experimental testing Jet-A fuel was used.

Each of the air flows within the JSL combustor is governed by pressure differential across the air slots. Therefore, a decrease in liner cooling air necessarily results in increases in the axial, radial, and hub cooling air flows. It is assumed that all the axial, radial, and hub cooling air flows participate in combustion, with negligible liner cooling air interaction. As combustion air is increased (by blocking liner cooling slots) for a fixed fuel–air ratio, the primary combustion zone burns leaner, resulting in lower predicted NO_x emissions (Fig. 3). Also, with higher combustion air come higher air slot velocities, which could increase the degree of fuel–air mixing from the greater momentum transfer between impinging jets. Combustor efficiency suffers slightly from increasing the combustion air (Fig. 4), which is attributed to higher unburned hydrocarbons emanating from a cooler combustion zone.

It has been determined through CFD analysis that the radial location of the axial air slots has a direct effect on NO_x emissions. This was also shown in the work of Abdul-Hussain et al. (1988a, b). The axial slot position was varied from radially inward, toward the central premixing duct, to radially outward, toward the combustor liner wall. The maximum and minimum radial positions in the CFD analysis were limited due to the axial slot thickness and the position of the hub cooling holes. Therefore, the radial position of an axial slot, having an aspect ratio, AR, of 2.49, was varied from an r/R of 0.58 to 0.88 where r is the radial location within the combustor of radius R.

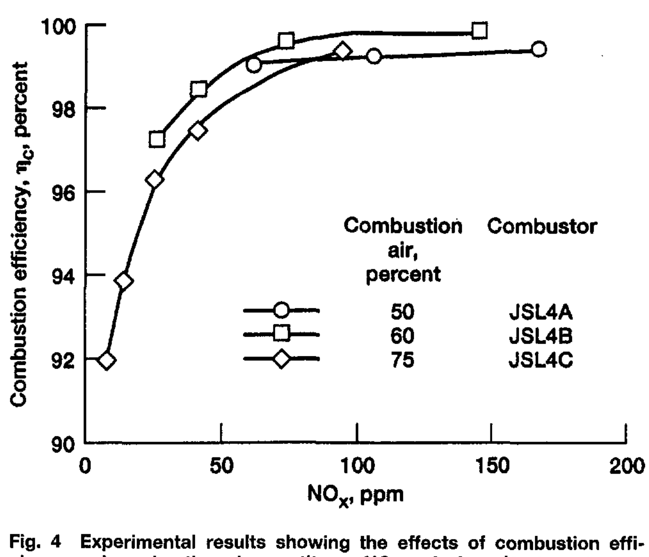

Fig. 4 Experimental results showing the effects of combustion efficiency and combustion air quantity on NO_x emissions (fuel-to-air ratio is varying); T_A = 551 K; P_A = 0.48 MPa

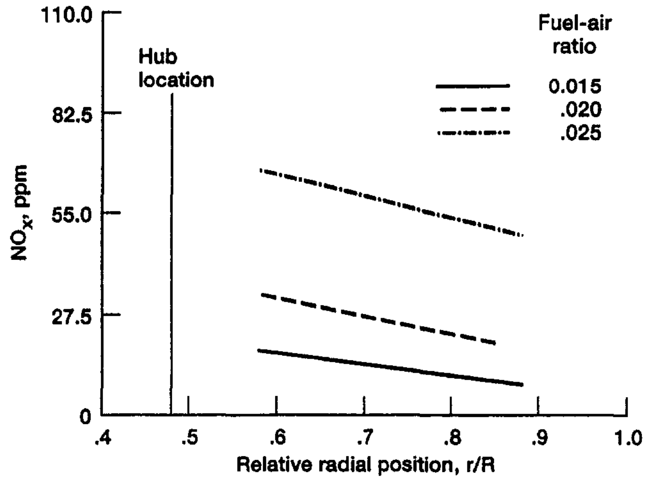

Fig. 5 CFD predictions of the effects of axial slot radial position and fuel–air ratio on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

The AR is defined as the slot arc length divided by the slot width. The arc length is calculated from the slot's circumferential centerline as indicated in Table 2.

