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A Liquid Fueled, Lean Burn, Gas Turbine Combustor Injector

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A need exists to develop and demonstrate a low pollutant emission gas turbine combustor design that uses liquid fuel for propulsion applications. The present work addresses this need by developing and demonstrating design guidelines for a liquid fueled, lean burn, gas turbine combustor injector. This injector is designed to accommodate all the combustion air, and includes a fuel and air mixing section with an internal venturi contour that contains an aerodynamic swirler, and an atomizer. The atomizer is a plain jet, airblast type with eight ports that spray radially into a high-velocity cross-stream of combustion air. Reacting test results show that the fuel and air are sufficiently well mixed to create a uniform distributed reaction which is (1) of finite length, and (2) free from pulsation or other combustion-induced instabilities. Emissions data at elevated pressure and temperature establish that this injector has low pollution emissions, and high combustion efficiency.

Keywords: Gas turbines; NO_x

INTRODUCTION

One of the major challenges to gas turbine engineering today is the requirement to reduce pollutant emissions, especially oxides of nitrogen (NO_x), from next-generation aeroengines (Prather *et al.*, 1992; Stolarski *et al.*, 1995). One strategy is to operate the combustor lean overall with little or no wall jet injection of primary or secondary air. While a number of lean burn, low NO_x, gas turbine combustor concepts have been demonstrated using only gaseous fuel, there is a need to develop and demonstrate a design that uses liquid aviation fuel (Tacina, 1990). Design guidelines and

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operating parameters of an injector for lean burn, liquid fueled combustors are presented here with results applicable to future automotive, stationary and aircraft gas turbine engines.

Conventional gas turbines have less than complete mixing because the fuel and air are separately introduced into the primary reaction (dome) zone. In the design presented here, the injection is accomplished such that the fuel and air are well mixed prior to reaction. Furthermore, the fuel-to-air ratio of this mixture is lean relative to conventional combustors, and all the combustion air enters through the injector. As a result, the reaction temperature is lower than that of conventional combustors. Lower reaction temperatures results, in principle, in a direct reduction of thermal oxides of nitrogen (Zeldovich, 1946).

The injector design developed in this work is designated as the Lean Burn Injector (LBI). The LBI has two main components, the injector and a mixing region dubbed the "quarl". The quarl defines the dome geometry, and utilizes a design similar to a swirl cup (Wang *et al.*, 1994) with an internal venturi contour.

The LBI design was tested at atmospheric and elevated pressure (5 atm). The goal of the atmospheric pressure testing was to develop the LBI concept into a simple, low cost, reasonably sized, and low maintenance injector with a relatively uniform reaction. The goal of the elevated pressure testing, which followed the atmospheric pressure testing, was to evaluate the emission performance of the final LBI design at inlet conditions which were representative of practical gas turbine engine applications.

Atmospheric pressure tests were utilized to develop the LBI design for four reasons, namely, (1) to provide optical access for expeditious qualitative evaluation of the reaction, (2) to allow quick hardware changes, (3) to rule out poor designs because in general, poor performance at atmospheric pressure conditions is a good indicator of similar performance at elevated pressure conditions, and (4) to reduce the development cost since atmospheric pressure testing is significantly less expensive than elevated pressure testing.

DEVELOPMENT OF THE INJECTOR

The performance of the injector can have a major impact on the performance of the combustor in terms of the emissions of oxides of nitrogen. The combustion parameters that are influenced or determined by the injector design include (1) the atomization quality, (2) the initial dispersion of the droplets, (3) the time required for vaporization, and (4) the unmixedness of the fuel and air prior to reaction.

Most gas turbine combustors have fuel injectors that utilize an axial spray direction. This method of fuel injection results in a partially mixed (fuel and air) reaction zone. This unmixedness can result in significant levels of NO_x emissions (Fric, 1992; Gupta, 1992). In this work, the LBI injector design departs from conventional design by changing the primary injection direction of the fuel from axial to radial with the goal of inducing enhanced mixing of the fuel and air prior to reaction. The design uses eight radial injection points for improved spatial mixing.

A number of radial injected, lean burn combustors have been designed and demonstrated using gaseous fuels (Alkabie and Andrews, 1990; Alkabie, Andrews and Ahmad, 1988; Matsuzaki *et al.*, 1992; Smith, 1992). It is important to note, however, that the design developed in this work utilizes *liquid*, aviation gas turbine fuel (Jet A). The development of a liquid fueled combustor is more challenging than a gaseous fueled combustor due to the additional steps associated with atomization and vaporization.

The LBI incorporates a plain jet, airblast injector. An airblast injector was selected for a number of reasons including (1) simplicity of manufacture, (2) durability, (3) knowledge regarding atomization performance, and (4) suitability for gas turbine engine application (Lefebvre, 1989).

