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Hydrocarbon-Fueled Scramjet Combustor Investigation

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An experimental program to develop technology for a hydrocarbon-fueled scramjet engine for operation over the flight Mach number range from 3.5 to 7 is being conducted. As part of this program, a series of connected-pipe tests were performed to define scramjet combustor design criteria applicable to an engine concept which comprises a pair of modular axisymmetric combustors underslung on a supersonic/hypersonic missile. A novel air-breathing pilot was developed under this program and was tested to evaluate its flame stabilization and flame propagation characteristics. The air-breathing pilot also incorporates an external mainstream fuel injector which serves as the primary fuel injection stage for the supersonic combustor. During this program, it was demonstrated that the pilot promotes efficient combustion of either gaseous ethylene or preheated liquid Jet-A (JP-5) when it is injected into the supersonic mainstream flow as a primary fuel. The idea of using the air-breathing pilot and distributed primary and secondary fuel injectors to achieve efficient supersonic combustion over a wide range of equivalence ratios was also experimentally demonstrated. During staged fuel injection tests with gaseous ethylene fuel, high secondary fuel combustion efficiencies were achieved and smooth transitions from fully supersonic to dual-mode (supersonic/subsonic) operation were demonstrated. The air-breathing pilot was shown to isolate effectively the inlet from the combustion process even at the high combustor pressures experienced during dual-mode operation.

Introduction

MISSILE applications exist that require the performance benefits offered by the supersonic combustion ramjet (scramjet) propulsion system. Because these applications impose demanding volume constraints, a strong motivation exists for the development of a hydrocarbon-fueled airframe-integrated scramjet. Although studies of supersonic combustion of hydrocarbon fuels have been performed intermittently over the past 30 years,[1,2] they have yielded only a limited design data base. For example, an extensive ground-based experimental investigation of hydrocarbon-fueled scramjet technology was conducted under Air Force sponsorship from 1968 to 1972.[3,4] The results of those early tests clearly demonstrated that supersonic combustion of various hydrocarbon fuels could be achieved, although for many test conditions, special externally mounted piloting devices were required to initiate and stabilize the flame. In order to provide a firm technology base for the development of a dual-mode subsonic/supersonic hydrocarbon-fueled propulsion system, which could operate effectively without the need for external pilots, a Hydrocarbon-Fueled Ramjet/Scramjet Technology Program was undertaken. The program was carried out in two phases. Phase I[5] consisted of a study to identify and evaluate airframe/engine configurations satisfying performance requirements and packaging constraints typical of a missile application. The application chosen was a surface-launched missile. A combustor concept was designed and several potential schemes to enable efficient supersonic combustion of hydrocarbon fuels were evaluated. A staged-injection supersonic combustor employing a novel air-breathing pilot was selected as an effective approach to meeting the propulsion system needs and a plan was defined to develop and demonstrate this critical technology under phase II of the program. Phase II was an experimental program devoted to the development of the air-breathing pilot and the subsequent use of this pilot to initiate and sustain efficient supersonic combustion. The tests were conducted in a connected-pipe experiment at representative flight conditions.

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Engine/Missile Configuration

A nominal mission profile was chosen as a basis for evaluating candidate engine configurations. The missile is surface-launched in the vertical position using a tandem rocket booster. It is boosted to a ramjet or scramjet takeover Mach number at an altitude consistent with engine operating pressure limits, e.g., 200- or 300-psia maximum internal pressures. The missile then climbs and accelerates at maximum fuel equivalence ratio to a Mach number of 7. At Mach 7 and the desired cruise altitude, it is throttled back to a reduced fuel equivalence ratio to maintain thrust equal to drag.

The hydrocarbon-fueled scramjet missile configuration is shown in Fig. 1. The missile forebody incorporates a droop nose and a bielliptic cross section for inlet flow precompression. The engine is bottom-mounted and incorporates a three-dimensional inlet that transits to two combustors having circular cross sections. The inlet is a fixed-geometry, mixed-compression design employing corner-spillage to assist starting. Referring to Fig. 1, the inlet begins just upstream of section a where a splitter bifurcates the capture area. Section b is in the three-dimensional portion of the inlet which forms

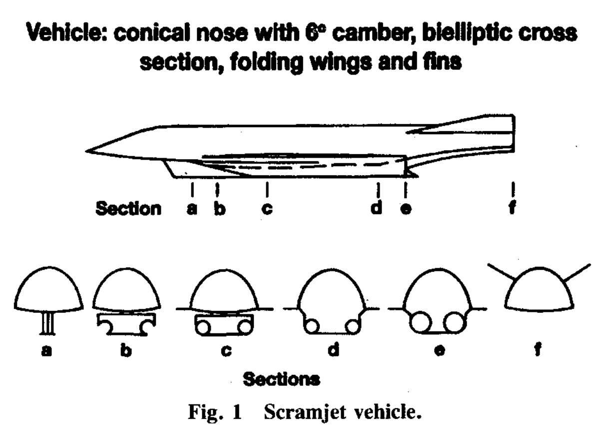

Fig. 1 Scramjet vehicle.

the transition to two circular throats at section c. (Note the corner-spillage aspect of this transition portion of the inlet.) The combustors extend from section c to section d; each is a slightly divergent axisymmetric duct. Each combustor feeds a nozzle internal expansion segment, from section d to section e. Downstream from section e the nozzle employs external expansion on the vehicle aft underbody.

