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Development of Hydrocarbon-Fueled Scramjet Engines: The Hypersonic Technology (HyTech) Program

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The Hypersonic Technology (HyTech) program was initiated in 1995 to maintain a core competency in hypersonic technologies after the cancellation of the National Aerospace Plane program. HyTech is focused on expanding the technology base for liquid-hydrocarbon-fueled scramjet propulsion systems and is complementary in many ways to similar hydrogen-fueled hypersonic programs, such as Hyper-X. The overall effort consists of government sponsored industry efforts and an in-house technology base program. The technical challenges of these efforts associated with successful scramjet operation are addressed, which include activity in inlet/isolator operation, combustor operation and stability, nozzle operation, material advancement, fuel system development and integration and operability. The program has positively demonstrated the technologies that are critical to successful scramjet operation. The current status of work in each of these areas is discussed, followed by a discussion of upcoming activities for the program.

Introduction

THE quest for efficient hypersonic airbreathing propulsion has driven scramjet engine development since its beginnings in the early 1960s. Since then, several engine concepts have been tested.[1,2] Eventually, these activities culminated in the National Aerospace Plane (NASP) Program in the mid-1980s, which was the premier hypersonics program in the nation for almost a decade. NASP was aimed exclusively at the goal of single-stage-to-orbit flight. It made many significant technological advances that increased confidence that hypersonic flight using airbreathing scramjet engines could be achieved successfully. Although NASP was terminated in the mid-1990s, the United States has maintained an investment in hypersonic technology development through continuing government programs, such as the Hypersonic Technology (HyTech) program discussed herein. Through successful demonstration of critical technologies, such as inlet self-starting, integration for freejet tests, fuel-cooled structural panels, and combustor performance and operability over the Mach 4–8 range, the HyTech Program has shown that scramjet operation is a reality.

HyTech Program Overview

The overall HyTech Program objective is to develop enabling technologies and demonstrate the operability, performance, and structural durability of an expendable liquid hydrocarbon supersonic combustion ramjet (scramjet) propulsion system that operates from Mach 4–8 (Ref. 3). The scramjet is the highest performing cycle in terms of specific impulse in this speed range.[4] HyTech is a technology development program designed to concentrate on engine development and focus on expendable missile applications. However, this application is just the first step toward the much broader goal of technology developments leading to higher Mach number, reusable scramjet applications.

A primary component of the HyTech Program was the Storable Fuel Scramjet Flowpath Concepts (SFSFC) Program, which comprised industry-based efforts. The SFSFC Program proceeded from component demonstrations to an integrated, regeneratively cooled ground engine demonstrator. The technology development was designed to apply to all hydrocarbon-fueled hypersonic vehicles. The SFSFC Program was initially structured into three phases.[3] The objective of phase 1, hereafter referred to as HyTech phase 1, was to develop two feasible hydrocarbon scramjet engine concepts and associated critical engine component technologies. To this end, inlet tests, heat sink combustor tests, hypersonic missile design studies, thermal management system design, and fuel-cooled structure demonstrations were conducted on two engine designs, a strut configuration[5–7] and a two-dimensional flowpath.[8,9] The objective of phase 2 was to integrate the critical technologies into integrated system demonstrators. Phase 3 activities center around a flight-type integrated engine demonstrator using flight-type structures that will be tested in a freejet facility to demonstrate engine performance and durability. At the start of phase 2 when the current (two-dimensional) design was selected for further development, the SFSFC Program was renamed the Hypersonic Scramjet Engine Technology (HySET) Program. Similarly, the development associated with each phase changed; HyTech phases 2 and 3 became HySET phases 1 and 2, respectively.

For each phase, quantified component, subsystem, and engine performance goals were defined to measure performance achievements. All operability and performance data obtained from tests and analyses were used to refine the engine and subsystem design and performance. These performance goals were incrementally increased in each phase, culminating in the final engine and missile performance goals required to achieve the system technology and mission goals.

Technology Challenges

There are several reasons underlying the decision to focus exclusively on the propulsion system and on flight at speeds from Mach 4 to 8 using hydrocarbon fuels.[3] Operationally speaking, hydrocarbon fuels are much easier and safer to handle than hydrogen, realistic ground testing can be accomplished in existing facilities, and Mach 8 arguably represents the useful upper limit for hydrocarbon

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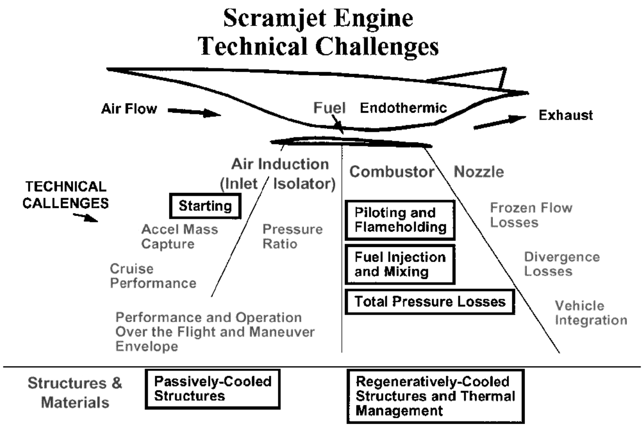


