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RETROFITTABLE DRY LOW EMISSIONS COMBUSTOR FOR 501-K INDUSTRIAL GAS TURBINE ENGINES

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Abstract

This paper describes progress in the development of a 25 ppm NO_x combustor that requires no diluent injection or post-combustion treatment. The combustor will be retrofittable in all existing Allison Model 501-K series industrial engines. The approach undertaken is based on lean-premix combustion design incorporating an efficient fuel and air pre-mixing, fuel staging, and advanced wall cooling.

Extensive use has been made of Computational Combustor Dynamics (CCD) codes in the design of the low NO_x combustor. Experimental work in support of the present effort includes atmospheric bench scale testing and high pressure rig testing. The bench tests have been performed to evaluate several candidate designs, to gain better understanding of general lean pre-mixed combustor behavior, and to verify model predictions. The bench test results have indicated good fuel/air mixing performance of the lean premixing domes. The high pressure simulated engine rig tests of the dry lean pre-mixed low emissions combustors using natural gas have demonstrated NO_x levels less than 15 ppmvd (15% O_2 corrected), well below the program goals.

Introduction

Control methods are necessary today to meet the increasingly stringent emissions requirements imposed by regulatory agencies worldwide. To control emissions of oxides of nitrogen (NO_x), current practices mostly include injection of large amounts of diluents such as water or steam, and in some cases use of selective catalytic reduction (SCR). These systems have specific limitations and problems including high installation cost, high operating cost, fuel consumption penalty, and poor reliability. The emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) are also significantly increased with the use of water injection. Improved abatement methods are needed to meet the increasingly stringent emissions requirements.

Many of the current state-of-the-art gas turbine combustion liners operate under the diffusion flame mode of operation in which fuel/air mixing and combustion processes take place simultaneously. The large regions of near stoichiometric flame temperature in the primary zone of the liner are consistent with the diffusion flame design of the liner. This approach has historically worked well to control burnout of CO and UHC and optimize combustion efficiency, ignition, pattern factor, and lean blowout goals. However, the high temperature regions in the primary combustion zone are for the most part responsible for the production of high thermal NO_x which has an exponential dependency on temperature.

In recent years, several gas turbine manufacturers, including Allison, have aggressive programs to develop dry lean pre-mix (LPM) low NO_x combustors (Solt and Tuzson, 1993). In these combustors, fuel and air are pre-mixed ahead of the primary combustion zone to produce low equivalence ratios thereby limiting the primary zone temperature and the production of NO_x (equivalence ratio is defined as actual fuel/air ratio divided by the stoichiometric fuel/air ratio). Allison is currently pursuing several dry low emissions development programs with increasingly stringent goals for NO_x emissions. The 25 ppm NO_x combustor development program is the subject of this paper. The development effort has been co-funded by Gas Research Institute (GRI) and Allison. The low NO_x liner developed under this program will be retrofittable in existing Allison 501-K series industrial engines.

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The goal of the present effort is to develop a cost effective low emissions combustion system. The emissions goals at 100% rated power for natural gas fueled 501-K gas turbine engine are:

- NO_x: 25 ppmvd (15% O_2 corrected)
- CO: 50 ppmvd (15% O_2 corrected)
- UHC: 20 ppmvd (15% O_2 corrected)

Current 501-K Combustion System

The Allison Model 501-K gas turbine engine, with an output ranging from 3000 to 8000 shp, is a compact, lightweight, industrial-derivative of the T56/501 aircraft engine, which has been in production since 1954. Most of the 501-K gas turbines power electric generators for either primary or standby electric installations, and many of them power units for driving pumps and compressors used in oil and gas recovery. The combustion system of the 501-K engine consists of six can-type combustion liners located in the annulus formed by the outer and inner engine casings. Each can is held at the inlet end by a fuel nozzle centered within a fitting in the combustor dome and at the exhaust end by the transition, which engages with the turbine inlet vane assemblies. Crossover tubes interconnect the cans and provide flame transfer for starting. The six fuel nozzles are connected to a fuel manifold attached to the external surface of the engine outer case. Table 1 shows nominal specifications for the Model 501-KB5S industrial engine.

The standard 501-K combustor is a convection film-cooled, reverse-flow dome-type liner designated as low emissions (LE) II liner. Recently, Allison has introduced a new low emissions III combustion liner that reduces emissions of NO_x by 30%-40% while maintaining low emissions of CO and UHC. The liner incorporates a simple design modification in which air is selectively introduced in the high temperature regions of the combustor to quench the primary zone hot spots thereby reducing NO_x emissions.

Lean Pre-Mix Combustion Approach

There are two major challenges of the LPM operation of a combustion system. First, the combustor must be operable throughout the gas turbine engine cycle from idle to 100% power. During the turndown operation of the combustion system, flame stability must be maintained for the lowest power operation when the fuel/air ratio is lowest. Second, during the lean low temperature reaction zone operation, the cooler combustor walls introduce quenching effects on the reactions involving CO and UHC, therefore resulting in increased emissions of these species.

These two challenges can be addressed by using any one or combination of the following: 1) fuel staging and 2) hot combustor wall design, 3) engine overboard air bleed, and 4) an active variable geometry.

TABLE 1. NOMINAL MAX POWER SPECIFICATIONS FOR THE 501-KB5S INDUSTRIAL ENGINE.

Air flow	33 pps
Pressure ratio	10
Burner inlet temperature	650°F
Burner outlet temperature	2,025°F
Turbine inlet temperature	1,935°F
Speed	14,200 rpm
Engine output	5,500 shp

Fuel Staging

Fuel staging is an effective way to control the combustor stoichiometry. In a fuel staged, multiple injection concept, fuel is staged in several pre-mixing modules to selectively control combustion stoichiometry over the range of engine operation. A simple fuel staged concept utilizes a single pilot nozzle and a main lean pre-mix module. The pilot module operates in a conventional diffusion flame mode of operation and is used for engine start-up and acceleration. The engine can be operated on the pilot fuel up to a part power point beyond which transition takes place to main lean pre-mix operation. Depending on the LPM design, a small amount of pilot fuel may be left on, providing the ignition source for the main LPM stage.

Hot Combustor Wall Design

In the LPM combustion mode, while maintaining the entire combustor volume at a high degree of uniformity in regards to fuel/air and temperature distribution, quenching effects from wall cooling air and dilution air must be minimized, and the combustor inside walls must be maintained at an elevated temperature. Maintaining the high combustor wall temperature also helps improve flame stability which in turn helps improve the range of turndown operation of the combustion system. Allison has demonstrated feasibility of several advanced cooling schemes for gas turbine combustors (Nealy, et al., 1985). These include enhanced convection film cooling techniques such as etched convective channels and impingement as well as other methods such as effusion cooling and transpiration cooling. Allison recently designed, fabricated, and tested a reverse flow annular combustor using complaint metal ceramic technology (Paskin, et al., 1990). All performance goals were met or exceeded while utilizing approximately 80% less cooling air than conventional film-cooled combustors. Allison has also successfully tested the ceramic thermal barrier coated effusion-cooled low emission hot wall liners as discussed later in this paper.

Engine Overboard Air Bleed

The engine overboard bleed of air at low power operation can be effectively used to control the minimum combustor fuel/air ratio. A major penalty of its use is the loss of engine thermal efficiency during the bleed operation.

<u>Active Variable Geometry</u>

In variable geometry operation, the portion of air introduced into the pre-mixing and the primary combustion zones is adjusted with power level, thus maintaining a nearly constant fuel/air ratio throughout the engine turndown operation. Allison has demonstrated active variable geometry control in several low emissions combustion applications (Ross, et al., 1983, and Novick and Troth, 1981 and 1982). However, use of an active variable geometry system in a gas turbine can introduce mechanical complexity and potential durability problems, and, therefore, its use is not preferred.

Lean Pre-Mix Combustor Configuration Design

Allison is currently pursuing designs of several lean premix combustor configurations. Two such configurations, which have been tested under simulated engine conditions, are briefly described below.

A schematic of the LPM dome of Configuration 1 is shown in Figure 1. In this LPM design the fuel is divided into multiple, discrete locations evenly distributed across the dome air flow path into the mixing zone. Fuel is supplied from the outside of the engine to the main ring manifold. Oval shaped fuel tubes carry the fuel radially inward from the manifold. The fuel tubes are placed between each of the ten swirler vane passages just upstream of the swirler. Each fuel tube has six small holes which distribute the fuel into the air flowing into the mixing cup. The cavities in the main fuel ring manifold and the fuel tubes are designed to minimize pressure losses, and to distribute the fuel uniformly through the fuel holes. The spacing of the holes is optimized for maximum fuel/air mixing efficiency. This partly mixed fuel and air mixture then passes through a curved vane axial swirler. Further mixing is accomplished downstream of the swirler in the pre-mixing cup.

