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Combustor Technology for Future Small Gas Turbine Aircraft

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COMBUSTOR TECHNOLOGY FOR FUTURE SMALL GAS TURBINE AIRCRAFT

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1. SUMMARY

To enhance fuel efficiency, future advanced small gas turbine engines will utilize engine cycles calling for higher overall engine pressure ratios, leading to higher combustor inlet pressures and temperatures. Further, the temperature rise through the combustor and the corresponding exit temperature are also expected to increase. This report describes future combustor technology needs for small gas turbine engines. New fuel injectors with large turndown ratios which produce uniform circumferential and radial temperature patterns will be required. Uniform burning will be of greater importance because hot gas temperatures will approach turbine material limits. The higher combustion temperatures and increased radiation at high pressures will put a greater heat load on the combustor liners. At the same time, less cooling air will be available as more of the air will be used for combustion. Thus, improved cooling concepts and/or materials requiring little or no direct cooling will be required. Although presently there are no requirements for emissions levels from small gas turbine engines, regulation is anticipated in the near future. This will require the development of low emission combustors. In particular, nitrogen oxides will increase substantially if new technologies limiting their formation are not evolved and implemented. For example, staged combustion employing lean, premixed/prevaporized, lean direct injection, or rich burn-quick quench-lean burn concepts could replace conventional single stage combustors. Due to combustor size considerations, staged combustion is more easily accomodated in large engines. The inclusion of staged combustion in small engines will pose greater combustor design challenges.

2. INTRODUCTION

This report describes a research and development program for small gas turbine combustors at the Lewis Research Center. The main objectives of the program are to provide the technology for higher operating temperature and pressure capability, improved performance and operability, as well as reduced nitrogen oxide (NOx) emissions and improved computational prediction and design methods.

Increasing the pressure and temperature of a gas turbine engine increases its thermodynamic efficiency, thrust-to-weight ratio, and specific fuel consumption. However, this puts an increased demand on gas turbine materials and the material temperature and strength becomes a limiting factor. Thus, higher operating temperatures and pressures require the development of higher performance materials.

Increases in engine pressure and temperature levels affect the combustor in several ways. First, new fuel injectors with large turndown ratios which produce uniform circumferential and radial temperature patterns will be required. Uniform burning becomes more important because hot gas temperatures are approaching turbine material limits, and since more air will be required for the combustion process, less air will be available for tailoring the combustor exit temperature profile. As the air temperatures and the combustion radiant thermal flux increase, the task of keeping the fuel flowing through the fuel injectors within temperature limits becomes more difficult.

The higher combustion temperatures and increased radiation at higher pressures will put a greater heat load on the combustor liners. At the same time, less air will be available for cooling as more of the air will be used for combustion and the air that is available will be higher in temperature. Increased inlet air temperature decreases the heat sink capability of the air used for cooling and makes conventional liner cooling techniques inadequate. Thus arises a need to develop improved cooling concepts for metallic liners, non-metallic liner materials, and/or metallic liners with non-metallic coatings.

Increased temperatures and pressures result in higher emissions of nitrogen oxides (NOx). NOx emissions are a problem in the stratosphere because it leads to ozone depletion. For aircraft flying at lower altitudes the problem is somewhat different. In the troposphere, additional ozone is produced leading to the formation of photochemical smog and acid rain. The effects of NO_x from the subsonic fleet are small compared with the overall problem because airplanes use less than 1 percent of the fossil fuels. However, as the emissions from other sources are reduced, there is increasing concern for controlling the NO_x emissions from airplanes.

Several programs at NASA Lewis address these problems. For small gas turbine engines, a joint program with the Army focuses on developing technology for combustor liners and fuel injectors. Research to control NO_x emissions is being done at Lewis as part of the High Speed Research (HSR) Program (ref. 1). The Program goal is to develop the technology for an environmentally acceptable High Speed Civil Transport (HSCT). Of particular environmental concern are the NO_x emissions and the noise. The NO_x

emissions from an HSCT would be particularly harmful because the plane will fly in the stratosphere, where the effect of NO_x on ozone depletion is the greatest. A reduction by a factor of 10 of the uncontrolled NO_x emissions is required to make the plane environmentally acceptable. The technology developed to control the NO_x emissions for the HSCT will be applicable (with some modifications) to the subsonic fleet and small gas turbines. As part of these efforts, computer models are being developed to predict the combustion process within combustors. Until recently, combustors have been developed primarily by empirical methods. However, computer models are becoming increasingly more useful in guiding development. There is great potential in further developing computer codes because of the ever increasing computer speed and storage, which, when accompanied by improved solution algorithms and physics, can increase the accuracy, reduce run time and computational cost. This is in contrast to increasing costs of experimental testing, particularly of full-scale hardware.

This report describes in greater detail current NASA-funded research on combustor subcomponents, NO_x emissions, and computer model development for small gas turbine engines.

3. SUBCOMPONENT TECHNOLOGY

3.1 Fuel Injection and Mixing

Fuel injection is a critical issue in gas turbine combustors. In the case of small gas turbines, the challenge becomes even greater as the engine operating conditions encompass higher pressures and temperatures. The need to double the fuel flow rate of current technology injectors becomes apparent. An increased burner temperature rise results in a higher fuel-to-air ratio at high power. Thus, if the fuel-to-air ratio at low power is kept constant the turn-down ratio for the fuel injector increases. Along with this increased turn-down ratio, the fuel spray is required to fulfill complex requirements such as patternation, droplet size and distribution. Circumferential uniformity is important to prevent the formation of local rich zones and lean zones. Controllable and consistent radial temperature profiles are desired. Rich zones produce local hot spots which reduce the life of turbine blades and produce soot, which leads to higher radiant heat loads to the combustor liner and to smoke emissions. Lean zones, particularly at low power conditions, can result in inefficient burning with resultant high unburned hydrocarbons and carbon monoxide emissions. Combustion uniformity must be achieved by improving the fuel injectors and the injector-combustor dome air interaction, enhancing primary zone mixing, and extremely rapid dilution zone mixing. As the rise in temperature across the burner increases, more air is used in the burning process and less air is available for dilution and trimming of the exit temperature profile to achieve a low pattern factor.

Another consideration is that as the heat load to the fuel injector increases, the temperature of the fuel in the injector increases if preventive measures are not taken. Since the fuel temperature in the injector is usually near maximum acceptable levels, any increase in fuel temperature will lead to gum and carbon formation. Also, fuel injectors must be designed considering the increased demand of manufacturing tolerances as fuel passages become smaller.