A fuel-rich radial jet intercepting an axial air jet produces a nominally fuel-lean jet downstream of the interception region. However, jet expansion into the combustor volume is critical for thoroughly mixing all the fuel with the axial air. The gaps between the adjacent axial jets increases with a more outward axial slot. As this gap decreases with a more inward axial slot, the jets are confined to expand and mix in the circumferential direction. As the axial slot is moved radially outward, the axial jet is less confined and can expand freely into the combustor volume in both the circumferential and radial directions. Figure 5 shows the CFD predictions of the effect of axial slot radial position on NO_x emissions for a four-slotted JSL combustor using 75 percent combustion air. Lower NO_x is produced with axial slots closer to the liner wall as compared to the central hub.

The AR was varied from 0.61 to 5.22 while maintaining the axial slot area constant. The outer radius of the axial slots was held at an r/R of 0.82. Figure 6 shows the CFD predictions of NO_x emissions as axial slot AR is varied for a four-slotted JSL combustor with 75 percent combustion air. The lowest NO_x is produced with an AR close to unity. This suggests that round axial holes might be superior to rectangular axial slots. Any change in AR away from unity increases NO_x. From CFD-

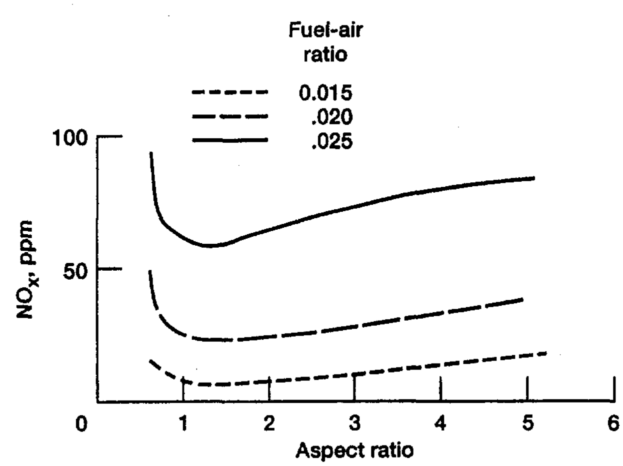

Fig. 6 CFD predictions of the effects of axial slot aspect ratio and fuel–air ratio on NO_x emissions; T_A, = 551 K; P_A = 0.48 MPa

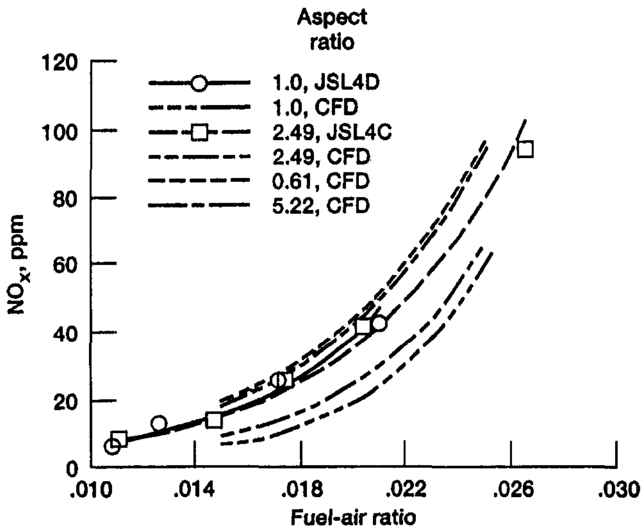

Fig. 7 Effects of fuel–air ratio and axial slot aspect ratio on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

