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Evaluation of Kerosene Fuelled Scramjet Combustor using a Combination of Cooled and Uncooled Struts

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ABSTRACT

The scramjet combustor a vital component of scramjet engine has been designed by employing fuel injection struts. Several experimental studies have been carried out to evaluate the propulsive performance and structural integrity of the in-stream fuel injection struts in the connect-pipe test facility. As the mission objective of hypersonic demonstrator is to flight test the scramjet engine for 20 s duration, in-stream fuel injection struts which are designed as heat sink devices encounter hostile flow field conditions especially in terms of high thermal and high convective loads in the scramjet combustor. To circumvent these adverse conditions, materials like Niobium C-103 and W-Ni-Fe alloys have been used for the construction of struts and a number of tests have been carried out to evaluate the survivability of the in-stream fuel injection struts in the scramjet combustor. The results thus obtained show that the erosion of leading edges of the Stage-II fuel injection struts in the initial phase and subsequently puncturing of the fuel injection manifold after 10-12 s of the test are noticed, while the other stages of the struts are found to be intact. This deteriorating leading edges of Stage-II struts with respect to time, affect the overall propulsive performance of the combustor. To mitigate this situation, Stage-II struts have been designed as cooled structure and other Stages of struts are designed as un-cooled structure. Material of construction of struts used is Nimonic C-263 alloy. This paper highlights the results of the static test of the scramjet combustor, which has been carried out at a combustor entry Mach number of 2.0, total temperature of 2000 K, with an overall kerosene fuel equivalence ratio of 1.0 and for the supersonic combustion duration of 20 s. Low back pressure has been created at the exit of the scramjet combustor using ejector system to avoid flow separation.Visual inspection of the fuel injection struts after the test revealed that all the Struts are found to be thermo-structurally safe in the combustor environment except for minor erosion of the leading edges of the struts. Stage-II struts made of two-passage cooled configuration are found to be thermo-structurally safe. Although other stages of struts used in the test are of un-cooled configuration, they too are found to be safe and intact. This demonstrates the fact that they experience thermally benign flow conditions compared to Stage-II struts in the scramjet combustor.

Keywords: Scramjet, cooled strut, nimonic C-263 alloy, ejector system, adverse pressure gradient

NOMENCLATURE

H	Height of the combustor
P	Pressure
T	Temperature
θ	Angle
Φ	Equivalence ratio

Subscripts

a	Ambient
f	Fuel
g	Gas
i	Inlet
t	Stagnation condition
w	Wall
wd	Wedge

1. INTRODUCTION

Researchers worldwide have revolutionised the aerospace propulsion systems with the intent to deliver payload to the desired destinations in a shortest possible time and at an affordable cost. To meet such demands aerospace vehicles obviously have to be designed using air-breathing propulsion systems. This laid the path for the development of turbojet class of engines, followed by ramjet engines and eventually pitched towards supersonic combustion ramjet (scramjet) engines. Studies reveal that the use of sub-sonic combustion ramjets beyond Mach 5.5 lead to inefficient combustion[1]. Scramjet is the highest performing cycle in terms of specific impulse in the speed range of Mach 4-8[2]. From the operation point of view, 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 fuels[3]. Compared to hydrogen, energy density and handling issues render liquid hydrocarbons as attractive candidates for fuelling the scramjet in the lower hypersonic flight regimes. However, the realisation of liquid-hydrocarbon-fuelled scramjets would require a number of scientific and technical problems to be resolved. For instance, the relatively higher ignition delay time of hydrocarbon fuel could substantially exceed the residence time of gas flow within

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the combustor. Additionally, the use of liquid hydrocarbon requires quick vapourization prior to mixing and combustion[4]. It is reported that through successful demonstration of critical technologies such as inlet self-starting, 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[3]. Based on the worldwide scenario especially on the hypersonic air-breathing engine technology, Panneerselvam[5], *et al.* have evolved the demonstrator concept and the design of engine airframe integrated scramjet. The scramjet combustor which is a vital component of scramjet engine has been designed by employing multiple fuel injection struts; and several experimental investigations of short duration (5 s) have been carried out to study the effect of kerosene ignition and combustion on the performance of the scramjet combustor[6-9].