The LBI injector is primarily constructed using three tubes, with a tube in tube configuration as illustrated in Figure 1. The outside tube diameter of the injector in 25.4 mm. The middle tube has a diameter of 12.7 mm and the inner tube is 6.35 mm in diameter. Fuel flows in the middle tube, and air flows in the inside and outside tubes. The fuel exits the middle tube through eight holes. Between this middle tube and the outside tube, the air and fuel interact. As the atomization air exits the eight air holes in the outer tube it accelerates, creating a shear force between the air, and the liquid jet. In addition to contributing to the total atomization air, the airflow exiting the inner tube provides cooling to the nose of the injector. The nozzle air and fuel hole diameters are 2.235 mm, and 0.343 mm respectively.

DEVELOPMENT OF THE QUARL GEOMETRY

The quarl assembly includes the swirler, and an internal venturi contour as illustrated in Figure 2. The contracting volume between the swirler and the throat of the venturi acts as a fuel and air-mixing zone.

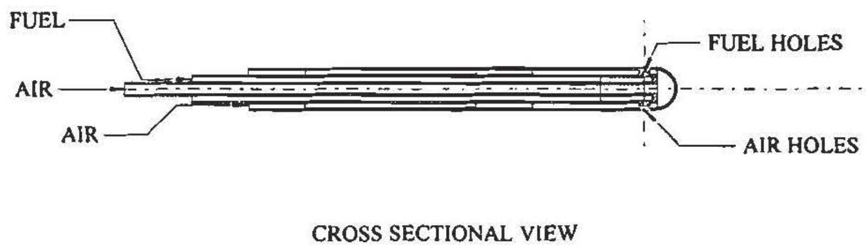

FIGURE 1 LBI injector design.

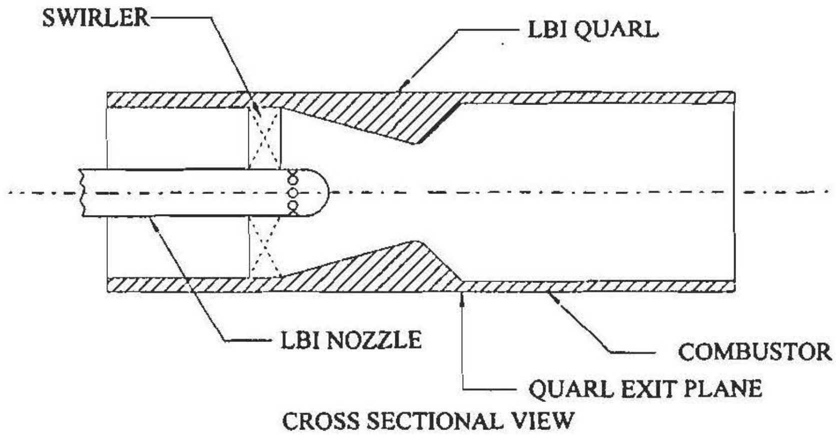

FIGURE 2 LBI dome configuration.

In the LBI design, all of the combustion air is sent through the swirler. This feature, in addition to producing a lean primary zone, eliminates the need to inject additional air downstream to complete the reaction. The overall length and total weight, therefore, of this design can be significantly less than a conventional combustor.

A conventional dome geometry, without the venturi, was tested using the LBI injector design. In this configuration, the reaction extended upstream to the LBI injector. This is undesirable due to the heat loading on the injector and the residual unmixedness in the fuel/air charge. Test results with this conventional dome geometry revealed high pollutant emissions, and poor stability. The venturi, therefore, is required to (1) prevent hot products from extending to the injector, and igniting the fuel at the injector, and (2) provide a region for mixing prior to reaction.

In the present application, the quarl outside diameter is 80.0 mm, and the quarl length is 57.15 mm. The throat diameter, and other dimensional information are given in Table I. The quarl configurations for the atmospheric and elevated pressure testing were slightly different due to the significantly different flow conditions, which are illustrated in Table II.