Configuration 2 is basically an extension of Configuration 1, with several refinements intended to further improve mixing. A schematic of its LPM dome is shown in Figure 2. In this design, the axial swirler is designed to have 12 airfoil-shaped hollow vanes. Fuel is distributed to the fuel jets through the hollow cores of these vanes. The number of fuel jets in this design are about twice that of Configuration 1. The airfoil shaped vanes reduce the total pressure loss through the swirler and simplify design by eliminating the need for fuel supply tubes. The airfoil design also prevents any flow separation from the vanes, thereby minimizing potential for establishing any self sustaining combustion within the premixing cup.

In both configurations, the pre-mixed fuel/air mixture exits through a throttling section formed by the centerbody and the pre-mixing cup. The purpose of the throttling section

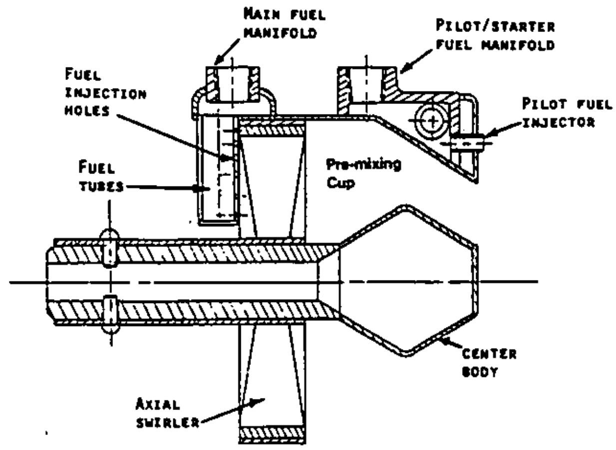

FIGURE 1. LEAN PRE-MIX DOME FOR DRY LOW NO_x CONFIGURATION 1.

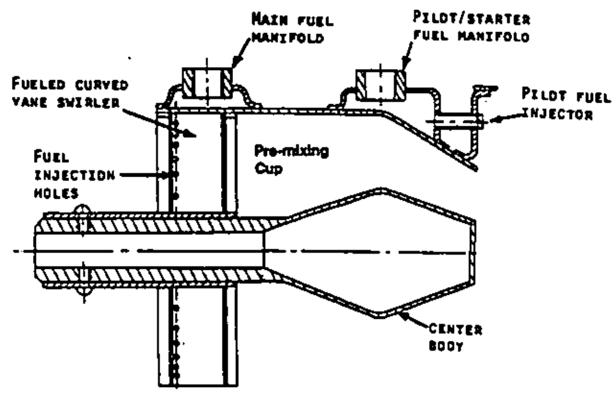

FIGURE 2. LEAN PRE-MIX DOME FOR DRY LOW NO_x CONFIGURATION 2.

is to accelerate the flow for preventing flashback into the premixing cup. The pre-mixing cup and the centerbody are designed such that there is no flow recirculation within the cup to stabilize combustion. The strong swirl introduced to the pre-mixed fuel/air flow by the axial swirler helps stabilize the flame just downstream from the LPM dome. Several small pilot fuel nozzles are located on the dome wall. The pilots are used during engine start-up and part power operation. Ignition is accomplished using a single spark igniter plug located in the ferrule near the pilot nozzles.

The LPM dome is attached to the forward end of a combustion liner. A transition section, which engages with the turbine inlet vane assemblies, is attached to the aft end of the combustion liner. The liner is nominally 5.5 inches inner diameter and 11 inches long. A photograph of the dry low NO_x combustor assembly is shown in Figure 3. The assembly shows the LPM dome, effusion-cooled combustor barrel, and the transition section.

The centerbody tip, dome wall, and liner wall are protected from the high temperatures by an efficient effusion cooling design. In this design, air passes through several

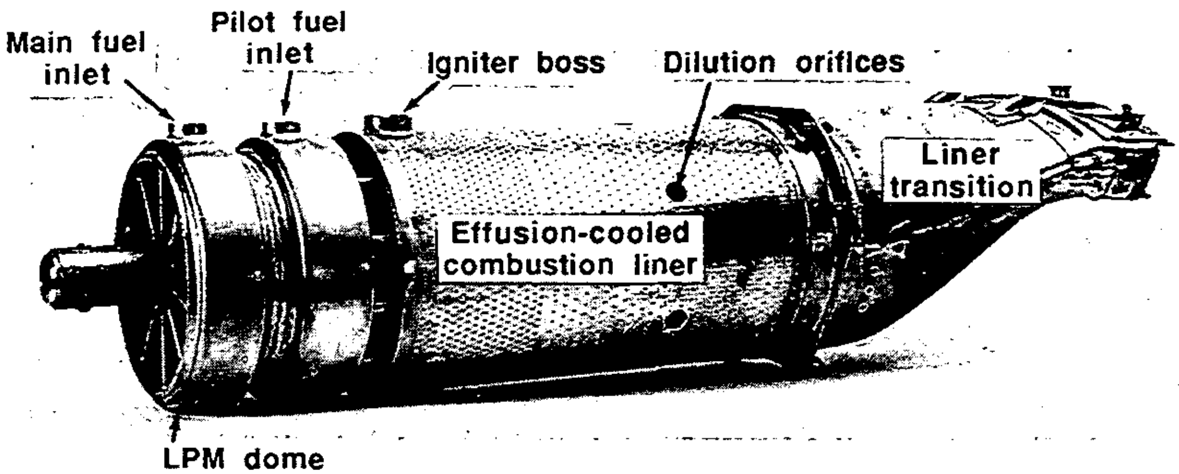

FIGURE 3. PHOTOGRAPH OF DRY LOW NO_x COMBUSTOR ASSEMBLY.

thousand small holes drilled at shallow angles through the wall. These small holes provide a large surface area for heat transfer from the wall to the cooling air. Allison's LE III combustion liner, which was released for production in 1991 for both natural gas and liquid fuel applications, uses the effusion-cooled design and has accumulated several thousand hours of field engine testing, indicating significantly enhanced liner durability.

In addition, to maintain "hot" combustor inside walls, the centerbody tip, dome wall, and liner wall are coated with a thermal barrier ceramic (TBC) coating. Any remaining air not used in the primary combustion zone and for wall cooling passes through the dilution holes in the combustor. The airflow distribution in the liner is chosen to provide fuel-lean conditions in the primary combustion zone when operating at the maximum power condition. The equivalence ratio of the mixture exiting the LPM dome at maximum power is in the range of 0.45 to 0.65.

Computational Design Analyses

The design of the low emissions combustors was guided by Allison's two- and three-dimensional computational combustion dynamics (CCD) codes. Extensive use of these codes was made to 1) provide design guidance in optimizing the fuel injection holes; 2) optimize recirculation strength in the primary combustion zone for improving stability; 3) ensure that there is no significant recirculation occurring in the mixing cup; 4) predict wall temperature and the effect of wall cooling on combustor performance; and 5) investigate fuel staging operation.

Figure 4 summarizes the results obtained from a simulation of dry low NO_x Configuration 2 using a three-dimensional computational combustion dynamics code. The predicted velocity field (Figure 4a) indicates no flow separation or recirculation within the pre-mixing chamber of the LPM dome. Downstream from the LPM dome, a recirculation zone is established to provide combustion stability in the primary combustion zone upstream of the dilution orifices. The fuel/air mixing efficiency is indicated by the predicted distribution of equivalence ratios throughout the combustor before ignition (Figure 4b). The predicted equivalence ratio at the exit of the LPM module is very uniform at a value of 0.5. Consistent with the equivalence ratio distribution, the predicted temperature within the combustor (Figure 4c) shows a fairly uniform temperature distribution with no high temperature peaks in the primary combustion zone. Finally, Figure 4d shows the predicted combustion efficiency throughout the combustor. The combustion efficiency is defined here as the predicted local temperature rise divided by adiabatic temperature rise. Nearly 100% combustion efficiency is predicted at the exit of the combustor.