The next phase of experimental studies has been conducted to demonstrate the operability and survivability of in-stream fuel injection struts in the scramjet combustor for 20 s duration, which is the mission objective of hypersonic demonstrator. The major issue encountered in this phase was the survivability of the in-stream fuel injection struts in the adverse flow field which is generated during supersonic combustion of kerosene fuel in the scramjet combustor. The adverse flow field viz., high thermal load, high speed, oxidizing and contaminating combustion products, severely affect the thermo-structural integrity of the fuel injection struts in the scramjet combustor. Various materials viz., Niobium C-103 alloy with silicide coating (anti-oxidation) and W-Ni-Fe alloy with alumina coating (acts as a thermal barrier coating (TBC) and anti-oxidation) have been employed for the construction of heat sink fuel injection struts in the scramjet combustor. The results thus obtained after every 20 s test have been found to be disappointing i.e., the recurrence of the thermo-structural failure of the Stage-II struts[10].

To overcome the thermo-structure failure of the fuel injection struts in the scramjet combustor in the 20 s duration tests, literature survey has been carried out to find out the approach adopted by various researchers on the topic under study. It is observed that the 20 s supersonic combustion test duration of our hypersonic demonstrator is unique. Anderson[11], *et al.* have configured strut using water-cooled leading edge and hydrogen-cooled aft part of the strut in their experimental studies to address the supersonic mixing and combustion using two strut injector configurations, one with parallel injectors and other with perpendicular injectors. Pure Copper was used for the construction of struts. Experimental investigations carried out by Vinogradov[12], *et al.* for kerosene fuel combustion in supersonic flow have used un-cooled struts in the short duration tests of 15 s. Material of construction of strut is not reported. Mach 8 testing of a scramjet engine model reported by Kobayashi[13], *et al.* and Kanda[14], *et al.* have employed water-cooled strut made of copper in both the cases for testing the hydrogen fuelled scramjet engine. Falempin[15], *et al.* have developed a carbon/carbon hydrogen cooled injection strut, which has been successfully tested in the scramjet combustor meant for PREPHA program.

It is quite apparent from the worldwide scenario on the issue under deliberation is that the metallic cooled struts using hydrocarbon fuel is not explicitly reported and hence, to bridge the gap on this front an experimental study has been undertaken by the authors to adopt the cooling of struts using kerosene fuel. Here the strategy employed is to cool only those fuel injection struts which are experiencing high heat load in the combustor while remaining struts have been designed as heat sink elements.

The current paper focuses on the results of the static test of the scramjet combustor which has been carried out at a combustor entry Mach number of 2.0 with total temperature of 2000 K for the supersonic combustion duration of 20 s by creating low back pressure at the exit of the scramjet combustor using ejector system. In this test, combination of cooled struts and un-cooled struts have been employed. They are made of Nimonic C-263 alloy. Liquid kerosene has been injected into the scramjet combustor at a global fuel equivalence ratio of 1.0. The performance of the combustor in terms of wall static pressure rise and gas temperature rise are found to be in line with the physics of scramjet engine. Fuel injection struts are found to have withstood the hostile flow conditions during the supersonic combustion in the scramjet combustor.

2. EXPERIMENTAL INVESTIGATIONS

The test article used to carry out the supersonic combustion studies is shown in Fig.1. It consists of five sections. Section-1 has two parts; first part is a constant - area combustor/ isolator of H_i=100 mm length. This is essential to prevent propagation of pre-combustion shock as well as disturbance produced by the struts to the air heater nozzle. Second part is a top wall diverging combustor with a length of $2H_i$. It consists of a fuel injection strut (Stage-I). The leading edge of the fuel injection

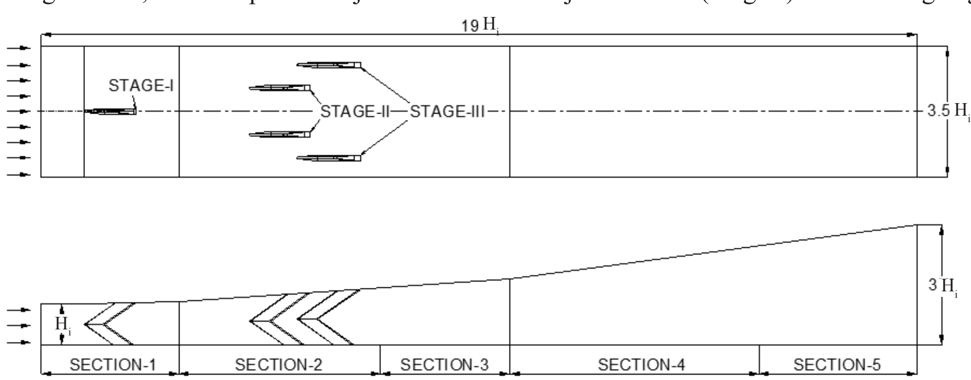

Figure 1. Schematic of multiple strut based supersonic combustor.

strut is positioned at the start of this section. Then follows the section-2 and section-3 with a same top wall divergence and their total length is 7H_i. In section-2 four fuel injection struts are located. The leading edges of the first two struts (called Stage-II) and the next two struts (called Stage-III) are positioned at 1.5H_i and 2.5H_i respectively from the inlet of this section in the flow direction. Sections-4 and sections-5 have same top wall divergence with a total length of 9H_i.

