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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Rocket-Based Combined Cycle Propulsion System Testing

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Introduction

ROCKET-based combined cycle (RBCC) engines combine the high thrust-to-weight ratio of rockets with the high specific impulse of ramjets in a single integrated propulsion system that is capable of generating thrust from sea-level-static to high Mach number conditions. The strutjet[1] tested at the NASA Lewis Research Center's (LeRC) Hypersonic Tunnel Facility (HTF) is one example of this engine concept that is being developed cooperatively by a government and industry team.

The strutjet is an ejector–ramjet engine in which small, fuel-rich mono-methyl-hydrazine (MMH)/inhibited red fuming nitric acid (IRFNA) rocket chambers are embedded into the trailing edges of the inlet compression struts. The engine operates as an ejector ramjet from takeoff to about Mach 3. At low Mach numbers, entrained air is completely consumed by the fuel-rich rocket exhaust. As freestream Mach number and airflow increase, JP-10 fuel is introduced to maintain the stoichiometric combustion of all available oxygen. At approximately Mach 3, the strut rockets are turned off. Above Mach 3, the engine operates as a thermally choked ramjet, and then transitions to supersonic combustion (scramjet) mode. For space-launch applications, the rockets are reignited at a Mach number beyond which air-breathing propulsion becomes impractical.

The purpose of this paper is to present the increased operating range achieved by the HTF and the high fidelity of previously completed subscale tests and computational fluid dynamics (CFD) simulations of this engine configuration as demonstrated by the HTF engine data.

Facility Description

The HTF is a blowdown, nonvitiated freejet test facility capable of testing large-scale propulsion systems at Mach numbers up to 7. Major features of the facility are shown in Fig. 1. Nitrogen from a 4500 psig GN_2 rail car is supplied at the desired test pressure to the 3-MW drilled core magnetic induction graphite storage heater, where it is heated to a temperature somewhat above the desired test total temperature. The maximum heater outlet conditions are 130 lb/s at 1200 psia and 4500°R. The heated GN_2 then passes out of the heater bed into the hot train section, where ambient temperature GO_2 and GN_2 are added to bring the flow to true air composition and the desired test total temperature. This flow then goes through a converging–diverging facility nozzle that expands the flow to supersonic conditions. Mach 5, 6, and 7, 42-in. exit diameter facility nozzles are currently available. The test flow then passes through and around the engine mounted on the overhead, translating thrust stand in the 25-ft-diam, 20-ft-high domed test cabin and enters the diffuser/spraycooler/steam ejector altitude exhaust train. The thrust stand was designed to handle a test article of up to 16,000-lb weight and 8500-lb thrust, and is capable of a 5-deg variation in angle of attack. Further details on the HTF are available in Ref. 2.

A number of upgrades to the HTF were required to perform the RBCC Strutjet test program. These consisted of the addition of systems for the supply of ambient temperature and heated liquid JP-10, 80% H_2/20% SiH_4 (silane), and high-pressure cooling water. Also, a 64-channel high-speed MassComp data system was added.

Test Article Description

The model used for this test series is a heat-sink-type engine constructed primarily of 2-in.-thick copper plates. The engine is shown schematically in Fig. 2. The inlet is a fixed geometry design that incorporates two windscreen/isolator struts that divide the inlet into three channels. There is no net geometric internal contraction aft of the cowl lip, which enables the inlet to self-start at a Mach number below 4. Behind each windscreen/isolator strut is a forward fuel injection block followed by an aft fuel injection block that can also accommodate three small rockets, although none were installed for this test series. The top surface of the diverging nozzle section is made up of hinged sections that allow the nozzle expansion angle to be changed between tests. All of the different sections used to construct the engine are sealed from leakage using red silicon O-rings compressed between the sections. A precompression plate is mounted in front of the inlet to partially simulate a vehicle forebody to provide the proper engine inlet conditions. The plate length was selected to place the plate bow shock at the engine cowl lip at Mach 6. The leading edges of the inlet, struts, and precompression plate are all water cooled.