TABLE I LBI quarl dimensions

Test pressure (atm)	*Quarl length (mm)*	*Quarl throat diameter (mm)*	*Quarl inlet diameter (mm)*	*Quarl contraction angle*	*Quarl expansion angle*
1	57.15	38.10	63.50	18.4°	45°
5	57.15	44.45	76.20	21.0°	45°

TABLE II Test configuration and conditions

Parameter	*Atmospheric pressure test value*	*Elevated pressure test value*
Fuel type	Jet A (liquid)	Jet A (liquid)
Injector type	UCI LBI 8 jet, air-blast nozzle with venturi quarl	UCI LBI 8 jet, air-blast nozzle with venturi quarl
Combustor inside diameter	76 mm	74 mm
Combustor material	Tubular quartz	Hastalloy-X, lined with refractory
Pressure	1 atm	5 atm
Inlet air temperature	444 K	700 K
Fuel mass flow rate	2.6–3.9 kg/hr	17.9–29.1 kg/hr
Total air mass flow rate	76 kg/hr	653 kg/hr
Reference velcoity	5.5 m/s	17.0 m/s
Combustor air pressure loss	5.3%	4.8%

QUARL RESIDENCE TIME, AUTOIGNITION, AND FLASHBACK

The residence time of the fuel droplets inside the quarl is an important parameter since it determines the amount of droplet evaporation prior to reaction. (The quarl residence time is herein defined as the time for a fuel droplet to travel along an axial path from the exit port of the atomizer to the throat of the venturi). In the elevated pressure reacting experiment the quarl residence time was approximately 0.7 msec.

Since the LBI quarl has a fuel and air mixing section, autoignition is a concern. Autoignition will occur if the residence time of the flammable mixture is greater than the autoignition delay time. The autoignition delay time for the elevated pressure reacting test conditions utilized in this work, as determined from Lefebvre, Freeman and Cowell (1986) for Jet A/air mixtures, is on the order of 10 to 100 msec. Consequently, since the quarl residence time was 0.7 msec, autoignition was neither expected, nor encountered in the reacting tests conducted for this reserach. (Autoignition was neither expected nor encountered in the atmospheric pressure tests. Further, at very high pressures, such as 30 to 40 atm, the autoignition delay times would be approximately an order of magnitude lower. The quarl residence time, however, would still be less than the autoignition delay time).

Flashback is also a major concern in any design that mixes the fuel and air prior to reaction. A LBI design feature that acts to resist flashback is the venturi itself. During both the atmospheric and elevated pressure testing, flashback was not observed.

ATMOSPHERIC PRESSURE TEST FACILITY

Air is supplied to the atmospheric test facility by three compressors which provide a maximum air pressure 1.14 MPa, and a total air mass flow rate of 2.05 kg/s. The air from these compressors is first dried, and then filtered prior to entering the test cell. This research utilized two airflow circuits, one for swirl air, and one for injector air. Both of these flows were individually metered using a sonic venturi orifice. The swirl air was heated using a 15 kW electrical heater. Jet A fuel was supplied from a pressurized stainless steel tank. The fuel flow rate was controlled by varying the tank pressure using a pressure regulator, and metered using a rotameter.

ELEVATED PRESSURE TEST FACILITY

The elevated pressure test facility primarily consists of three low-pressure compressors, one high-pressure (booster) compressor, three electric air circulation heaters, a fuel delivery system, a pressure vessel, and an exhaust system.

The low-pressure compressors are the same as those for the atmospheric pressure test facility. The high-pressure compressor boosts the low-pressure air to a maximum air pressure of 3.55 MPa, at a maximum air mass flow rate of 0.68 kg/s. Airflow control is provided by electropneumatic control valves, which regulate the air pressure upstream of sonic venturi nozzles which meter the air flow rate.

The air is electrically preheated prior to the pressure vessel by three electrical heaters, connected in series, which have power ratings of 250 kW, 157 kW, and 67 kW. These heaters can preheat the air up to 923 K. They are equipped with closed loop temperature controllers, which provide stable outlet temperatures over a wide range of operating conditions.

The fuel system consists of high-pressure fuel pump capable of producing pressures up to 10.4 MPa. The fuel system also includes a dampener, a fine filter, and a turbine meter coupled with a control solenoid valve to measure, and control the fuel flow rate.

The pressure vessel, which houses the injector and combustor, is constructed of 40.6 cm diameter, 12.7 mm thick, 1-1/4% Chrome–Moly steel. The vessel body is cylindrical with a top blind flange of which the nozzle feed tubes passes through. The bottom of the vessel is connected to a stainless steel tee that connects to the exhaust system. The vessel shell is rated for a maximum operating pressure of 18 atm at a temperature of 755 K. The inside of the vessel is insulated to accommodate temperatures exceeding 923 K. The plenum is oriented such that the combustor is downfired. In these tests, the swirl air was plenum fed, and the nozzle air was provided by a separately controlled, and metered circuit. Drennan, Sowa and Samuelsen (1990) provide a more detailed description of this vessel.

ATMOSPHERIC PRESSURE TEST DIAGNOSTICS

There were two primary diagnostics for the atmospheric pressure tests, namely, a highspeed video system, and a laser diffraction particle sizer. The high-speed video system was an Eastman Kodak Ektapro, which utilized a digital image processor, and an image intensified, gated camera. The video images were taken at 2000 frames per second (fps), and the camera gate was set at 15 μsec.