In this test Stage-II struts are designed as cooled structure and Stage-I and Stage-III struts are designed as heat sink elements. The combustor casing is made of Nickel-based alloy and struts are made of Nimonic C-263 alloy.

2.1.1 Strut Configuration

The schematic of the un-cooled fuel injection strut is shown in Fig. 2. It can be seen from the cross-section of the strut that the leading edge radius is R1.5 with θ_{wd} =12°. This cross-section from the leading edge is sweeping backwards in the upper and lower parts with a suitable included angle. A total of 110 injectors are used, each of 0.5 mm diameter. Perpendicular fuel injection pattern has been employed to inject the fuel.

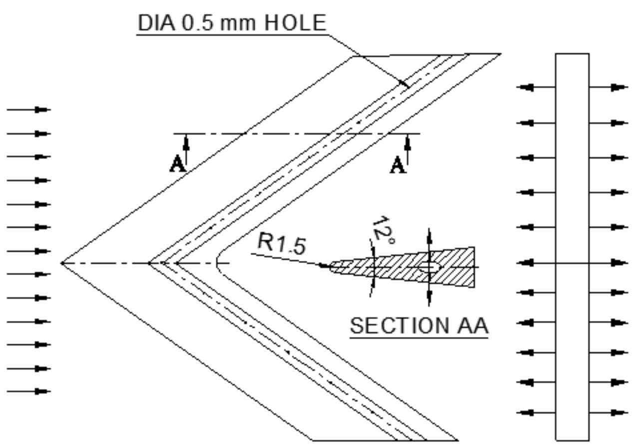

Figure 2. Schematic of the un-cooled strut configuration.

2.1.2 Cooled Strut Configuration

Two-passage cooled Stage-II strut configuration is shown in Fig. 3. It consists of two-passages for the fuel to flow through them which act as a heat exchanger. From the inlet of fuel adapter shown in the top, fuel flows through the leading edge coolant passage of the strut and extracts the heat from this region and subsequently flows through the injection passage from the bottom and in the process injects the fuel from the 0.5 mm injector holes into the combustor. The quantity of fuel used is same as that being injected into the scramjet combustor. Cooled strut is configured in two-halves. The geometry of the coolant passage channels have been arrived at by taking into account the constraints viz.,

a) the stresses induced by the pressure and thermal loads remain below the permissible levels of the material strength;
b) the maximum temperature distribution should not exceed the upper useable limit;
c) the fuel temperature should remain below that required for coking; and

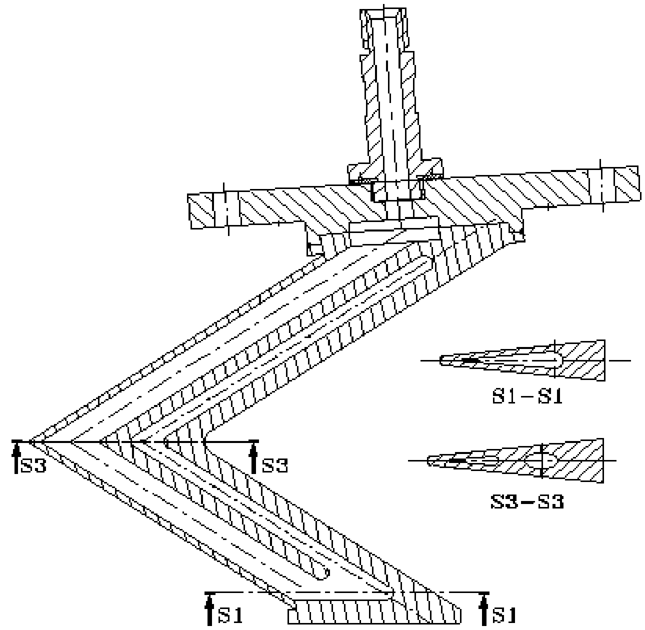

Figure 3. Two-passage cooled stage-II strut configuration.

d) the pressure drop through the coolant passage/channel should be low.