Combustor Concept

One of the two circular cross section combustors is shown in Fig. 2. Air-breathing pilot injectors[6] are located at the combustor entrance. The three wall-mounted pilots, which are described in more detail below, serve to initiate the combustion process and stabilize the flame. Staged combustion, whereby the engine fuel is injected at three axial stations corresponding to the pilot location and two downstream stations, is employed to distribute the combustor heat release. This leads to high combustion efficiency while controlling the combustor pressure distribution and preventing combustor-inlet interaction that could unstart the inlet. Also, by tailoring the fuel distribution, it is possible to operate as a dual-combustion scramjet where the combustion process is either all supersonic or mixed supersonic/subsonic, depending on overall equivalence ratio and flight Mach number.

The air-breathing pilot injector is illustrated in Fig. 3. The pilot is mounted on the combustor wall and consists of a semiconical supersonic inlet that captures approximately 1.5–3.0% of the combustor airflow. This air is diffused to subsonic conditions within the cowl region. Pilot fuel is injected into the recirculation zone formed around the base of the conical forebody. The pilot fuel autoignites and burns subsonically at near-stoichiometric conditions producing a hot, high-pressure pilot flame which expands into the main supersonic combustor flow at the exit of the pilot. Primary fuel is injected from the pilot cowl into the supersonic combustor where it mixes with air and is ignited as it mixes into the hot pilot flame.

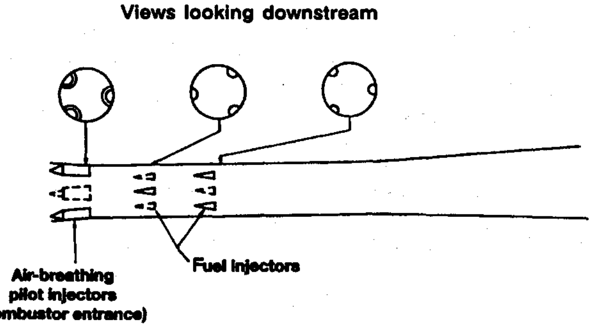

Fig. 2 Combustor concept.

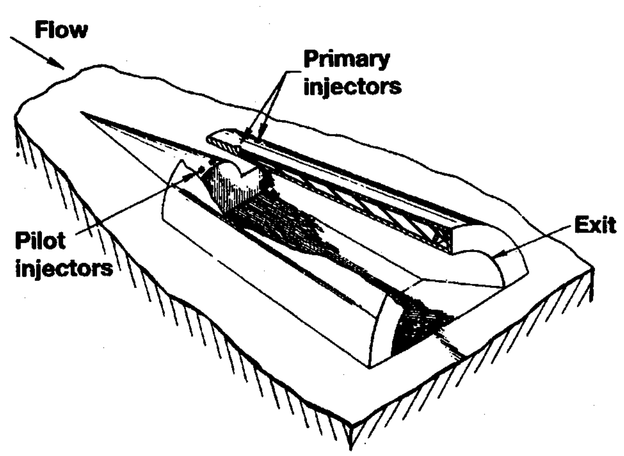

Fig. 3 Air-breathing pilot/injector.

Experimental Program

The initial stage of the experimental program was undertaken to provide critical design criteria for the pilot. The viability of using an energetic pilot to promote supersonic combustion of hydrocarbon fuel was demonstrated and important air-breathing pilot sizing and stability criteria were developed.[7] In the second stage of the experimental study, a thorough evaluation of the selected scramjet combustor concept was performed through direct-connect tests in which important combustor and combustor component design criteria were developed and high levels of combustor performance were achieved. This section includes descriptions of the facilities and models used in the second stage of experiments and the results of the pilot development and supersonic combustion tests.

Model Descriptions

The experimental program was performed in a connected-pipe type ramjet/scramjet test facility located at UTRC. A complete description of that facility is presented in Ref. 7. The tests described herein were conducted in two-dimensional hardware to allow the widest possible range of flexibility in varying the geometry of the test configurations. The applicability of the two-dimensional test results to the axisymmetric configuration was ensured by maintaining a proper simulation of combustor entrance conditions (i.e., Mach number, pressure, and temperature) and local fuel distributions in the regions surrounding the pilot and fuel injector components and by preserving the actual length scale in the two-dimensional test configuration.

