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Design and Verification of a Turbofan Swirl Augmentor

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Basic research has indicated that flamespreading velocities well in excess of those attainable through conventional turbulent flamespreading techniques can be obtained through application of a strong centrifugal field. The use of this concept in turbojet/turbofan augmentors offers potential for improved performance and reduced augmentor length. In the augmentor application, the strong centrifugal field is generated by swirling the flow with vanes at the augmentor inlet, hence the name, swirl augmentor. An annular pilot burner on the outer diameter of the augmentor provides a continuous ignition source. In operation, the hot pilot gases are displaced towards the center of the swirl by buoyant forces. As the hot pilot gases move into the mainstream, they ignite the mainstream fuel-air mixture. The resulting hot gases are likewise buoyed towards the center until the entire stream is burned. No flameholders are required in the swirl augmentor since the radial motion of the hot pilot gases and subsequent combustion product provide a continuous ignition source across the stream. A full-scale swirl augmentor has been designed and evaluated at sea level conditions for an existing augmented turbofan engine to enable direct comparison of swirl and conventional augmentor performance characteristics. More than 20 h of augmentation have been recorded at sea level and altitude on an F100 turbofan engine as the testbed. Test results are presented that validate the concept application.

Nomenclature

C_{vp} = peak thrust coefficient
C_{vpo} = ideal peak thrust coefficient with no swirl
P = pressure, psia
P_{AB} = afterburner pressure, psia
S_O = observed flamespread, ft/s
T_{FAN} = afterburner cold-side temperature, °F
α_I = augmentor inlet swirl angle, deg
α_E = theoretical exit swirl angle, deg
Δ = difference or decrement
ϕ = equivalence ratio

Introduction

IN the military application of high thrust-to-weight ratio turbofan engines for advanced fighter aircraft, additional thrust is usually required during the mission scenario for takeoff, acceleration, and maneuvering. This additional thrust is generated by employing a thrust-augmentation system called an afterburner. The afterburner on a turbofan engine is usually configured to: 1) accept all the hot turbine-discharge flow and all the cold fan-stream air except for liner and nozzle-cooling flow; 2) attempt to thoroughly mix the two streams; 3) add additional fuel to the vitiated core air and the unvitiated fan air; and 4) combust with high combustion efficiency at temperatures approaching stoichiometric. Augmentation systems in turbojets have been in use for more than twenty years employing the basic flameholding technology depicted in Fig. 1 and summarized by Ozawa.[1] A flameholder system creates a low-velocity recirculating air region that allows flameholding and propagation in what is generally a very high-velocity stream. Since the advent of augmented turbofan engines, much effort has been expended to apply the same concept to the two-stream problem as described by Marshall et al.,[2] with the intent of maximizing combustion efficiency and thrust while minimizing the associated stability problems. These stability problems arise from the requirement to mix the two streams, and distribute and vaporize jet fuel, such as JP-4, to form a uniform fuel-air mixture for efficient combustion. In the flight regime where the fan-stream airflow is cold (i.e., 200 to 300°F) and the pressure is low (i.e., 6 to 12 psia), normally referred to as the upper left-hand corner of the flight operating envelope, jet-fuel vaporization is poor. Hence, uniform gaseous fuel-air mixtures are nonexistent, and two-phase mixtures create ignition and combustion problems that may result in rumble blowouts as discussed by Ernst.[3] Other important performance characteristics of turbofan augmentors that require optimization include smooth modulation, low pressure loss, low weight, and short length.

In recent years, new ideas to enhance mixing and burning in two-stream (turbofan) systems have emerged and have been verified to the point of full-scale concept development. One system is called the VORBIX, an acronym for Vortex Burning and Mixing, and relies on the introduction of swirling jets to create high-rate mixing and burning mechanisms. This concept is presented in detail by Reilly et al.,[4] and is under a full-scale development test contract with the Naval Air Propulsion Center, Trenton, N.J. Another recent development in augmentors is the full-swirl augmentor depicted in Fig. 2 and contrasted to a conventional or flameholder-type augmentor. Note that no flameholders are required for the swirl augmentor. The initial conceptual development is traced by Lewis et al.,[5] from combustion-centrifuge testing through subscale single-stream (turbojet) rig verification. This paper extends that work and discusses the details of the design and verification testing of a full-scale swirl augmentor at sea level and altitude. Results of rig testing of this full-scale swirl augmentor on an F100 engine, which are very encouraging, and future development plans are presented.