In addition to these, coolant channel dimensions should be accommodated in the given volume of the strut leading edge which is the critical region from heat transfer point of view and the designed coolant channels should not pose serious manufacturability issues. Results of the thermo-structural analysis of the cooled strut reveal that the configuration of the cooled passage/channel provided at the leading edge of the strut is effectively maintaining the surface temperatures and stresses well within the permissible limits of the material.

2.2 Test Set-up

To evaluate the performance of the scramjet combustor, water-cooled vitiated air heater is used to simulate the desired T_t and P_t with oxygen replenishment. Figure 4 shows the photograph of the test set-up. It consists of vitiated air heater with facility nozzle (connect-pipe scramjet test facility), strut based scramjet combustor assembly and ejector system. The connect-pipe test facility consists of air, oxygen and hydrogen feed systems connected to the respective injectors of the water-

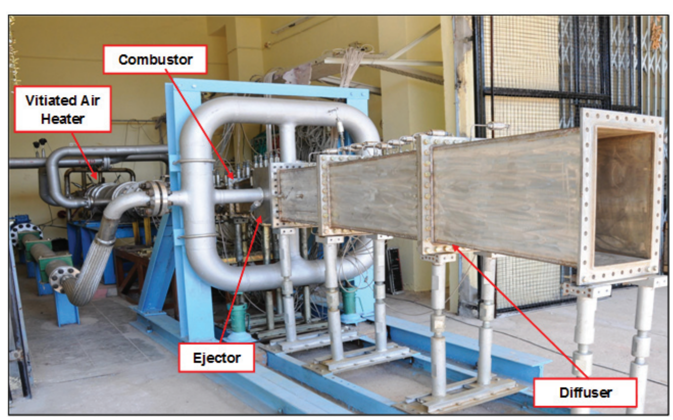

Figure 4. Photograph of test set-up.

cooled vitiated air heater. It also consists of pyro ignition system, interfacing components, instrumentation section, transition duct and convergent-divergent facility nozzle. This transition duct converts the circular flow passage to 2D geometry. To this 2D facility nozzle is connected wherein the vitiated air is accelerated to Mach 2.0. In addition to these, the test facility also consists of kerosene feed system and Data Acquisition system.

The inlet of the strut based scramjet combustor assembly is integrated to the exit of the connect-pipe scramjet test facility i.e., at the exit of the C-D nozzle. At the exit of the scramjet combustor ejector system is integrated. The ejector system consists of four Mach 4.0 nozzles placed on all the four surfaces parallel to the combustor duct at the exit and a sub-sonic diffuser assembly. Manifold of the ejector feed system supplies the high pressure cold air (motive fluid) to the Mach 4.0 nozzles. The expansion of motive fluid through these four nozzles entrains the supersonic combustion products (working fluid) from the scramjet combustor. During this process low back pressure of the order of 0.2 bar is created at the exit of the scramjet combustor. This avoids flow separation in the scramjet combustor and establishes full supersonic flow at the exit of the combustor. The sub-sonic diffuser at the exit of the nozzles is attached to compress the low static pressure flow to ambient pressure through a normal shock wave system. The performance of the scramjet combustor with and without ejector system is highlighted[16].

The scramjet test facility is remotely operated with automatic control of the flow parameters viz., pressure and mass flow rate of the fluids and opening, and closing of valves. Sequencing of the test is automatically controlled by the SCADA system with in-built safety features incorporated.

2.3 Combustor Testing Conditions

The vitiated air heater generates the hot air at a stagnation temperature in the range of 1900 K - 2000 K and stagnation pressure between 0.4 MPa - 0.5 MPa. It is accelerated through a contoured facility nozzle to a Mach number of 2.0. Liquid kerosene fuel is injected from the staged fuel injection struts into the scramjet combustor wherein supersonic vitiated air stream flows. An overall fuel equivalence ratio of 1.0 is used in this test.

2.4 Instrumentation Plan

The test article has been instrumented for measuring center line top wall static pressures and center line bottom wall gas temperatures. The low range (0-5 kgf/cm^2) strain gauge type of pressure transducers have been used to measure the wall static pressures. For gas temperature measurement, 'R' type thermocouples are used.

Gas flow meters for air, pilot hydrogen, main hydrogen and oxygen have been used in the respective feed systems. Liquid flow meter is used to measure the kerosene mass flow rate.