Lewis has two projects to address the technology requirements of small gas turbines. One is a contract with the Allison Gas Turbine Division of General Motors to develop a fuel injector that improves the spray uniformity (as measured by the resulting burner exit temperature pattern factor), provides for a larger turn-down ratio, and keeps the fuel temperature within acceptable limits (ref. 2). Table I lists the goals of the program. Allison is working cooperatively with two fuel injector manufacturers (Parker-Hannifin and Textron Fuel Systems) to develop the fuel injector. The injector will be tested in newly-designed, low pattern factor combustors developed under an Army-funded program. A simplex airblast nozzle will incorporate spill return technology (figure 1). This improves atomization at low fuel pressure (low engine power) as seen by the smaller fuel droplet sizes produced when compared to conventional nozzles. The improved atomization allows ignition using only half as much fuel, thus doubling the turndown ratio of the injector. Spill return also provides continuous high fuel flow rates which keep the nozzle cool. The airblast nozzle will be tested with both conical and elliptical spray patterns (figure 1). The elliptical spray patterns enable combustors to have fewer fuel injectors which would have higher minimum fuel flow rates.

The second of Lewis's projects to develop small gas turbine technology involved the development of an innovative, effervescent fuel injector through a grant with Professor A. Lefebvre of Purdue University (ref. 3 and 4). The effervescent fuel injector is shown in figure 2. A small amount of air, approximately 1 percent of the fuel flow rate, is mixed with the fuel before it is injected. When the air-fuel mixture is injected into the combustor, the air expands and shatters the fuel into small droplets. The resulting drop sizes are plotted in figure 3. A particularly useful feature of the injector is that the drop sizes are not a function of the fuel injector orifice diameter, thus allowing the use of large orifices that will be more tolerant of fouling.

The effervescent fuel injector was very successful both in performance and in NOx reduction. A proto-type can combustor was tested using a conventional pressure swirl fuel atomizer and then an effervescent atomizer. The fuel-to-air ratio, inlet air temperature and pressure were varied. The results, shown in figure 4, show the effervescent atomizer having performance levels 5-10 percent better than the conventional injector. The nitrogen oxides were much lower using the effervescent atomizer. Further development of this concept is being pursued under a contract with Allison Gas Turbines.

3.2 Liners

Higher pressure ratios and turbine inlet temperatures not only increase the engine cycle efficiency, but also increase the severity of the liner thermal environment. As the combustor temperature increases, more air would be required for liner cooling if conventional film cooling were used. However, as the temperature rise across the combustor increases, more air is required for combustion, thus leaving less for cooling. Also, increased pressure ratios increase the air temperature coming into the combustor from the compressor, thus reducing the heat sink capability of the cooling air. Consequently, improved use of the cooling air and/or new liner materials will be required. Ceramics that can withstand combustor temperatures without the use of cooling air would be the ultimate material. However, ceramics are prone to stress failures induced by thermal shock.

A joint NASA and Army program makes use of the high temperature capability of ceramics and reduces the thermal cyclic fatigue problem by spraying a ceramic on a pliable metal substrate. The program objective is to develop a liner concept capable of withstanding combustor temperature levels of 1922 K (3000 F), while providing improved cyclic durability with little or no coolant flow.

The concept being investigated is called a compliant metal/ceramic liner (fig. 5 from ref. 5). The liner concept consists of a plasma-sprayed ceramic coat of yttria-stabilized zirconia on a compliant nickel-alloy substrate. This compliant metal substrate yields at low stress levels, thereby absorbing the differential expansion that develops between the metal and the ceramic as heat is applied. The compliant metal substrate was made from randomly oriented fibers which are sintered for strength. In particular, a Brunsbond Hoskins-875 compliant pad with a Hastelloy X metal substrate was used, and a NiCrAlY bond coat was used between the ceramic and the compliant metal substrate. Results from an experimental study using this concept (ref. 6) are shown in figure 6. The compliant metal/ceramic liner is compared with a conventional splash film-cooled liner (SF) and two other advanced concepts, one a counterflow film-cooled liner (CFFC), and the other a simulated transpiration-cooled liner (TRANS). The CFFC and TRANS configurations used from 40 to 50 percent less air than the conventional SF configuration, and the liner temperatures were 12 percent lower than the SF. The compliant metal/ceramic liner coolant flow was 80 percent less than that of the SF, and the liner temperatures were 13 percent lower than the corresponding SF temperatures.

A more recent study done at Allison (ref. 7) under NASA/Army sponsorship confirmed the benefits of the compliant metal/ceramic liner concept. Figure 7 compares the performance of the compliant metal/ceramic liner with conventional film-cooled liners and advanced CFCC liners on the basis of coolant flow used per unit surface area. On this basis, the compliant metal/ceramic liner uses 50 percent less wall cooling than the advanced wall cooling technology. The burner outlet temperature in this study was 1922 K. The pattern factor for these tests was 0.15.

Other liner concepts are also being evaluated both through joint NASA/industry programs and through the High Speed Research Program's Enabling Propulsion Materials Program. As part of these programs, coupons, or panels, of advanced ceramic and ceramic matrix liner materials will be tested at Lewis. Figure 8 is a schematic of the test facility which is capable of supplying airflows of up to 3.9 kg./sec., at 2200 K inlet air temperatures and pressures up to 2070 KPa (ref. 8). Cooling flow can be controlled to obtain material temperatures between 1400 K and 1900 K. Initial liner materials to be evaluated include ceramic matrix composites such as silicon-carbide and silicon-nitride. Sets of four, eight, or sixteen wall panels can be tested simultaneously.

4. EMISSIONS

The important emissions from a gas turbine are, at low power conditions, carbon monoxide and unburned hydrocarbons from incomplete combustion and, at high power conditions, nitrogen oxides (NOx) and soot. Conventional combustors have been designed to provide the following desired characteristics: high combustion efficiencies (99.9 percent), temperature profiles tailored to the turbine, minimum length, high stability, and altitude relight capability. This design has resulted in a slightly rich, diffusion flame primary zone with near maximum flame temperatures (see fig. 9). Unfortunately, burning at near maximum flame temperatures produces highest NO_x. Emissions of NO_x are a function of combustor inlet air temperature, exit temperature, pressure, and residence time. Correlations of NO_x emissions as functions of combustor inlet temperature, pressure, residence time and exit temperature were developed in the 1970's by NASA, General Electric (GE), and Pratt & Whitney (P&W) (refs. 9 to 11). Based on these correlations, extrapolations of the GE and P&W NO_x emissions trends as a function of inlet air temperature and pressure are shown in figure 10. The basis for the GE data is the NO_x emissions from the NASA/GE ECCP (Experimental Clean Combustor Program), and the basis for the P&W data is the PW2037. The strongest dependence is on inlet temperature, where approximately a 200 K increase in inlet temperature doubles (P&W correlation) or triples (GE correlation) the NO_x emissions.

The design of a low emission gas turbine combustor consists of a balance of providing enough time and sufficiently high temperatures to complete the hydrocarbon reactions (through flame product recirculation) and yet low enough time and temperatures to keep the formation of NO_x to a minimum. Since the formation rate of nitrogen oxides is an exponential function of temperature, NO_x occurs primarily at high power operation and will be particularly difficult to control as advanced engine cycles increase combustor inlet and exit temperatures. The emission levels of carbon monoxide and soot in present conventional engines are low at high power conditions, although they can be a problem at low power conditions such as idle. In the design of low NO_x combustors, that which decreases NO_x usually increases CO or soot. However, because of other environmental considerations, carbon monoxide, unburned hydrocarbons, and soot must not be substantially increased.