Experimental Justification

Basic research has indicated that flamespreading velocities well in excess of those attainable through conventional turbulent flamespreading techniques can be obtained through the

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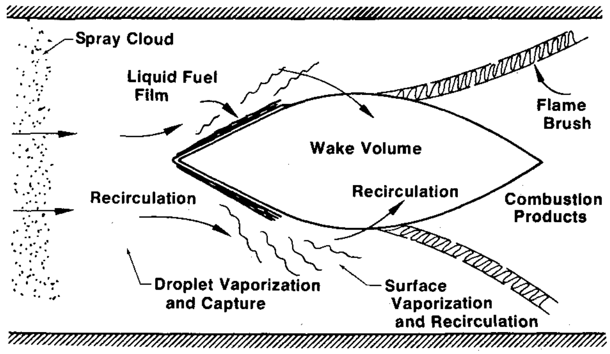

Fig. 1 Ducted flameholder model at cold inlet temperatures.

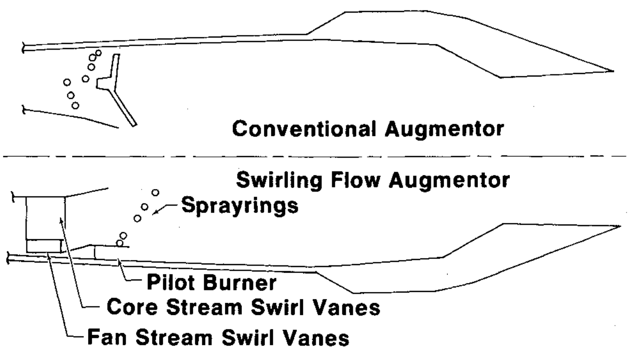

Fig. 2 F100 augmentor compared to swirl augmentor.

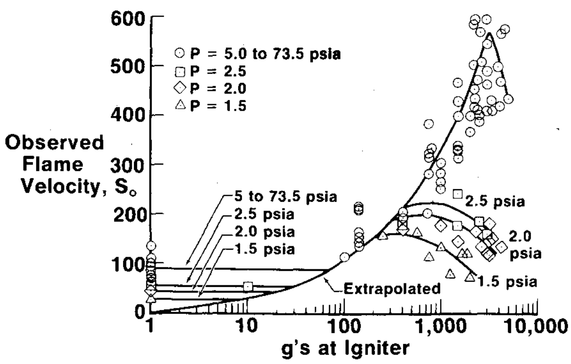

Fig. 3 Pressure effect on flamespreading rate for propane in a combustion centrifuge (Ref.8).

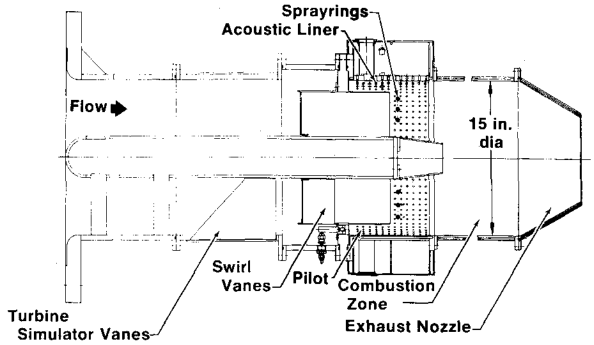

Fig. 4 Single-stream swirl-augmentor test rig.

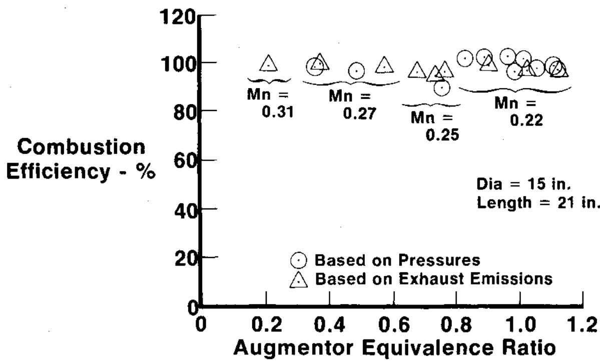

Fig. 5 Swirl-augmentor rig demonstrates high combustion efficiency.

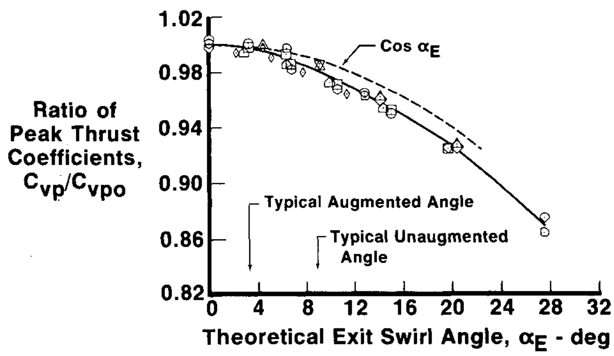

Fig. 6 Effects of swirl on exhaust-nozzle thrust coefficient.

application of a strong centrifugal force field. This hypothesis was first demonstrated in the combustion centrifuge experiments of Lewis,[6-8] which conclusively showed a greater than fivefold increase in observed flamespeed with a centrifugal force of up to 3500 g's (Fig. 3). Experimental data also showed no variation in observed flame velocity with pressure above 5 psia. A rapid falloff was found above 3500 g's and further testing above 3500 g's was limited by the test apparatus.