Fig. 1 Scramjet engine technical challenges.

fuels. Additionally, given their higher density, hydrocarbon fuels are competitive with hydrogen for vehicles.[10] Furthermore, over this speed range, a fixed-geometry flowpath can be used instead of a variable-geometry one, thereby removing the mechanical complexities associated with a variable-geometry flowpath. Last, by initially focusing on an expendable missile application, the reliability requirements associated with a reusable or piloted vehicle are eased.

There are many technological challenges to be addressed for successful scramjet operation, as shown in Fig. 1. These issues, as they relate to the engine/vehicle components, are air induction (inlet/isolator), combustor, nozzle, fuel and fuel system, and structures and materials. A sixth area, not specifically depicted, is the integration and operability of all components. Each of these issues is discussed in turn hereafter.

Inlet/Isolator

Challenges for the compression system components include both performance and operability issues, the latter tending to dominate the design. The challenges are characterized as starting, air mass capture, contraction ratio, thermodynamic efficiency, and pressure ratio. The term "started" in an inlet operating at supersonic speeds indicates that supersonic flow is established in the internal compression portion of the inlet (the desired condition). When the inlet is unstarted, strong shocks appear ahead of the inlet cowling, which cause diversion of flow around the inlet (spillage), resulting in high drag and structural loads. The amount of spillage affects the thrust produced by the scramjet because thrust is directly proportional to the air mass flow rate processed by the cycle. Starting also plays a significant role in contraction ratio because the starting contraction ratio is much more restrictive. Therefore, the maximum contraction tends to be a major challenge in fixed geometry flowpaths. The challenges associated with starting, mass capture, and contraction often dominate the design, such that thermodynamic efficiency is a byproduct of design compromises rather than a design goal. Last, the pressure ratio of the integrated inlet/isolator combination is perhaps the most important operability challenge issue in a dual mode fixed geometry scramjet design. This is due to a number of design factors including aspect ratio, sidewall configuration, inlet shock interactions, combustor fuel injectors, and boundary-layer characteristics around the perimeter of the isolator.

Combustor

The challenges associated with the combustor are primarily focused on the fuel, namely, piloting and flameholding resulting in stable combustion from thorough air/fuel mixing (see Fig. 1). The fuel ignition delay has a significant impact on the pilot geometry. Under most conditions, the spontaneous ignition delay time is significantly larger than the residence time of the air flowing through the engine, which is typically on the order of 1 ms or less.[11,12] To overcome this difference, recirculation zones are typically created in the pilots and/or near the fuel injection points where the residence time is sufficient to allow fuel ignition and combustion. These pilot geometries, also called flameholders, are designed to cause the fuel and air mixture to recirculate, thereby increasing the residence time to enable ignition and stable combustion. However, in the design of these flameholders, a tradeoff exists between geometry and total pressure loss.

Combustion stability is also dictated by the stability loop, which is another relevant fuel property for piloted flames (with flameholders). The stability loop shows the equivalence ratio at which a combustor extinguishes as a function of the stability parameter (S'). The stability parameter is a function of velocity, flameholder geometry, and the reciprocal of temperature and pressure. The stability loop becomes wider as one proceeds from methane (CH_4), through ethane (C_2H_6) and ethylene (C_2H_4), to hydrogen.[13] Liquid fuels have stability loops roughly equivalent to ethane, and so it is expected that the stability loop will widen as the hydrocarbon fuel is cracked (but will still be much narrower than that for hydrogen). The maximum flameholding velocity is increased substantially with silane (SiH_4) addition.

Nozzle

Unlike the inlet and combustor, nozzle challenges are related to performance and efficiency rather than to operability. The nozzle thrust coefficient is the most sensitive parameter in determining overall scramjet cycle efficiency. However, because the flowpath design is generally dominated by operability concerns in the inlet, isolator, and combustor, the nozzle performance tends to receive comparatively less attention. The nozzle performance challenges are characterized by loss mechanisms in the exhaust flowpath: underexpansion, divergence, chemical kinetics, and friction. The underexpansion and divergence losses are the most severe for a fixed geometry flowpath intended for missile applications, with chemical kinetics and frictional losses accounting for less of a loss. A major challenge of the nozzle, which does not relate directly to the scramjet performance but rather to the vehicle performance, is the nozzle thrust vector and resulting pitching moments. If the nozzle thrust vector is excessive, or in the wrong direction, excessive trim from the vehicle flight control surfaces is required, which results in added drag. The thrust vector angle can be easily controlled in the design process by changing engine cant and nozzle surface angles. This has always been an iterative design and vehicle integration challenge.