Concepts that have experimentally demonstrated low emissions include the lean-premixed-prevaporized (LPP), the rich-burn/quick quench/lean-burn (RQL), and the lean-direct injection (LDI) combustors see (fig. 11). The LPP concept for controlling NO_x first appeared in the early 1970's. The principle involves providing a uniform mixture of fuel vapor and air that burns at low temperatures where NO_x formation is a minimum. This provides NO_x emissions that are ultra-low, near theoretical minimum levels. The disadvantages of the LPP combustor concept are that it has narrow stability limits and is subject to auto-ignition and flashback. Emissions data from the LPP flame tube experiments are given in references 12 to 18.

The RQL concept was conceived to control NO_x from fuels containing nitrogen. In a lean burn system, nearly 100 percent of the fuel-bound nitrogen is converted into NOx, whereas in a rich burn system, very little of the fuel-bound nitrogen is converted to NO_x. The rich-burn zone can be thought of as a fuel preparation zone. It is followed by quick mixing with the remaining combustion air in the quench zone. And, finally, in the lean-burn zone the burning process is completed at the relatively low temperatures where thermal NO_x formation is minimum. For fuels not containing nitrogen, the RQL offers the advantages of low NO_x formation and the stability of a rich front end. The disadvantages are the combustor length and complexity due to the quench zone. References 19 to 22 describe the RQL combustor and provide emission data.

In the lean direct injection (LDI) concept, all the combustion air enters the front end, and the fuel is injected directly into the combustion zone. The fuel-air mixture is lean so that the burning temperature and NO_x levels are low. No dilution air is used for cooling or for tailoring of the temperature profile. Although the NO_x levels are slightly higher than the LPP concept, the stability margins are widened using LDI. References 23 to 25 describe the LDI concept and provide emission data.

The NO_x emissions obtained experimentally were correlated for the three concepts by the adiabatic combustion temperature over a wide range of inlet temperatures, pressures, and (lean) fuel-air ratios (see fig. 12 from ref. 26). The NO_x emission index is an exponential function of adiabatic flame temperature. Although inlet air temperature has a strong influence on the emissions from an RQL combustor, there was not a strong effect of inlet temperature for the LPP concept; thus it was not considered an independent variable but is contained in its effect on adiabatic combustion temperature. No definite pressure effect was noticed. The NO_x emissions are also a function of time at the adiabatic combustion temperature; however, a simple correlation of NO_x formation with time was not found.

Comparisons of the three concepts show that the lean-premixed-prevaporized (LPP) concept produces the lowest NO_x emissions. However, the low NO_x potential of LPP is offset by the operational disadvantages of its narrow stability limits and its susceptibility to auto-ignition and flashback.

The rich-burn/quick-quench/lean-burn (RQL) concept has the advantage of good stability because of its rich zone, although variable geometry may be necessary. The higher NO_x emissions (compare with the LPP data) are probably due to the stoichiometric temperatures and production of NO_x during the quench step. Chemical kinetics calculations show that only a small amount of NO_x is produced in the rich zone and that the NO_x produced in the lean zone is approximately the same as the LPP. It is likely that innovative quick-quench mixing schemes can significantly reduce the overall RQL NO_x levels.

The LDI concept produced nearly the same low levels of NO_x as using the LPP concept. A major advantage of the LDI concept is that it has the stability of conventional combustors. These results were obtained primarily with gaseous fuels. Similar trends were found using liquid jet fuel.

The NO_x emissions from conventional diffusion flame combustors are compared with the LPP combustor NO_x emissions in figure 13. The conventional combustor NO_x emissions values are based on the data correlations in table II. The calculations were made by increasing the inlet temperature and exit temperature by the same amount and determining the change in the NO_x emission index. For example, with the GE data the exit temperature plotted is equal to the inlet temperature plus a temperature rise of 790 K. For simplicity, the pressure effect is ignored. The NO_x emission levels are approximately an order of magnitude greater for the conventional combustors than for the LPP flame tube combustors. The reason for this is that in the diffusion flame combustor, the fuel is injected into the primary zone where it is burned at near stoichiometric flame temperatures, then the gas temperature is reduced through the addition of dilution air to the combustor exit temperature. In the LPP combustor, the fuel is burned in a lean mixture at a much lower temperature, which produces less NO_x.

Conventional combustors must operate over the entire duty cycle and thus represent a compromise design that can operate efficiently at both low power and high power conditions. Low NO_x combustors, such as the LPP, have narrow stability limits and will not be able to operate over an entire engine cycle. Thus, staged or parallel burners may have to be used. One approach is the RQL combustor with a rich zone for stability and a lean zone for low NO_x. Another approach, shown in figure 14, incorporates two burners: a pilot stage burner designed for maximum stability for low power conditions and a main stage burner designed for operation at high power conditions. The main stage burner can then be optimized for low NO_x production within its narrow operation range. At low power conditions only the pilot burner is operated, and at high power conditions the main burner will be fueled with or without the pilot burner fueled.

To implement this program we have in-house and contract activities. The effort at Lewis consists of experimental flame tube studies of the LPP and RQL concepts. The flame tube studies will include non-intrusive measurements of fuel injection characteristics and combustion chemistry using laser diagnostics. The flame tubes will also include simulated sector tests.

At the University of California-Irvine, RQL flame tube experiments are being performed in which advanced diagnostics will provide detailed information on combustion processes. To take the technology beyond the flame tube stage to the development of combustors, contracts have been signed with General Electric, Pratt & Whitney, and Allison. The goal of this effort will be to demonstrate, by 1995, combustors that reduce NO_X emissions by 90 percent from uncontrolled levels.

5. COMPUTATIONAL METHODS

The development of computational numerical computer models to predict combustor performance is an area of research at Lewis that has great potential benefits. The advantages of such methods are that they can provide detailed analyses of temperatures and emissions at low cost and with short turnaround times and can be evaluated with actual operating conditions. However, at present, computer modeling of a combustor is a quasi-quantitative tool that can be time-consuming and expensive and requires experienced personnel to operate.

The objective of this effort is to develop and use computer models that will analyze and design combustor components and subcomponents, to understand the physics, and to determine how to optimize the design to improve performance. The approach is to improve code capabilities for modelling the physics and chemistry and to improve the numerical method of solution and then to use test cases and measurements from experiments for code validation.