Signals from pressure transducers and thermocouples were amplified by signal conditioners, digitized by a 12-bit analog to digital converter, and stored in the memory of personal computers. Using the calibration data, pressure, temperature and mass flow rates are computed. The uncertainty in the measurement system is less than 1%. During the test, video recording of the test article from the top and exit views have been taken to examine the ignition and sustained combustion characteristics of the kerosene fuel with supersonic vitiated air.

2.5 Test Procedure

The experimental test setup consists of five feed systems viz., air, oxygen, pilot hydrogen, main hydrogen and kerosene. All the feed systems have been calibrated to establish the required tank pressures for desired flow rates of fluid to be injected from the respective feed systems. After pressurising the feed systems to the desired pressures, the following test sequence has been followed to carry out the tests:

To start with, at t_0 s, air supply line valve is opened. At t_0+3 s oxygen supply line valve is switched on, at t_0+10 s pilot hydrogen is switched on, at t+14 s pyro ignitor power is switched on and at t+18 s main hydrogen valve is opened. At t+19 s pilot hydrogen valve is switched off. After t+20 s when the steady vitiated hot air flow is established, liquid kerosene is injected into the combustor. After t+26 s, ejector system is switched on to create low back pressure at the exit of the combustor. Then, at t+40 s kerosene line valve is closed and subsequently at t+41 s hydrogen and oxygen valves are closed. Finally, air valve is closed. During the test, pressures, temperatures and mass flow rates of the fluids are recorded. Additionally, video recording has been done for off-line visual analysis. In case of any malfunctioning or failure noticed during the test from the live video, decision can be taken to shut off the fuel lines to make the system safe from any further damage.

3. RESULTS AND DISCUSSION

3.1 Combustor Entry Conditions

The performance of the scramjet combustor is experimentally evaluated using hydrogen based vitiated air heater facility. The mass flow rate of the vitiated air and the total test duration obtained during the test are 4.3 kg/s and 22.5 s respectively. The computed Mach number based on the stagnation pressure measured in the heater and the nozzle exit static pressure is 2.0. The stagnation temperature obtained in the test is 1950 K. The computed mole fraction of oxygen using NASA CEC-71 software package in the vitiated air for the test is 21 per cent.

3.2 Performance of Kerosene Feed System

The performance of kerosene feed system plays a key role to get the desired performance of the combustor as the fuel is injected into the scramjet combustor from the multiple staged fuel injection struts. The kerosene feed system temporal pressures at various locations viz., kerosene tank and upstream of struts are found to be steady during the entire test duration of 20 s. Figure 5 shows the temporal variation of kerosene mass flow rate. It illustrates that the mass flow rate of kerosene injected into the combustor is found to be steady throughout the test duration except for the initial peak, which is caused by sudden opening of the electro-pneumatic valve of the kerosene feed system. From this it is apparent that the leading edge coolant channels and fuel injection manifolds of the fuel injection struts are intact during the test. Any thermo-structural failure of the coolant channel or injection manifolds of the

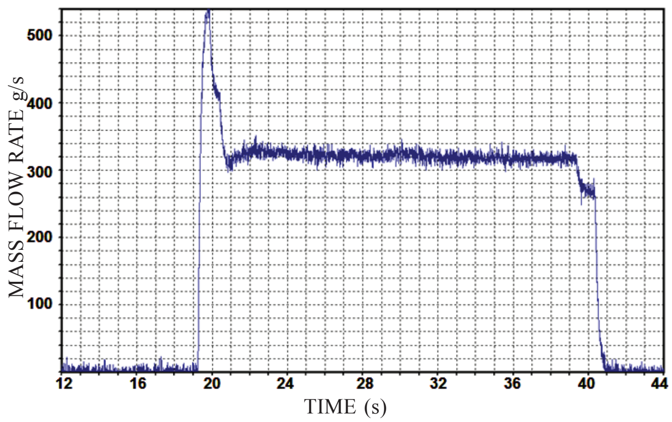

Figure 5. Temporal variation of kerosene mass flow rate.

struts during the test period would have increased the mass flow rate of kerosene injected into the scramjet combustor. The amount of kerosene injected in the current test into the supersonic vitiated air stream in the combustor in terms of an overall fuel equivalence ratio (Φ_f) is about 1.0.

