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Experimental Investigations of Hydrocarbon Fueled Scramjet Combustor by Employing High Temperature Materials for the Construction of Fuel Injection Struts

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ABSTRACT

For the Hypersonic Technology Demonstrator Vehicle (HSTDV) programme half-width strut based scramjet combustor has been designed, developed and tested for the short durations (5 s) as well as for the long durations (20 s) using various materials for the construction of fuel injection struts. Extensive experimental investigations have been carried out to identify suitable material for the long duration (20 s) tests. Niobium C-103 alloy and W-Ni-Fe alloy materials have been used for the construction of fuel injection struts and they have been employed in two different tests. In the first test struts made of Niobium alloy is used and in the second test struts made of W-Ni-Fe alloy is used. It is inferred from the results of the static tests for the 20 s test duration that the leading edges of the struts are eroding due to high thermal load, shear force and oxidizing environments in the five-strut scramjet combustor configuration. The failure of the struts is noticed in the Stage-II injection of the scramjet combustor. The thermo-structural failure of the stage-II fuel injection struts in the scramjet combustor in both the tests has detrimental effect on the performance of the combustor. In the case of Niobium C-103 alloy struts, erosion of the leading edges is found to be severe compared to W-Ni-Fe alloy struts. Hence, the total pressure loss in the former is found to be more compared to the latter. In the first test (Niobium struts used) the flow separation is occurring earlier compared to the second test (W-Ni-Fe struts employed). This is indicative of the onset of the severe leading edges erosion of Niobium C-103 alloy struts compared to W-Ni-Fe alloy struts resulted in more skin friction drag and hence the flow separation at a shorter length. Struts made of W-Ni-Fe alloy seem to be promising candidate material compared to Niobium C-103 alloy.

Subsequent tests carried out by employing struts made of W-Ni-Fe alloy divulged that the powder metallurgy route to realise the W-Ni-Fe alloy plate is unable to deliver/impart consistent mechanical properties in all the directions of the plate i.e., anisotropy is prevailing. On this front, it is found that the material developed at this juncture is found to be unsuitable for the scramjet application. To circumvent such scenario two strategies have been proposed for the realization of fuel injection elements.

Keywords: *Hypersonic, Scramjet, Strut, Niobium C-103, W-Ni-Fe, Nimonic C-263*

NOMENCLATURE

H = height of the combustor
P = pressure
T = temperature
ϕ = equivalence ratio

SUBSCRIPTS

f = fuel
i = inlet
t = stagnation condition
w = wall
wd = wedge

1. INTRODUCTION

DRDL is pursuing Hypersonic Technology Demonstrator Vehicle (HSTDV) programme, wherein the mission objective is to demonstrate autonomous air breathing sustained hypersonic flight using kerosene fuel for 20 s duration. The special feature of hypersonic flight is that the airframe and scramjet engine components, especially in-stream fuel injection elements are subjected to high thermal environment. The supersonic combustor encounters high enthalpies which can heat known materials beyond their allowable working temperature ranges which affect the mechanical strength. Due to chemical reactions, the oxidation or hydrogen embrittlement occur rapidly, leading to the need for cooling the walls of the fuel injection elements reported in Heiser & Pratt, 1994, [1].

The baseline combustor is configured using seven fuel injection struts reported in Chandrasekhar *et al.,* 2007, [2] with 120 injectors, each of 0.5 mm diameter. The cross-section of the combustor is varying along the length of the combustor as the top wall angle is varying at different angles. As the contribution by the last row of 2-struts to the combustor performance has been found to be negligible, the combustor design is altered by making use of 5 fuel-injection struts i.e., by removing last stage of struts reported in Ramanujachari *et al.,* 2009, [3]. As the heat flux experienced by the in-stream fuel injection struts is severe and the mission duration is 20 s, the fuel injection struts are designed as heat sink elements using high temperature resistant exotic materials viz., Niobium alloy and Tungsten alloy.

This paper focuses on the performance of the struts made of Niobium C-103 and W-Ni-Fe alloys which have been employed in two different tests in the scramjet combustor. The analyses of these tests revealed that the Niobium C-103 and W-Ni-Fe alloys have inherent limitations which posed severe threat to the structural integrity of the struts in the scramjet combustor flow field when subjected to 20 s test duration.

2. OBJECTIVE OF THE TESTS

In our previous work reported in Chandrasekhar *et al.,* 2007, [2]; Ramanujachari *et al.,* 2009, [3]; Chandrasekhar *et al.,* 2008, [4], it has been concluded that the ignition and sustained combustion of the kerosene fuel in the Mach 2.0 vitiated air flow in the strut based scramjet combustor has been achieved and the structural integrity of the combustor casing made of nickel based alloys has been found to be intact under the adverse supersonic flow conditions in the multiple tests each of 5 s of supersonic combustion test duration. Among the combustor casing and fuel injection struts, struts are subjected to severity of the flow as they are submerged in the high speed and high temperature flow field. Hence, the objective of the current tests is to identify the suitable material for the fuel injection struts by adopting heat sink design approach.