Figure 5 shows predicted effects of dome and combustor liner wall cooling flux (cooling air flow rate per unit surface area) on the temperature distribution within the combustor. The combustor dome and liner wall are cooled using an efficient effusion cooling design. About 20% of the available combustion air is used in the baseline cooling design (Figure 5a). However, relatively cooler (800 to 1200°F) near wall regions are predicted in the primary zone. These regions for the most part are responsible for introducing quenching effects on the reactions involving CO and UHC, resulting in increased emissions of these species. Figure 6 shows predicted effects of wall cooling flux on combustion efficiencies. For the baseline wall cooling case (Figure 6a), the efficiency at the combustor exit is poor at no more than 90%. The effect of reducing the effusion cooling flux by 50% is significant as indicated by the results of Figures 5b and 6b. The temperature distribution is relatively uniform and the near wall cooling region is eliminated. The corresponding predicted combustion efficiency is much improved as shown in Figure 6b. Figures 5c and 6c show the results obtained when the effusion cooling flux is completely eliminated, and the liner cooling is solely dependent on the back side convective cooling and the liner inside wall is TBC coated. These results show further

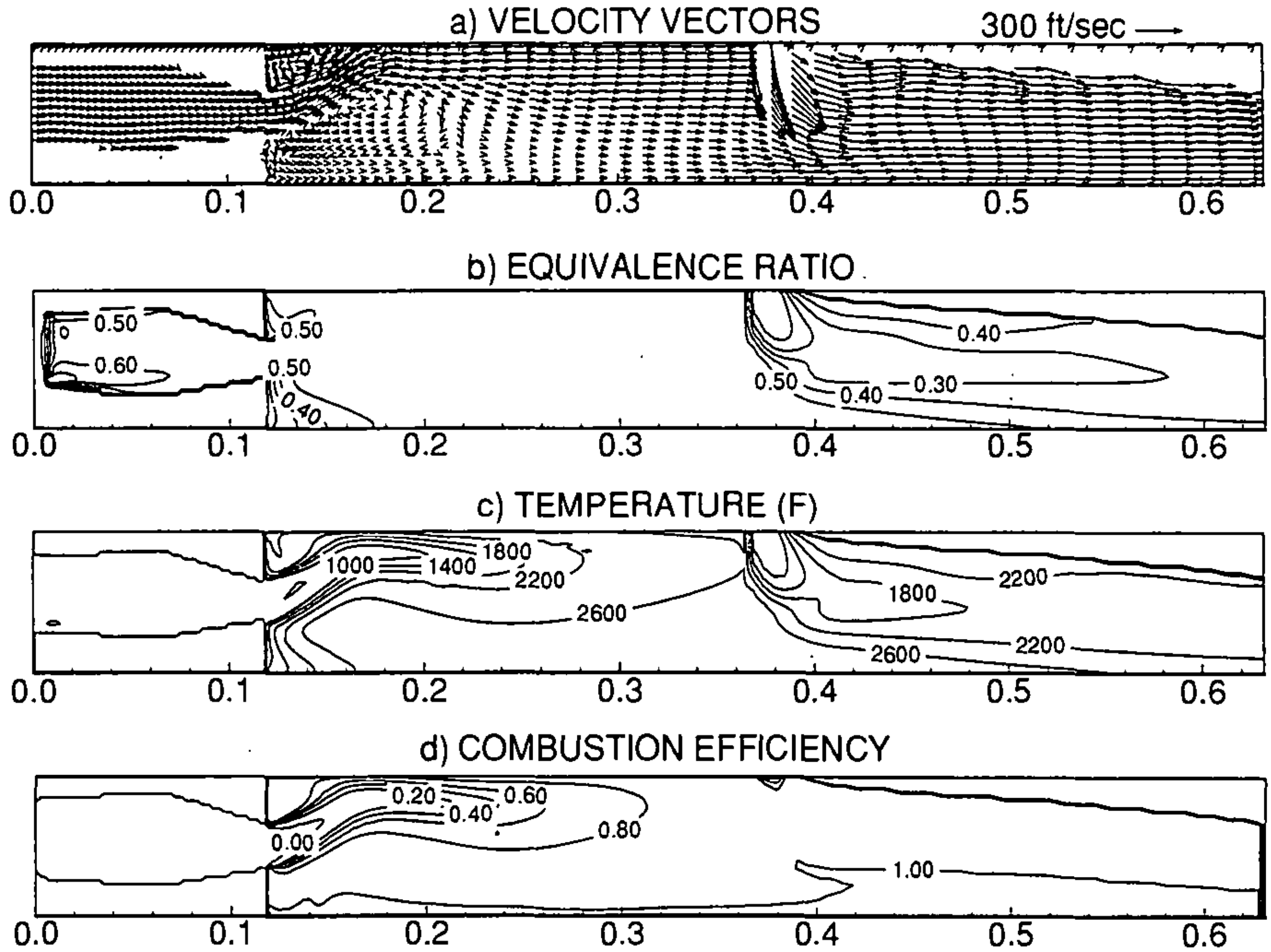

FIGURE 4. PREDICTED KEY FLOW FIELD PARAMETERS FOR DRY LOW NO_x CONFIGURATION 2.

improvement in temperature uniformity and combustion efficiency.

It should be noted that in all the above cases, the excess air from reduced wall cooling is directed into the dilution zone while maintaining a constant primary-zone equivalence ratio. The predicted results and trends have been confirmed by the rig test results discussed later in this paper. Maintaining high combustor wall temperature also helps improve flame stability.

Bench Testing of LPM Modules

LPM modules were bench tested to (1) obtain insight into the mixing processes and overall performance of each premixing concept, (2) establish the relationship between the mixing processes and the NO_x emissions, and (3) verify combustion model predictions. A schematic of the bench test facility is shown in Figure 7. Bench tests were performed on actual LPM dome hardware at ambient pressure conditions. The combustor barrel was replaced by a quartz tube which provided optical access into the combustion zone. The dome and quartz tube assembly was fixed, while an optical table was mounted on a X-Y-Z traverse to map out the flow field inside the combustor. Spatially-resolved measurements of gas velocities were obtained using two-component laser anemometry (LA) mounted on the optical table (Figure 7). In addition, a water-cooled gas sampling probe was used to extract samples from within the combustor and at the exit plane of the combustor. The gas samples were analyzed with conventional source emission monitoring instruments designed to detect hydrocarbons, O_2, CO, nitric oxide (NO), nitrogen dioxide (NO_2), and carbon dioxide (CO_2). Temperature was measured within the combustor and at the exit plane using a thermocouple probe. Spatially-resolved mapping was conducted by positioning the traverse at select locations throughout the combustor.

The air flow to the dome was selected to simulate a range of pressure drops (2 to 4%) covering the pressure drop expected in the actual combustion system. The dome equivalence ratio was varied.

A number of bench tests were conducted to characterize fuel/air mixing in LPM domes. A tracer gas was injected through the fuel holes, and samples of fuel/air mixtures were