In order to aid in the development of the injector designs, a number of tests using a laser diffraction particle sizer (Malvern Model 2600), were conducted under non-reacting conditions to determine the global atomization quality. The receiving lens utilized in these tests had a focal length of 300 mm, which allowed for a measuring size range of 5.8 to 564 μm. Prior to each injector performance test, the alignment and performance of the Malvern were verified using a calibrated recticle. This recticle is a glass plate that has randomly position particles with 23 discrete sizes that together approximate a continuous size distribution. The recticle was manufactured and certified by Laser Electro-Optics.

ELEVATED PRESSURE TEST DIAGNOSTICS

An emission measuring system, denoted as Emission Console II (ECII), was utilized for the elevated pressure testing. The species measured were carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_x), and unburned hydrocarbons (UHC).

Two Horiba PIR-2000s gas analyzers were used, one each for CO and CO_2 measurements. These instruments were calibrated with a CO/CO_2 gas standard before each test. A zero calibration was also conducted before each test using nitrogen. A Beckman Model 755 analyzer was used for the O_2 measurements. This instrument was calibrated before each test with a certified O_2 span gas. Nitrogen was used to zero this instrument. A Horiba Model Mexa-1120TFI-F hydrogen flame ionization detector (FID) was used for the analysis of total unburned hydrocarbons. This instrument was calibrated before each test using a propane gas standard. Nitrogen was used to zero this instrument. The instrument used for the NO_x measurements was a Thermo-Electric Model 10. This instrument is capable of measuring both NO_x and NO. This instrument was calibrated before each test using a NO gas standard.

The sampling probe utilized to draw the gas sample from the combustor was water cooled to prevent the probe from overheating. This water cooling also helped quench the reaction, thus freezing the process such that the measured gas sample was representative of the emissions at the sampling point. The sampling probe was made from 316 stainless steel, and had a 12.7 mm outside diameter. The sampling line between the probe, and ECII was Teflon.

ATMOSPHERIC PRESSURE TEST RESULTS

The atomspheric pressure tests were observed using a quartz combustor. Visual observations were assisted by the Ektapro high speed video system. The atmospheric pressure test configuration, and conditions are summarized in Table II.

Initial reacting tests were conducted using a conventional quarl without a venturi along with the LBI injector. Ektapro video images from these tests clearly illustrated that the reaction started directly at the injector exit, and that it was not steady with time. This resulted in eight distinct reaction zones, which corresponded to the eight ports of the LBI injector. Representative images from the conventional quarl test Ektapro videos are illustrated in Figure 3.

With the LBI quarl installed, high-speed video images revealed that the reaction was located downstream of the quarl venturi throat. A thermocouple inside the quarl confirmed the absence of reaction inside the quarl, upstream of the throat. The reaction appeared well mixed, with a remarkably uniform blue emission that was steady in both space and time.

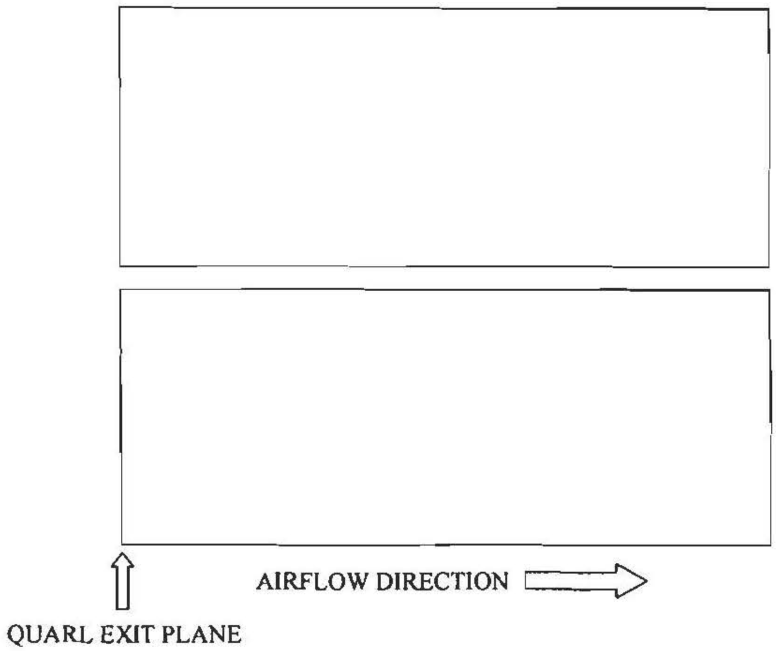

FIGURE 3 High speed video images of a conventional dome configuration.

The reaction had a finite length of approximately one combustor diameter. Representative images from the LBI quarl test Ektapro videos are illustrated in Figure 4.