In the augmentor application, the strong centrifugal field is generated by swirling the flow with vanes at the augmentor inlet, hence the name swirl augmentor. An annular pilot burner on the outer diameter of the augmentor provides a continuous ignition source. In operation, the hot pilot gases are displaced towards the center of swirl by buoyant forces. As the hot pilot gases move into the mainstream, they ignite the mainstream fuel-air mixture. The resulting hot gases are likewise buoyed towards the center until the entire stream is burned. No flameholders are required in the swirl augmentor since the radial motion of the hot pilot gases and subsequent combustion products provides a continuous ignition front across the stream. The concept was first verified in a subscale turbojet augmentor rig (Fig. 4) where high combustion efficiency was obtained in a short length.[9] Combustion efficiency was high over a wide range of equivalence ratio and inlet Mach number as shown in Fig. 5.

In another experimental program the effect of swirling flow on exhaust nozzle thrust coefficient was ascertained. Fig. 6 shows the experimental falloff in nozzle-thrust coefficient for both convergent and convergent-divergent nozzles. The various symbols denote the combinations of five swirl vane angles and five nozzle configurations used to generate the correlation. At the expected augmented swirl angle, the thrust penalty is on the order of only 0.5%. This is less than would be attributed to the flameholder pressure losses in conventional augmentors. At nonaugmented conditions, the thrust loss rises to about 1.6%, which is roughly equivalent to the losses caused by flameholders in conventional augmentors. Variable swirl vanes are being considered for swirl augmentors to eliminate swirl and associated losses for nonaugmented or cruise operation, resulting in thrust and TSFC improvements over conventional systems.

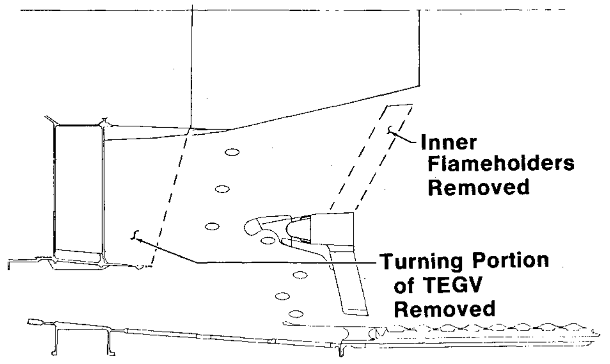

Fig. 7 F100 partial swirl-augmentor configuration.

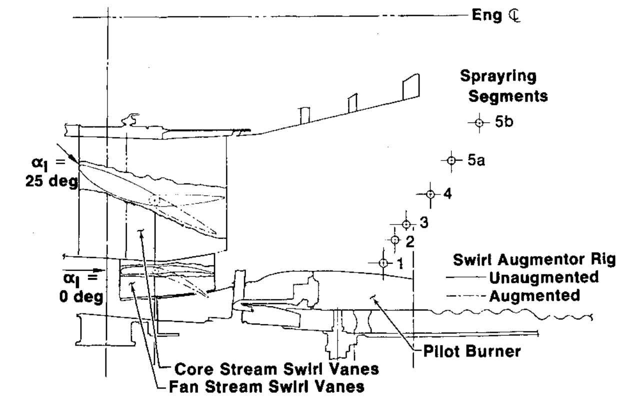

Fig. 8 Swirl-augmentor configuration.

A further experiment to verify the effects of swirl in an engine augmentor was performed when an F100 turbofan engine was tested with 25 deg of residual turbine swirl in the core stream and the flameholders inboard of the pilot were removed (Fig. 7). This engine was tested at altitude and found to have increased altitude-transient capability. The improvement at 0.8 flight Mach number was 4000 ft in idle-to-maximum capability, 2000 ft increase in intermediate-to-maximum capability, and 8000 ft in zoom-climb capability. Steady-state performance was comparable to the baseline augmentor in the upper left-hand corner of the flight envelope (high altitude/low flight speed). A decrement of 1.5% at the intermediate thrust was found. This was attributed to C_v penalty due to the swirling flow at the nozzle. A small decrement in sea level maximum thrust was also found due to untailored fuel distribution.