Materials/Structures

Hypersonic vehicles represent an extraordinary challenge for structures and materials due to the extreme conditions associated with hypersonic flight. The engine application represents a particularly challenging problem because of the severe combustion environment in the flowpath. It is characterized by high thermal, mechanical, and acoustic loading along with an aggressive, corrosive mix of hot oxygen and fuel decomposition products. Left uncooled, material temperatures would exceed the melting point of most metallic structural materials.[14] Actively cooled structures may be required and will certainly be required for engines designed for any combination of long life, reusability, high Mach number operation, and human-rated reliability.

Candidate flowpath materials need to be formable into lightweight wall panels and complex-shaped components, such as fuel pilots and injectors, using advanced processing methods. The manufacture of structures, specifically actively cooled structures, requires significant developments in a variety of fabrication methods with attention directly focused on durability for long-life vehicles and sealing interfaces between surfaces in the hot flowpath environment. Further development and validation of thermostructural design methods is also needed.

Fuels

Challenges in the area of fuels are focused on their use as an endothermic coolant and improving their ignition delay and burning velocity. The high air velocities in hypersonic flight lead to very significant aerodynamic heat loads on the vehicle structure, especially in the combustor. In fact, uncooled combustor temperatures can exceed 3000 K (Ref. 14), well in excess of known structural material capabilities. Regenerative cooling of the engine structure with fuel is required based on the resulting fuel heat sink.[11] However, exposing hydrocarbon fuels to high temperature can result in coking (deposition), which would restrict or block cooling passages and could cause catastrophic structural failure.

In terms of ignition delay, hydrogen has the shortest ignition delay and methane the longest, with liquid hydrocarbons, in general, lying somewhere in between. As long, liquid hydrocarbon chains are broken or cracked through their use as endothermic coolants, the ignition delay changes as the chemical composition of the injected fuel changes.[15] This change in ignition delay affects combustion stability. Changes in ignition delay can also be altered through the use of fuel additives.[12,16,17]

Integration and Operability

Airbreathing dual-mode hypersonic engines operate quite differently during ramjet (subsonic combustion) and scramjet (supersonic combustion) modes. The different modes of operation can require different fueling locations to adjust the heat release in the combustor for efficient engine operation. Variable engine geometry can also be used to adjust the air flow and heat release profile in the engine. Given these varying fuel schedules, fuel entering the combustor can be under significantly different conditions for the various Mach numbers, with resulting differences in density, viscosity, and other physical properties. Density can vary by an order of magnitude and viscosity by two orders of magnitude over the Mach number range.[11] Thus, it is a significant challenge to demonstrate that a given engine design will operate robustly over the flight envelope.

Results

The scramjet propulsion system design, discussed in the present contribution and shown in Fig. 2, includes the propulsion system structures (passively and actively cooled) and engine subsystems. The results of the major demonstrations undertaken under the HyTech Program are described in the following paragraphs.

Inlet/Isolator

Inlet starting, performance, and operability have been addressed in a series of subscale inlet tests. In HyTech phase 1, a subscale inlet model was tested to verify the performance and operability of the flight engine inlet that was developed from the preliminary design.[8] During HyTech phase 1 testing 121 runs were performed to simulate inlet operation across the Mach range from 4–8.

Inlet throat convergence angle, start door angular velocity, pilot area blockage, and isolator divergence angle were investigated. A second entry of the inlet model was made with investigations focused on isolator length, isolator divergence angle, potential self-start configurations, and sidewall configurations. A self-starting inlet with cutback sidewalls was developed during this entry.[9] The results of these tests showed a significant increase in static pressure ratio through the inlet and isolator. This feature was incorporated into the baseline HySET engine configuration.

As vehicle applications for this scramjet continue to evolve, the scramjet flowpath width can be increased or decreased to meet varying levels of vehicle thrust requirements. Discussions have been held regarding the possibility that aspect ratio (the ratio of flowpath width to flowpath throat height) may have an effect on inlet isolator performance. During HySET phase 1, a third inlet model was constructed to investigate this potential interaction. The model was tested and the results were nearly 100% of the final component objectives.[9] The inlet performance, as described by the aerodynamic contraction ratio, kinetic energy efficiency, and weight flow ratio, either achieved or exceeded the final inlet technology objectives. However, inlet operability, as described by the pressure ratio, fell short of the final objectives and will continue to be addressed.

