Design and Performance Evaluation of a Two-Position Variable Geometry Turbofan Combustor

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Variable geometry combustors offer the potential for reductions in ignition and lean blowout fuel-air ratios required for expanded operational envelopes, while maintaining acceptable levels of combustion efficiency and pattern factor at high-temperature-rise operating conditions. Following a screening procedure that evaluated simulated variable geometry configurations, a variable geometry mechanism was incorporated into the combustion system and test evaluated. The testing included ground level ignition, altitude ignition, stability, combustion efficiency, and discharge temperature quality as functions of three fuels: JP-4, JP-5R, and a blend of JP-5R and DF2. The test conditions were consistent with high-temperature-rise, advanced turbofan engine systems operating over a wide flight envelope. The test results showed a definite improvement in combustion performance and the variable geometry system functioned properly and sealed adequately. The lean blowout fuel-air ratio goal of 0.002 was achieved for the majority of test conditions with JP-4 fuel and the ignition fuel-air ratio goal of 0.008 was achieved for all conditions. The temperature spread factor and combustion efficiency as well as liner temperatures were within the normal operating limits for maximum power conditions. A slight degradation in combustor operating characteristics was noted after changing to JP-5R fuel and further degradation after changing to JP-5R/DF2.

Nomenclature

P = combustor inlet pressure, psia
T = combustor inlet temperature, °F
T_4 = combustor discharge average temperature, °F
T_{4max} = combustor maximum discharge temperature, °F
TSF = temperature spread factor = $(T_{4max} - T_4)/\Delta T$
V = combustor volume, ft^3
V_R = combustor reference velocity, ft/s
W_a = combustor airflow rate, lb/s
δ = nondimensional combustor inlet pressure = $P/14.7$
ΔT = combustor temperature rise, °F
θ = nondimensional combustor inlet temperature, $(T+460)/519$
ϕ = combustor loading parameter = $W_a/\delta^{1.75}$, $Ve^{(T+460)/540}$, lb/s·ft^3

Introduction

CONTEMPORARY production propulsion gas turbine engines employ fixed geometry combustion systems that perform satisfactorily. However, future aircraft demands necessitate the development of higher-performance engines. The current trend in high-performance engines is toward increased turbine inlet temperatures, requiring a higher temperature rise across the combustion system. Associated with the high temperature rise are high combustor fuel-air ratios, which, for some proposed advanced engines, approach stoichiometric conditions. Since combustors are generally designed at maximum power for primary zone operation slightly lean of stoichiometric, the primary zone becomes extremely lean at low-power operation, which adversely affects lean blowout and ignition characteristics, especially at the high-altitude operation. This becomes a more severe problem as the vehicle flight envelopes expand for both unmanned and man-rated applications. Variable geometry and stage burning techniques are considered the best means available for significantly improving stability and ignition performance for future high-temperature-rise combustors.

In November 1978, the Air Force Wright Aeronautical Lab. (AFWAL) and Naval Air Propulsion Center (NAPC) awarded the Garrett Turbine Engine Company a contract for a two-phase variable geometry combustor development program. The objective of this program was to screen various methods for controlling variable geometry and stage burning, followed by a demonstration of an operational variable geometry combustor system based on the best concept identified during the

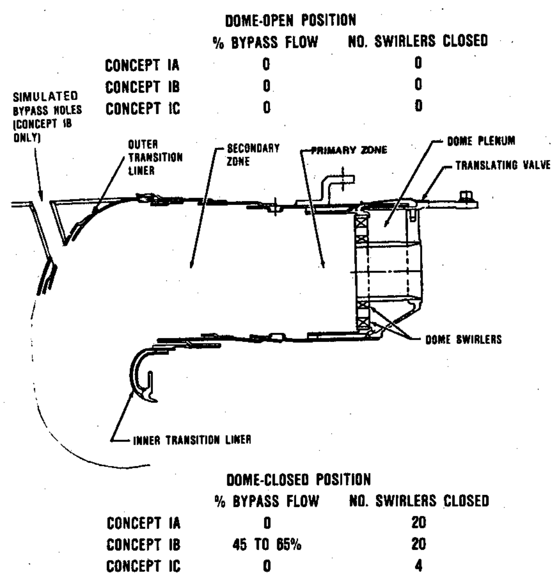

Fig. 1 Concepts IA, IB, and IC with variable geometry open and closed.

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screening process. Initially, advanced liner cooling configurations were part of the program requirements, but these were later dropped due to the associated high development costs.