3.3 Effect of Ejector System on the Wall Static Pressure at the Exit of the Combustor

The temporal variation of non-dimensional wall static pressure measured near the exit of the combustor is depicted in Fig. 6. Wall static pressure has been non-dimensionalised using burner stagnation pressure. The demarcations of occurrences of various events during the test are shown in this figure. It can be inferred from the figure that the supersonic combustion phenomenon due to kerosene fuel injection into the combustor is occurring between 18.6 s and 39.0 s. During this period the mass flow rate of kerosene injected into the combustor is steady and is equivalent to a fuel equivalence ratio of 1.0. The wall static pressure captured during the non-reacting flow is found to be unsteady and this effect can be seen between 17.5 s and 18.6 s. This unsteady pressure fluctuations persisted even during the initial part of supersonic combustion of kerosene fuel with vitiated air i.e., between 18.6 s and 21.4 s. At 21.4 s, a clear cut demarcation of supersonic combustion phenomenon in the combustor is noticed, which is in the form of steady non-dimensional pressure of 0.12 and it continued till 26.3 s. During this period adverse pressure gradient is observed at this location and in the immediate upstream locations to the extent of 6H_i. To overcome this adverse pressure gradient ejector system is used and its effect is seen between 27.3 s and 39.1 s during the supersonic combustion. Due to the ejector action the non-dimensional pressure has dropped from 0.12 to 0.064. This shows establishment of full supersonic flow. Neverthless, it is to be noted that the ejector system transient operation during the start is observed in the form of pressure spike between 26.3 s and 27.3 s.

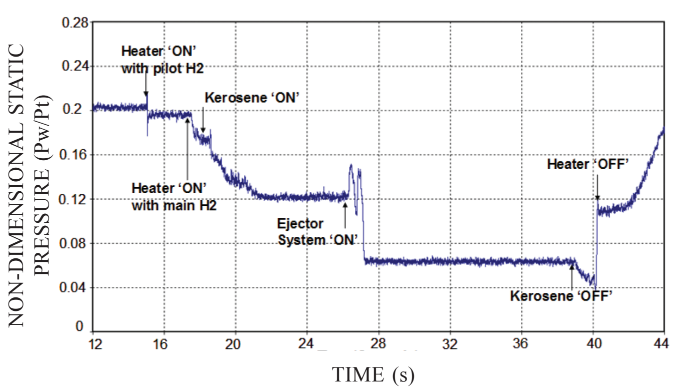

Figure 6. Temporal variation of non-dimensional wall static pressure near the exit of combustor.

3.4 Wall Static Pressure Distribution in the Combustor

The ratio of reacting flow wall static pressure to the burner stagnation pressure distribution along the non-dimensional length of the scramjet combustor is illustrated in Fig. 7. The effect of ejector system is clearly visible from the figure as the flow separation has not taken place in the combustor as it occurred in the earlier tests reported[6-10]. It can also be observed that at 2 H_i from the combustor inlet non-dimensional wall static pressure rise has been observed due to supersonic combustion and the maximum rise in non-dimensional wall static pressure in the combustor is found to be 0.24 at 6.5 H_i from the combustor inlet. The wall static pressure between 3.5 H_i and 9.5 H_i is found to be near plateau which shows that the intensive supersonic combustion is occurring in the Sections-2 and 3 of the combustor. Whereas, in the Sections-4 and 5 the non-dimensional wall static pressure drops steeply from 0.22 to 0.09. This shows that the area relief provided in these sections of the combustor is predominant towards flow acceleration in the divergent section to produce necessary thrust.

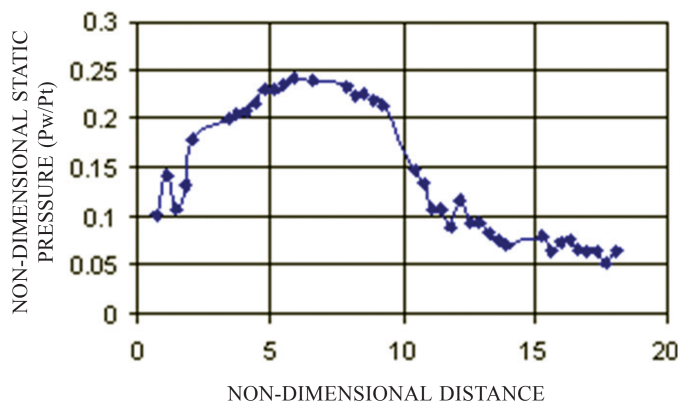

Figure 7. Non-dimensional wall static pressure distribution.