Combustor

Combustor testing utilizing a heavyweight rig was performed in HyTech phase 1 and continued in HySET phase 1 to verify the performance and operability of the flight engine combustor that was developed from the preliminary design. There were 172 HyTech phase 1 and 115 HySET phase 1 direct-connect combustor runs performed to study fixed geometry combustor operation on JP-7 at simulated conditions of Mach 4–8.

Combustor entrance pressure, fuel/air equivalence ratio, fuel temperature, fuel composition, fuel injector location, fuel scheduling, baseline pilot geometry, and alternate piloting concepts were investigated during both HyTech phase 1 and HySET phase 1. During HyTech phase 1, two alternate piloting concepts[9] were derived by extending the design tools used to create the baseline pilot geometry. The driving metrics to investigate the alternate pilots were manufacturing complexity and cost. A swept ramp and swept strut hardware were fabricated and tested in direct connect combustor testing. Combustor performance and operability was comparable to the levels demonstrated by the baseline pilot.

A new direct connect combustor rig has been tested. HySET phase 1 testing for this direct-connect rig, shown in Fig. 3, focused on performance optimization. The combustor tests showed nearly 100% success relative to the final combustor technology objectives. Combustor performance, as described by the combustion efficiency and maximum pressure rise, were further examined during HySET phase 2 semi-freejet testing.

The flight conditions for this freejet test series included 60 runs at Mach 6.5 and 35 runs at Mach 4.5 (Ref. 18). The test data showed that the engine met or exceeded the performance goal based on combustion efficiency for an equivalence ratio near unity. The data further showed that the copper test hardware experienced significant heat loss. The loss of heat resulted in lower than expected fuel and wall temperatures compared with those temperatures expected to be present in the real engine. To more thoroughly heat the engine walls prior to injection of the hydrocarbon fuel, the vigorous combustion time using silane was extended.

Materials/Structures

Although work in this area has been primarily focused on thermal protection throughout the engine flowpath, there are ongoing efforts

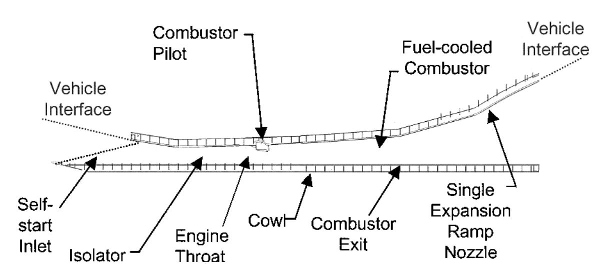


Fig. 2 Scramjet preliminary design (two-dimensional flowpath).

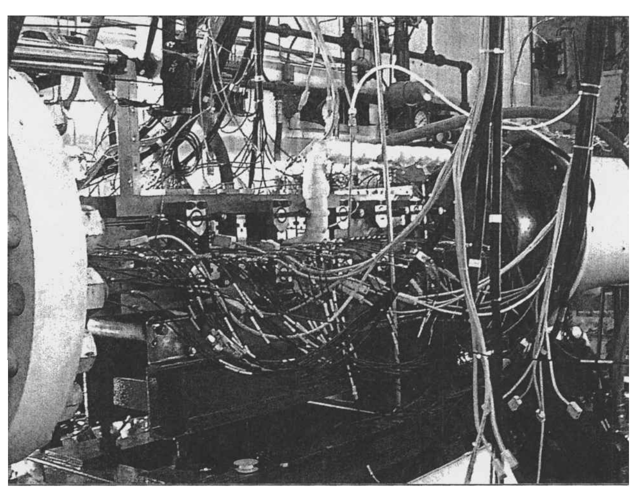


Fig. 3 HySET phase 1 direct connect combustor rig installed in the test facility.

focusing on the structural integrity of the combustor section of the engine, as well as developing/improving manufacturing techniques such as low-cost prototyping.

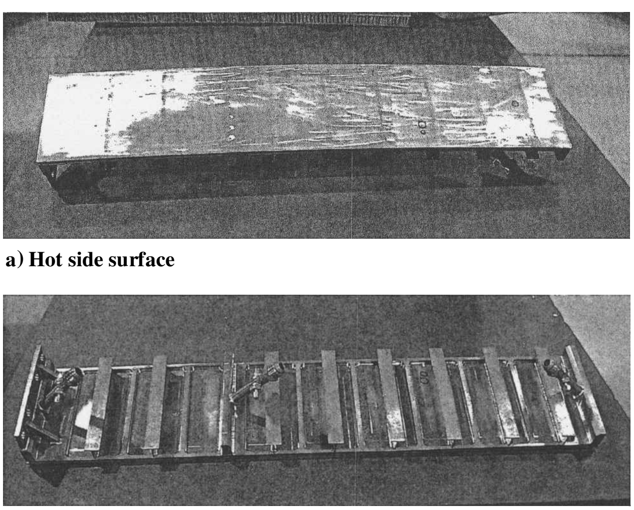
Actively Cooled Heat Exchanger Panels

Given the need for active cooling in portions of the engine, a great deal of effort has been dedicated to the development of actively cooled heat exchanger panels during the HySET Program.