Lean blow out (LBO) occurred at equivalence ratios that ranged from 0.40 to 0.45. LBO events were consistently preceded by a fire whirl, a condition where the reaction is confined to the core of vortex, and extends to, and out of the combustor exit (Gupta, Lilley and Syred, 1984).

In addition to the reacting tests, the LBI injector atomization performance was tested. The primary objective of this test was to determine the relative performance of different injector designs. The secondary objective was to determine the probable impact of the injector atomization performance on the combustor operation.

Since the laser diffraction measurement was along the laser beam path, numerous points were simultaneously measured in the droplet field. As a result, the injector evaluation experiments took size measurements at only two laser beam locations in the droplet field. These locations are designated as Side A and Side B, and were on opposite sides of the injector. For each location the laser beam passed through the center of the droplet field of one of the eight individual injector jets, at a measurement plane located approximately 25.4 mm from the injector exit plane. These measurement

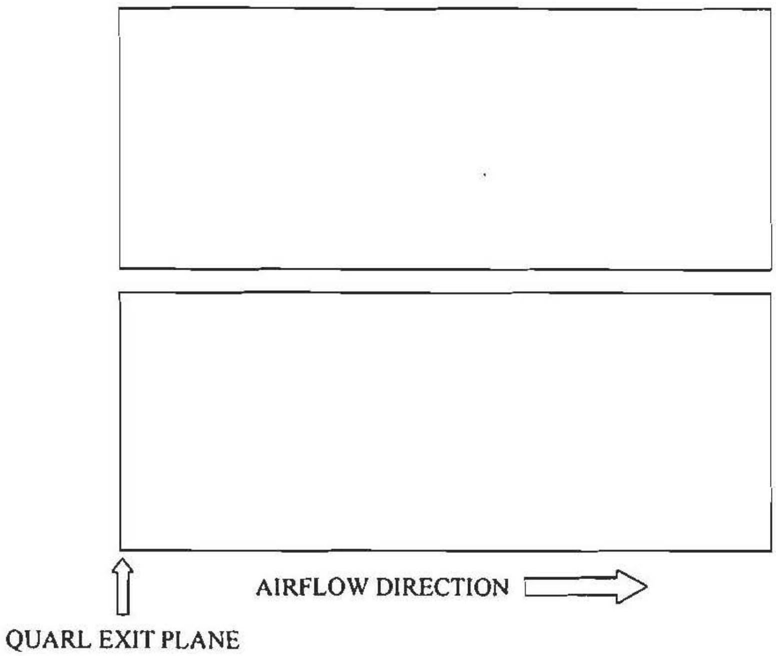

FIGURE 4 High speed video images of the LBI dome configuration.

locations were selected based on engineering judgment and geometrical considerations. Two major concerns in these tests were (1) to insure a reasonable alignment of the laser diffraction instrument, and (2) to protect the instrument from being soaked with liquid.

While the combustion tests in this work utilized Jet A fuel, the use of Jet A for the atomization tests presented safety issues with respect to both the removal of vapor and the containment of the liquid. Consequently, water was utilized as the test fluid for the atomization tests.

For plain jet, airblast atomizers, Rizkalla and Lefebvre (1975) have conducted extensive studies of the influence of fluid properties on the atomization quality. These results show that, for this type of injector, the important liquid properties are surface tension, and viscosity. They report that increases in surface tension or viscosity result in a decrease in atomizer performance (larger droplets). Lorenzetto and Lefebvre (1977) also clearly showed that for plain jet, airblast injectors, kerosene has much better atomization performance (smaller droplets) than water. This is primarily because kerosene has a significantly lower surface tension than water. Therefore, since Jet A has properties that are very similar to kerosene, the choice of using water in the atomization tests conducted in this work was conservative.

The atomization performance of different injector designs currently cannot be determined from first principles because the physical processes of atomization are complex and not well understood. Lorenzetto and Lefebvre (1977) however, have empirically developed an expression to predict the Sauter mean diameter (SMD) of plain jet, air-blast injectors. Their expression plain jet, air-blast expression is as follows:

$$\mathrm{SMD} = 0.95 \cdot \left[\frac{(\sigma_{\mathrm{fuel}} \cdot \dot{m}_{\mathrm{fuel}})^{0.33}}{(V_{\mathrm{r}} \cdot \rho_{\mathrm{fuel}}^{0.37} \cdot \rho_{\mathrm{air}}^{0.30})}\right] \cdot \left[1 + \frac{1}{ALR}\right]^{1.7} + 0.13 \cdot \left[\mu_{\mathrm{fuel}}^{2} \cdot \frac{d_{\mathrm{fuel}}}{\sigma_{\mathrm{fuel}} \cdot \rho_{\mathrm{fuel}}}\right] \cdot \left[1 + \frac{1}{ALR}\right]^{1.7}.$$

In this expression d_{fuel} is the fuel hole diameter, $\dot{m}_{\mathrm{fuel}}$ is the fuel mass flow rate, V_{r} is the relative velocity between air and fuel, ρ_{fuel} is the fuel density, σ_{fuel} is the fuel surface tension, and μ_{fuel} is the fuel viscosity. This expression was selected to model the LBI injector because (1) it is applicable to plain jet, air-blast injectors, and (2) Lorenzetto and Lefebvre (1977) empirically developed it using kerosene.