During phase I of the program, the combustor conceptual screening was completed and the most promising configuration was selected for further evaluation in phase II. The phase I work was presented in detail in Ref. 1, but for continuity a brief summary is included herein. A detailed description of the variable geometry systems and results of tests conducted during phase II of the program are presented in this paper.

Combustor Envelope and Operating Condition Description

Prior to the first phase of the program, a combustor envelope, operating conditions, and program goals were established. A reverse-flow annular combustion system for an advanced turbofan engine was selected due to the improved packaging and reduced shaft dynamic problem associated with the relatively short engine. The operating conditions were consistent with an advanced engine operating over a wide flight envelope:

Combustor inlet pressure	2-400 psia
Combustor inlet temperature	−40 to 1100°F
Maximum to minimum fuel-flow ratio	1600
Maximum to minimum fuel-air ratio	20
Correlating parameter ($V_R\delta\theta$) range	1.5-3600 ft/s
Air loading parameter range	0.2-6.0 lb/s·ft^3

To meet the above combustor operating requirements for advanced missions, the following program goals were established:

Combustion efficiency at maximum power	>99%
Lean blowout fuel-air ratio	<0.002
Ignition fuel-air ratio	<0.008
Temperature spread factor	<0.200

Phase I Summary

During phase I of the program, four variable geometry combustor configurations were evaluated with various forms of staged fuel nozzle burning. The variable geometry system was not duplicated, but was simulated by changing airflow rates in the test rig and moving the variable geometry system between tests, which required rig teardown. All testing was conducted with JP-4 fuel and the ignition limits were inferred from lean blowout test results to eliminate the costly and time-consuming ignition test procedures. This pseudoignition testing was conducted by measuring lean flame stability while approximating windmilling flow conditions. The corresponding lean blowout fuel-air ratio goals were ≤0.004, which was half the allowable ignition fuel-air ratio of 0.008. Gas turbine engine experience has shown the ratio of ignition to lean blowout fuel-air ratio of 2 to be conservative.

Of the four concepts, identified as IA, IB, IC, and II, the three concepts based on configuration I utilized the same combustor liner and fuel injection system but differed in the variable geometry system. Concept I combustor incorporated 20 dome swirlers, each concentric about a piloted airblast fuel atomizer. The liner was cooled using conventional film cooling and the inside of the combustor was coated with a thermal barrier coating. The combustion air was supplied through the airblast atomizers, dome swirlers, and primary jets. To adequately cool the liners and provide the desired primary zone stoichiometry, dilution air was eliminated in concept I.

The differences between concepts IA, IB, and IC are summarized in Fig. 1. Concept IA closed the airflow to the dome swirler and the first panel liner cooling when the variable geometry was closed. Concept IB closed the dome in the same manner as IA, but also simulated opening of the bypass area to maintain an approximately constant combustor flow area. Concept IC did not have the bypass area, as did IB, and closed off airflow to only four of the dome swirlers adjacent to the igniter. Concept IA was eventually rejected because of its high pressure drop at the lean deceleration and altitude ignition condition when the variable geometry was closed. Concepts IB and IC had acceptable pressure drops when the variable geometry was closed. At this condition, the primary zone air was supplied only through the airblast atomizer and primary orifices; concept IC also supplied primary air through the 16 unblocked swirlers.

Concept II was designed to alleviate the complexity of controlling both dome and bypass flow. As shown in Fig. 2, concept II used 14 radial fuel injectors. During ignition, deceleration, and taxi-idle conditions, the pilot pressure atomizers were used and the dome air was shut off by spoon valves at each atomizer location. At high power, the spoon valves were opened and secondary fuel was injected through the airblast portion of the fuel nozzles. The only variable geometry actuation was on the dome of the combustor. There was no bypass provision with this design.

The testing during phase I was mainly concerned with lean blowout and the pseudoignition testing. All four combustors were tested in a high-pressure rig. Stage burning was employed on all the concepts to provide reasonable fuel pressure drop across the pressure atomizers at the extremely low fuel flows associated with lean blowout and altitude ignition operation. Figure 3 shows the nozzle staging arrangement for the 20 nozzle system of concepts IA, IB, and IC and the 14 nozzle system of concept II. All concepts were tested with the simulated variable geometry in the open and closed positions and with the various forms of staged burning. Concept IB was also tested for two bypass flow rates when the dome was closed: 45 and 65% of combustion airflow bypassed.