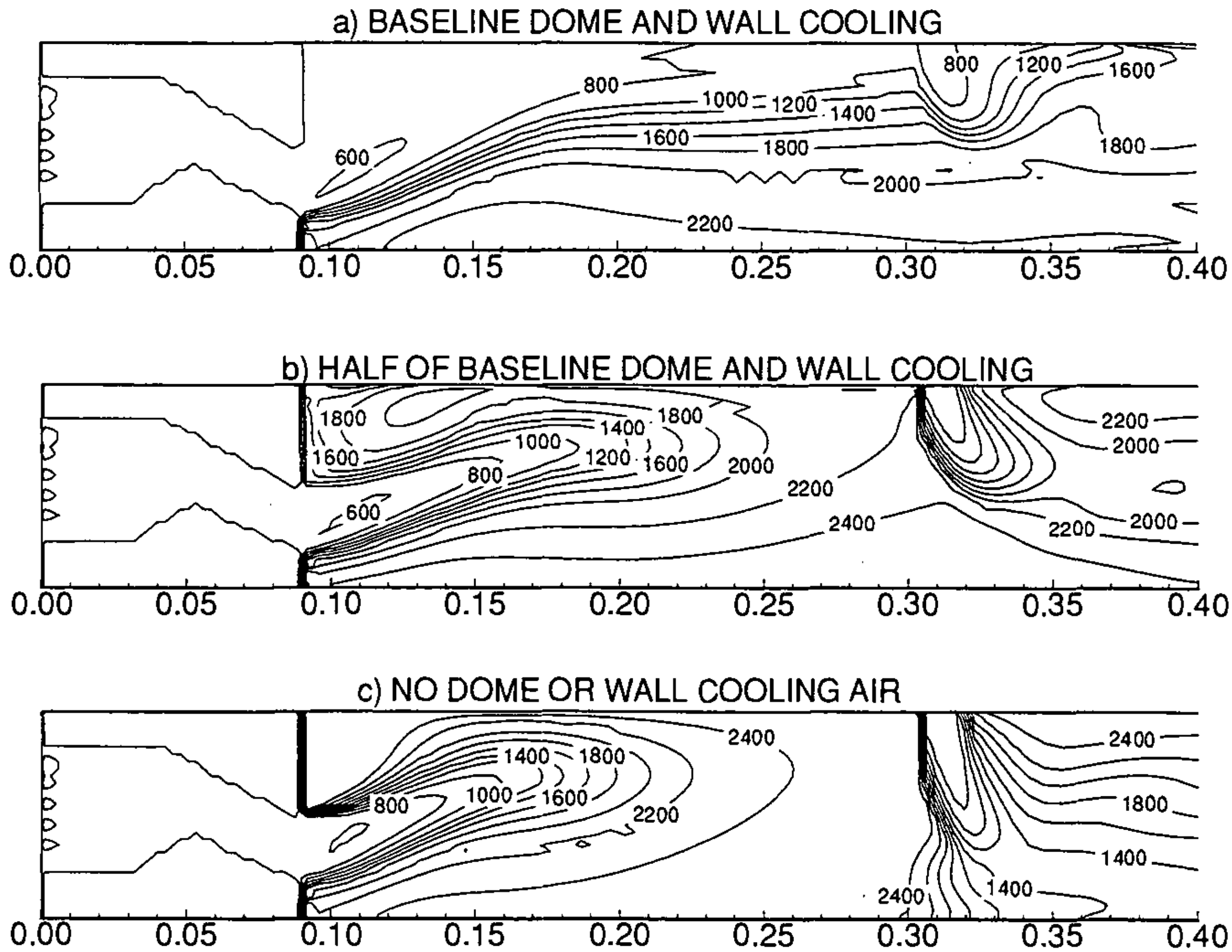

FIGURE 5. PREDICTED EFFECT OF WALL COOLING ON COMBUSTOR TEMPERATURE DISTRIBUTION.

extracted using a 1/8-inch sampling probe. The samples were analyzed with a hydrocarbon analyzer. The tracer gas consisted of a known mixture of air and natural gas. Measurements were taken inside the dome as well as at the exit of the dome to study the progression of fuel/air mixing.

Figure 8 shows the fuel/air mixing characteristics of dry low NO_x Configuration 1. The measured local concentrations (C) of the tracer gas, normalized by the average concentration (Cavg), are plotted against circumferential position at a fixed radial location. The expected average concentration of the tracer gas is obtained from the measured LPM dome air flow rate and the flow rate of the tracer gas. For perfectly mixed tracer gas, C/Cavg is expected to be equal to 1. The tracer measurements were carried out within the dome at several axial locations downstream from the swirler vanes. For all circumferential positions, at x = 0 mm (swirler exit), measured concentrations in Figure 8 show maximum deviation from the perfectly mixed line. The peaks and valleys in the concentration profile correspond to the locations of the sample point with respect to the fuel injection tubes for this configuration. Note that the magnitude of the peaks and valleys varies along the circumferential position. This is partly due to difficulty in maintaining the same relative radial position of the sampling probe while traversing in the circumferential direction. The results of Figure 8 indicate that substantial unmixedness of fuel and air remains at the exit of the individual swirler passages. However, a small distance downstream from the swirler at x = 5 mm, significant reduction of the concentration peaks occurs. At the exit of the LPM dome (x = 64 mm), the concentration profile has significantly leveled off. The exit concentrations were measured at 3 and 4% dome air pressure drops. No significant impact of the pressure drop on the dome exit fuel/air mixing is noted.

Figure 9 compares the overall fuel/air mixing performance of the dry low NO_x Configurations 1 and 2. The normalized measured concentrations are plotted against radial location at the exit of the LPM domes, at several circumferential positions. The measurements were performed at

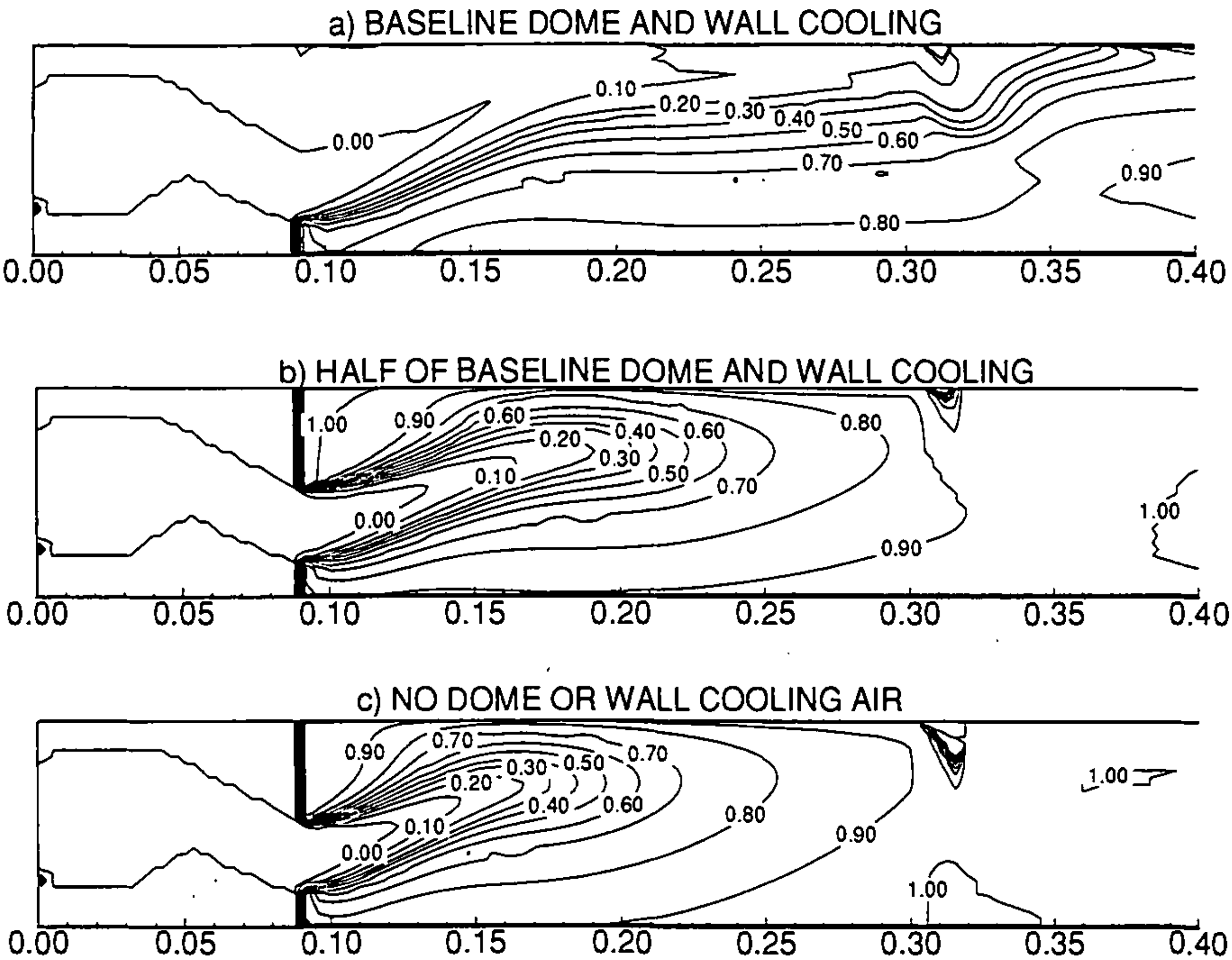

FIGURE 6. PREDICTED EFFECT OF WALL COOLING ON COMBUSTION EFFICIENCY.

dome fuel/air ratios of 0.032 and 0.038, and dome air pressure drops of 3 and 4%. No significant effect of the dome fuel/air ratio or dome air pressure drop is apparent from the results. However, due to improved design, the fuel/air mixing is more efficient for Configuration 2. The analysis of the data indicates that the standard deviation divided by the mean concentration for Configuration 1 is about 12% and that for Configuration 2 is 5.3%.