Two parallel model developments are being pursued at NASA Lewis. One involved a joint NASA/Los Alamos Laboratory program to modify a Los Alamos code (KIVA II). Originally developed for modeling internal combustion engines, it is now capable of modeling gas turbine engine combustors as a result of this joint effort. The other is the development of a new 3D combustor code (ALLSPD). ALLSPD will combine advanced numerics with state-of-the-art physical models for sprays, combustion, turbulence and combustion-turbulence interactions. Presently, a 2D version of the code is available (ref. 27). Work at Lewis continues to provide increased capability for the ALLSPD code, including automated grid generation, more efficient algorithms, improved turbulence models, and extending the code to 3D. KIVA II is the mature code being employed to support experimental programs as well as assist in the design of future advanced low-emissions combustors. KIVA II has been successfully employed to analyze several new combustion concepts (ref. 28). For example, figure 15 shows the temperature distribution in an advanced low-pattern-factor small gas turbine combustor. Figure 16 shows the prediction of a swirling fuel spray in a non reacting air stream using the KIVA II code and a comparison with the experimental results. The predictions agree very well with the data. Fuel injection and mixing become increasingly important as more air is used for the combustion process and less is available for trimming of the temperature profile to the turbine. Detailed models of the interaction of the swirler and the fuel injector can provide valuable insight into the effect of different variables that presently can only be evaluated experimentally on a global scale.

6. CONCLUDING REMARKS

Increased temperatures and pressures will make the aircraft gas turbine more efficient and reduce costs. The increased temperatures and pressures will present new challenges to the combustor design, including combustor durability and acceptability of the pattern factor for the durability of the turbine. The NO_X emissions will also increase as the pressures and temperatures in the combustor increase. New combustor designs that employ staged combustion must be developed if the emissions are to be reduced substantially below the uncontrolled levels. However, it should be kept in mind that even though the emissions are discussed in terms of concentrations or emission index, a more meaningful emission criterion for aircraft application is the amount of pollutant per passenger seat mile. Thus, substantial improvements in emissions per passenger seat mile can be made by increasing the fuel efficiency of the engine even if the emissions are held to their present levels. The goal for future small gas turbine combustors will be to reduce NOx by up to 40-percent of the uncontrolled levels by the end of the century with more significant reductions required for engines entered into service in the years 2005 and 2015. Present high quality fuels should be available for the near future, and thus there is not a current program in fuels research. However, based on previous research, provisions for utilizing lower quality, broader specification fuels should also be considered.

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Table I. - Advanced Fuel Injector Program Test Conditions and Performance Goals

Test Conditions:	
Inlet pressure, MPa	2.5 to 5.0
Inlet temperature, K	750 to 1060
Exit temperature, K	1800 to 2250
Engine size, Kw	1100 to 2600
Performance goals:	
Efficiency (at all power conditions)	>99.95%
Pattern factor	<0.12
SAE smoke number	<25
Lean blow out fuel to air ratio	0.003

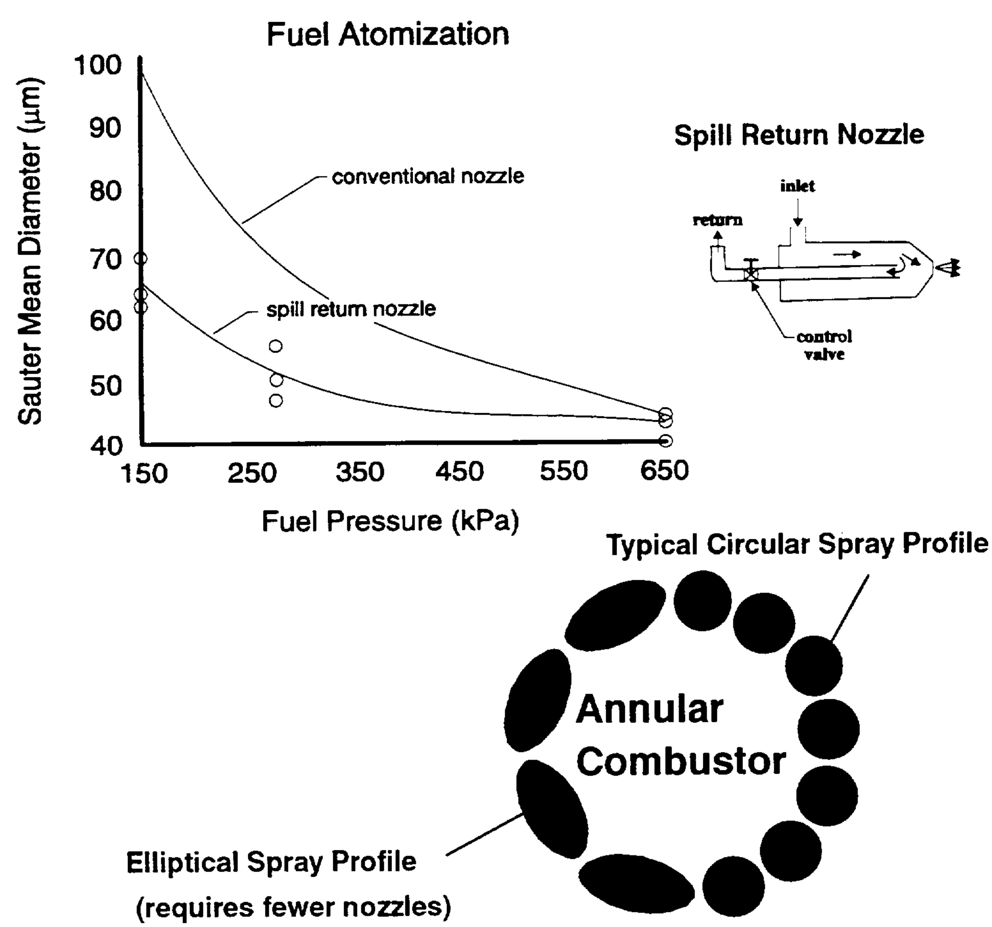


Figure 1. - Spill return fuel injector.