Design Considerations

The aforementioned experiments and results provided the confidence and technical background to apply the centrifugal force, swirling-flow concept to a turbofan augmentor. Previous engine development programs at Pratt & Whitney Aircraft had shown that augmentors developed in full-scale rigs required redefinition when installed on an engine, due to differences in airflow distribution and transient phenomena. Subscale rigs have the additional problem of scaling to full size. Thus, for a low-risk, high-confidence demonstrator, the rig should be full size, should be tested on an engine as a test bed, and should use as much current augmentor hardware as possible.

To maximize the chances of a successful program and obtain maximum design system information, test rig flexibility is required. Adjustable swirl vanes, movable sprayrings, replaceable pilot fuel nozzles, and flexibility of fuel control to enable pilot and individual spraying fuel-flow optimization are all important considerations. Reduced length is possible but not desirable in a first-generation experimental model. The pilot must be stable to engine operating envelope extremes while maintaining the screech-liner acoustic and cooling characteristics of the baseline augmentor. The exhaust nozzle and fuel-injection system should be typical engine hardware. A manual fuel control should be used to enable optimization of fuel distribution for initial performance determination.

Experimental Design

The engine test bed selected was the Pratt & Whitney Aircraft F100 Advanced Turbofan Engine. This is the most modern turbofan in production in the military inventory. Since the swirl augmentor is envisioned as a candidate for the next generation military augmentation system, the F100 development program yields a natural progression for augmentor hardware verification. The engine test bed made available was an F100 (1) designated P026.

Swirl Vanes

The inlet conditions to the augmentor require swirling flow. Analysis had indicated that 20 to 25 deg of swirl was sufficient to propagate combustion through the augmentor in the available length. To provide test flexibility and to enable evaluation of variable vanes for reducing nonaugmented losses, the turbine exit-guide vanes are designed to be fully variable from 0 to 25 deg. The bypass stream-swirl vanes are designed to be variable from 0 to 35 deg. At unaugmented conditions, the fan-vane turning angle is 0 deg and core-vane turning angle is 25 deg (to take out the turbine residual swirl), and for the augmented mode, the fan is at 25 deg and the core at 0 deg (to use the turbine residual swirl). This arrangement is depicted in Fig. 8. The turbine exhaust case supports the rear bearing, and the eight exit-guide vanes have tie rods and oil lines passing through them. Thus, movable trailing-edge flaps are the method of achieving the proper amount of swirl. In the fan stream, a similar arrangement is used in that the leading edge is stationary while the trailing edge varies. Twenty-four vanes are required based on the gap-to-chord criteria employed. The vane trailing edges are manually adjustable; the fan stream from outside the engine and the core stream from inside the tailcone. In a flight version the vanes would be automatically positioned.

Pilot Burner

The centrifugal force, swirling-flow concept requires a continuous ignition source on the outside diameter to sustain the buoyant flame-propagation process. The pilot burner is located in the colder fan stream and must be capable of continuous sustained combustion down to 200°F and 3 to 4 psia. Main burners perform in this region on altitude-relight conditions and the F100 main burner, in particular, has demonstrated ignition and acceleration from even lower temperatures at these pressures. Thus, an F100 main-burner front end was chosen and kept intact for the pilot. This provides maximum confidence and minimum risk since it is desired to verify an augmentor concept and not a pilot design. Nozzle-spacing criteria were chosen from the F100 and single-stream augmentor rig tests and led to 48 fuel nozzles for the pilot burner. The pilot annulus height is set by the fuel-nozzle/swirler requirements of 2.4 in. and gives a cold reference velocity of 25 fps. The length of 6 in. gives a heat release rate of approximately 10 million Btu/h/ft^3/atm. A schematic of the pilot configuration is presented in Fig. 8. More information on design and development of the F100 main burner is presented by Holladay et al.[10] To maximize the probability of augmentor ignition, the pilot is designed for stoichiometric operation. Thermal analyses of the inner and outer walls were performed and coolant flows were adjusted to keep wall temperatures below 1500°F. The fan-stream air cools the inner wall with a high scrubbing velocity. The outer wall is cooled convectively and by transpiration. The transpiration comes from the requirement to provide acoustic suppression in the pilot region as learned from the single-stream testing. The acoustic-suppression liner was designed as a broadband absorber and has about 1.5% open area. Hollow-core rivets with an i.d. = 0.1 in. were used for the Helmholtz resonator oscillator volume. The liner backing distance to the outer case required a change from the conventional augmentor liner to supply the Helmholz backing distance required for a broad-range acoustic absorber.

Augmentor Model

The aerodynamics of the turbofan augmentor involves two streams of differing pressure, temperature, and swirl interacting at the turbine exhaust-case plane and mixing out as the flow progresses downstream. The swirling flows create a static pressure gradient across the two streams. However, since the colder, denser gas is on the outside, it tends to stay on the outside and the fan-stream mixing is diminished. Thus, without the pilot on the o.d. and the distributed (radially and circumferentially) fuel sources to combust in the fan-stream air and raise the temperature, the two streams might never mix in a reasonable distance. Based on these facts, no mixing is assumed for the two streams upstream of the pilot exit.