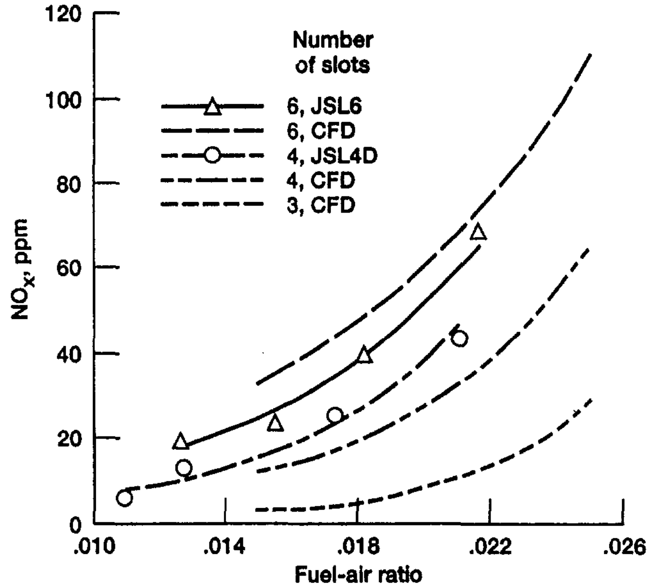

Fig. 9 Effects of fuel–air ratio and number of in-line jets on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

generated temperature profiles within the combustor (Colantonio, 1993) a circumferentially thin axial jet appears to act like a wedge for the incoming fuel-rich radial jets, preventing the radial jet from breaking up the axial jet adequately. Instead, the radial jet only partially breaks up the bottom portion of the axial jet, with high-temperature combustion occurring at the sides of the axial jet. A higher AR restricts the axial jet from expanding and mixing circumferentially into the combustor volume. Figures 7 and 8 show the experimental results obtained for a four-slotted JSL combustors having ARs of 1.0 and 2.4, respectively. The higher AR yielded a slightly lower NO_x. However, the combustion efficiency for an AR of 1.0 is greater than that for an AR of 2.4.

The axial and radial jet pairs were varied from 3 to 6. In each case the axial and radial slot areas remained constant. Also, the AR of the axial slot was kept constant at 1.00. The gap between adjacent axial jets decreases with an increase in number of in-line jets. As this gap becomes narrower, the axial jets cannot expand and mix adequately into the combustor volume without interfering with adjacent jets. Figure 9 shows the CFD predictions of number of in-line jets on NO_x emissions. Lower NO_x was produced with fewer in-line jets. Figures 9 and 10 show the experimental results obtained from JSL combustors having four and six pairs of in-line jets, respectively. The four-slotted combustor produced lower NO_x emissions with higher combustion efficiency as compared to the six-slotted combustor. These results verify the CFD trends in varying the number of in-line jets.

It has also been determined from experimental and CFD results that the radial jet hole diameter has a direct effect on NO_x emissions. The radial hole size was varied from 9.93 to 17.46 mm. Increases in premixing air lower NO_x emissions. However, an increase in radial hole size does not, in all cases, decrease NO_x emissions. The flow through all the air ports in the combustor is governed by pressure differential, hole area, and discharge coefficients. The annular gap cross-sectional area between the effervescent atomizer and the inner wall of the premixing duct is fixed (Fig. 1). If the total radial jet hole area is greater than the total annular gap area, then the air flow through the premixing tube will be controlled by the annular gap region. As the hole diameter is continually increased, a critical radial hole diameter is reached where further increases in hole diameter cannot increase the premixing flow rate. At this point, the flow rate will be metered by the annular gap region and the radial jet velocity is reduced.

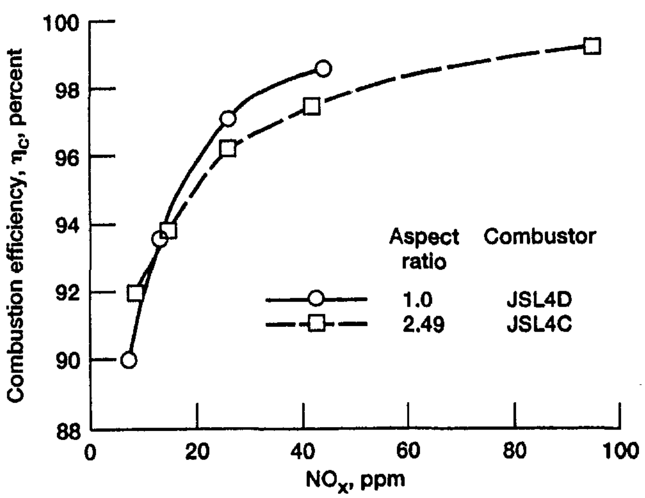

Fig. 8 Experimental results showing the effects of combustion efficiency and axial slot aspect ratio on NO_x emissions (fuel-to-air ratio is varying); T_A = 551 K; P_A = 0.48 MPa