In HyTech phase 1, a 15.2 × 38.1 cm (6 × 15 in.) fuel-cooled heat exchanger panel test was performed to verify the fabrication, performance, operability, and durability of a subscale fuel-cooled structure consistent with the flight engine preliminary design. Fabricated from conventional materials, the heat exchanger channels were end milled into the face sheet and the backstructure was subsequently brazed to the face sheet. Eight runs were performed with the panel installed in the HyTech phase 1 direct-connect combustor rig.[9] The panel was actively cooled with JP-7 and tested at conditions representative of flight at Mach 7. The panel materials, manufacturing processes, assembly processes, catalyst coating processes, seals, and design and analysis tools were all investigated during the course of this panel activity. The performance, operability, and durability of the panel as characterized by the panel bulk heat load, JP-7 coolant performance (temperature rise, pressure drop, heat sink, and composition), backface surface temperatures, and structural integrity compared very well with the pretest predictions.

The investigation of cooled panels has continued in HySET phase 1 with efforts focused on low-cost manufacturing technologies, scale-up issues, and panel durability testing. Three 15.2 × 76.2 cm (6 × 30 in.) heat exchanger panels, similar to the one shown in Fig. 4, were fabricated from a nickel-based superalloy as part of the HySET phase 1 effort. Figure 4a shows the hot or combustor flow side of the panel, and Fig. 4b shows the backstructure of the panel. As part of the effort to examine low-cost manufacturing technologies, the flow channels were machined into the panels using waterjet milling. This technique has proven to be quite effective in milling complicated channel geometries such as those around the fuel injection ports in the panel (see Fig. 5).

Another low-cost manufacturing technique examined during HySET phase 1 was laser welding. Two of the three 15.2 × 76.2 cm panels fabricated for this phase used laser welding to join the face sheet to the backstructure (note, the third panel was brazed). One of the concerns with this technique is that the weld bead does not cover the entire width of the land (see Fig. 6). However, testing performed to date indicates that this technique yields bonds of adequate strength. Another concern with laser welding is that the technique introduces distortion into the panel, but it has been demonstrated that the distortion resulting from laser welding can be adequately controlled.



a) Hot side surface

b) Cold side (backstructure)

Fig. 4 Fuel-cooled 15.2 × 76.1 cm panel.

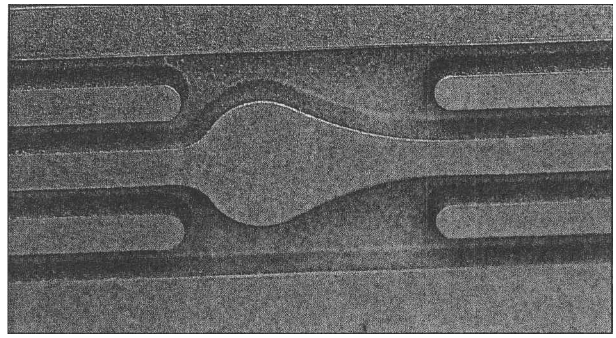


Fig. 5 Details of channels in vicinity of fuel injection location.

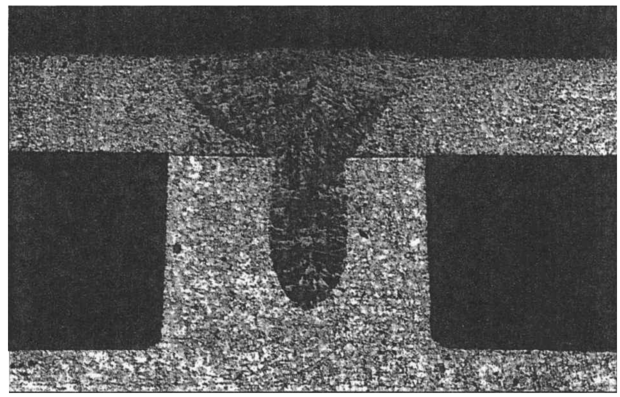


Fig. 6 Cross-sectional detail of laser weld.

The two laser welded 15.2 × 76.2 cm panels were tested during the spring of 2000. The first panel was tested in a scramjet test rig. In this testing, the panel was installed in the rig as a cowl-side combustor panel. All tests were run with ethylene fuel at Mach 6.5 and a dynamic pressure of 750 psf. For the majority of testing, the panel was cooled with JP-7 fuel, but, for one test, the panel was cooled with gaseous nitrogen. The purpose of this test, which was successfully completed, was to demonstrate the effectiveness of the panel design, validate thermal/structural models, and gather data on shock amplification factors.