The variable-geometry test section used during these tests is shown in Fig. 4. The test section is uncooled and is 6 in. wide. In this installation, candidate pilot and fuel injector configurations can be interchanged and the lateral and axial spacings between elements can be varied to closely simulate the spatial patterns appropriate to an axisymmetric engine model. The variable geometry features 1) afford a convenient means for varying the divergence angle of the upper wall of the test section as a way to evaluate the anticipated strong effect of the rate of increase of combustor area ratio on flame propagation rate, and 2) provide an efficient means of parametrically determining the requirements for staged fuel injection to achieve high combustion efficiencies. During this program, the secondary fuel was always injected through a single pair of injectors that were laterally spaced 3 in. apart straddling the test section centerline. Instrumentation provisions in the variable-geometry hardware include an extensive array of approximately 150 wall static pressure taps, distributed on the top and bottom walls of the test section, and two pairs of sidewall-mounted rectangular viewing windows in the vicinity of the pilot and fuel injector locations.

Three separate models of the air-breathing pilot, having different internal geometries, were fabricated for use in the pilot development phase of the test program. These parametric models were uncooled except for the cowl, which in-

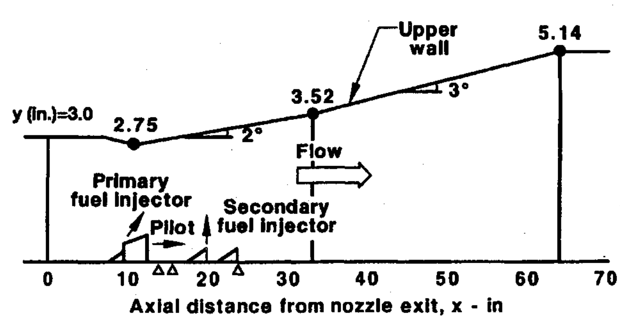

Fig. 4 Test section geometry.

corporated a water-cooling circuit. The parametric pilot models comprised a baseline configuration, a configuration with a base region step height equal to twice the baseline value (deep base), and a configuration with an exit/capture area ratio equal to 90% of the baseline value (reduced exit area). Each model was also provided with a capability for varying the geometry of the forebody via interchangeable 10-deg and 18-deg semiconical inlet ramps.

The primary fuel injection stage of the supersonic combustor entails external mainstream fuel injection from the cowl of the air-breathing pilot. This feature was incorporated into two of the parametric pilot test models described above (the baseline configuration and the configuration having the reduced pilot exit area) for use in the supersonic combustion phase of the test program. In each of these models a tubular injection manifold was flush mounted in the upstream portion of the water-cooled cowl. Injection holes were then drilled into the manifold. The primary fuel was injected from three holes, located at top dead center and at 45 deg from top dead center on each side of the cowl and angled downstream at 60 deg to the mainstream flow direction.

A separate fuel-cooled pilot model was fabricated to demonstrate the flash-vaporizing capabilities of the piloting injector. In the fuel-cooled configuration, the primary liquid hydrocarbon fuel is routed under pressure through a network of passages in the bottom and sidewalls that surround the base cavity and subsequently through the cowl. During its passage, the fuel cools the test hardware and is heated by the combustion products inside the pilot cavity and by the hot mainstream flow passing over the outside of the cowl. The primary fuel is ultimately injected into the supersonic mainstream flow through three throttling orifices located at the upstream end of the cowl. The orifices are located at top dead center and at 45 deg from top dead center on each side of the outer cowl surface and the fuel is injected normal to the mainstream flow direction. The pilot is designed so that, over its design flow rate range, the primary fuel will be heated sufficiently so that it will flash-vaporize upon injection into the low-pressure combustor flow.

Test Results

The pilot development and combustor evaluation tests described below were conducted at a single simulated combustor entrance condition, comprising a Mach number of 3.0 and a stagnation temperature of 2675 R simulating flight at Mach 5.6. The combustor entrance static pressure is 4.5 psia. Test durations in the heat-sink hardware were generally in the range from 1 to 2 min. Observations of the combination processes were made through the sidewall windows and performance evaluations were made on the basis of calculated air and fuel flow rates and measured wall static pressures within the pilot and throughout the test section. Most of the tests were made using gaseous ethylene to simulate the ignition characteristics of vaporized Jet-A (JP-5) fuel and limited tests were made using Jet-A.

Pilot Development Tests

Extensive development tests of the air-breathing pilot were performed to define a configuration that produced acceptable autoignition and flame stabilization characteristics. A series of diagnostic combustion tests with hydrogen fuel were performed with the parametric models, in which autoignition was achieved and stable combustion was demonstrated over wide ranges of pilot equivalence ratio without excessive flow spillage. These tests proved the viability of the pilot concept and, on the basis of the hydrogen results, some geometric parameters were selected to simplify the continued development of the pilot for operation with hydrocarbon fuels. For example, because the pilot operated at higher internal pressures (which would be more conducive to autoignition of hydrocarbon fuels) with the 18-deg forebody than with the 10-deg forebody, the 18-deg forebody was selected for further development tests.