An analytical model derived and verified during the work presented in Refs. 8 and 9 was employed to determine the flamefront location in the augmentor. An annular streamtube analysis of the two streams allows the model to determine the flamefront location for that streamtube and then step to the next smaller diameter annulus. Thus, the position of the flamefront can be tracked until it intersects the engine centerline. The locus of these points forms the predicted flamefront. It is also assumed combustion is completed when the centerline is intersected. The fuel drops entering the flamefront are all assumed to be consumed. A parametric study was performed using this analytical model, and predicted 25 deg of swirl would keep the flamefront well upstream of the exhaust-nozzle throat. Figure 9 shows the predicted flamefront locations for several angles of swirl superimposed on the augmentor cross-section.

Fuel System

The fuel distribution is accomplished by F100 flight-type variable-area pintle sprayrings placed to give the optimum fuel-air ratio distribution based on assumed uniform airflow profiles both radially and circumferentially. All five zones are individually fed by either a manual or hydromechanical fuel control. Two sprayrings are necessary to feed the required amount of fuel to the fan-stream flow, and three to feed the core (the two small-diameter sprayrings are manifolded together). These zones must be sequentially operated from o.d. to i.d. to build the hot gas zone toward the center. The sprayring locations are axially adjustable for refinement of fuel-spray distribution as it encounters the flamefront. The fuel injected into the swirling flow is centrifuged outward at a rate depending on inital droplet size and vaporization rate.

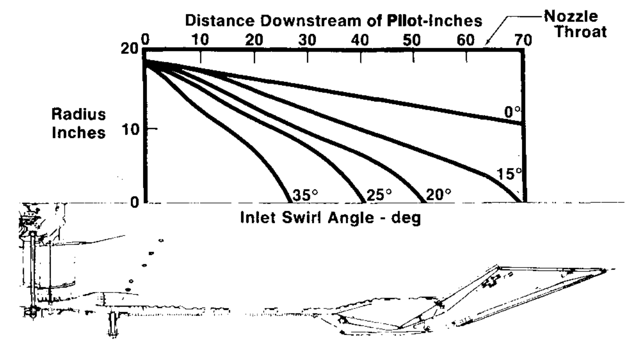

Fig. 9 Predicted flamefront location as a function of inlet swirl angle.

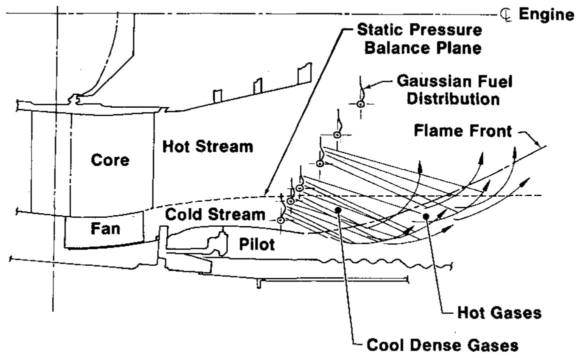

Fig. 10 Swirl-augmentor flow-field schematic.

By moving the sprayring location fore and aft, the spray-fan of fuel depicted in Fig. 10 can be located to intersect with the flamefront and not cover another spray-fan of fuel. The droplet vaporization and distribution is determined from a computer model of Priem's vaporization analysis,[11] and the data from a study of fuel distribution in a simulated core engine stream.[12] A manual fuel control was assumed during the design since the existing F100 engine fuel-control zones are sequenced from the central pilot zone to the core-stream sprayings, then to the fan stream. This sequence does not satisfy the o.d. to i.d. zoning requirements of the swirl augmentor.

Screech Liner and Exhaust Nozzle

Turbofan augmentors require coolant liners to protect the engine case and nozzle. Normal practice also dictates a screech liner to damp out a broad range of combustion frequencies. These two are usually combined into one augmentor liner. A typical liner requires 8 to 13% of total engine airflow to cool the liner and nozzle. Since screech liners have holes to absorb acoustic fluctuations, the pressure across the liner must always be positive and have coolant flow passing into the augmentor. No hot gases are allowed under the liner as they will destroy the coolant effectiveness.

The coolant liner for the swirl augmentor has approximately 12 to 13% total engine airflow underneath it which keeps the liner pressure drop positive. The design makes extensive use of the F100(3) liner with minor changes to the front end to accommodate the pilot section.

The exhaust nozzle is an F100(1) convergent-divergent nozzle as original to P026 engine. Thus, except for the pilot and main augmentor sprayrings, extensive use of existing hardware was maintained.