The second laser welded 15.2 × 76.2 cm panel was subjected to durability testing in a radiant heated facility. In this testing, the panel was installed in a nitrogen-filled test chamber and operated for long durations (5–10 min) under radiant heat fluxes simulating actual combustor conditions. Heated JP-7 fuel, supplied at varying flow rates, was used as the coolant for these tests. The panel test demonstrated not only the ability to survive at nominal flight conditions, but also demonstrated significant margin at conditions far more severe than those expected in flight.

In addition to the 15.2 × 76.2 cm panels, a full-scale cooled sidewall panel was developed in HySET phase 1. This panel was fabricated using the same waterjet machining and laser welding techniques used to construct the 15.2 × 76.2 cm panels. The heat exchanger design for the sidewall panel accommodates divergence by maintaining constant channel widths while increasing the land widths toward the aft end of the panel. The maximum allowable land width thickness is limited by conduction and by the available cooling effectiveness. A land width that is too thick cannot be adequately cooled. To accommodate these factors, the sidewall cooling channels were subdivided into subsections. Each subsection was separated by a transverse groove machined into the metal surface to intersect the channels. The transverse grooves acted as redistribution manifolds for the coolant and were intended to ensure an even distribution of flow across the width of the panel.

Before fabrication of the sidewall panel, ambient water flow tests were conducted on a stereolithography generated sidewall model to verify coolant flow distribution. Flow distribution was measured at the exit of the panel and was found to be uniform within ±6% of the averaged flow. Dye injection was used to evaluate differences between in-line passages, that is, flow channels that are lined up with the passage across the plenum between them, and not-in-line passages, that is, channels fed from an upstream channel where flow must turn sharply to enter the downstream passage. A 25% reduction in flow velocity was noted with the not-in-line channel tests. A photograph of the dye test focused on the center sidewall passages is shown in Fig. 7.

The sidewall panel was subjected to durability testing in the same radiant heated facility used to test the second 15.2 × 76.2 cm panel. The quartz lamp array was configured to simulate the intensity and distribution of panel heating expected in flight. Testing was initiated with calibration runs using nitrogen. A series of tests was then run where JP-7 coolant was used. For early runs, the heating array was run at reduced power, and the panel was overcooled. Ultimately, the panel was run at the expected heat distribution and cooling flow rate, and the panel performed extremely well.

Leading Edges

Another area of concern in the thermal/structural design of the scramjet engine is the cowl leading edge. This area is subjected to high heat fluxes concentrated over a small surface; therefore, the leading edges are highly stressed. A continuing effort has focused on materials and designs for cowl leading-edge structures.

A series of test specimens have been tested in an arc-heated facility. A representative leading-edge test specimen is shown in Fig. 8. Specimens have been fabricated from and coated with a variety of ceramic matrix materials. In addition, numerous fiber weaves have been examined in an attempt to minimize damage to the leading edge and provide a pathway for heat to efficiently travel away from the leading-edge tip. The better performing materials have demonstrated the ability to survive the severe leading-edge heating conditions for durations up to 10 min. Testing has been successfully completed to examine methods for mating ceramic leading edges to the metallic main engine structure. Additional efforts will also be undertaken to scale up leading-edge widths to the full engine width. This scale-up can be achieved either by manufacturing wider sections or by joining a series of smaller-leading-edge sections to create an engine width leading edge.

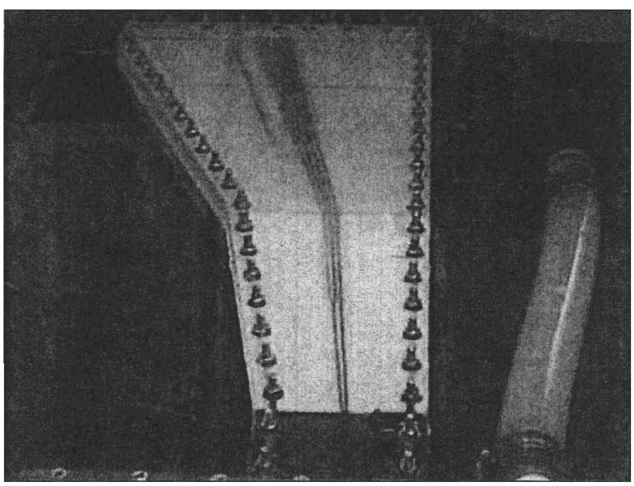


Fig. 7 Dye test of sidewall center passages.

Combustor Box Acoustic and Pressure Testing

Dynamic pressure (acoustic) loads in a scramjet combustor can be quite extreme, with an overall sound pressure level exceeding 180 dB. Therefore, an effort is underway to examine the performance of the main engine structure under both acoustic and static pressure loads. A section of the HySET scramjet combustor was fabricated from materials and designs representative of the current engine design. This box structure includes panels with integral cooling channels, the pilot ramp/cavity region, and a divergent section downstream of the cavity. The final test article is an open-ended combustor box.