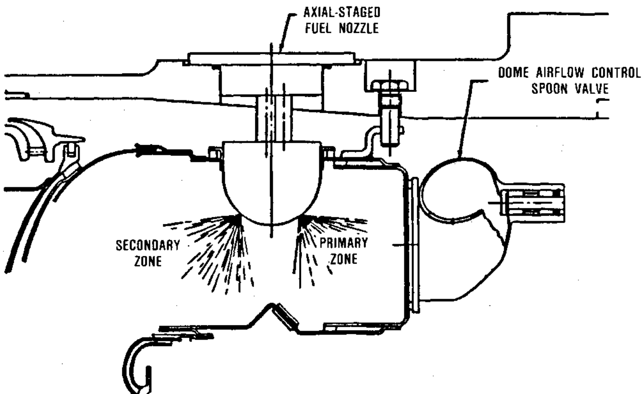

Fig. 2 Concept II schematic.

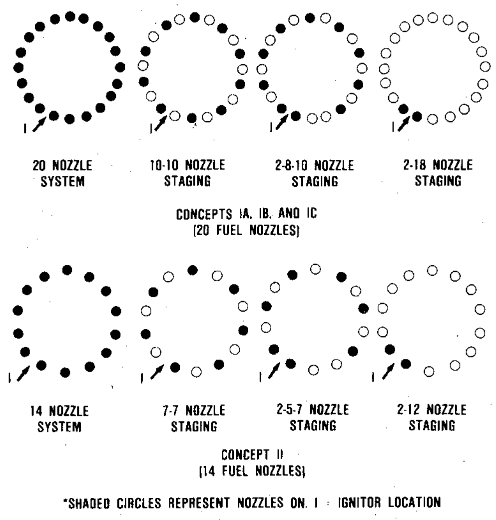

Fig. 3 Fuel staging configurations, concepts IA, IB, IC, and II.

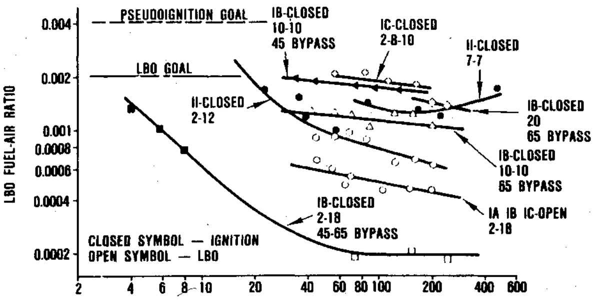

Fig. 4 Phase I, concepts IA, IB, IC, and II lean blowout characteristics.

The lean blowout fuel-air ratios were plotted against the stability correlating parameter $V_R\delta\theta$. Based on a previously conducted study of various correlating parameters, $V_R\delta\theta$ provides the best correlation for ignition and lean blowout fuel-air ratios for a variety of engine operating conditions and combustor configurations. A summary of the lean blowout fuel-air ratios for the best configurations tested is presented in Fig. 4. Of the configurations tested, 11 were equal to or less than the 0.002 goal (VG = variable geometry):

1) Concepts IA, IB, IC: VG closed/2-18 nozzle staging.
2) Concept IB: VG closed/20 nozzle staging (65% bypass).
3) Concept IB: VG closed/10-10 nozzle staging (65% bypass).
4) Concept IB: VG closed/10-10 nozzle staging (45% bypass).
5) Concept IB: VG closed/2-18 nozzle staging (65-45% bypass).
6) Concept IC: VG closed/2-8-10 nozzle staging.
7) Concept II: VG closed/7-7 nozzle staging.
8) Concept II: VG closed/2 = 12 nozzle staging.

Concept IB was the best performing configuration of all the concept I configurations for any of the staged burning in the variable geometry closed position. Concept II performed better than IB will all nozzles flowing and the variable geometry open, but IB had a lower lean blowout fuel-air ratio than II for any staged burning test when the variable geometry was closed and a 65% bypass was simulated.

For the pseudoignition altitude ignition test conditions, the lean blowout fuel-air ratios for concept IB with the dome closed and 2-18 staged burning were below the 0.004 goal and also lower than those measured with concept II with the dome closed and 2-12 staged burning. The major reason for the improvement of concept IB over II was the difference in relative recirculation zone strengths. The primary jet stabilized recirculation zone was much stronger in concept IB and therefore created a higher local primary zone fuel-air ratio than the weaker concept II film-cooling air-induced recirculation zone.