Developmental testing was then continued using gaseous ethylene fuel which has ignition characteristics similar to those of vaporized Jet-A.

With ethylene fuel, autoignition was generally achieved in the pilot models but rich blowout always occurred at relatively low equivalence ratios. The narrow flame stability limits indicated that the airflow was jetting through the pilot and forming an undesirably small internal recirculation zone. To improve the flame stabilization characteristics of the pilot, the internal blockage was increased and tests were conducted with a variety of internal fuel injection configurations in the parametric test hardware. As a result of these tests a pilot configuration was developed whereby the pilot operated stably with minimal inlet flow spillage over a wide range of internal equivalence ratios (from 0.3 to 1.3) at combustion efficiencies (based on internal pressure measurements) close to 100%. Autoignition was readily achieved without the use of any external ignition devices or fuel additives. As developed, the selected pilot configuration produces a sonic exhaust stream having a stagnation pressure of approximately 25 psia and a stagnation temperature of approximately 4500 R for the simulated combustor entrance conditions cited above. As described below, the hot pilot was subsequently shown to be very effective in promoting supersonic combustion of primary mainstream fuel injected from the outside of the pilot cowl.

To date, the pilot has been operated hot at Mach 3 combustor entrance conditions where the boundary layer at the pilot entrance was approximately 0.5 in. thick. Prior to the hot-flow testing, cold-flow calibrations were performed over a range of Mach numbers from 3 to 4.[7] Those tests defined the mass capture characteristics of the pilot and showed that stable operation with minimal spoilage could be achieved over the entire Mach number range of interest with a single design. While the pilot mass capture characteristics were well-behaved over this Mach number range, the sensitivity to entrance boundary-layer thickness has not yet been established.

Supersonic Combustion Tests—Ethylene Fuel

During the test program, efficient supersonic mainstream combustion was effectively promoted by the air-breathing pilot. Furthermore, the idea of using air-breathing pilots and distributed primary and secondary fuel injectors to achieve efficient supersonic combustion over a wide range of equivalence ratios was experimentally demonstrated. Supersonic combustion tests were performed using gaseous ethylene fuel with primary fuel injection alone and with staged fuel injection over a wide range of spacings between the primary and secondary injection stages.

Photographs of the appearance of the flame zone (as viewed through a pair of sidewall windows) for a representative supersonic combustion test sequence are presented in Fig. 5. For this sequence the secondary fuel injectors were located at $x = 20$ in. (see Fig. 4). Separate frames as shown in Fig. 5 for cases with: 1) the pilot operating alone, 2) the combustor operating with primary fuel injection alone, 3) the combustor operating with both primary and secondary fuel injection in a fully supersonic mode, and 4) the combustor operating with a higher level of secondary fuel injection leading to an increased spreading of the flame upstream of the secondary injection size. (This suggests that the boundary layer has separated locally.) The above behavior is typical of what is often referred to as dual-mode combustion, wherein, depending on conditions (e.g., fuel flow rate, combustor entrance Mach number, etc.), the combustor process occurs supersonically, subsonically, or as a combination of the two. Corresponding static pressure distributions measured on the lateral centerline of the lower wall of the test section are presented in Fig. 6. Wall static pressure distributions were also obtained for positions displaced laterally from the centerline and on the upper wall during these tests. Although not presented herein, those distributions showed the same relative pressure changes as