Testing of this article was undertaken to demonstrate the structural performance of the combustor design. Particular attention was focused on the corner regions where the sidewall panels meet the cowl and body panels. The combustor box was subjected to room temperature acoustic loads, and sound pressure levels as high as 178 dB were achieved in these tests. The combustor box performed well. Testing of the combustor box under a static pressure load is planned for the immediate future.

Additional Efforts

A number of other efforts are underway as part of the structures and materials activity. A fuel-cooled pilot structure is being designed that will be tested for its thermal/structural performance. This complex part represents both a design and manufacturing challenge. Low-cost methods for manufacturing complex parts such as the fuel-cooled pilot are being examined. One candidate method that shows promise is to cast these parts using molds generated by stereolithography. A number of sample parts have been cast using this method with excellent results.

Efforts to develop and improve thermal and structural models also continue. Of significant interest in this area is the effort to understand shock amplification factors. Shock amplification of heat loads can generate localized areas of extremely high heating, and failure to properly account for this phenomenon can have serious consequences. Initial estimates of these shock amplification factors are obtained from computational fluid dynamics, and these estimates are validated and refined from test data for the various thermal/structural tests. In addition, recent tests have incorporated copious thermal instrumentation that can provide data for validating thermal models.

Integration and Operability

A heavyweight, semi-freejet engine was designed, built, and tested during HyTech phase 1 (Ref. 9). This engine incorporated the flowpath lines and pilot design of the HyTech phase 1 flight engine design. Testing was performed at Mach 8 cruise conditions to demonstrate combustor performance with realistic inlet distortion and to demonstrate production of positive thrust. Both objectives were achieved: the combustor pressure rise and (positive) net thrust were found to agree very well with the pretest predictions. These results also served to validate the flowpath design and analysis tools. The test results were also compared to results obtained earlier in

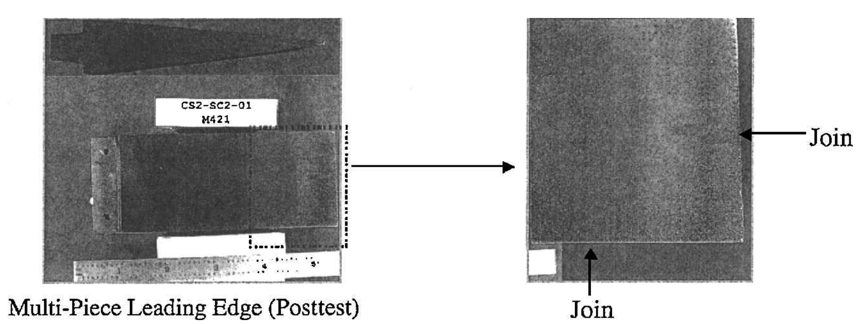


Fig. 8 Representative leading-edge specimen (posttest).

direct-connect combustor tests, which indicated that the pressure rise through the freejet engine compared well to the levels of pressure rise seen in earlier direct-connect combustor rig testing.[9] Similar comparisons were performed during HySET phase 2, which displayed similar agreement with pretest analyses.[18]

Technology Base Efforts

The intent of the HyTech Program is to continue the development and demonstration of enabling technologies required for efficient hypersonic flight using a scramjet engine. To this end, there has been considerable research addressing each of the technical challenge areas mentioned earlier.

Fuels Development

A number of fuel-related technologies have been pursued as part of, or coordinated with, the HyTech Program. Increasing the reactivity of the liquid hydrocarbon fuel is one such effort. Mach 4 is an especially difficult flight condition due to the relatively low air temperatures. Increased reactivity includes reduced ignition delay and increased combustion efficiency under heavily piloted conditions. Many chemical approaches have been used in the past to increase the reactivity of hydrocarbon fuels, relying on fuel and/or additives that are pyrophoric under engine conditions. In one scramjet engine,[2] chlorine trifluoride (ClF3) was used as an additive to the airstream to improve the combustion. In another scramjet engine,[1] highly reactive hydrocarbons (such as alkyl boranes) demonstrated high combustion efficiencies, whereas less-reactive fuels performed more poorly. As part of the HyTech Program, it was decided that these reactive fuel approaches were not desirable for a regeneratively cooled engine, where the stability of the fuel under endothermic cooling conditions is a key fuel property. Ground and flight safety and handling of the reactive fuels was also a concern. What was desired was an additive under relatively low concentration (from tens to hundreds of parts per million) that would still cool effectively and not change the fuel reactivity under storage and handling, but would yield enhanced combustion properties. The benchmark additive was 2-ethyl hexyl nitrate (EHN), an additive used commercially to enhance the autoignition of diesel fuel by increasing the cetane number. In shock-tube ignition delay tests, it was found that EHN was relatively ineffective under scramjet engine conditions, requiring about 1% additive to achieve significant ignition delay reductions. Several additives were found that were significantly more effective than EHN.[12,16] It was also anticipated that endothermic reactions of the fuel during regenerative cooling would also reduce the ignition delay. This was examined by measuring the ignition delay of heptane and of a heptane mixture with methane and ethylene, simulating a partially cracked fuel.[15] The ignition delay of the cracked fuel simulant was reduced compared to the unreacted fuel (heptane), although the ignition delay did not match that of ethylene, the most reactive hydrocarbon in the mixture, and certainly fell well short of hydrogen. The effect of ions on the reaction rates of hydrocarbons has also been investigated, showing potentially significant decreases in ignition delay.[19]