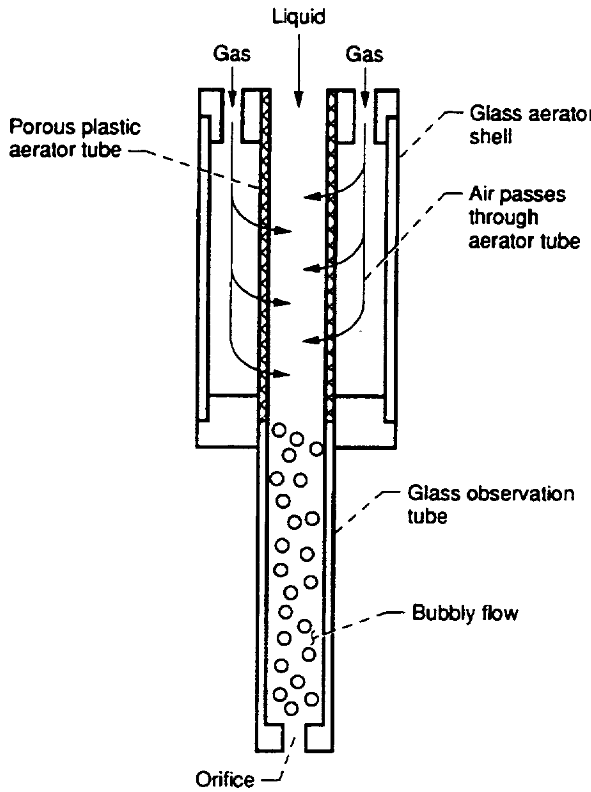


Figure 2. - Effervescent Atomizer

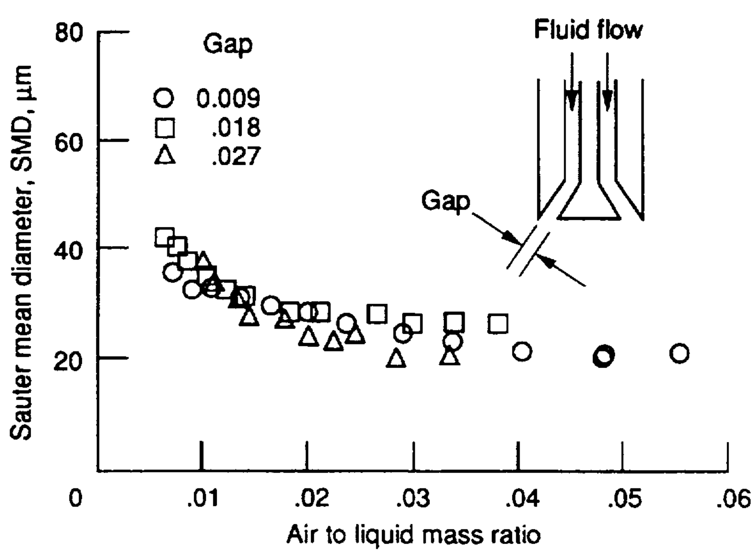


Figure 3. - Droplet Sizes from an Effervescent Atomizer.

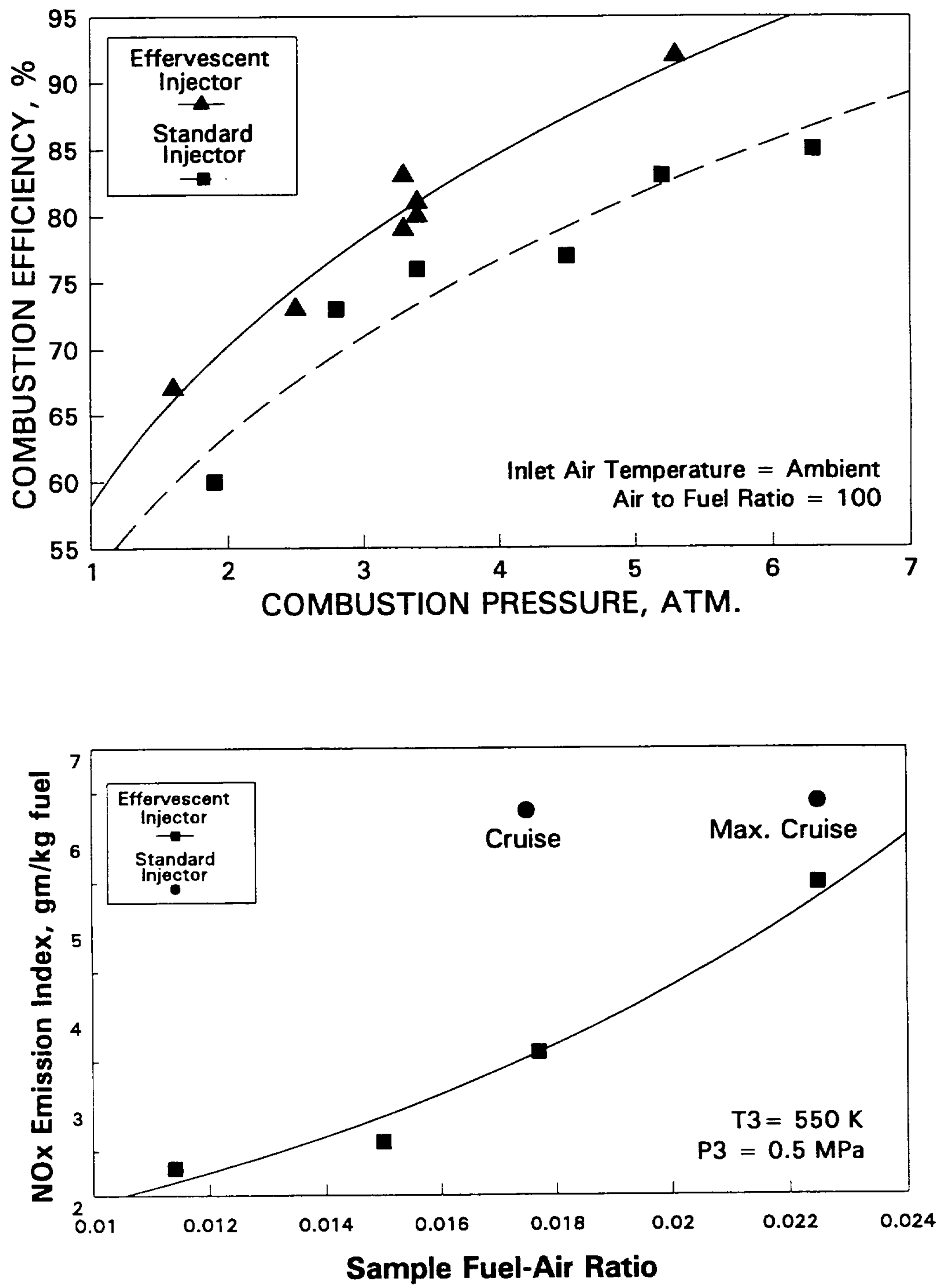


Figure 4. - Comparison of combustion performance between a standard and an effervescent fuel injector in an Allison T56 combustor.

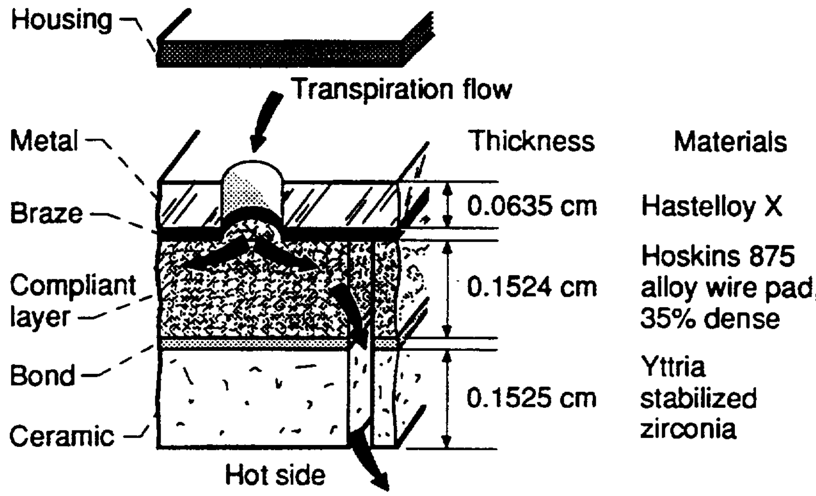


Figure 5.—Compliant metal liner concept.