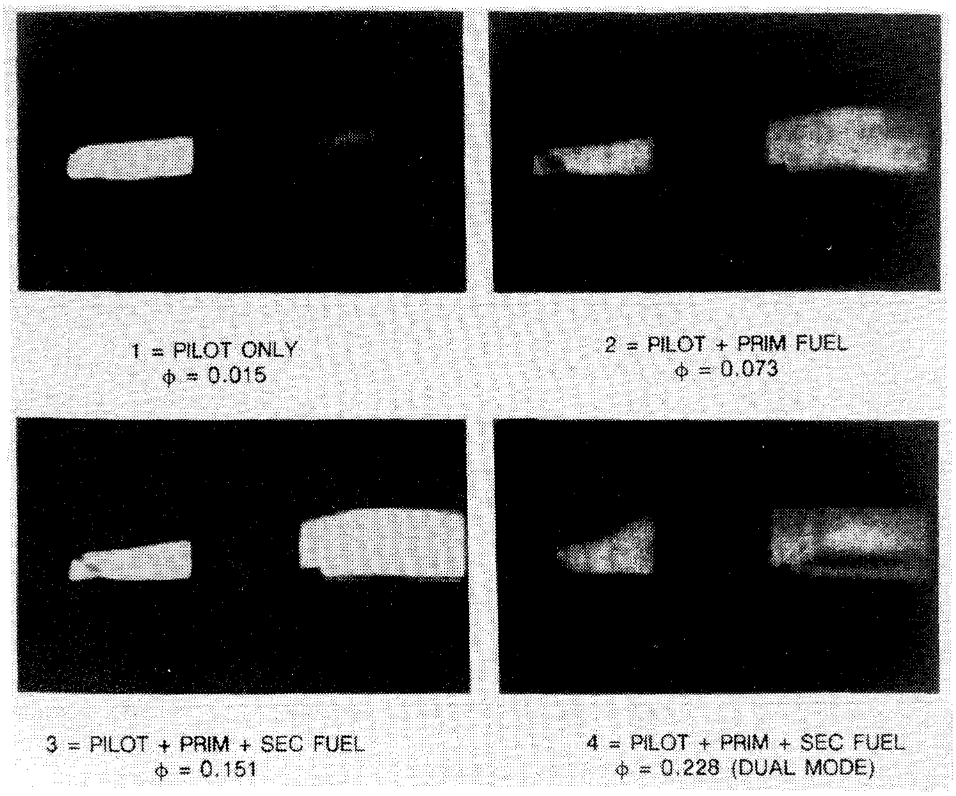

Fig. 5 Supersonic combustion of ethylene.

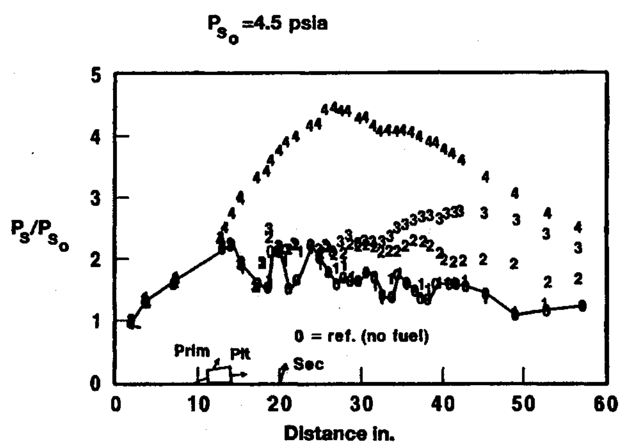

Fig. 6 Combustor pressures.

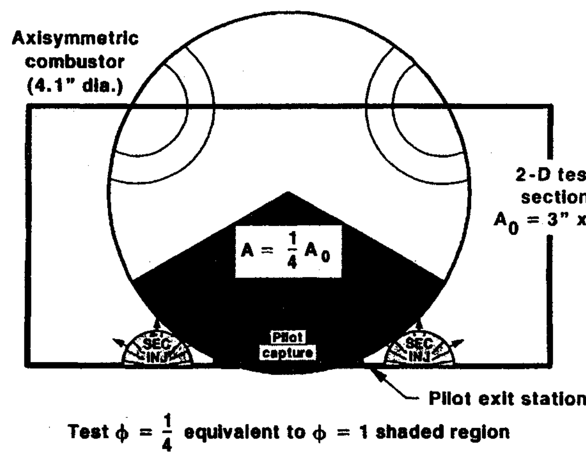

Fig. 7 Two-dimensional test geometry.

the curves of Fig. 6. The peaks and valleys were, however, generally shifted downstream in the axial direction.

As shown in Fig. 6, the pressure distribution corresponding to the pilot-only condition (curve 1) shows that the combustor perturbations associated with the small, high-temperature pilot flow alone are small relative to the reference (no-fuel) pressure distribution. More significant pressure increases were measured under conditions of supersonic primary fuel combustion (curve 2) and both supersonic and dual-mode combustion of staged primary and secondary fuel (curves 3 and 4). For the staged fuel injection cases, two generic types of wall static pressure distributions were measured during the test program. At lower secondary fuel flow rates, the pressure increases attributable to the secondary fuel combustion process always occurred downstream of the point of secondary injection, and the peak pressures were consistently less than three times the combustor entrance pressure, P_{s_0}. At higher secondary fuel flow rates, much larger pressure increases were measured (in the range from three to six times the combustor entrance pressure) and in those cases the disturbances were observed to propagate upstream of the point of secondary injection. This type of behavior was also visually evidenced by a marked increase in the observed initial flame spreading angle as shown, for example, in frame 4 of Fig. 5. The second type of combustor behavior was attributed to the formation of a "precombustion" shock[8] in the test section just downstream of the pilot exit resulting in a dual-mode combustion process. It is important to note that in both types of combustor flow, the combustor entrance conditions upstream of the pilot remained unperturbed in the presence of significant levels of primary and secondary combustion.