Using this expression, the atomization performance of the LBI injector can be estimated. Table III illustrates results using this expression for the LBI injector, and clearly shows that the relative velocity between the air and the liquid is almost the same as the air velocity since the liquid velocity is very low. This demonstrates that the size of the air holes is the most important design parameter for plain jet, airblast injectors. It also shows that for a given air velocity, the liquid mass flow should not greatly affect the atomization performance. This is due to the fact a very large change in liquid mass flow rate would be required to have a significant effect on the relative velocity and therefore the droplet diameter.

Table III also illustrates both experimental, and calculated droplet diameters (SMD) for the LBI. These data show that there is good agreement

TABLE III Estimated and measured performance for the LBI injector

Air to liquid ratio (ALR)	*Liquid velocity (m/sec)*	*Air velocity (m/sec)*	*Relative velocity (m/sec)*	*Predicted SMD(μm)*	*Measured (Side A) SMD(μm)*	*Measured (Side B) SMD(μm)*
3.10	1.99	118.5	116.5	22.5	16.9	21.8
4.02	1.99	153.3	151.3	15.9	11.4	13.5
4.93	1.99	188.1	186.1	12.2	9.3	9.9
5.84	1.99	222.9	220.9	9.8	8.4	8.2
6.75	1.99	257.7	255.8	8.3	7.4	7.2

(within a few μm) between the experimental, and calculated atomization performance. This demonstrates that the performance of the LBI injector design can be reasonably predicted using the Lorenzetto and Lefebvre expression for plain jet, airblast injector.

Tests on the LBI injector were also conducted using variable fuel hole sizes. The results showed that the size of the fuel hole had no significant effect on the atomization performance. This conclusion is in agreement with data presented by Lorenzetto and Lefebvre (1977) where, for liquids of low viscosity such as water and kerosene, the fuel hole size has virtually no effect on the drop size. This is because the atomization process is caused by the shear forces between the air and the liquid. These shear forces are a function of the relative velocity between the air and the liquid. Since the velocity of the liquid is generally very small compared to the air velocity, the relative velocity is essentially the same as the air velocity. Therefore, changes in the fuel hole diameter effects only the liquid velocity, which has almost no effect on the relative velocity between the air and the liquid.

A series of tests were also conducted on the LBI injector with various air hole diameters. Laser diffraction results from these tests indicate that smaller air holes have much better atomization performance than larger air holes (given a constant air mass flow rate). This is expected since the size of the air hole affects the air velocity. This result agrees with work done by Rizk and Lefebvre (1983) which showed that for airblast injectors, the SMD is proportional to the square root of the diameter of the air hole.

ELEVATED PRESSURE TEST RESULTS

The elevated pressure reacting test was conducted by holding the total air mass flow rate constant. Equivalence ratios were varied over a range of 0.45 to 0.70 by changing the fuel mass flow rate. This test procedure allowed for a constant combustor air pressure drop (4.8%), and reference velocity (17.0 m/s) for all equivalence ratios tested. The plenum pressure was 5 atm, and the inlet air temperature was 700 K. The complete elevated pressure test configuration, and conditions are summarized in Table II. The estimated LBI nozzle SMD for these conditions, as determined using the Lorenzetto and Lefebvre expression for Jet A, is 20–27 μm, depending on the equivalence ratio.

The measured oxides of nitrogen for the elevated pressure test are shown in Figure 5 as a function of adiabatic flame temperature. These adiabatic flame temperatures were determined from the inlet conditions using a