Test Results—Sea Level

The swirl augmentor was tested at sea level on P026 engine in May and June 1976. Twenty hours of sea-level augmentation were accomplished during two rig builds with no durability problems. The initial testing optimized the pilot burner using the manual fuel control. The augmentor was heavily instrumented with static and dynamic pressures, and with metal and air thermocouples to observe all critical parameters. No distress in the pilot region was observed. Optimum equivalence ratio in the pilot seemed to be about 0.8 based on overall augmentor efficiency measurements. This corresponds to an overall fuel/air ratio of 0.003. The pilot airflow is approximately 6% of total airflow.

The first tests of the augmentor mapped out the efficiency curves for each sprayring at 25 deg of air swirl. The peak of each sprayring efficiency was found and then held as the next zone was brought on (Fig. 11). Thus, pressure differences in the sprayrings were observed when all segments were flowing. It was discovered in the initial testing that zone 3 (Fig. 8) was not required. In fact, efficiency fell of drastically when zone 3 was flowing..Thus, subsequent tests eliminated zone 3. Some

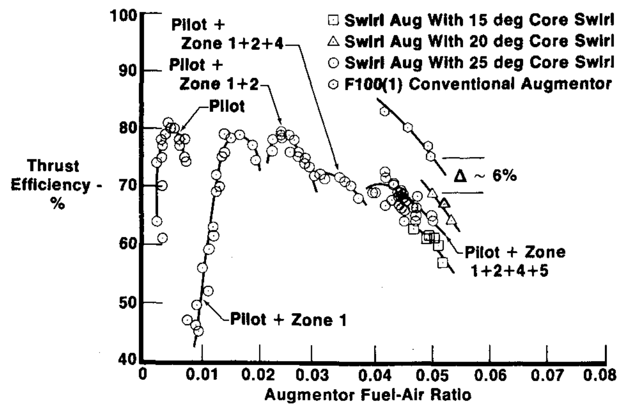

Fig. 11 Swirl-augmentor to conventional augmentor efficiency comparison.

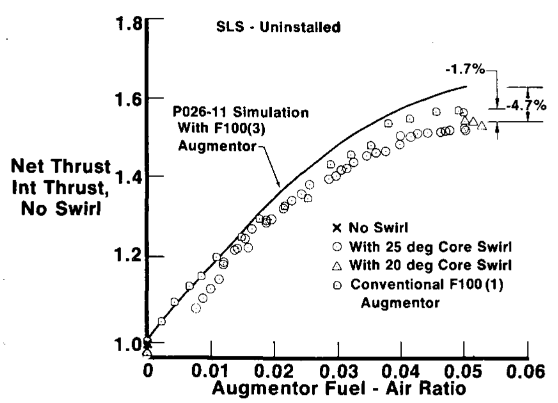

Fig. 12 Swirl-augmentor performance compared to conventional on an F100 engine.

augmentor instability was noted when zone 5 was brought on. Attempts to remove the instability were successful when the air-swirl angle was changed to 15 deg. However, efficiency fell of drastically (Fig. 11). A compromise of 20 deg was tried, which both maximized efficiency and eliminated acoustic instability problems. The analytical model predicts with 20 deg of swirl that the flamefront reaches the augmentor centerline just upstream of the nozzle throat, whereas 15 deg is outside the augmentor, and 25 deg shows a shorter augmentor length than necessary (Fig. 9). The current theory is that the extra length with 25 deg of swirl causes pressure fluctuations to be reflected from the converging nozzle walls back to the flamefront in the region where all the combustion has taken place. The maximum augmentor power points, fuel/air = 0.05, are compared in Fig. 11 to a back-to-back run on engine P026 with a conventional augmentor. A thrust-based combustion-efficiency decrement of 6% was found. The thrust decrement was 1.7%, as shown in Fig. 12. These results are considered excellent for the first test of a new concept with no tailoring of fuel to air. Also shown in Fig. 12 is a computer simulation of engine P026 with an F100(3) augmentor. The marked improvement between the F100(1) and F100(3) is due to detailed fuel-to-air tailoring. During all phases of testing, the augmentor was continuously monitored by scanning the instrumentation channels and viewing the output on video displays. No durability problems were encountered during the testing.

A second build of engine P026 was tested in September 1976 with a modified hydromechanical fuel control to verify transient capability at sea level. Previous tests showed spraying adjustments were needed since all spraying manifolds optimized at different pressures. However, the pressure variations were judged small enough to permit a transient demonstration, although some thrust would be lost.