Measurements of axial and tangential velocity components were performed inside the combustor under ambient bench test conditions using a two-component laser anemometry (LA). The measurements are compared with predictions from a 2-D model in Figure 10. The comparison is shown at several axial locations, x/h (h is the dome exit annulus height, h = 28 mm). The model predictions compare very well with the measurements. Both the measurements and the model predictions indicate a center recirculation established just downstream from the dome exit. As indicated earlier, an LPM dome design not only must be efficient in mixing fuel and air but also establish a sufficiently strong recirculation zone down stream in the combustor to stabilize lean combustion.

Rig Test Results

All the high pressure simulated engine tests of the dry low NO_x combustion liners were performed in Allison's single-burner rig test facilities. The single-burner rig has a flow path that simulates the flow path of the 501-K engine. The rig is designed to the exact dimensions of a 60-degree engine segment. This simulation includes the compressor discharge passage, diffuser air passage, inner and outer cases, and the turbine inlet passage. Figure 11 shows a schematics of the Allison Model 501 single-burner rig. Dedicated facilities are available to supply conditioned air to the test facility so that virtually all engine operating conditions can be simulated. The test facility capabilities include air flow rates up to 120 lb/sec, air temperature from -75 to 1000°F, and air pressure up to 300 psia. Air flow is measured using a standard thin plate orifice, fuel flow is measured using Flotron flowmeter, temperatures are measured using Chromel-Alumel and Platinum- Platinum/Rhodium thermocouples, and pres-

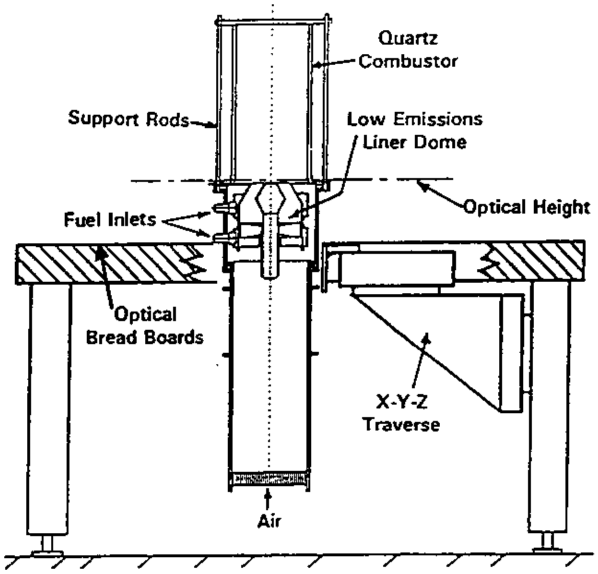

FIGURE 7. SCHEMATIC OF BENCH TEST FACILITY.

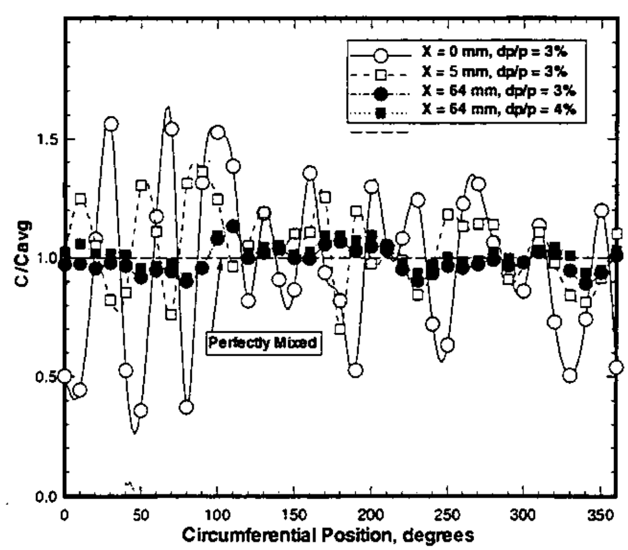

FIGURE 8. MEASURED FUEL/AIR MIXING CHARACTERISTICS IN CONFIGURATION 1 LPM DOME.

sure is measured using pressure transducers.

Combustion gas samples were extracted at the exit of the combustor transition section (Figure 11). The sample probes are designed to obtain a representative exhaust gas sample for accurate measurement. Five probes with four sampling ports per probe were used. The 20 gas samples from across the cross-section of the combustor exit are mixed in a manifold mounted just above the rig. A single sample line carries the sample from the manifold to the emissions analyzers. Electric

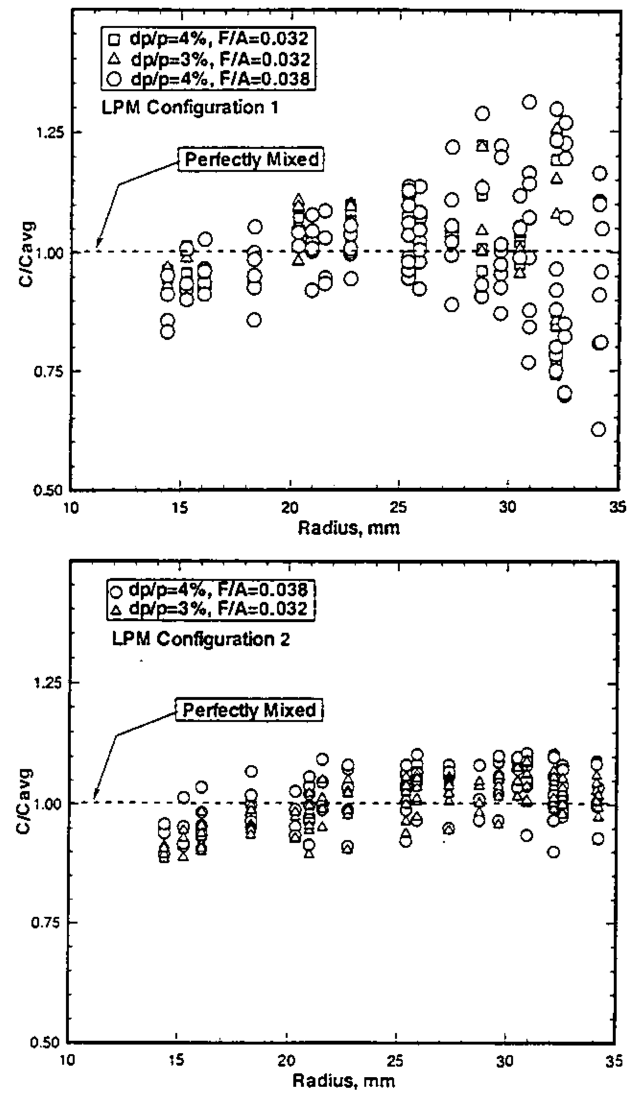

FIGURE 9. MEASURED FUEL/AIR MIXING PERFORMANCE OF DRY LOW NO_x CONFIGURATIONS 1 AND 2.

heaters are used to regulate the sample line temperature from the manifold to the instruments. The emissions measurements are made through the use of equipment and test methods called out in the SAE Aerospace Recommended Practice, ARP 1256A. Total UHC are measured using flame ionization detector, CO and CO_2 are measured using a non-dispersive infrared (NDIR) analyzers, NO_x is measured using chemiluminescence analyzer, and O_2 is measured using Polarography.

Data is recorded automatically and manually. Some of the data is processed on-line to give the test operators immediate feedback to confirm that the test conditions are met and all instrumentation is functioning correctly. For example, during the present rig testing of the dry low NO_x liners, thermocouples were placed at strategic locations within the LPM dome and on the face of the centerbody. The tempera-