Test Results

Test Facility Conditions

The RBCC engine test plan called for the facility to be operated at a Mach 6 enthalpy (3000°R), with the Mach 5 facility nozzle to simulate a Mach 6 flight condition. The lower engine inlet entrance Mach number was used to account for the bow shock of the vehicle on which the engine would be installed in flight. The test plan similarly called for the facility to be operated at a Mach 7 test gas enthalpy (3900°R), with the Mach 6 facility nozzle to simulate a Mach 7 flight condition. For the given test conditions, the HTF as configured was able to achieve a maximum test gas enthalpy simulating Mach 6.6 (3500°R) at 1065 psia total pressure during this test series. The

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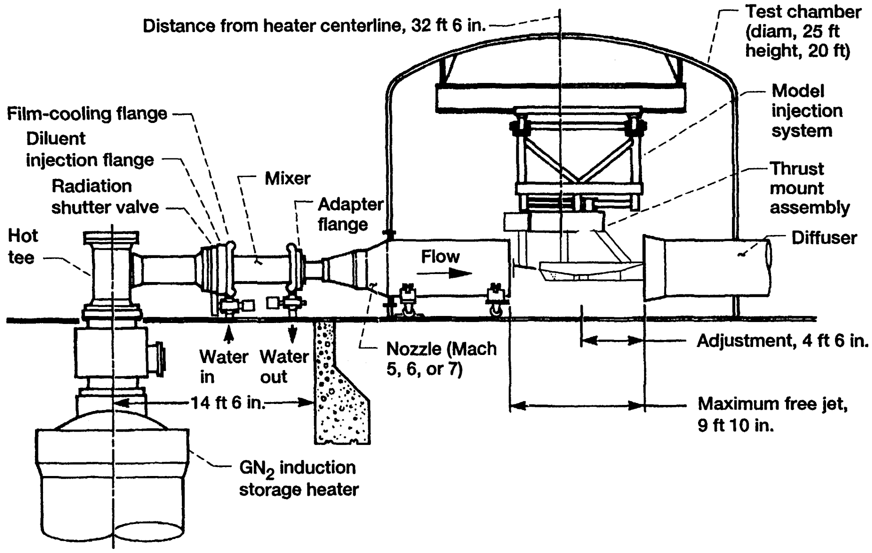

Fig. 1 HTF hot train and test chamber.

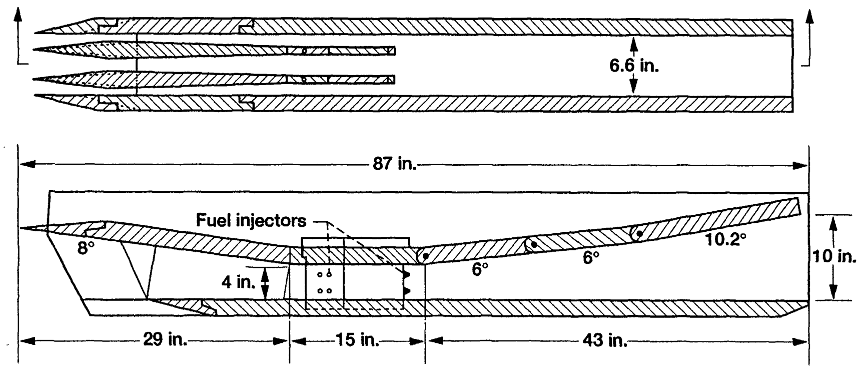

Fig. 2 Schematic of RBCC strutjet engine with fuel injection blocks installed.

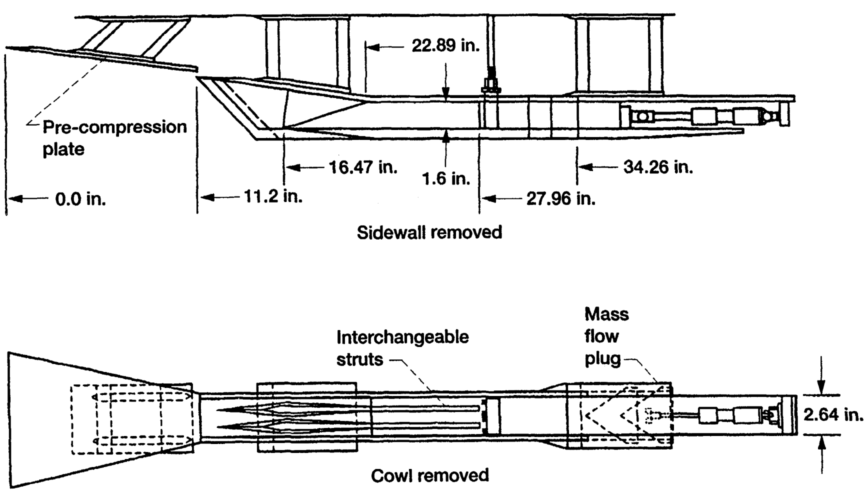

Fig. 3 40% scale RBCC strutjet inlet model run in LeRC 1 × 1 SWT.

maximum test condition previously demonstrated since the HTF reactivation was completed in 1994 was 3000°R total temperature at 1050 psia total pressure.