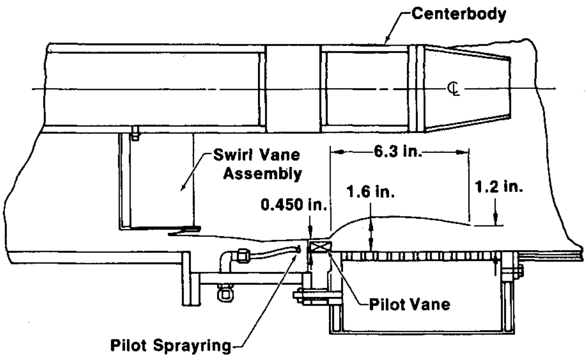

Fig. 13 Subscale rig with swirl pilot installed.

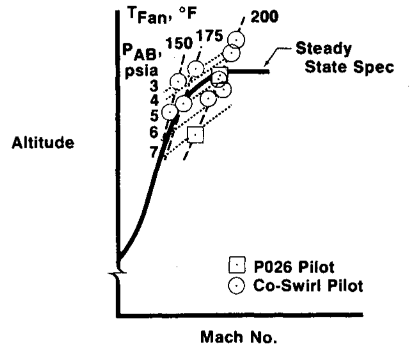

Fig. 14 Co-swirl pilot demonstrates best altitude relight capability in subscale rig tests.

The fuel control employed supplied all sprayrings at equal pressures at maximum augmentation. Minor problems in transfer and quickfill were noted, but allowed the transients to be accomplished.

The major result of the sea-level tests was verification of the swirl augmentor concept for turbofan-engine application. The augmentor pressure loss did not decrease as predicted due to removal of the flameholder. The cause for this is related to the blockage of the pilot in the fan stream. The thrust decrement of 1.7% and efficiency decrement of 6% are acceptable for the first build of the new swirl augmentor since it is being compared to a developed conventional augmentor. Airflow swirl angle of 20 deg optimizes the performance of the untailored sprayrings (fuel/air mismatch) for the F100 engine augmentor length. No combustion instabilities were found under these conditions.

Pilot Imrovements

A re-examination of the design philosophy concerning the pilot blockage led to an experimental test program of various pilot configurations. The subscale single-stream test rig (Fig. 4) was used to evaluate smaller height pilots. The minimum height considered reasonable from a combustion standpoint was 1.6 in. The current F100 fuel-nozzle/swirler combination was too large and many nozzles were required. Other concepts evaluated included premix tube injectors with a conventional main-burner dome, bluff body with sheltered spraying, and a full-swirl pilot. In the full-swirl pilot, the dome is composed of a set of 50-deg turning vanes with a sprayring upstream (Fig. 13) and a recirculation region downstream. In total, six concepts were tested to determine altitude lean and rich blowout and relight capability. All pilots were full scale in height but with reduced circumferences to fit the subscale rig. Since the objective was to define ignition characteristics, subscale testing would have led to wall-quenching effects. Only curvature effects which were considered to have minimal effect on ignition were not full scale. The full-swirl or co-swirl pilot, initially considered the highest risk design, exceeded all

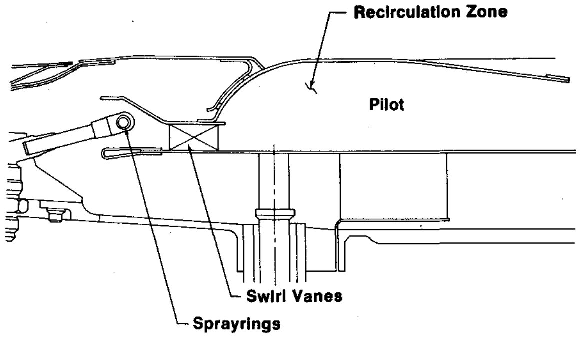

Fig. 15 Swirl-augmentor altitude-test configuration with swirl pilot.

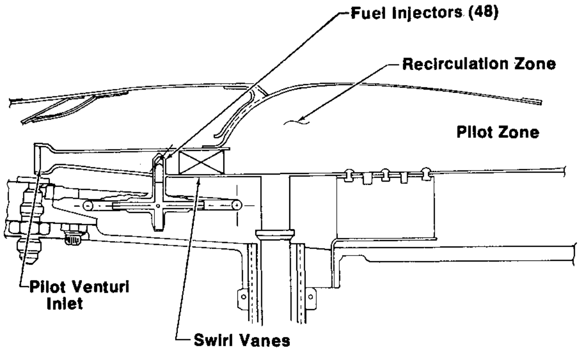

Fig. 16 Swirl-augmentor pilot configuration to minimize fuel leakage.

others by several thousand feet (Fig. 14) by sustaining combustion to the lowest inlet temperatures and pressures.

The smaller height pilot will reduce blockage but the sprayrings must now be relocated and moved outward to optimize the fan-stream fuel-flamefront interaction zone. These modifications are predicted to improve the comparisons of Figs. 11 and 12, and thus, the swirl augmentor is predicted to exceed the F100(1) data.