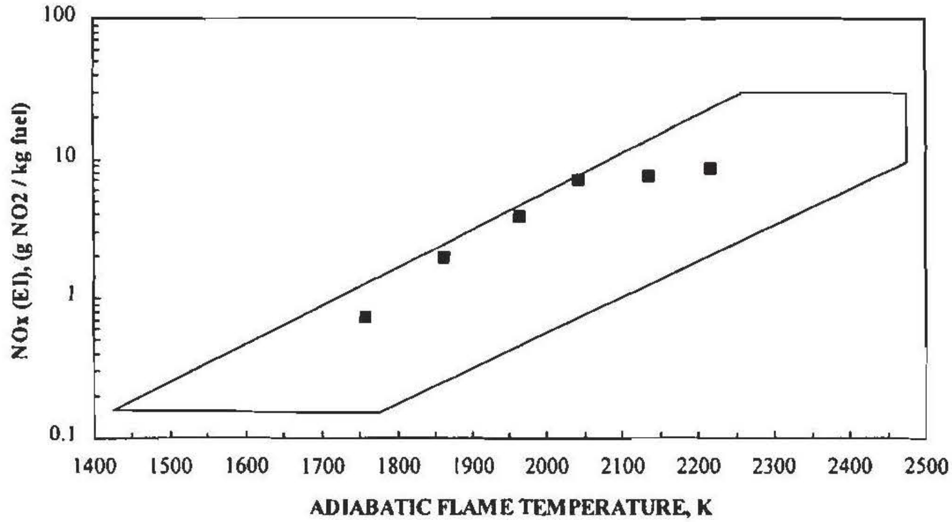

FIGURE 5 Oxides of nitrogen emission index (the box represents the LPP range, the symbols are the measured NO_x data).

NASA equilibrium code (Gordon and McBride, 1976). Included in this figure is a box that represents a range of NO_x data as reported by Tacina (1990) for various Lean Premixed Prevaporized (LPP) combustors. It is clear from Figure 5 that the LBI NO_x emission indices are all within this LPP range.

The measured oxides of nitrogen for the elevated pressure test are also shown in Figure 6, as a function of the inverse of adiabatic flame temperature. This parameter is important because thermal NO formation, as described by Zeldovich (1946), is controlled by Arrhenius kinetics, *i.e.*, a function of $\exp(-E/RT)$, where E is the activation energy, R is the universal gas constant, and T is the adiabatic flame temperature. Figure 6, therefore, indicates that the formation mechanism was thermal NO because of the strong correlation with inverse temperature.

The measured unburned hydrocarbons emission indices were very low, all being less than 0.31. The CO emissions were also very low, and illustrated the typical 'cup' shape as shown in Figure 7. This figure also clearly shows that the combustion efficiency exceeded 99.8%.

The following expression, as derived from Goodger (1977), was utilized to determine combustion efficiency:

$$\eta_c = 1 - \frac{[\dot{m}_{c/co} \cdot (\Delta H_{c/co_2} - \Delta H_{c/co})]}{\dot{m}_{fuel} \cdot CV_{fuel}}$$

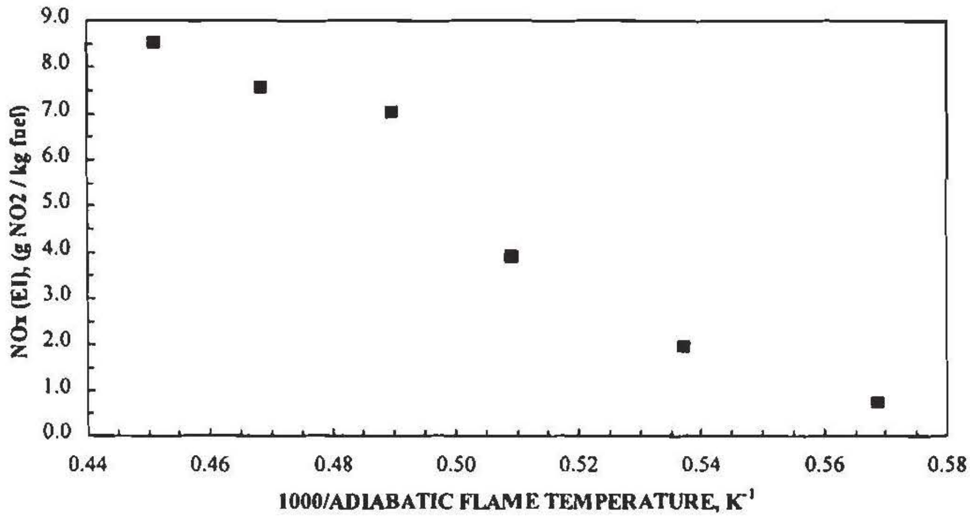

FIGURE 6 Oxides of nitrogen emission index (as a function of inverse temperature).