Based on both the lean blowout and pseudoignition testing conducted during phase I, concept IB was selected as the system to be further developed into an actuated variable geometry system in phase II of the program. The phase I testing indicated that variable geometry alone would meet the 0.002 goal for engine deceleration operation, but would require staged burning to meet the goal with adequate margin. Also, staged burning was necessary to meet the 0.004 pseudoignition goal because of the extremely low fuel flow required at the ignition test conditions.

Description of the Phase II Combustor

The design of the phase II combustor was directed toward obtaining the airflow splits simulated during the phase I testing. The bypass orifices were sized to pass approximately 56% of the airflow when the dome was closed. Although the 45% bypass met the goals during phase I, the value of 56% was selected for the phase II design to insure the goals were met even with a slight dome airflow leakage in the variable geometry system. With the variable geometry open, the airflow splits and overall combustor pressure drop were designed to be the same as in the concept I, phase I combustor.

The major goal for the phase II variable geometry mechanism was to design a simple and reliable system that would provide adequate sealing in both the dome and bypass regions. Several concepts were evaluated. The controlling mechanism selected was a set of sliding plates to control both the dome and bypass air feed regions. The system is shown in Figs. 5 and 6. Figure 6 includes some setup blocks required to adjust the variable geometry system prior to assembly into the rig. The variable geometry system was articulated by a single air-operated actuator mounted on the outside of the rig plenum and connected to a translating rod passing through a seal in the dome cap.

The rod was connected to a unison ring supported by carbon rub blocks. The rotating unison ring was connected to four equally spaced bell cranks, which converted the rotational motion of the unison ring into a translating motion in a direction along the combustor axis. The bell cranks were also fastened to the dome seal ring and to rods that were fastened to the bypass seal ring. The bell cranks provided an opposite motion to the dome and bypass seal rings. As the dome seal moved away from the combustor, thus opening the dome, the bypass seal moved toward the transition liner and closed the bypass area. The bypass actuation rods were supported and located by mounts in the combustor outer plenum.

In the dome area, the sliding seal rode on two piston rings, both fore and aft. The piston rings were sized to provide a tight seal since leakage in the dome area was known to greatly affect the lean blowout and altitude ignition operation. A single piston ring seal was used in the bypass area since leakage was not as critical in this area. The number of piston rings was kept to a minimum to reduce the drag force on the system. Flexible links were provided to compensate for misalignment between hot and cold running.

The dome seal/ring-controlled area opened a plenum feeding the first panel cooling slots and the swirlers. Airflow to the fuel nozzle was not affected by the variable geometry. The bypass variable geometry also fed a plenum to which 60 tubes were connected. The 60 tubes, located in the transition liner, allowed bypass flow to pass when the dome was closed.

Phase II Test Results

The testing conducted on phase II of the program included sea-level and altitude ignition testing and sea-level lean blowout and performance testing. Various staged burning concepts were evaluated and fuel effects were quantified by using three different types of fuels: JP-4, JP-5R, and a blend of JP-5R and DF2 (JP-5R/DF2).

Altitude Ignition Testing

The combustor rig was tested in the altitude test facility to perform altitude ignition tests at actual combustor inlet temperature and pressure. Three of the test points were at a combustor rig inlet pressure of 2 psia. All fuels were evaluated with a pilot fuel atomizer system that consisted of two fuel atomizers adjacent to the igniter. The other 18 nozzles were disconnected from the fuel supply (2-18 staged burning). Six test points representative of altitude ignition conditions were evaluated. The test procedure consisted of setting a fuel-air ratio of 0.007, which was 0.001 below the goal, and determining whether or not a successful ignition occurred within 1 s. Time measurement began when full fuel manifold pressure was attained. If ignition did not take place within 1 s, the fuel-air ratio was increased to 0.008 and the procedure was repeated.

The results of the 2-18 staged burning tests with variable geometry closed are shown in Table 1. Successful ignition (fuel-air ratio 0.008, time 1.0 s) was observed at all six test points on JP-4. Successful ignition was observed on five of the test points with JP-5R. With JP-5R/DF2, successful ignition was observed on three of the test points. The ignition points where the goal was not achieved corresponded to the higher altitude, lower combustor inlet pressure test conditions.

Fuel properties control the ignition process to a certain extent. Of the three fuels, JP-4 has the lowest values of viscosity and surface tension, which results in better fuel atomization for a given fuel injector. Better atomization produces smaller droplets, resulting in a higher surface-area-to-volume ratio, which creates a larger surface area for evaporation to take place. Also, the lower (10%) recovery temperature of JP-4 aids evaporation. Thus, JP-4 produces vaporized fuel at a faster rate and ignites more easily.