It should be noted that in this paper, all of the referenced mainstream equivalence ratios are calculated on the basis of the total airflow in the entire 6-in.-wide × 3-in.-high test section. Since the injected fuel is concentrated in the region of the pilot and the injectors, the actual local equivalence ratios are in fact significantly higher and are closely representative of the mixtures that would prevail in an actual engine installation. As shown in Fig. 7, in the actual engine, three sets of pilots and secondary injectors of the same size would be distributed in a modular combustor having a somewhat smaller cross-sectional area than the two-dimensional test section used in these tests; by design the actual local equivalence ratios are therefore approximately four times larger than the average values presented herein. However, it should also be emphasized that the results achieved with the single pilot configuration cannot be taken as fully representative of the axisymmetric configuration because the heat release rates and the associated combustor divergence would be substantially different in the fully complemented engine.

For the supersonic combustion tests, combustor performance evaluations were performed by comparing measured pressure-area integrals with analytical values calculated for the same conditions using a one-dimensional cycle analysis code, RASCAL. Results of this analysis for cases involving pilot and primary fuel injection only, wherein both the experimental and the analytical pressure-area integrals were normalized with respect to a condition with no pilot or mainstream fuel, are presented in Fig. 8. It can be seen that primary fuel utilization efficiencies in the range from 80% to 100% were achieved up to total (i.e., pilot plus primary fuel) equivalence ratios of approximately 0.1. At higher primary fuel flow rates, the observation that further pressure increases did not occur as the primary fuel flow rate was increased suggests that the primary combustion process had become mixing limited for this injector geometry.

Similar analyses were performed for staged fuel injection cases which were performed with fixed pilot and primary fuel flow rates. In the cases where the flow remained fully supersonic (corresponding to pressure traces like curve 3 of Fig. 6), the pressure-area integrals were normalized with respect to the conditions with pilot plus primary fuel only. The results of that analysis are presented in Fig. 9. From these data, it can be seen that the supersonic secondary fuel utilization efficiencies generally decrease significantly with increasing spacing between the primary and secondary injection stages and to a lesser extent (as shown by the data for the 20-in. secondary injector location), with increasing secondary equivalence ratio. For those cases at higher overall equivalence ratios in which dual-mode combustion occurred (corresponding to pressure traces like curve 4 of Fig. 6), the analysis treated the primary and secondary fuel equivalence ratios in a combined form and imposed a precombustion shock at the pilot exit station. The strength of the shock was related to the total amount of fuel that was assumed to be reacted in accordance with a minimum entropy solution to the governing equations.[8] The results of that analysis, in which the pressure-area integrals were normalized with respect to conditions with pilot combustion only, are presented in Fig. 10. The dual-mode fuel utilization efficiencies were generally in the range from 90% to 100% with the secondary injectors located nearest the pilot station and approximately 80% with the secondary injectors located in the most downstream position. In comparison to the fully supersonic data, the dual-mode efficiencies were somewhat higher and did not show as much of a dependence on equivalence ratio.

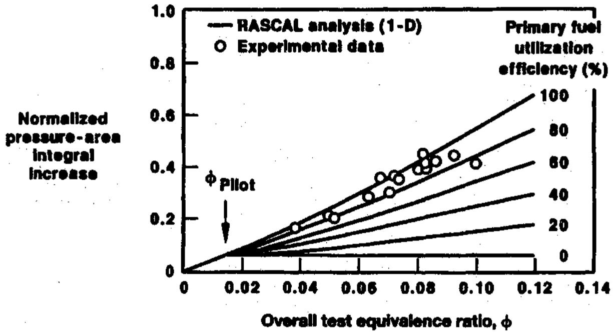

Fig. 8 Primary fuel utilization efficiency–ethylene.

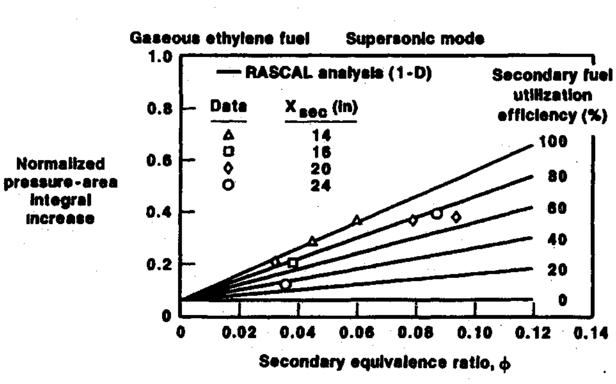

Fig. 9 Secondary fuel utilization efficiency.