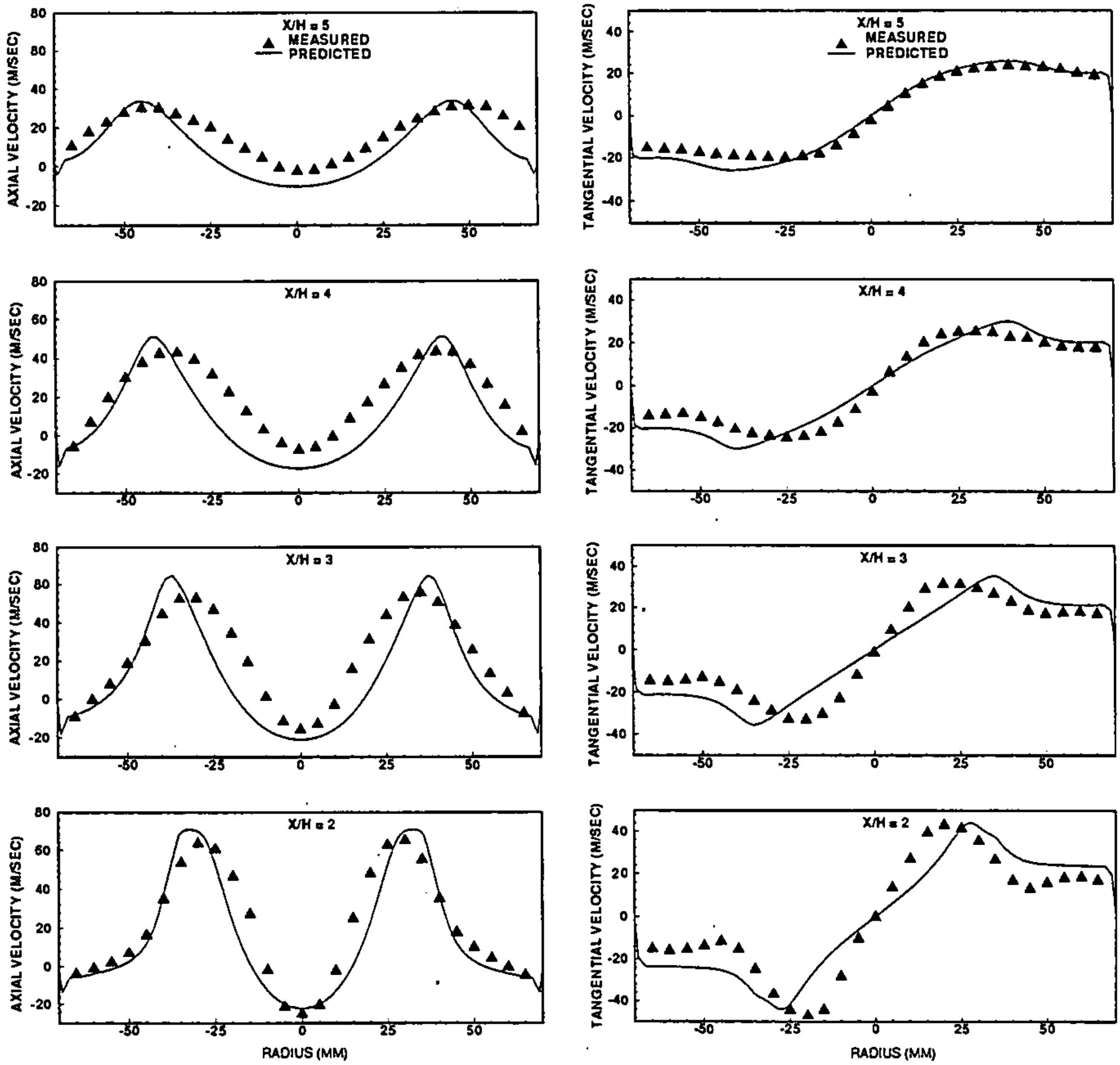

FIGURE 10. COMPARISON BETWEEN MEASURED AND PREDICTED VELOCITY PROFILES.

ture readings from these thermocouples were always displayed and monitored during the tests so that any flame flashback into the LPM dome could be detected and corrective action taken.

Figure 12 shows the emissions results obtained for Configuration 2 which was rig tested under simulated 501-KC5 engine cycle conditions for burner inlet temperature (BIT= 655°F), and pressure (BIP = 150 psia). The measured NO_x, CO, and UHC are presented in parts per million dry on volume basis (ppmvd) and are corrected to 15% O_2 {measured value * (20.9-15)/(20.9-$O_{2,\ measured}$)}. The results are plotted against the burner outlet temperature (BOT) which was varied by varying the fuel flow rate. The BOT was calculated from the measured fuel and air flow rates. These results were obtained with LPM dome equivalence ratio estimated at the design point to be about 0.5. Note that the dome equivalence ratio is estimated from the measured fuel flow rate and the estimated dome air flow fraction. The dome air flow fraction is estimated from the measured effective flow areas of the combustion liner. The liner effective flow areas were mea-

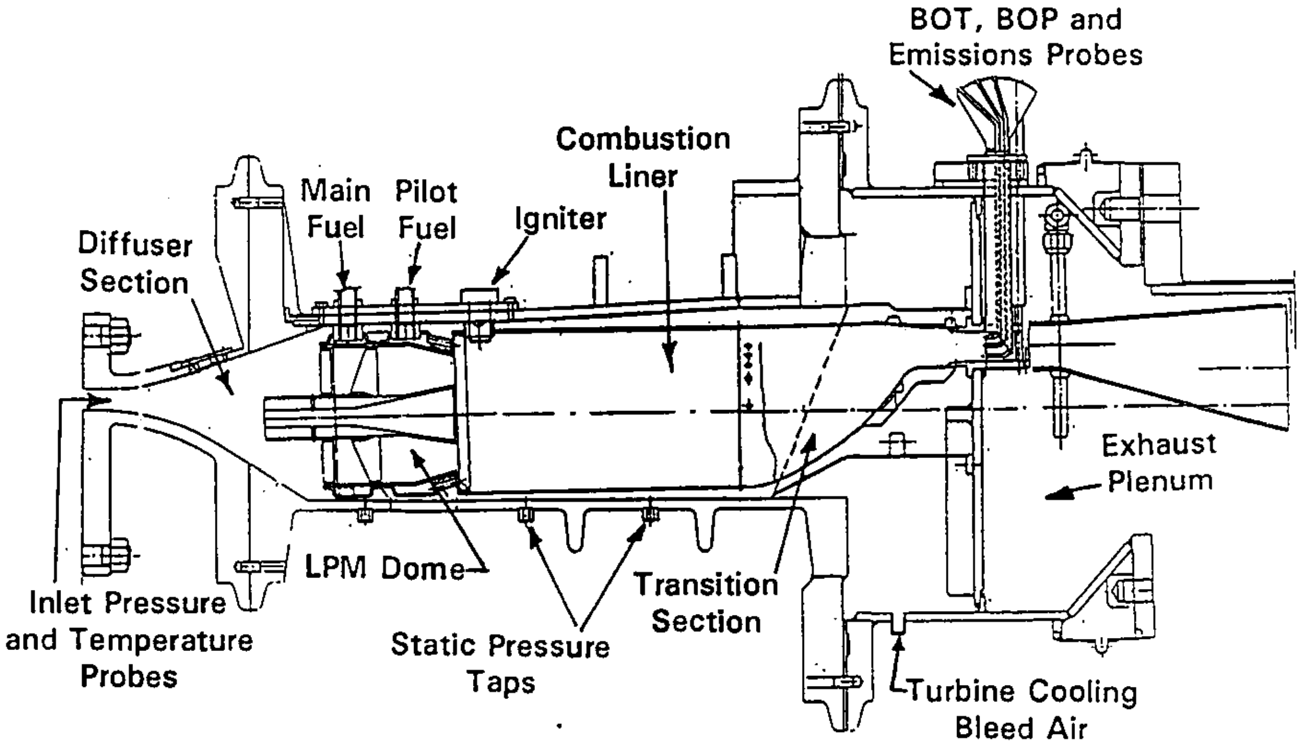

FIGURE 11. SCHEMATIC OF RIG TEST FACILITY.

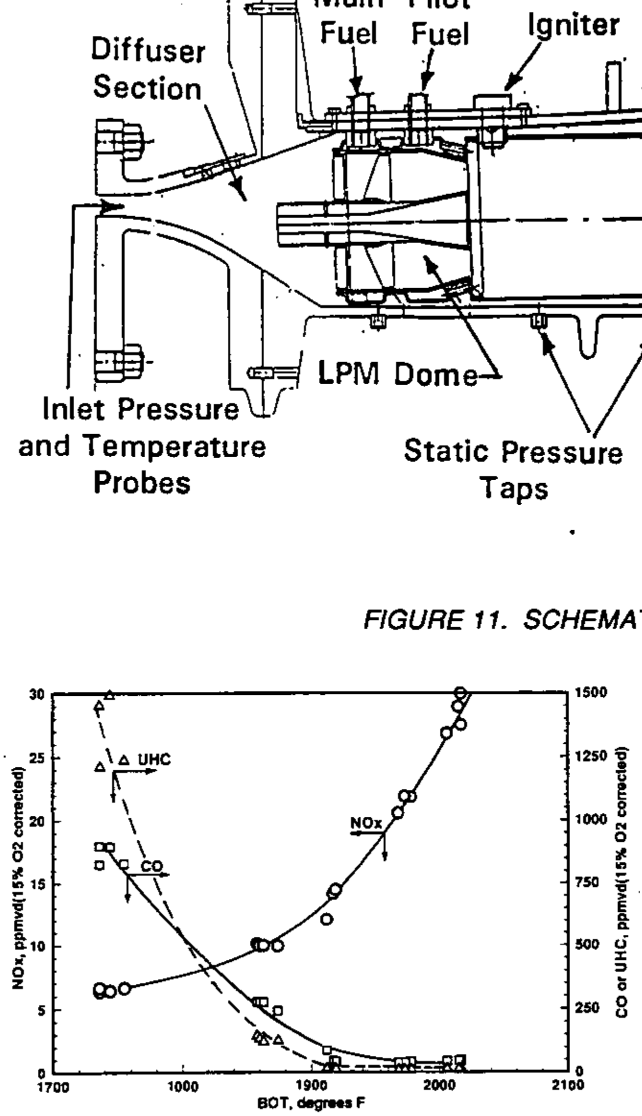

FIGURE 12. MEASURED EMISSIONS FOR CONFIGURATION 2 RIG TESTED UNDER 501-K SIMULATED ENGINE CYCLE.