In addition to the 2-18 staged burning, limited altitude ignition tests were run with the full 20 nozzle system. These tests were run on JP-4 fuel only. Table 2 shows the results of the 20 nozzle system tests. The required fuel-air ratio for ignition with this fuel manifold was approximately five times as high as 2-18 staged burning for both test points and did not meet the program goals.

The higher ignition fuel-air ratios required with the 20 nozzle system were attributed to poor atomization considerations. For the JP-4 fuel results with 2-18 staged burning, the fuel pressure differentials were greater than 100 psid for test points 3, 5, and 6. This produced good fuel atomization and successful ignition at fuel-air ratios of 0.008 and less. For the 20 nozzle system, a fuel pressure differential of only 32 psid was measured for a fuel-air ratio of 0.0395 at test point 3. For the pressure atomizing fuel injectors used in these tests, a fuel pressure differential of approximately 50 psid was required to insure a sufficient degree of atomization for ignition. The staged burning increased the fuel pressure for a given fuel flow, thus producing better atomization and ignition performance at the altitude ignition conditions.

Following the altitude ignition tests, the combustion rig was placed in the sea level combustion facility to evaluate sea-level ignition. Between the altitude and sea-level ignition and lean blowout tests, the taxi-idle and part-power tests were conducted. Running the combustor at elevated temperatures caused the piston ring holder, which was welded to the dome at 10 equally spaced locations, to expand and bow radially outward. The distorted condition of the piston ring holder allowed air to leak into the dome and swirlers, drastically affecting the ignition tests with the variable geometry closed. This problem was initially identified after an ignition fuel-air ratio of 0.009 was achieved with the 10-10 staged burning. The sea-level ignition tests were repeated after sealing the separated area. Using a 10-10 staged burning configuration, ignition fuel-air ratios of 0.00652, 0.00590, and 0.00532 were obtained with JP-4, JP-5R, and JP-5R/DF2 fuel, respectively. These fuel-air ratios were all below the 0.008 goal.

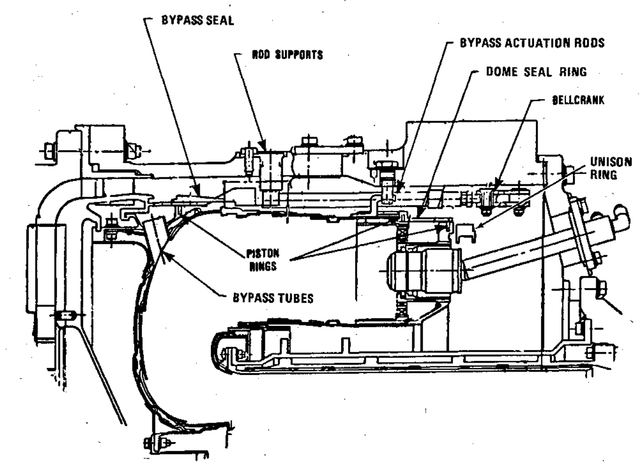

Fig. 5 Phase II variable geometry combustor, concept IB, as installed in test rig.

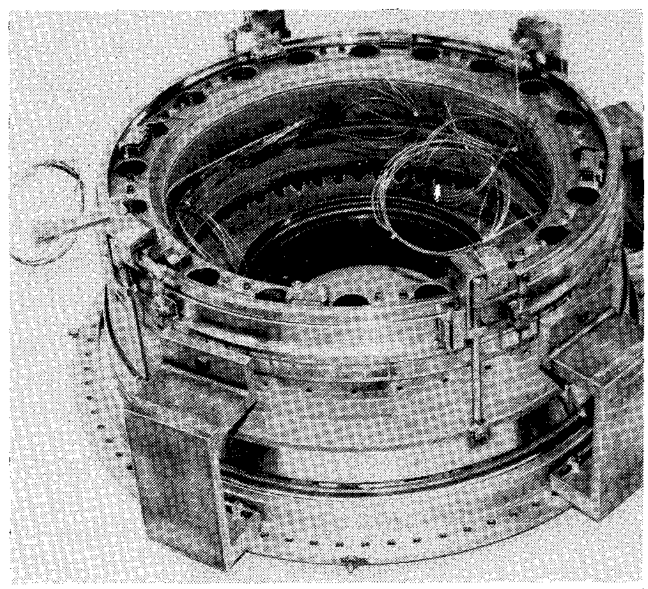

Fig. 6 Variable geometry combustor with linkage adjustment blocks.