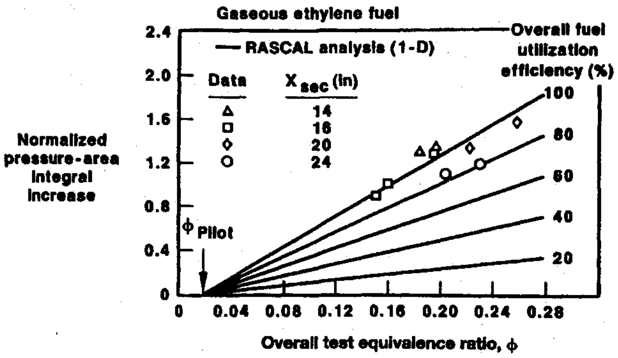

Fig. 10 Fuel utilization efficiency in dual mode.

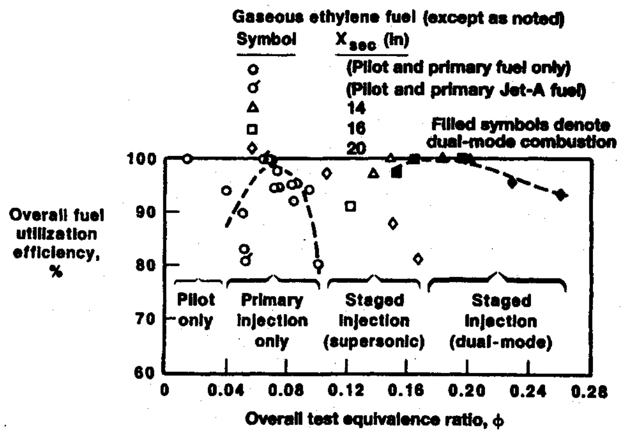

Fig. 11 Composite combustor performance.

A composite performance map for the combustor, in which the staged-injection data are limited to those cases with the secondary injectors located at the 14-in., 16-in., and 20-in. axial stations, is presented in Fig. 11. The staged injection data include cases in which the primary equivalence ratio was held approximately (but not exactly) constant from point to point. For the Mach 5.6 flight condition simulated in the present experiment, the benefits of staging the fuel injection process and inducing dual-mode operation as the overall equivalence ratio is increased are graphically illustrated in Fig. 11. In interpreting these data, it should be emphasized that the relatively low equivalence ratios presented in Fig. 11 were calculated on the basis of the total airflow in the entire 6-in.-wide × 3-in.-high test section. As described previously, the local equivalence ratios in the vicinity of the pilot and fuel injector components (which more closely simulate the average conditions that would prevail in an actual engine installation) would be higher by a factor of approximately four.

Combustor Performance with Liquid Fuel

In addition to the ethylene-fueled combustor performance tests described above, significant combustor testing was also performed under this program in which Jet-A, a liquid hydrocarbon, was used as the primary fuel while the pilot was fueled with ethylene. During early tests, the Jet-A was injected as a liquid from the parametric piloting test hardware. In later tests, the fuel-cooled piloting hardware was used and the fuel was preheated within the pilot cooling passages, as it would be in an actual engine, to a thermodynamic state such that it flash-vaporized upon injection into the combustor.

During the tests with the fuel-cooled pilot, the Jet-A fuel was deaerated prior to its use to minimize the possibility of coking in the fuel passages at the anticipated high temperatures. During these tests, the thermodynamic state of the fuel at the point of injection was established by monitoring the fuel temperature and pressure in the injection manifold. In all tests with the fuel-cooled pilot, the injection pressure was maintained at levels above the 350-psia critical pressure for Jet-A fuel. Fuel temperature-time histories measured during two tests conducted at different primary fuel flow rates are presented in Fig. 12. As shown in Fig. 12, the fuel temperatures in the injection manifold did not quite reach steady values before the ends of the tests. Each of the tests was terminated when the manifold temperature exceeded the level needed to ensure complete flash vaporization. The relatively slow transient thermal behavior experienced in these tests was attributable to the heat-sink nature of the test section hardware in which the pilot model was mounted. In a flight implementation of this piloting concept, the transient heat-sink effects would be drastically reduced by virtue of the nature of the flightweight-type design. Post-test inspection of the fuel-cooled piloting hardware showed no damage of any kind and no evidence of fuel coking. Based on the demonstrated hardware durability and on the fuel temperature rises that were achieved in these tests (at and above the design fuel flow rate), it was concluded that the fuel heating capabilities of the fuel-cooled piloting injector were successfully demonstrated and the adequacy of its thermal design was confirmed.