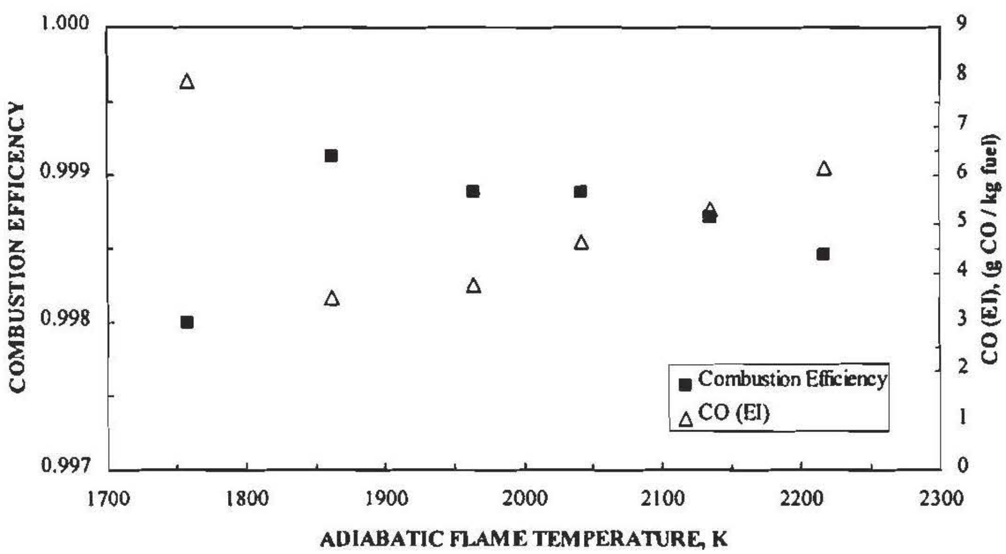

FIGURE 7 Combustion efficiency and carbon monoxide emission index.

where:

$$\dot{m}_{c/co} = \text{mass rate of C reacting to CO},$$
$$\dot{m}_{fuel} = \text{mass rate of fuel supplied},$$
$$\Delta H_{c/co_2} = \text{enthalpy of C reacting to } CO_2,$$
$$\Delta H_{c/co} = \text{enthalpy of C reacting to CO},$$
$$CV_{fuel} = \text{heating value of the fuel}.$$

These emission data were all taken at the same axial and radial locations, namely, the centerline of the combustor, at 70 mm from the LBI quarl throat (the start of the reaction). This represents an estimated residence time of 1.6 ms. A radial sampling probe traverse to evaluate emission uniformity, however, was made at this axial location, from the centerline to the combustor wall. These emission data indicated a highly uniform emission profile. All of these emission data were also shown to balance in terms of mass. These observations, along with the Ektapro images, strongly suggest that the LBI injector provides excellent fuel and air mixing.

DESIGN GUIDELINES

The following design guidelines are suggested for the design of a liquid fueled, lean burn gas turbine combustor injector as described herein:

1. A radial injection of the liquid into a high-velocity cross-stream is required to enhance the fuel and air mixing.
2. The injector should have multiple injection ports (*e.g.*, eight) to enhance spatial distribution.
3. The atomization performance should produce a Sauter mean diameter that is as small as possible, preferably less than approximately 30 µm. Smaller droplets reduce the time required for vaporization, which helps to prevent wall wetting and improves mixing.
4. The quarl design must include an internal venturi contour. The area of the venturi throat should be selected based upon the maximum acceptable pressure loss. The length of the quarl should be selected such that the residence time is sufficient to provide vaporization and mixing, but not greater than the autoignition delay time. (The residence and autoignition delay times are determined from the inlet conditions. Further, the extent of vaporization can be evaluated experimentally by observing the quarl throat and expansion surfaces for visible liquid fuel).
5. A strong swirl component is required to improve fuel and air mixing, and establish a zone of recirculation downstream of the quarl. The swirl strength should be appropriately selected to assure closure on the recirculation, an unusually challenging requirement in the absence of wall jet injection of primary air.
6. The inlet air must have an elevated temperature sufficient to promote vaporization of the droplets.

CONCLUSIONS

- Injector design guidelines are required for liquid fueled, lean burn gas turbine combustors.
- Guidelines have been established and demonstrated with a design that utilizes plain jet, airblast atomization injecting radially into a high-velocity combustion air cross-stream.
- In rapid mixing concepts, a finite amount of time is required for vaporization and mixing prior to reaction. In gas turbine type combustors with recirculation, a strategy is required to preclude reaction from reaching the injector. In the present example, a quarl with a venturi contour is shown to successfully meet this requirement.
- A finite delay for mixing presents an opportunity for autoignition and/or flashback. As a result, the mixer must be sized to preclude either from occurring. The present design demonstrated success in precluding both autoignition and flashback.
- The reacting test results show that the fuel and air are sufficiently well mixed to create a uniform distributed reaction which is (1) of finite length (approximately one duct diameter), and (2) free from pulsation or other combustion-induced instabilities.
- Emissions data at elevated pressure and temperature establish that the injector has low pollution emissions, and high combustion efficiency.

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