3.5 Comparison of Temporal Gas Temperatures Variation in Combustor Sections

The temporal variation of non-dimensional (T_g(gas temperature)/T_a (ambient temperature)) inner wall gas temperatures measured in the section-2, section-4, and section-5 of the scramjet combustor are shown in Figs. 8(a), 8(b) and 8(c) respectively. In the section-2 the gas temperature is measured near the exit is shown in Fig. 8(a). From the figure, it is observed that the moment kerosene is injected (i.e., at 45.6 s) into the scramjet combustor spontaneous rise in gas temperature is noticed. The rise in non-dimensional gas temperature is about

2.8. This indicates that the supersonic combustion of kerosene with vitiated air is occurring. The other aspect inferred from the figure is that at 53.3 s drop in gas temperature is observed and subsequently temperature rise is noticed. At the instant of drop in gas temperature, the other event that has taken place during the test is the operation of ejector system for creating low back pressure at the combustor exit. The flow field before the ejector operation is a separated flow due to the back pressure at the exit of the combustor being 1 atm. During the operation of the ejector, reattachment of the boundary layer takes place due to low back pressure at the combustor exit. The drop in gas temperature at the instant of ejector starting operation must have been due to change of flow conditions at the temperature measurement location communicated upstream through the hydrodynamic layer.

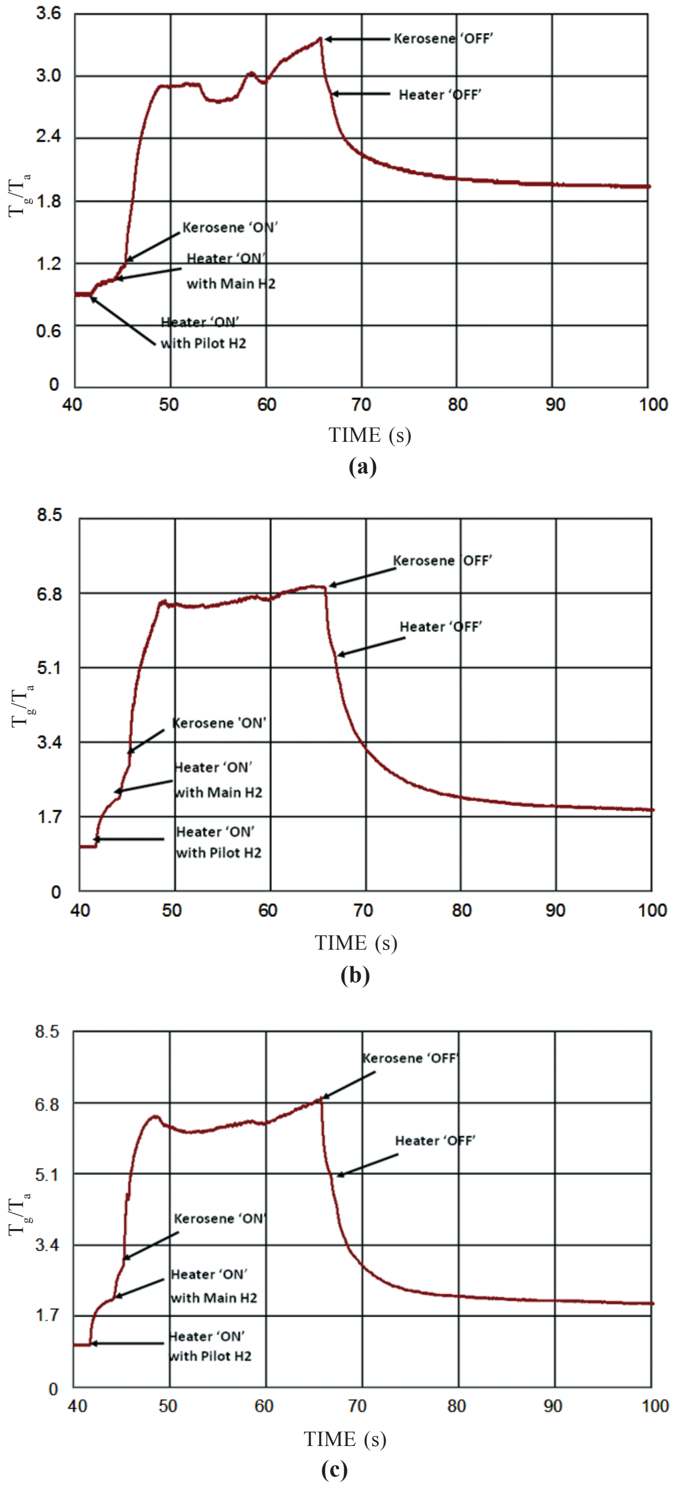

Figure 8. Temporal variation of non-dimensional gas temperature in (a) Combustor section-2, (b) Combustor section-4 and (c) Combustor section-5.