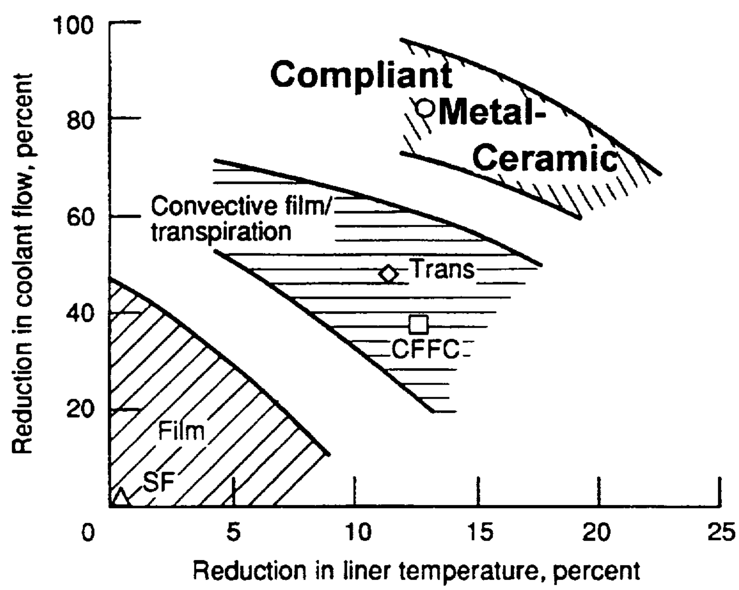


Figure 6.—Comparison of cooling effectiveness of a **compliant metal - ceramic liner, a counterflow** film-cooled (CFFC) liner, a lamilloy (trans) liner, and a splash film (SF) liner.

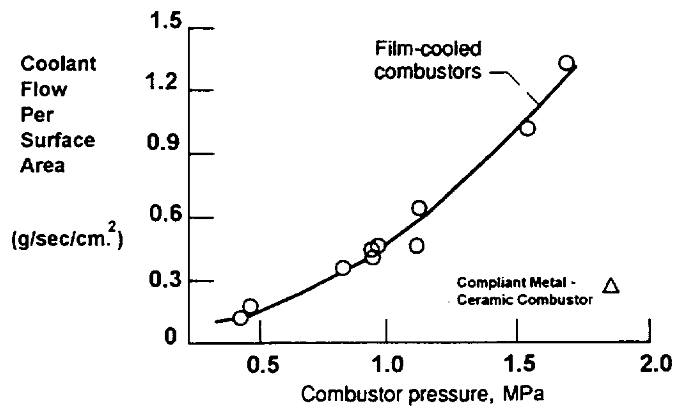


Figure 7.—Comparison of cooling effectiveness of a compliant metal/ceramic liner and a film cooled liner (Allison study).

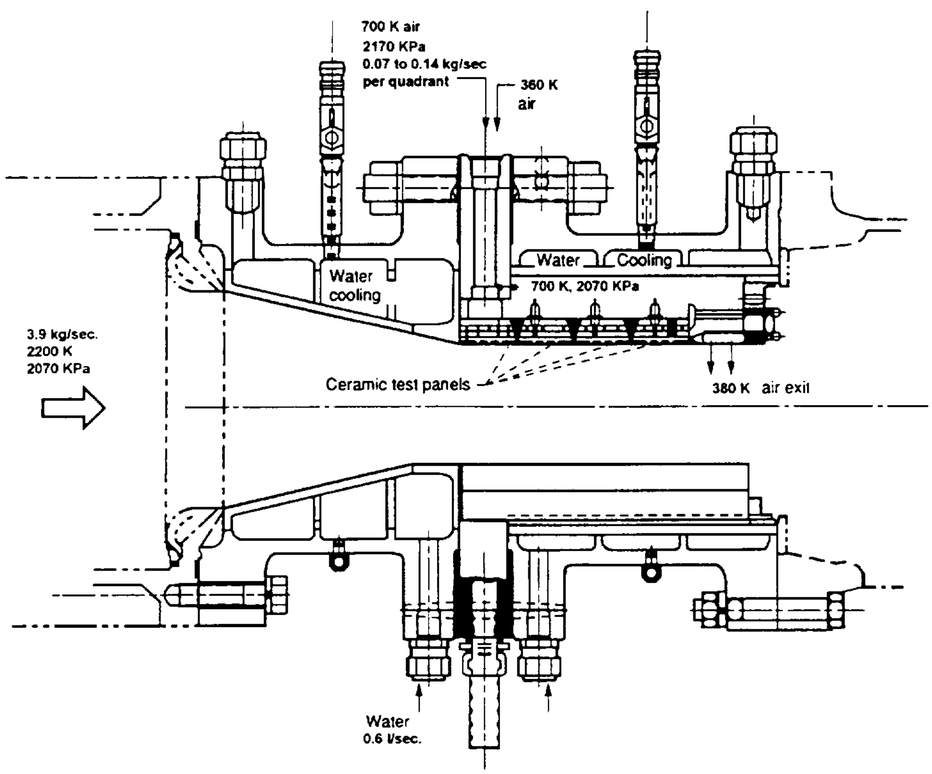
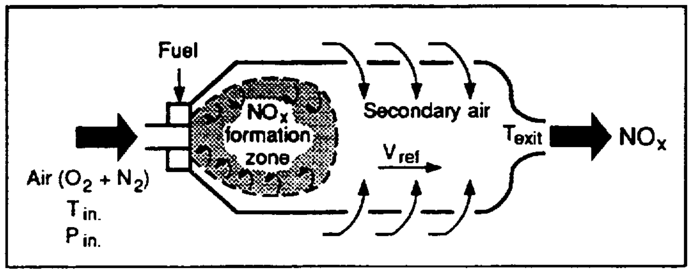


Figure 8.- Liner Test Rig.



Prompt NO_x

- Fast reactions
- Hydrocarbon fragments
- 0 to 1 g/kg fuel (E.I.)
- Uncontrollable

Thermal NO_x

- Slow reactions
- $N + O_2 \longleftrightarrow NO + O$
- $N_2 + 3O \longleftrightarrow 2NO + O$
- Controllable

Correlation: $NO_x \; \alpha \frac{e^{T_{in.}/k} P_{in.}^{1/2} T_{exit}}{V_{ref}}$

Figure 9.—Oxides of nitrogen.

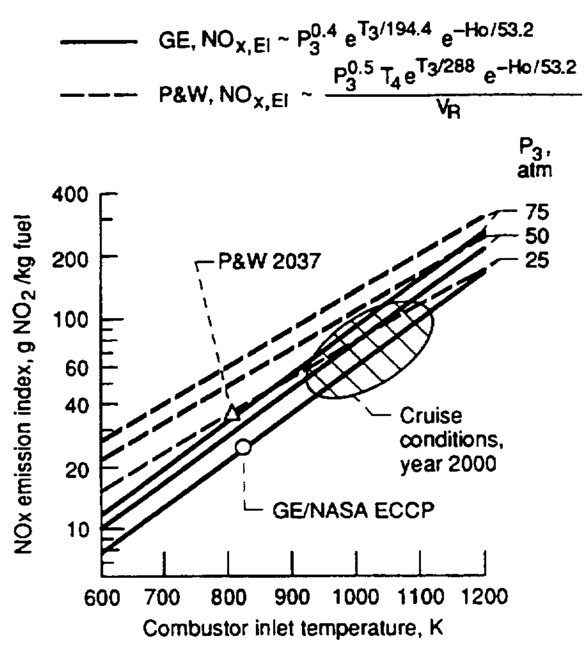


Figure 10.—Oxides of nitrogen as function of combustor inlet temperature and pressure; conventional diffusion flame temperature.