The use of additives to modify fuel behavior under various conditions falls into the general category of smart fuels or controlled chemically reacting fuels.[12,17] Other targets for fuel behavior modification include deposition reduction under fuel cracking conditions and emissions reductions.[12,17,20,21] The overall goal is for the additive to be inert until fuel system and/or combustor conditions are reached where the improved fuel behavior is needed. In many cases, the triggering condition is fuel temperature. The behavior of fuels under high heat flux conditions was also examined[22,23] to study heat transfer instabilities observed in earlier investigations.[24] Fuel/material compatibility at high temperatures was also an issue.[22,25] Fuel attack on iron- and nickel-containing materials was observed through the formation of filamentous carbon. Careful selection of materials can minimize the formation of filamentous carbon, leaving deposition of amorphous carbon as the main route of surface fouling. The use of hydrogen donors and diene suppressors has shown some promise, but falls far short of the order-of-magnitude reductions desired.[12,17,20,21]

Combustor Development

Barbotage

Tests have been conducted to examine the effects of barbotaged liquid on the combustion process.[26] Effervescent (or barbotaged or aerated liquid) atomization is characterized by introducing a gas into the liquid stream upstream of the injection site. Atomization of the liquid is accelerated by the gas through either the rapid expansion of bubbles contained in the liquid or by destabilization of the liquid sheet by the co-flowing, high-speed gas. Enhanced penetration of the fuel into the cross flow and fuel-air mixing also result from this injection approach. Typically, less than 4% by mass of gas in liquid is sufficient to achieve the desire effect. Tests have shown successful ignition and sustained combustion of aerated liquid fuel in a scramjet flowpath at simulated flight Mach numbers between 4 and 5 and dynamic pressures of 23.9 and 47.9 kPa.

Injection Schemes

As shown in Fig. 1, fuel injection and mixing are technology challenges facing successful scramjet engine operation. To this end, several different injection schemes have been analyzed.[27,28] In the recent work of Mathur et al.,[27] a series of test were performed to evaluate the potential of a "streamlined, flush-mounted, locally pressure-matched fuel injection" system using nitrogen as the fuel simulant. The authors concluded that this injector exhibited excellent penetration but was not optimal for the flight conditions tested (dynamic pressure of 0.26 MPa at Mach 3) based on the presence of strong shocks and their reflections.

In the recent work of Gruber et al.,[28] two aerodynamic ramps were evaluated to determine their impact on fuel injection and mixing. Both injector configurations utilized trailing cavities to act as flameholders. The utility of cavities has been well documented.[29–32] The injectors were evaluated at simulated flight Mach numbers between 4 and 5 at flight dynamic pressures between 35.9 and 47.9 kPa. The results showed noticeable differences in pressure rise and flame uniformity between the two configurations.

Material Development

A tradeoff exists between thermal management and weight. Typically, high-temperature metal alloys are chosen for thermal management systems (as mentioned) due to their ability to endure high temperatures. However, a weight reduction potential exists if advanced composite materials are used.[33] These materials typically have lower density than metals and may increase the thermal management margin. This margin may be enhanced through the use of direct fuel cooling using a storable hydrocarbon fuel through an endothermic reforming process.

Summary

The HyTech Program is demonstrating and developing technologies that will culminate in a regeneratively cooled ground freejet demonstration of a dual mode ramjet/scramjet engine capable of Mach 4–8. Progress to date has indicated no areas for setback, although achieving good combustion efficiency and operability in a fixed-geometry combustor over the Mach number range with liquid hydrocarbon fuels has proven to be quite difficult. The state-of-the-art in piloting systems for hydrocarbon fuels and manufacturable fuel-cooled structures has been significantly improved. The critical technologies for successful scramjet operation, fuel-cooled structural panels, integration for freejet testing, a self-starting inlet, and combustor performance and operability, have all been demonstrated.

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