3. EXPERIMENTAL INVESTIGATIONS

The test article used to carry out the supersonic combustion studies is illustrated in Fig.1.

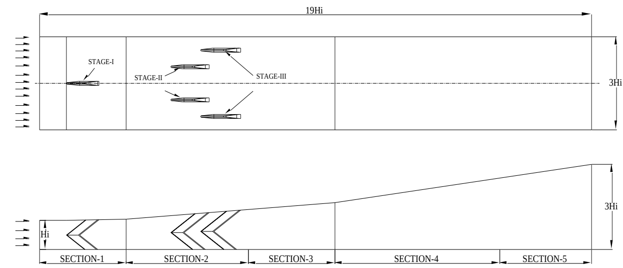


Fig.1 Schematic of 5-Strut Scramjet combustor configuration

It consists of five sections. Section-1 has two parts; first part is a constant - area combustor/ isolator of H_i length. This is essential to prevent propagation of pre-combustion shock as well as disturbance produced by the struts to the air heater nozzle. The second part is a top wall diverging combustor with a length of $2H_i$. It consists of one fuel injection strut (Strut-1/Stage-I). The leading edge of the fuel injection strut is positioned at the start of this section. Then follows the section-2 and section-3 with 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 Strut-2/Stage-II) and the next two struts (called Strut-3/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 5 have the same top wall divergence with a total length of $9H_i$.

4. TEST FACILITY

To evaluate the performance of the scramjet combustor through experimental investigations, ground based test facility has been developed using a vitiated air heater. Two stage air heating technique is used to simulate the desired T_t and P_t with oxygen replenishment. Air is heated by hydrogen in the primary stage upto 1200-1300 K followed by raising the temperature of air in the secondary stage to 1800-2000 K. The excess oxygen that is injected into the heater replenishes oxygen content in the vitiated hot air. The vitiated hot air after oxygen replenishment contains oxygen mole faction fraction equal to that of normal air (21% by volume).The vitiated air thus obtained flows through the transition duct to transform the circular flow passage to 2-D geometry. A two-dimensional contoured nozzle connected to the transition duct is used to accelerate the vitiated air to the required combustor entry Mach number of about 2.0.

5. STRUT GEOMETRY

The geometry of the 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 with $\theta_{wd} = 12^0$. This cross-section from the leading edge is sweeping backwards in the upper and lower parts. The other features to be noticed are that the 'V' gutters/cavities are provided in the aft part of the strut and the fuel injectors are positioned at exactly upstream of the vertex of the `V' gutters. A total of 110 injectors are used, each of 0.5 mm diameter. Perpendicular fuel injection pattern has been selected to inject the fuel. These 'V' gutters/cavities on either side of the strut generate axial vortices, which are in turn help in efficient mixing and combustion of fuel and vitiated air. The in-stream fuel injection struts are designed as heat sink elements for the test duration of 20 s. Niobium C-103 and W-Ni-Fe alloys are used for the construction of the struts. In the first test, Niobium C-103 alloy struts are used and in the second test, W-Ni-Fe alloy struts are employed in the scramjet combustor.

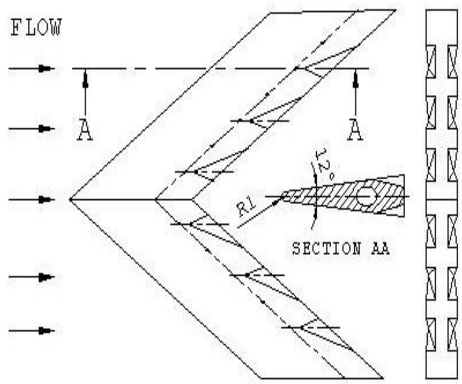


Fig.2 Schematic of fuel injection Strut

5.1 Fabrication Technique adopted to Realise Fuel Injection Struts

In the event of selecting passively cooled design for the fuel injection struts due to non-availability of desired mass flow rate of coolant (i.e., fuel itself) to maintain the surface temperatures of the material below the permissible temperature limits, material with high heat capacity and low thermal conductivity are chosen for the realization of fuel injection struts to function in the thermally adverse flow conditions of the scramjet combustor.