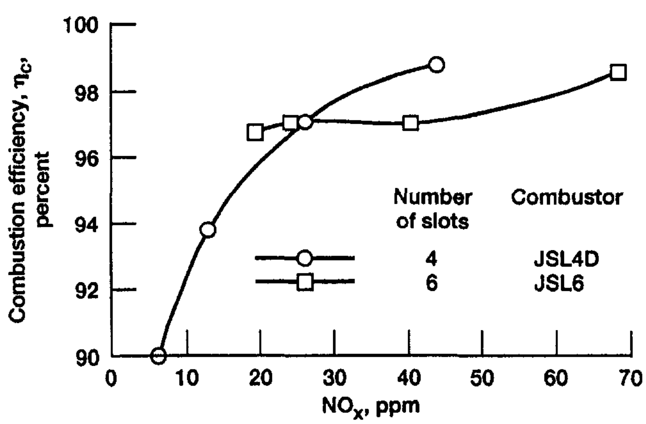

Fig. 10 Experimental results showing the effects of combustion efficiency and number of in-line jets on NO_x emissions (fuel-to-air ratio is varying); T_A = 551 K; P_A = 0.48 MPa

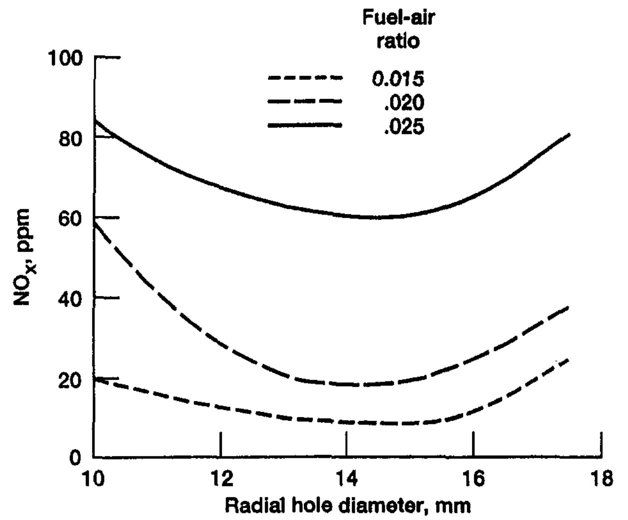

Fig. 11 CFD predictions of the effects of radial hole diameter and fuel-air ratio on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

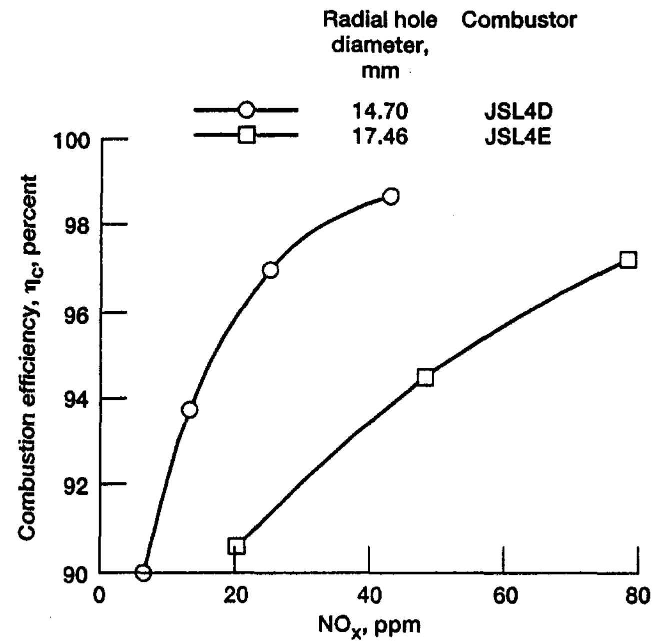

Fig. 13 Experimental results showing the effects of combustion efficiency and radial hole diameter on NO_x emissions (fuel-to-air ratio is varying); T_A = 551 K; P_A = 0.48 MPa