sured under ambient non-reacting test environment. At the simulated maximum power point tested (about 2000°F BOT), the results of Figure 12 show emission levels close to the present goal with measured NO_x near 25 ppm, CO less than 45 ppm and UHC less than 15 ppm. For this equivalence ratio design, combustor was stable down to about 25% simulated power point without requiring pilot flame.

Measured combustion efficiency for the above design is plotted against BOT in Figure 13. Better than 99.8% efficiency is measured at or near the maximum power point.

Configuration 2 was modified to increase the fraction of air flow through the LPM dome. The resulting dome equivalence ratio at the rig tested maximum power point was reduced to about 0.45. The emissions results from rig testing of this configuration are summarized in Figure 14. In this case, due to very lean operation of the LPM dome, it was necessary to support combustion with pilot fuel. Results were obtained at pilot fuel flow rate of 4.6%, 13.7% and 15.6 % of the total fuel flow rate. At the maximum simulated engine power point, NO_x levels of less than 15 ppmvd (15% O_2 corrected) were obtained. However, at these ultra-lean conditions, the CO levels near 250 ppm, and UHC of about 100 ppm were obtained.

Effect of Wall Cooling and Fuel/Air Mixing

Figure 15 shows the effect of reducing the liner wall cooling flux on measured CO emissions. As discussed earlier, Allison's 3-D computational design analysis has indicated that relatively cool walls are mostly responsible for introducing quenching effects on the reactions involving CO. The data presented in Figure 15 confirm these predictions. For the baseline cooling scheme, about 20% of the combustion air was used for the liner dome and wall cooling, and for the no effusion cooling case, effusion cooling was eliminated and only back side convective cooling and ceramic coating of

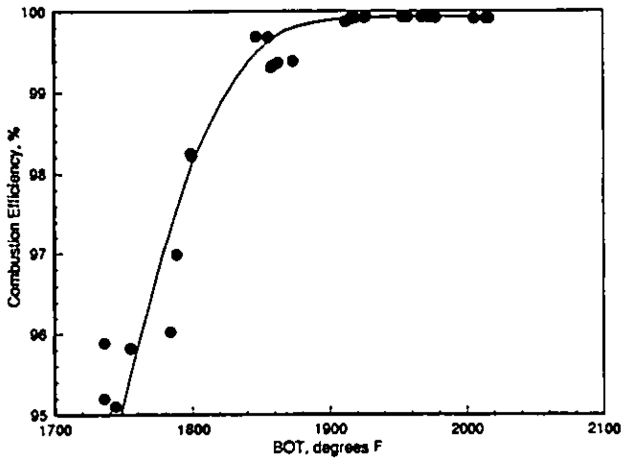

FIGURE 13. COMBUSTION EFFICIENCY OF DRY LOW NO_x CONFIGURATION 2.

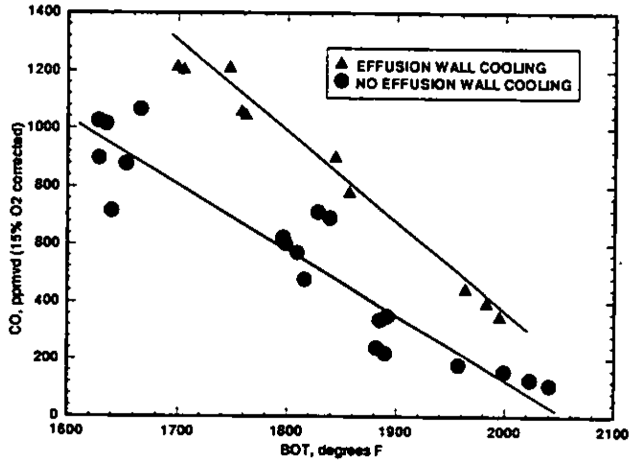

FIGURE 15. EFFECT OF WALL COOLING ON CO EMISSIONS.

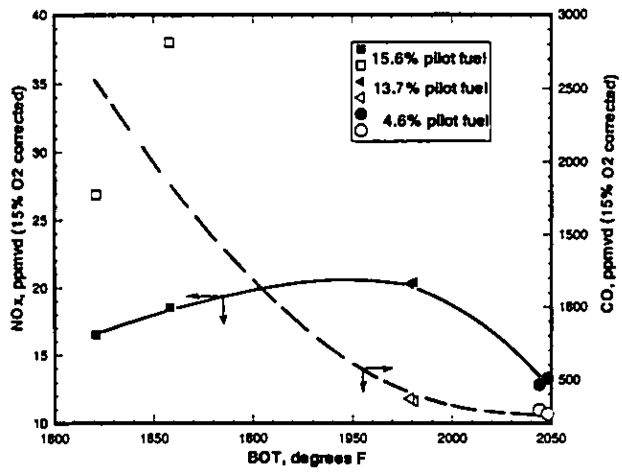

FIGURE 14. EMISSIONS RESULTS OF PILOT SUPPORTED ULTRA-LEAN COMBUSTION IN CONFIGURATION 2.

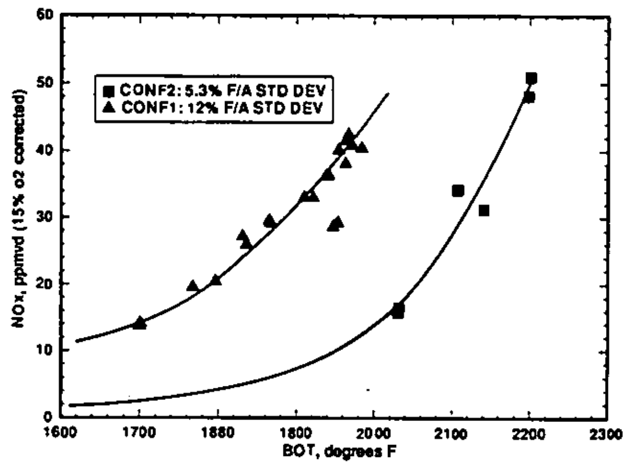

FIGURE 16. EFFECT OF FUEL/AIR MIXING EFFICIENCY ON NO_x EMISSIONS.

the inside wall was used. The dilution orifices of the liner were re-sized to accommodate additional air for the no effusion cooling case. For the same aerodynamic combustor design when wall cooling flux is reduced, about 50% reduction in CO results throughout the range of power points tested. Similar reductions were observed in UHC emissions.

Effect of fuel/air mixing on NO_x emissions is shown in Figure 16. Configuration 1 has a pre-mixed fuel/air ratio with a standard deviation of 12% at the exit of the LPM dome while Configuration 2 has a pre-mixed fuel/air ratio with a standard deviation of 5.3%. The effect on NO_x emissions is significant. At the maximum power point (about 2000°F BOT), NO_x emissions for Configuration 2 are reduced by more than 60%.

Figure 17 shows effects of fuel/air mixing, wall cooling flux and increased swirl on the NO_x versus CO tradeoff. The rig results clearly indicate significant reduction in not only NO_x but also CO due to both better fuel/air mixing and operation with "hot" liner dome and wall.