5.1.1 Niobium C-103 Alloy Struts

Amongst the refractory materials Niobium C-103 alloy possesses the lowest density with melting point of 2350 ^{0}C. In the event of this advantage, it's handling during the manufacturing (viz., Niobium C-103 is prone to severe oxidation at 400 ^{0}C) is difficult. Under these constraints posed by the material the fuel injection struts made of Niobium C-103 alloy have been realized using the following methodology:

- Strut, mounting bracket and blank are machined from the Niobium C-103 alloy plate using conventional CNC machining as per the drawings.
- All other components viz., adaptor made of AISI-304 material and washer made of pure copper are realized.
- As the conventional TIG welding process for joining strut with mounting bracket made of Niobium C-103 alloy is impossible due to oxidation of Niobium C-103 alloy, Electron Beam (EB) welding process is chosen. Hence, joint design compatible for EB welding is designed for the strut-mounting bracket and strut-bottom blank of the strut assembly. In addition to these steps taken to reduce oxidation during joining of Niobium C-103 alloy components, a similar care is adopted while machining of the components.

- Since the fuel injection struts have to function in adverse flow conditions viz., high temperature, high speed and oxidizing environment, the fuel injection struts are coated with silicide using Pack cementation technique which act as anti-oxidation layer. Photograph of the Niobium C-103 alloy strut assembly illustrating EB weld joints is shown in Fig. 3.

Fig.3 Niobium C-103 alloy Strut

5.1.2 W-Ni-Fe alloy struts

W-Ni-Fe alloy is a heavy machineable refractory alloy with a distinct feature of high temperature withstanding capability. The demerits are in the realization of raw material by adopting powder metallurgy route which in turn leads to anisotropic properties in the plate, poor oxidiation resistance and manufacturing limitations viz., conventional TIG welding process cannot be used. Under these limitations the fuel injection struts made of W-Ni-Fe alloy have been realized using the following methodology:

- W-Ni-Fe alloy plate is made with desired mechanical properties using powder metallurgy route. Strut and blank are machined using conventional CNC machining.
- All other components viz., mounting bracket and adaptor made of AISI-304 material and washer made of pure copper are realized.

- As the conventional joining process viz., TIG welding process of Tungsten alloy to Tungsten alloy or Tungsten alloy to any other ferrous alloy is not yet established, vacuum brazing process to join components made of above materials is established by suitable selection of braze joint design, brazing filler alloy, vacuum brazing cycle temperature and soaking duration with proper fixture design to hold the assembly at desired orientation. Once the strut assembly is made oxidation resistance coating viz., Alumina is coated on the W-Ni-Fe alloy strut using Plasma spray coating. Photograph of the W-Ni-Fe alloy strut assembly depicting vacuum braze joints is shown in Fig. 4.

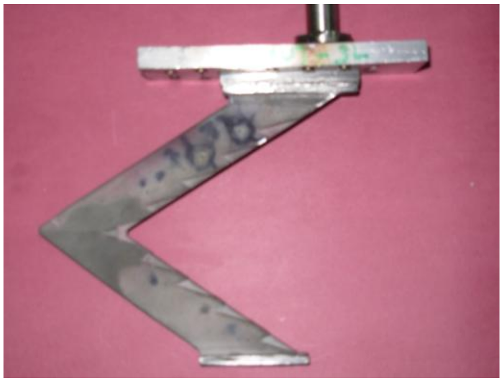


Fig.4 W-Ni-Fe alloy Strut

6. COMBUSTOR TESTING CONDITIONS

The vitiated air heater generates the hot air at a stagnation temperature of 1800-2000 K. The vitiated air is accelerated through a contoured facility nozzle to a Mach number of 2.0. The overall amount of kerosene fuel injected from the three staged fuel injection struts into supersonic vitiated air stream in the scramjet combustor corresponds to the fuel equivalence ratio (ϕ_f) of 1.0.

7. INSTRUMENTATION PLAN

The measurement plan for the test article consists of center-line top wall static pressures and at certain locations wall static pressures on all the walls in the same plane to ascertain the pressure pattern in the combustor. The low range strain gauge type of pressure transducers have been used to measure the wall static pressures. For heater temperature and external combustor skin temperature measurements, 'R' type thermocouples and 'K' type thermocouples are used respectively.

Calibrated gas flow meters for air, hydrogen and oxygen have been installed in the feed systems to measure mass flow rates of the gases. Calibrated liquid flow meter is used to measure the kerosene flow rate. The uncertainty of 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 ascertain the ignition and sustained combustion of the kerosene fuel with supersonic vitiated air.

8. TEST PROCEDURE

The experimental setup consists of four feed systems viz. air, oxygen, hydrogen, and kerosene. All the feed systems have been calibrated to establish the required tank pressures/ dome regulator downstream pressures for desired mass flow rates of fluid to be injected by the respective feed systems. After pressurising the feed systems to the desired level, the following test sequence has been followed to carry out the tests:

To start with, at t-10s, air supply line valve is opened followed by oxygen supply line valve at t-7s and ignition system is switched on at t-2s. At t=0s valve of hydrogen feed system is opened. After t+4s when the steady vitiated hot air flow is established, kerosene is injected into the combustor for supersonic combustion studies as well as to ascertain the structural integrity of the heat sink fuel injection struts. After t+24s, kerosene valve is closed. Then at t+25s, hydrogen, oxygen and ignition switch are turned off. Finally, air valve is closed at t+70s. During the test, wall static pressures, temperatures and mass flow rates of the fluids are recorded. In addition to these video recording has been done for off-line visual analysis.