Table 1 Staged burning altitude ignition data (2-18 VG closed)

Test point	Ignition[a] JP-4	JP-5R	JP-5R/DF2	Fuel-air ratio JP-4	JP-5R	JP-5R/DF2	P_F, psid JP-4	JP-5R	JP-5R/DF2
1	I	NI	NI	0.0079	—	—	32	—	37
2	I	I	NI	0.0078	0.0078	—	63	43	—
3	I	I	I	0.0079	0.0080	0.0051	121	80	59
4	I	I	NI	0.0076	0.0075	—	89	59	—
5	I	I	I	0.0045	0.0045	0.0067	119	79	167
6	I	I	I	0.0070	0.0085	0.0065	164	166	76

[a] I = ignition, NI = no ignition.

Table 2 Altitude ignition data (20 nozzles VG closed)

Test point	Ignition[a] JP-4	JP-5R	JP-5R/DF2	Fuel-air ratio JP-4	JP-5R	JP-5R/DF2	P_F, psid JP-4	JP-5R	JP-5R/DF2
5	I	—	—	0.0218	—	—	42	—	—
3	I	—	—	0.0395	—	—	32	—	—

[a] I = ignition.

Table 3 Performance test summary

Fuel type	Power setting	Combustion efficiency, %	Max liner temperature,[a] °F	Measured fuel-air ratio	Temperature spread factor
JP-4	Idle	97.2	—	0.0134	0.45
JP-5R	Idle	95.1	—	0.0133	0.53
JP-5R/DF2	Idle	91.3	—	0.0133	0.65
JP-4	Part	99.9	—	0.0307	0.29 at 2261 avg
JP-5R	Part	99.9	—	0.0306	0.29 at 2221 avg
JP-5R/DF2	Part	99.9	—	0.0302	0.28 at 2183 avg
JP-4	Max	99.8	Paint 1650 T/C 1680	0.0349	—[b]
JP-5R	Max	99.7	Paint 1700 T/C 1750	0.0366	—[b]
JP-5R/DF2	Max	99.6	Paint 1650 T/C—	0.0415	—[b]

[a]Thermal sensitive paint, T/C = thermocouple. [b]Thermocouple data at maximum power could not be collected and the emissions data were not collected in sufficient detail to calculate pattern factor.

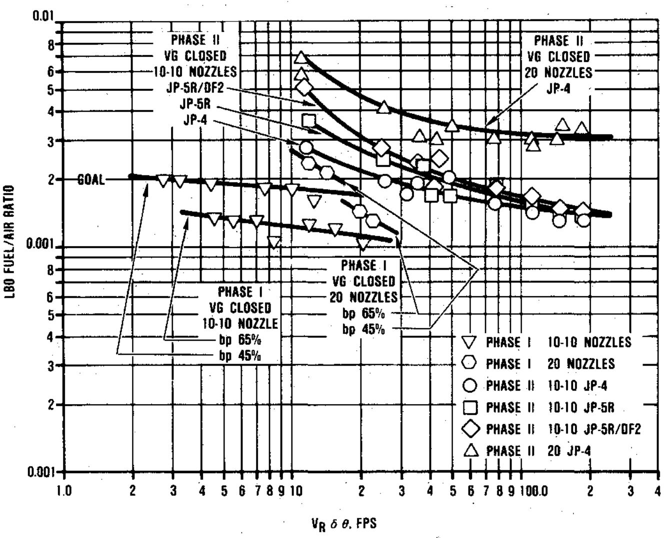

Fig. 7 Lean blowout mapping fuel-air ratio vs blowout correlating parameter.

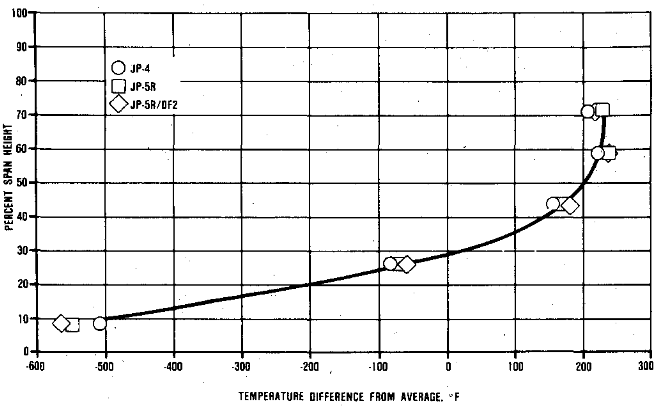

Fig. 8 Effect of fuel properties at derated part power.