Based on the success of the subscale pilot evaluation program, a full-scale co-swirl pilot design was initiated. The details are presented in Fig. 15 and comprise a 1.6-in.-high combustion section, a fixed orifice sprayring upstream of the swirl vane to distribute the fuel, an annulus of 50-deg turning vanes to add the swirl, and a recirculation zone. The parameters determined from the initial pilot tests in the subscale rig were held in this design. New sprayring locations were assessed and zone 3 was eliminated. The fan-stream sprayrings were moved upstream to increase the centrifugal displacement of the fuel spray to accommodate the smaller pilot.

Test Results—Altitude

The altitude testing was performed at NASA Lewis Research Center in September to November 1977, under Contract NAS3-20588. The configuration for the initial build was the same as the sea-level build 2 testing, i.e., modified hydromechanical fuel control and fuel-nozzle-type pilot. The hydromechanical fuel control caused some manifold underfill problems during transient attempts, but the augmentor operated to 0.8 Mn and 30,000 ft. The maximum altitude attained during this build was 0.8 Mn and 35,000 ft, where the pilot blew out. Transient capability was demonstrated even though the fuel control was not properly tuned to the augmentor, nor was the fuel-distribution pattern tailored to the nonuniform airflow profiles.

Additional altitude capability was required, so the co-swirl pilot, which had been fabricated just prior to build 1 altitude testing, was installed. A manual fuel control was used, allowing both pilot and sprayring optimization to be accomplished. Unfortunately, during the first test sequence, hardware damage in the nozzle case prevented a proper evaluation. However, the co-swirl pilot was shown to light and have wide flammability limits prior to hardware damage. A very limited amount of data was obtained during altitude testing, but the transient capability of the concept was verified during build 1.

Future Plans

The co-swirl pilot fuel-injection system is being revised to eliminate potential durability problems Fig. 16. This pilot will be installed for sea-level and altitude testing during 1979. Sprayrings are also being redesigned to accommodate the pilot diameter change and the fact that the fuel will vaporize immediately in the hot core stream.[12]

This concept can be extended to short-length swirl augmentors and main-burner applications. The short-length swirl augmentor leads to lower weight and cost configurations for advanced fighters. The main-burner configuration has been designed, and initial testing in an F100 main burner rig supports the theory as applied to the smaller diameter main burner.

Acknowledgments

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References

[1]Ozawa, R. I., "Survey of Basic Data on Flame Stabilization and Propagation for High-Speed Combustion Systems," AFAPL-TR-70-81, Air Force Aero Propulsion Laboratories, Wright-Patterson AFB, Ohio, November 1970.

[2]Marshall, R. L., Canuel, G. E., and Sullivan, D. J., "Augmentation Systems for Turbofan Engines," presented at Cranfield International Symposium, April 4-6, 1967.

[3]Ernst, R. C., "A Combustion Model for Low-Frequency Instability in Turbofan Augmentors," AIAA Paper 76-680, AIAA/SAE 12th Joint Propulsion Conference, San Francisco, Calif., July 1976.

[4]Reilly, R. S., and Markowski, S. J., "Vortex Burning and Mixing (VORBIX) Augmentation System," AIAA Paper 76-678, AIAA/SAE 12th Joint Propulsion Conference, San Francisco, Calif., July 1976.

[5]Lewis, G. D., Shadowen, J. H., and Thayer, E. B., "Swirling-Flow Combustion," *Journal of Energy,* Vol. 1, July-Aug. 1977, p. 201.

[6]Lewis, G. D., "Combustion in a Centrifugal-Force Field," 13th Symposium (International) on Combustion, The Combustion Institute, Salt Lake City, Utah, 1971.

[7]Lewis, G. D., "Centrifugal-Force Effects on Combustion," 14th Symposium (International) on Combustion, The Combustion Institute, University Park, Pa., 1973.

[8]Lewis, G. D., and Smith, C. E., "Investigation of Centrifugal Force and Reynolds Number Effects on Combustion Processes," AFOSR-TR-75-1167, 1975.

[9]Clements, T. R., "Effect of Swirling Flow on Augmentor Performance," NASA CR-134639, NASA Lewis Research Center, Nov. 1974.

[10]Holladay, T. E., Barlow, G. C. and Henderson, R. E. "Development of a High-Heat-Release Combustor for the F100 Gas Turbine," ASME Paper 75-GT-86, Houston, Texas, March 1975.

[11]Priem, R. J. and Heidman, M. F., "Propellant Vaporization as a Design Criterion for Rocket-Engine Combustion Chambers," NASA TR R-67, 1960.

[12]Clements, T. R., "Effect of Swirling Flow on Augmentor Performance, Phase II," NASA CR-135024, June 1976.