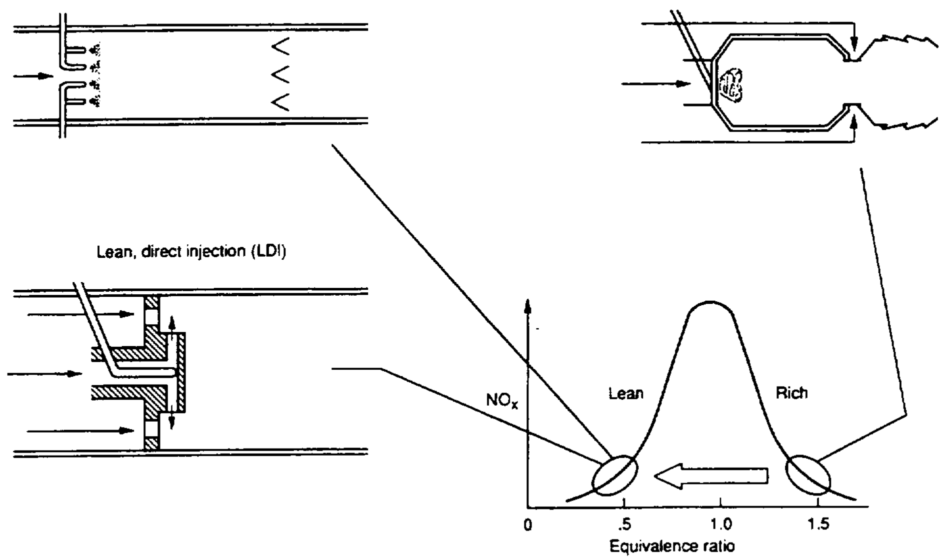


Figure 11.—Low NO$_x$ combustor concepts.

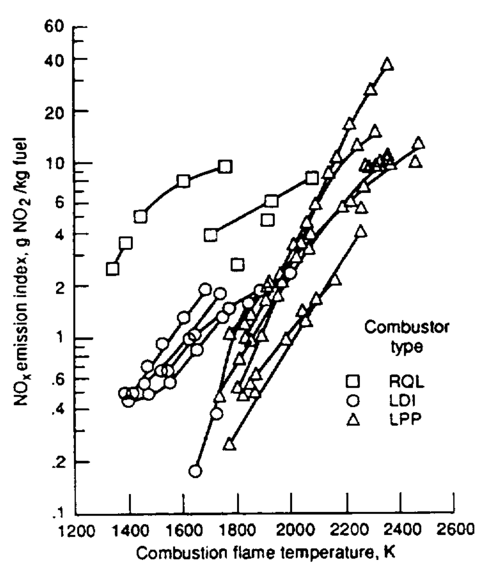


Figure 12.—Oxides of nitrogen from LPP, RQL, and LDI flame tube combustors.

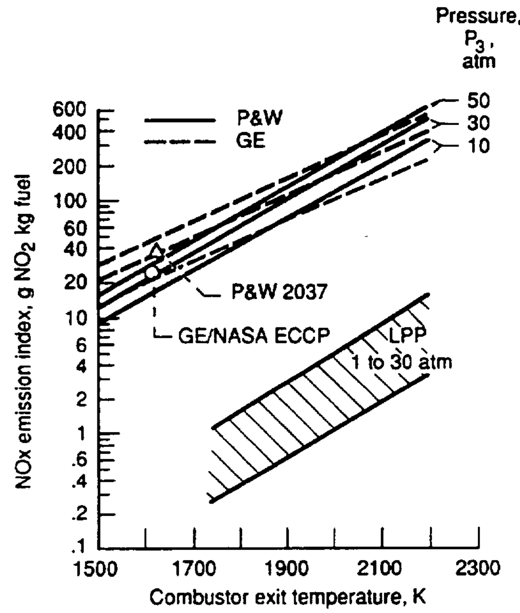
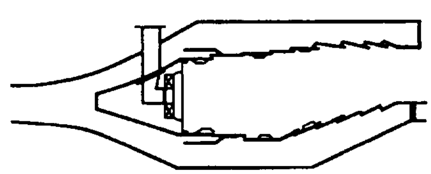
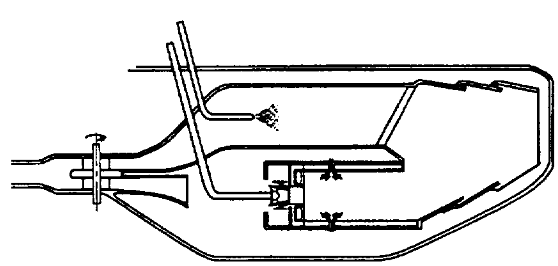


Figure 13.—Comparison of state-of-the-art diffusion flame combustors with LPP flame tube data.



Conventional combustors

Single burning zones, film-cooled louver liners, fuel rich burning zones, single-point fuel injection, fixed geometry



Future combustors

Multiple burning zones, advanced liner cooling, lean burning zones, multiple-point fuel injection, variable geometry

Figure 14.—Comparison of current and future combustors.