Combustor performance evaluations were performed for the Jet-A fuel tests using the same techniques applied to the ethylene data as described previously. The results of these analyses are presented in Fig. 13. For the tests with the fuel-cooled pilot, it can be seen that when the Jet-A fuel was heated to the flash-vaporization point prior to injection, primary fuel utilization efficiencies in the range from 80% to 100% were achieved. At early times during the fuel-cooled pilot tests, where the fuel temperatures were slightly lower and the injected fuel would only be partially vaporized upon injection, the combustor performance levels were slightly lower. It can also be seen in Fig. 13 that the fuel utilization efficiencies achieved with heated fuel with the fuel-cooled pilot are significantly higher than those achieved with the parametric piloting hardware with liquid Jet-A fuel at lower injection temperatures. As shown in Fig. 11, the fuel utilization efficiencies achieved during the tests with the flash-vaporized Jet-A fuel are nearly identical to the levels achieved previously with gaseous ethylene fuel at similar test conditions. The Jet-A data are limited, however, to a relatively low range of primary equivalence ratios because of fuel-heating limitations of the present fuel-cooled piloting injector design. In order to expand the operating range of the piloting injector with heated Jet-A fuel (e.g., to match the range covered with gaseous ethylene fuel), the vehicle fuel handling system would have to be designed so that additional primary fuel heating could be accomplished using heat extracted with the combustor wall.

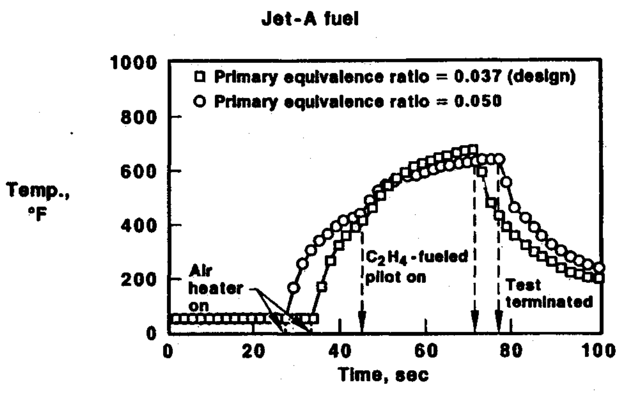

Fig. 12 Primary fuel heating.

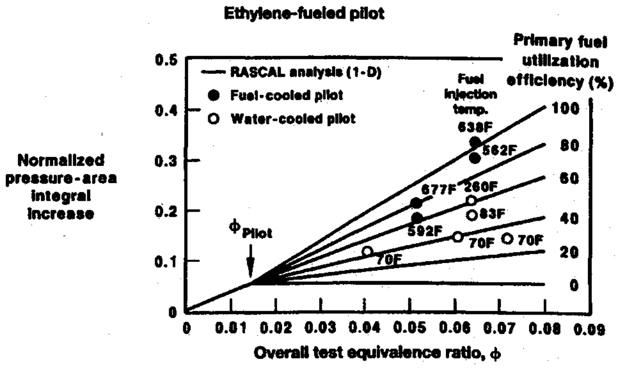

Fig. 13 Primary fuel utilization efficiency–Jet-A.

Conclusions

Development of the air-breathing piloting concept has resulted in the establishment of a stable, efficient supersonic combustor capable of operation with hydrocarbon fuels over a wide range of equivalence ratios. The use of staged mainstream fuel injection has allowed the heat release process to be tailored such that high combustor pressure ratios have been achieved without generating combustor/inlet interactions. The performance benefits of providing for the flash-vaporization of a liquid hydrocarbon fuel in such applications was demonstrated over a limited range of equivalence ratios.

Acknowledgments

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References

[1]Northam, G. B., and Anderson, G. Y., "Supersonic Combustion Ramjet Research at Langley," AIAA Paper 86-0159, Jan. 1986.

[2]Waltrup, P. J., "Liquid Fueled Supersonic Combustion Ramjets: A Research Perspective of the Past, Present and Future," AIAA Paper 76-0158, Jan. 1986.

[3]Kay, I. W., Chiappetta, L., and McVey, J. B., "Hydrocarbon-Fueled Scramjet, Combustor Investigation," Technical Rept. AFAPL-TR-68-146, Vol. IV, May 1969.

[4]Kay, I. W., McVey, J. B., Kepler, C. E., and Chiappetta, L., "Hydrocarbon-Fueled Scramjet, Piloting and Flame Propagation Investigation," Technical Rept. AFAPL-TR-68-146, Vol. IX, May 1971.

[5]Peschke, W. T., Sobel, D. R., and Karanian, A. J., "Hydrocarbon-Fueled Ramjet Scramjet Combustor Investigation," *Proceedings of the 22nd JANNAF Combustion Meeting*, Pasadena, CA, Oct. 1985.

[6]Guile, R. N., and Peschke, W. T., "Piloting Ignitor for Supersonic Combustion," U.S. Patent 4,821,512, April 1989.

[7]Kay, I. W., "Scramjet Design Definition Tests," *Proceedings of the 1987 JANNAF Propulsion Meeting*, San Diego, CA, Dec. 1987.

[8]Billig, F. J., "Combustion Processes in Supersonic Flow," *Journal of Propulsion and Power*, Vol. 4, No. 3, 1988, pp. 209–216.