Combustor Thermal Performance

In addition to the low emissions performance, there are other combustor performance parameters of interest for a successful and durable gas turbine combustion system. These

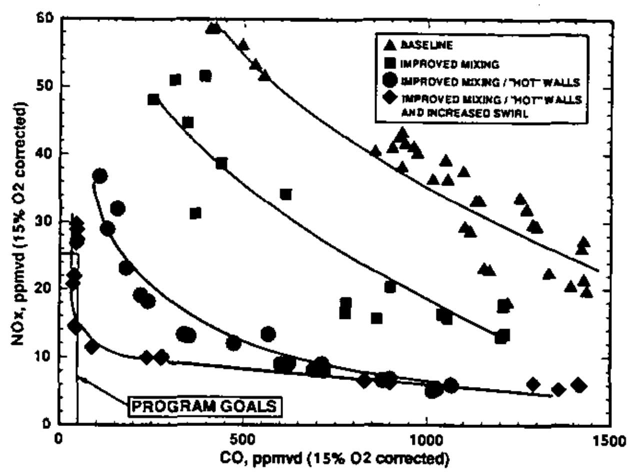

FIGURE 17. EFFECT OF FUEL/AIR MIXING EFFICIENCY AND WALL COOLING ON NO_x VS. CO TRADEOFF.

include the combustor exit temperature distribution and the wall temperature. Figure 18 shows comparison of measured temperature contours at the exit of the production diffusion flame type combustor and the dry low NO_x combustor. The temperature profile has been normalized by the average measured BOT. The plots are based on 30 thermocouple readings placed at equal area increments at the exit of the combustor transition section. The comparison of the results in Figure 18 shows clear advantage of the dry low NO_x combustor with mostly uniform temperature distribution throughout the exit area. The maximum temperature ratio reaches only about 1.03, while for the production liner, this ratio is as high as 1.11. Figure 19 shows comparison of the radial temperature profile, one of the key design parameters for the first-stage turbine vanes and blades. The flatter temperature profile with significantly reduced peak temperature is typical of a pre-mixed dry low NO_x combustion system.

One other important thermal performance measure is the wall temperature distribution of the combustion liner. During the rig testing of the dry low NO_x liners, the liner dome and walls were first painted with temperature sensitive thermal paint. Following rig testing, color changes of the thermal paint provided an indication of liner wall temperature distribution and hot spots. Furthermore, after identifying the highest temperature regions of the liner, the dome and wall were instrumented with thermocouples to provide an accurate reading of the liner skin temperatures. Thermocouples were installed at several axial positions along two circumferential positions 180 degrees apart. Figure 20 shows measured axial wall temperature distribution (X = 0 inches represents LPM dome exit) for the baseline effusion cooled wall using about 20% of the liner air flow, for 50% baseline cooled wall using about 10% of the liner air flow, and 0% effusion cooled wall. With baseline effusion and 50% baseline effusion cooling, the wall temperature of less than 1100°F were observed. With 0% effusion cooled wall (only back-side convectively cooled) and thermal barrier coated design, most of the wall thermocouple readings were at temperatures less than 1600°F which is below the design limit for the combustor material.

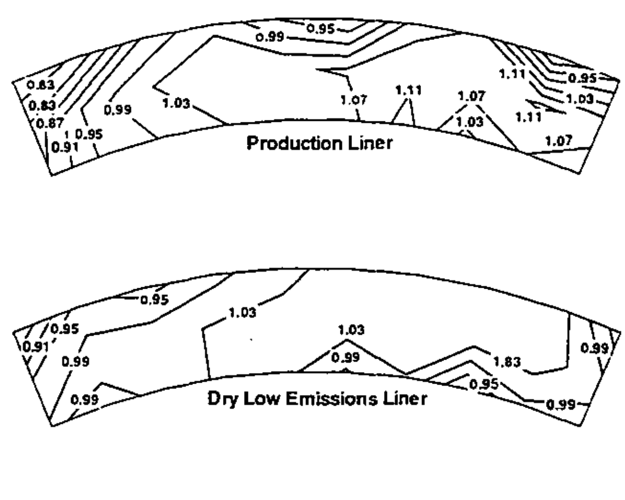

FIGURE 18. COMPARISON OF MEASURED COMBUSTOR EXIT TEMPERATURE DISTRIBUTION BETWEEN PRODUCTION LINER AND DRY LOW NO_x CONFIGURATION 2.

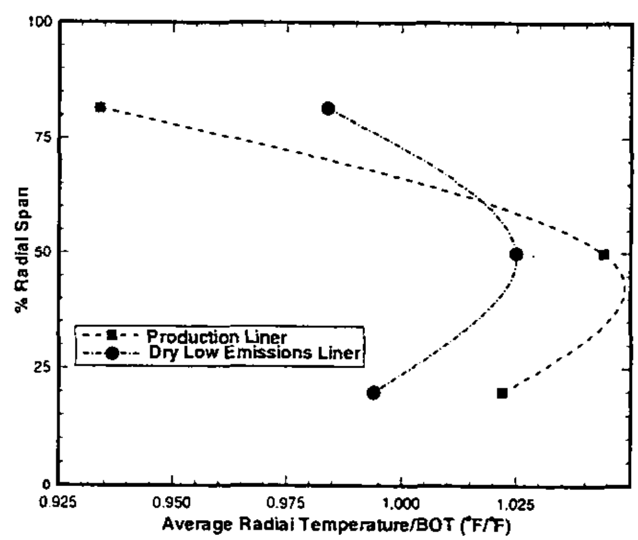

FIGURE 19. COMPARISON OF MEASURED RADIAL TEMPERATURE PROFILE BETWEEN PRODUCTION LINER AND DRY LOW NO_x CONFIGURATION 2.

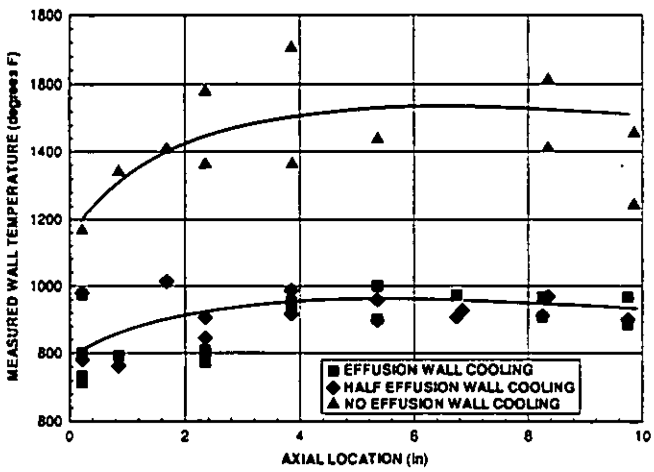

FIGURE 20. MEASURED WALL TEMPERATURE FOR DIFFERENT LINER WALL COOLING FLOW RATES.

Conclusions

The high pressure rig tests of the dry lean pre-mixed low NO_x combustion liners have demonstrated emissions levels which meet the present goals. At the simulated maximum power point of a 501-K series engine, NO_x levels of 25 ppm, CO less than 45 ppm and UHC less than 15 ppm were measured. Better than 99.8% combustion efficiency was measured. For this design, combustor was stable down to about 25% of maximum power without requiring pilot flame.

The rig tests for an ultra-lean liner design demonstrated NO_x levels lower than 15 ppmvd (15% O_2 corrected), well below the goal, at the design point. The corresponding CO and UHC levels were, respectively, 250 ppmvd, and 100 ppmvd. Design improvements are underway to further improve the emissions of CO and UHC for this design.

Rig tests have shown uniform temperature distribution throughout the exit of the dry low NO_x combustor. The exit radial temperature profile is much flatter with significantly reduced peak temperature than the production liner. Measured liner wall temperatures ranged from 1100 to 1600°F for baseline effusion or 50% baseline effusion cooling design as well as with 0% effusion-cooled and TBC-coated design. These temperatures are below the design limit for the liner material.

The present design and development work is guided by advanced computational combustion dynamics models and ambient bench testing. The bench tests were used to characterize fuel/air mixing of the LPM domes. The mixing efficiency was not very sensitive to the dome fuel/air ratio or the dome pressure drop.

The 3-D computational design analyses have indicated that relatively cool walls and the amount of wall cooling air are mostly responsible for introducing quenching effects on the reactions involving CO. The rig test results have confirmed these predictions. For the same aerodynamic combustor design when wall cooling flux is reduced from 20% to no effusion cooling with only back side convective cooling, about 50% reduction results in CO emissions throughout the range of power points tested.

The fuel/air mixing efficiency has significant impact on NO_x emissions. By improving the mixing from a fuel concentration with a standard deviation of 12% to 5.3%, a 60% reduction in NO_x emissions at the maximum power point have been demonstrated. Improved fuel/air mixing and "hot" liner wall design significantly improve NO_x versus CO tradeoff.

Further refinements in the liner design are continuing in the present development effort to improve margin on emissions. Engine tests of the dry low NO_x liners are scheduled for 1994.

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