Engine Aerodynamic Test Data and Comparison to Subscale Inlet Aerodynamic Test Data

A series of aerodynamic studies of a 40% scale model of the inlet region down to the end of the fuel blocks were conducted previous to the fabrication of this full-scale RBCC engine to aid in the design and characterization of the inlet. These tests were conducted at NASA LeRC's 1 × 1 supersonic wind tunnel over a test Mach number range of 4 to 6. Details of this test program are contained in Ref. 3. The test hardware configuration used for these subscale tests is shown schematically in Fig. 3. Figure 4 shows a plot of this data for the Mach 6 case, corrected for scale, overlaid upon a plot of RBCC engine data for the same conditions vs CFD prediction. The Mach numbers listed throughout this section refer to the facility nozzle exit Mach number, as opposed to the simulated flight Mach number. All pressure distributions shown were measured along the top wall (body side) of the engine on the engine centerline. A scaled drawing of the HTF engine is in-

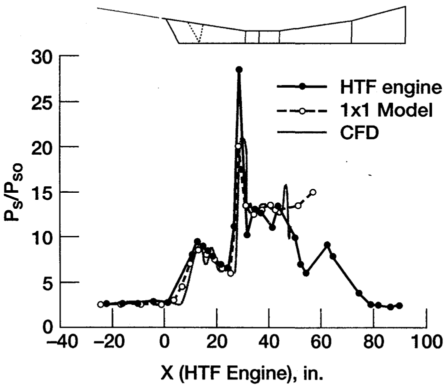

Fig. 4 Mach 6 unfueled top wall centerline static pressure distributions of HTF full-scale engine, 1 × 1 subscale inlet model, and CFD analysis results, with scaled engine schematic shown at top of figure.

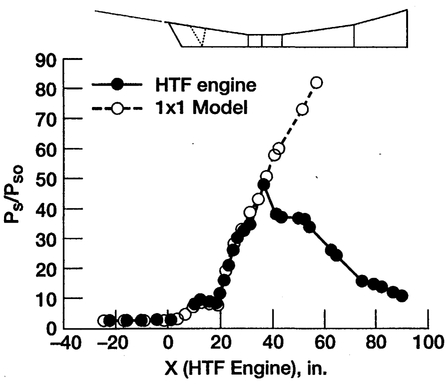

Fig. 5 Fueled top wall centerline pressure distribution of HTF full-scale engine and mechanically back-pressured 1 × 1 subscale inlet model with scaled engine schematic shown at top of figure.

cluded above the plot to help correlate the pressure distributions with the engine hardware. As shown, the zero position is referenced to the leading edge of the inlet top wall. Distances are shown linearly along the top wall of the engine uncorrected for angle. The pressure rise in the inlet reaches a maximum at the cowl leading edge, where the strut thickness is a maximum. The divergence between the subscale and full-scale pressure distributions beyond the strut base is indicative of differences in geometry in that area. The good agreement of these results helped to validate the use of pitot survey data from the subscale tests in determining flow distribution within the RBCC engine and air capture by the inlet.

During the subscale inlet study, a series of tests were run with the inlet back-pressured by a flow plug to simulate the effect of high pressures in the combustor/nozzle region upon the inlet. Figure 5 shows a fueled static pressure distribution for the full-scale RBCC engine overlaid with a plot of the subscale inlet back-pressured to the same combustor static pressure at the 38-in. location. As shown, the subscale testing accurately predicted the pressure profile in the inlet/isolator region. This result gives further confidence to the use of this subscale testing methodology for predicting combustor/inlet interaction.

Comparison to CFD Analysis Results

A CFD analysis of the HTF engine at Mach 5 and 6 without fuel (supercritical) was conducted in parallel with the freejet test activity using NPARC, a full Navier–Stokes analysis code. One-half of the symmetric flow path was modeled for these calculations, including the precompression plate, center duct, side duct, combustor, and nozzle, with a grid size of 1,536,663 points. A k-ε turbulence model was employed for this perfect gas analysis. Additional details are contained in Ref. 4. The CFD result shown in Fig. 4 accurately predicts the pressure distribution within the engine, capturing the position and magnitude of the pressure peaks along the flow path. This validation of the CFD analysis allows for the use of the computational model to determine flowfield details not available from the subscale or full-scale engine tests.

Summary

A series of 15 tests of an RBCC strutjet engine were conducted at the NASA LeRC HTF. These tests further demonstrated the operability of the HTF, including the achievement of test conditions above those previously demonstrated. The HTF was upgraded to include heated and ambient hydrocarbon fuel systems, a silane ignition system, a high-pressure cooling water system, and a high-speed data system. Mach 5 and 6 unfueled and liquid JP-10 fueled engine performance data were taken and shown to agree well with subscale test data and CFD analysis.

References

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