During phase I testing, the altitude ignition results were deduced from lean blowout tests at ambient air temperatures to reduce time and cost. These were referred to as "pseudoignition" tests. To correlate results, it was assumed that the pseudoignition fuel-air ratio would be equivalent to half the altitude ignition fuel-air ratio. To verify this assumption, during phase II, a pseudoignition test was included with the sea-level ignition. For all three fuels, the pseudoignition fuel-air ratio was approximately half the altitude ignition fuel-air ratio, as was previously assumed.

Lean Blowout Testing

Lean blowout combustor tests were performed in the high-pressure combustor cell. The lean blowout testing consisted of running 10 conditions using 10-10 staged burning for all three fuels. The 20 nozzle system was also tested on JP-4 only. All testing was conducted with the variable geometry mechanism in the closed position. Results of the phase II lean blowout mapping and the phase I data are shown in Fig. 7. The lean blowout fuel-air ratios measured during phase II mapping were higher than the phase I values. These higher values were attributed to the dome swirler air leakage caused by the bowed piston ring holder, as previously described.

Lean blowout mapping was not repeated since the checkout lean blowout testing has already verified that the phase II configuration met the program goal of a 0.002 fuel-air ratio. However, the lean blowout mapping was useful in comparing the effect of staged burning and fuel property effects on the lean blowout fuel-air ratio. Referring to Fig. 7, the 10-10 staged burning and the 20 nozzle system data, taken while using JP-4 fuel, were nearly parallel lines, with the 20 nozzle system producing much higher values. Reducing the number of fuel nozzles by half created a fourfold increase in fuel-nozzle pressure drop for a fixed fuel flow, which allowed better atomization.

Performance Testing

Performance testing of the variable geometry combustor was conducted in the high-pressure combustion facility. Three power settings were tested (maximum, part, and taxi-idle power) using three fuels, resulting in a total of nine test conditions.

The information recorded during the performance testing was dependent on the power setting. At the taxi-idle and part-power points, combustion efficiency and temperature spread factor were measured; at maximum power, the combustion efficiency and wall temperatures were recorded. The temperature spread factor could not be measured at maximum power due to temperature/structural limitations of the thermocouples at the high discharge temperatures. At taxi-idle and part power, the temperature spread factor was recorded using five platinum/platinum/10% rhodium thermocouples mounted on a rotating drum that was indexed through 360 deg in 10 deg increments. The fuel-air ratio was increased and the temperature spread factor recorded until a peak gas temperature of 2800°F was reached. At the maximum power setting, the liner temperature was recorded using skin thermocouples and thermal sensitive paint. The maximum power testing was intended to be run by increasing the fuel-air ratio until a wall temperature of 1750°F, as indicated by thermocouples, or the desired fuel-air ratio was attained. A value of 1750°F maximum wall temperature was selected to insure that no damage to the liner would occur. During the initial testing with JP-4, the wall temperature goal was lowered to 1680°F, as this was the first time the test rig had been operated at maximum power and there was some uncertainty as to whether the wall thermocouples were located at the maximum-temperature locations. The JP-5R and JP-5R/DF2 fuel testing at maximum power was conducted as originally planned.

Table 3 summarizes the data from the performance testing. The taxi-idle combustion efficiency was 97.2% for JP-4 fuel, with a decrease to 95.1 and 91.3% for the JP-5R and JP-5R/DF2 fuels, respectively. This reduction was attributed to the lesser spray quality and vaporization characteristics previously discussed. The temperature spread factor at idle also indicated greater fluctuations and higher peak discharge temperatures for the JP-5R and JP-5R/DF2 fuels.

The part-power combustion efficiency of all three fuels was greater than 99.9%. At the higher inlet temperature and hot primary zone temperature of part power, compared to taxi-idle power, the burning process was not limited by the evaporation rate, but was mixing limited. The slight variation in temperature spread factor was more a function of the variation of the fuel-air ratio than of the fuel type. The effect of fuel type on the temperature spread factor was minimal at part power, as shown by the comparison of radial temperature profiles in Fig. 8. In Fig. 8, the deviation from the average discharge temperatures is plotted as a function of radial span height at the transition liner discharge for the three fuels. These results indicate that the variation due to fuel properties was negligible.