Figure 8(b) depicts the temporal variation of non-dimensional gas temperature in the combustor section-4 measured near its exit. Here too the moment kerosene is injected (i.e., at 45.6 s) into the scramjet combustor spontaneous rise in gas temperature is noticed. The rise in non-dimensional gas temperature recorded at this location is 6.85. In this section, the drop in gas temperature is marginal at 53.3 s during the operation of the ejector system. This marginal drop must have been due to the less tendency to drop the temperature due to flow disturbance as a result of flow attachment downstream of this location.

Figure 8 (c) illustrates the temporal non-dimensional gas temperature variation in combustor section-5. The maximum non-dimensional gas temperature recorded at this location is 6.8. This thermocouple is located near the inlet of this section wherein the intense heat release is taking place. The temperature variation is similar to the one obtained in section-4.

3.6 Visual Inspection of the Hardware

It was observed that the fuel injection pressures of all the five struts and the mass flow rate of kerosene injected into the scramjet combustor are steady for 20 s supersonic combustion test duration. This corroborates the fact that the leading edge coolant passages of the cooled struts and injection manifolds of all the fuel injection struts through which fuel was injected from the holes of diameter 0.5 mm were structurally safe and intact during the entire test duration. After the test, visual inspection of the fuel injection struts has been carried out to ascertain the fact noticed from the fuel injection pressures of the struts and mass flow rate of kerosene. It was observed that the Stage-I and Stage-III un-cooled struts were thermo-structurally safe in the combustor environment for the test duration of 22.5 s. The photograph of one of the cooled fuel injection struts employed for the Stage-II (after the test) is shown in Fig. 9. The photograph

Figure 9. Photograph of one of the stage-II struts (strut-2L) after the test.

exhibits the condition of cooled Stage-II Strut-2L (i.e., placed in the left side of the combustor flow path when viewed from the upstream to downstream) after experiencing severe flow field conditions in the scramjet combustor for 22.5 s test duration. This clearly demonstrates that the leading edge of the strut has eroded marginally. Similar erosion has been noticed in Strut-2R. Although erosion is noticed, the coolant channels and fuel injection manifolds are found to be intact in both the struts.

4. CONCLUSIONS

The static test of the kerosene fuelled scramjet combustor has been carried out for the supersonic combustion test duration of 20 s by creating low back pressure at the exit of the scramjet combustor using ejector system. In this test, cooled strut configuration for the Stage-II and heat sink design for the Stage-I and Stage-III struts have been used. They are made of Nimonic C-263 alloy. Test was carried out at a global fuel equivalence ratio of 1.0.

The performance of the kerosene feed system along with the fuel injection struts is found to have met the desired requirement based on the performance parameters viz., Strut injection pressures and mass flow rate of kerosene. These parameters are found to be steady with respect to time for the entire test duration.

Ignition and stable combustion of kerosene fuel with vitiated air have been achieved at a combustor entry Mach number of 2.0 for 20 seconds test duration.

During the supersonic combustion of kerosene fuel with vitiated air, the maximum rise in non-dimensional wall static pressure and non-dimensional gas temperature measured near the inner wall of bottom wall are obtained to be 0.24 and 6.85 respectively.

Adverse pressure gradient has been overcome by employing ejector system and its effect is seen between 27.3 s and 39.1 s during the supersonic combustion. Due to the ejector action the non-dimensional wall static pressure at the exit of combustor has dropped from 0.12 to 0.064. Low back pressure created by the ejector system has aided in generating full supersonic flow in the entire length of the scramjet combustor.

It is concluded from the results of the scramjet combustor test carried out for 22.5 s (i.e., 20 s supersonic combustion (reacting flow) + 2.5 s vitiated air flow (non-reacting flow)) using kerosene fuel that the fuel injection struts have withstood the severe flow field conditions during the test. This is corroborated from the steady fuel injection pressures of the struts and from the mass flow rate of kerosene injected into the combustor. The combustor performance in terms of the thrust is found to be meeting the mission requirement. Hence, the cooled strut configuration used for the Stage-II and heat sink configuration for the other two stages with Nimonic C-263 alloy as material of construction would suffice the 20 s hypersonic flight mission requirement.

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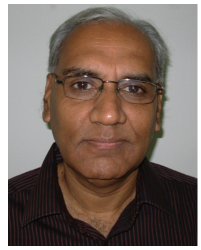

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