Figure 11 shows the CFD predictions of radial hole diameter on NO_x. The lowest NO_x was produced with a radial hole diameter around 15 mm and increases for smaller and larger diameter holes. For small-diameter holes, higher NO_x is caused by low premixing air flow. For large diameter holes, higher NO_x is caused by the low velocity radial jets not mixing adequately with the axial jet air.

Figures 12 and 13 show the experimental results obtained for the JSL combustor having an axial slot AR of unity. Experimental results verify the NO_x trends of the CFD results, but the quantitative agreement of the NO_x prediction was poor. The large holes produce high NO_x emissions and low combustion efficiency. From this parametric study it appears that the radial hole diameter is critical for a given premixing duct size. No attempt was made to optimize the effervescent atomizer. A smaller diameter atomizer should be designed to allow more premixing air and a resulting higher radial jet velocity.

Conclusions

By incorporating an effervescent atomizer in a fuel–air premixing duct and using a three-dimensional CFD code to optimize the mixing in the primary combustion zone, a low-NO_x, liquid-fueled JSL combustor was successfully developed and tested. The CFD code was used as a tool to facilitate a parametric analysis that led to optimum fuel–air mixing and low NO_x production within the combustor. From the experimental and CFD analysis it was found that the percentage of total air employed in combustion had the strongest effect on NO_x emissions. A high combustion air quantity leads to a cooler primary zone temperature. Optimum fuel–air mixing was demonstrated by varying a number of geometric features of the basic JSL configuration. It was found that a low number of in-line jets and an outboard axial air slot having an aspect ratio of near unity produced the highest degree of fuel–air mixing within the combustor. An optimum radial hole diameter was also found to provide the largest amount of fuel–air premixing with the highest radial jet velocity for a given JSL geometry. NO_x emission between the baseline combustor, JSL4A, and the optimized combustor, JSL4D, was reduced by a factor of three with the combustion efficiency increasing slightly. NO_x emissions were over three times lower for the JSL4D combustor as compared to a conventional T-56 combustor at equivalent operating conditions. Small differences in combustion efficiency were noted: For the JSL4D and T-56 combustors the efficiencies were 98 and 99 percent, respectively. Further combustor development and effervescent atomizer optimization promises even lower NO_x while maintaining high combustion efficiency, thus making it highly competitive with other low-NO_x combustor concepts.

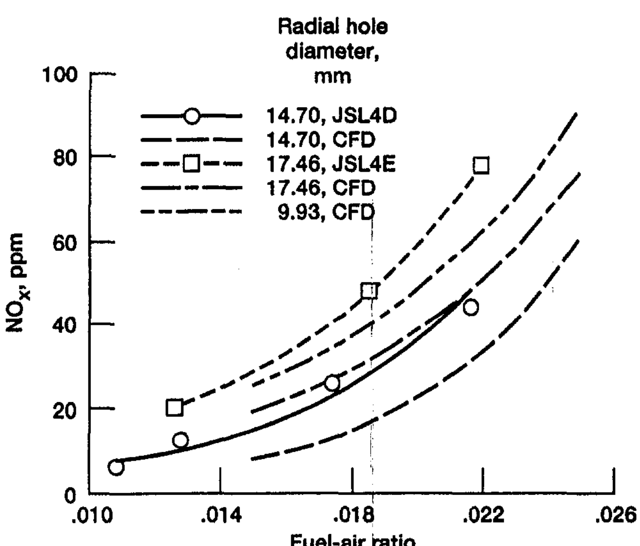

Fig. 12 Effects of fuel–air ratio and radial hole diameter on NO_x emissions; T_A = 551 K; P_A = 0.48 MPa

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