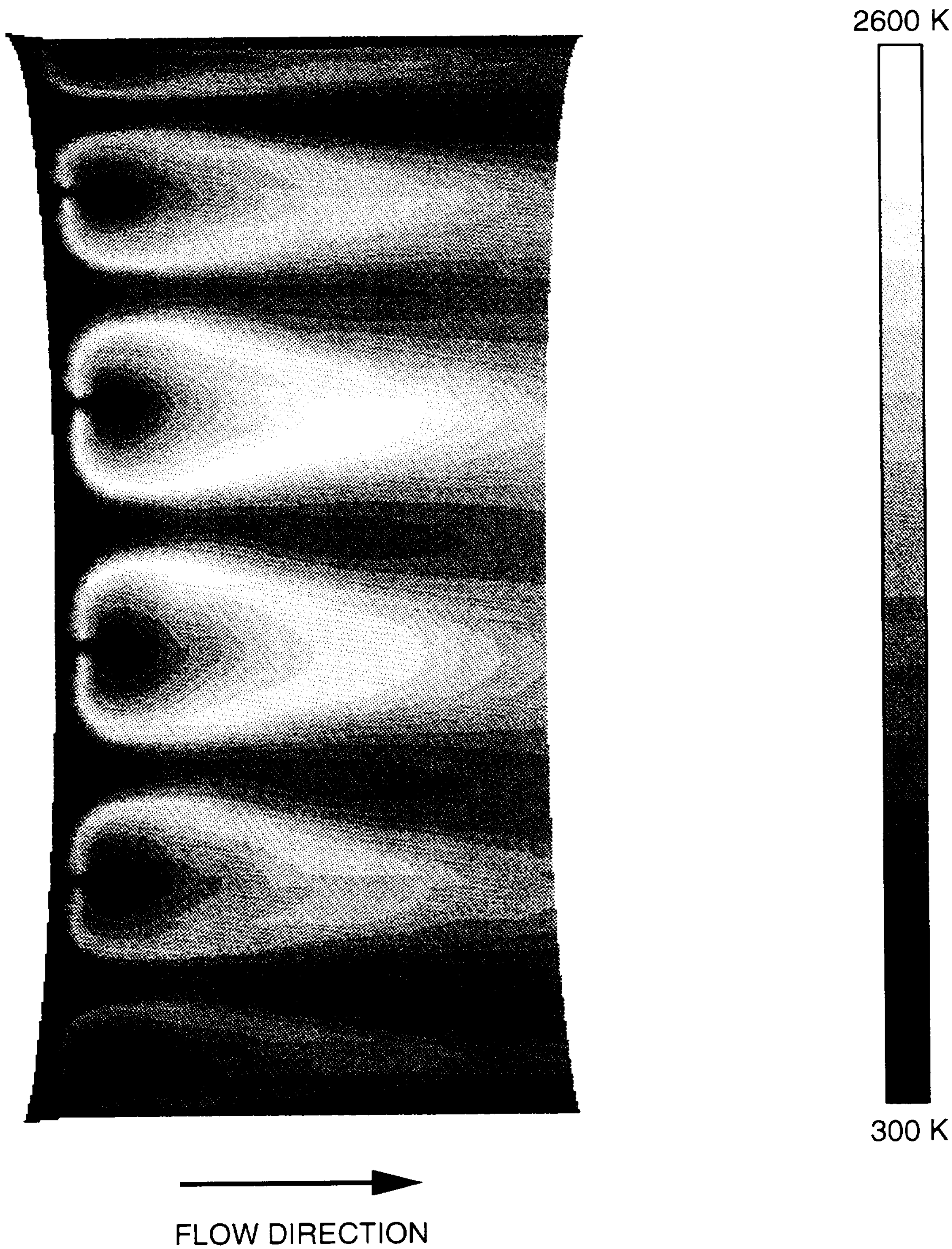
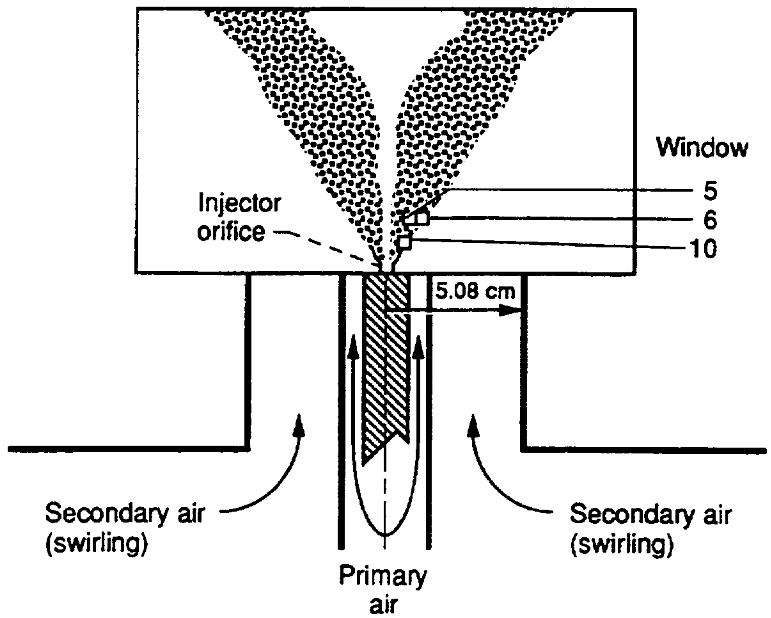
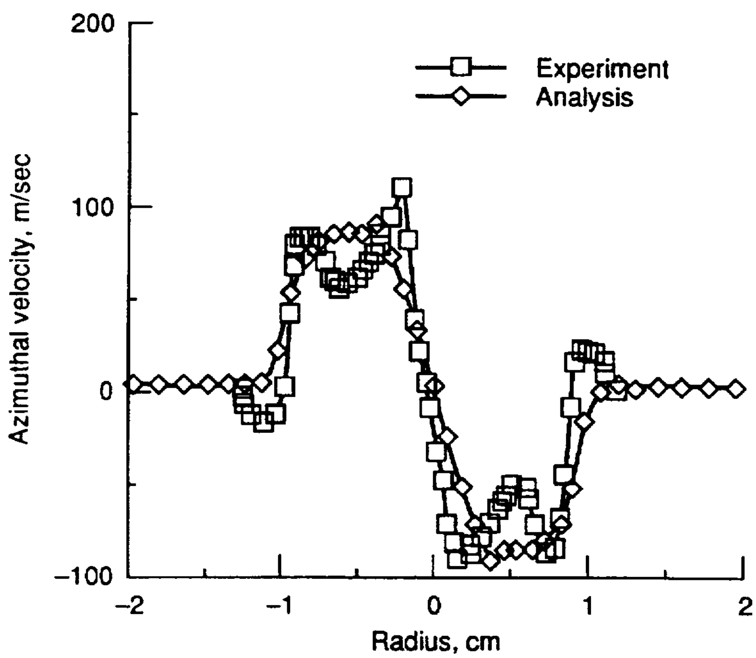


Figure 15. Centerline Temperature Contours in a Small Annular Gas Turbine Combustor.



(a) Experimental rig.



(b) KIVA azimuthal velocity comparison.

Figure 16.—Comparison of experimental fuel spray results with KIVA II code predictions.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT (*Maximum 200 words*)

Future engine cycles proposed for advanced small gas turbine engines will increase the severity of the operating conditions of the combustor. These cycles call for increased overall engine pressure ratios which increase combustor inlet pressure and temperature. Further, the temperature rise through the combustor and the corresponding exit temperature also increase. This report describes future combustor technology needs for small gas turbine engines. New fuel injectors with large turndown ratios which produce uniform circumferential and radial temperature patterns will be required. Uniform burning will be of greater importance because hot gas temperatures will approach turbine material limits. The higher combustion temperatures and increased radiation at high pressures will put a greater heat load on the combustor liners. At the same time, less cooling air will be available as more of the air will be used for combustion. Thus, improved cooling concepts and/or materials requiring little or no direct cooling will be required. Although presently there are no requirements for emissions levels from small gas turbine engines, regulation is expected in the near future. This will require the development of low emission combustors. In particular, nitrogen oxides will increase substantially if new technologies limiting their formation are not evolved and implemented. For example, staged combustion employing lean, premixed/prevaporized, lean direct injection, or rich burn-quick quench-lean burn concepts could replace conventional single stage combustors.

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