Combustion efficiency at the maximum power point was not affected by fuel type. The slight change in the combustor efficiency was attributed to the differences in fuel-air ratio. The fuel-air ratio was high enough that the ability of the fuel to mix with fresh air became the reaction-limiting factor. As the fuel-air ratio was increased, the fuel had a more difficult time competing for the available oxygen, resulting in a lower combustion efficiency. Temperature spread factors were not recorded since the discharge temperature was too high to be measured using the thermocouple rake.

The liner wall temperatures recorded were in the range of 1300-1400°F average, with hot spots of 1650-1700°F. A significant liner temperature increase would be expected for the JP-5R/DF2 blend based on its higher aromatics content (29.1%) as compared with the JP-4 (16.3%) and JP-5R (16.2%). Also, the JP-5R and JP-5R/DF2 are heavier fuels with higher average distillation temperatures, often associated with increased combustor liner temperatures. The hydrogen contents of the three fuels, however, were quite similar, 13.49-13.73% for the three fuels. This would imply that the combustor liner temperatures would not differ greatly.

Past researchers[2,3] have found combustion wall temperatures to correlate quite well with hydrogen content, which affects the luminosity of the flame and, in turn, alters the radiation heat loading on the combustor liner. For the combustor in question, it was apparent that the hydrogen content of the fuel was a better predictor of combustor liner temperature than either the aromatics content or the average distillation temperature.

Normally, aromatics and hydrogen contents correlate reasonably well. However, the aromatics content measurement method[4] considers a fuel molecule to be aromatic if the molecule contains one or more aromatic rings. For a JP-5 or diesel fuel with an average molecular carbon number of 12-14, the hydrogen content can vary greatly depending on whether or not the molecule is an alkylbenzene (single aromatic ring) or a polycyclic aromatic (multiring) molecule. For example, a 14-carbon number molecule having a single aromatic ring with an attached paraffinic side chain would have a hydrogen content of about 11.6% by mass. A 14-carbon number molecule that is 100% aromatic (i.e., all 14 carbon atoms are in the aromatic rings) would have a hydrogen content of only about 5.6% by mass. Thus, aromatic measurements of fuels can be quite misleading in terms of their combustion performance.

Conclusions

A variable geometry combustor, along with staged burning, allowed lean blowout and altitude ignition fuel-air ratio goals of 0.002 and 0.008, respectively, to be met for a majority of lean deceleration and altitude ignition test points using JP-4, JP-5R, and JP-5R/DF2 fuels. Adequate combustion efficiency at taxi-idle and acceptable temperature spread factor at high power were also demonstrated.

The combustion efficiency, wall temperature, and temperature spread factor were all within acceptable limits. The fuel properties had no measurable effect on the combustor operation at part and maximum power. At the taxi-idle power setting, there was a slight decrease in combustor efficiency with the heavier, more viscous fuels. The major effect of the fuel type was found during the ignition and lean blowout testing, especially at the low values of the correlation parameter, $V_R\delta\theta$. The JP-5R and JP-5R/DF2 volatility and viscosity adversely affected the combustor operation to the extent that the lean blowout and altitude ignition goals were not met at the lower $V_R\delta\theta$ operating conditions. All goals were met using JP-4 fuel, except for the lowest $V_R\delta\theta$ test conditions.

The variable geometry combustor system operated satisfactorily during the test program. The piston ring holder mounted on the dome of the combustor warped and bowed after high-temperature operation. This problem could be resolved by improving the mechanical design, such as by matching thermal growths more accurately and/or by fastening the piston ring holder to the combustor in a continuous manner, rather than locally, as was done for the rig testing. Meeting the program goals with variable geometry alone was not possible for the system tested, but when the variable geometry system was used in conjunction with staged burning, the majority of the program goals were achieved.

The test conditions selected were consistent with high-temperature-rise advanced turbofan engine systems operating over a wide flight envelope. The performance of the combustor was evaluated along with the durability and sealing of the variable geometry controlling devices. The test results showed a definite improvement in combustion performance and the variable geometry system functioned properly and sealed adequately. The lean blowout fuel-air ratio goal of 0.002 with JP-4 fuel was achieved except for the extreme high-altitude condition and the altitude ignition fuel-air ratio goal of 0.008 was achieved for all conditions. Pattern factor and combustion efficiency as well as liner temperatures were within normal operating limits for the maximum power conditions. A slight degradation in combustor operating characteristics was noted after changing to JP-5R fuel and further degradation after changing to JP-5R/DF2.

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