9. RESULTS AND DISCUSSION

9.1 Combustor Entry Conditions

The performance of the scramjet combustor is evaluated using vitiated air supplied by a hydrogen based heater. The combustor entry conditions are fixed by the measured mass flow rates of air, oxygen and hydrogen supplied to the heater to produce vitiated air. In addition, stagnation pressure developed in the heater is also measured. The Mach number computed based on the stagnation pressure measured in the heater and the nozzle exit static pressure for both the tests is 2.0. The stagnation temperature obtained in the first and second tests are 1840 K and 1820 K respectively. The computed mole fraction of oxygen using NASA CEC-71 software package in the vitiated air for both the tests is 20.5% and 21% respectively.

9.2 Performance of Kerosene Feed System

The performance of kerosene fuel feed system plays a vital role in the overall performance of the combustor. The kerosene mass flow rate - time history plots for the first test is shown in Fig. 5. In the first test, the amount of kerosene mass flow rate injected into the combustor is varying from 450 g/s to 407 g/s for 10 s duration and subsequently mass flow rate of kerosene drastically increased to 870 g/s for 9 s of kerosene injection into the combustor. This shows that the fuel injection struts have failed while there was no feed system failure.

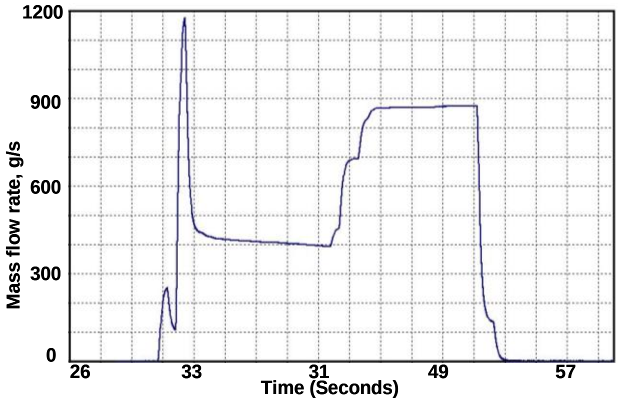


Fig.5 Mass flow rate of Kerosene in the first test

The kerosene mass flow rate - time history plots for the second test is shown in Fig. 6. In the second test, the amount of kerosene mass flow rate injected into the combustor is varying from 294 g/s to 260 g/s for duration of 12 s and consequently it increased to 353 g/s for the remaining 8 s of kerosene injection into the combustor. Here also the failure of the fuel injection struts is the reason for the increase in the quantity of fuel injected into the combustor.

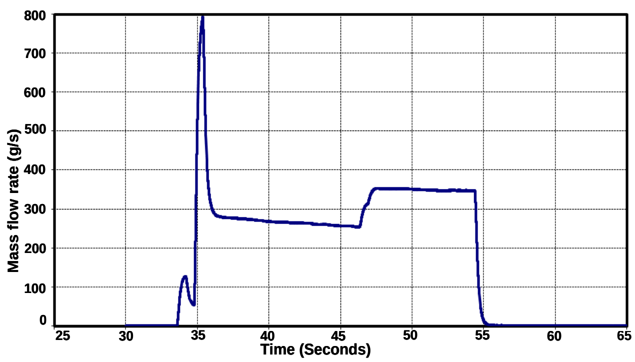


Fig.6 Mass flow rate of Kerosene in the second test

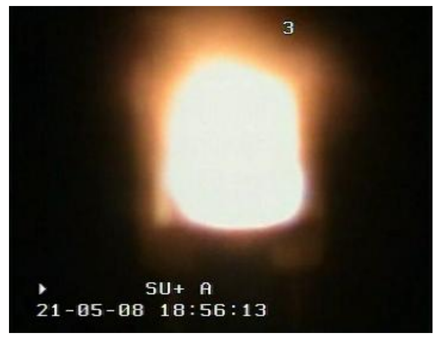
9.3 Inferences from Video Recording

The combustor exit view (end view) video recording for the first test is shown in Fig. 7.

Splinters emanating from the combustor when the struts fuel injection passage is intact

Condition of the exit plume when the strut fuel injection passage failed

Fig.7 Exit Plume captured during the first test



Exit plume when the struts fuel injection passage is intact

Condition of the exit plume when the strut vacuum brazed bottom blank failed

Fig.8 Exit Plume captured during the second test

9.4 Wall Static Pressure Distribution along the Combustor

The non-dimensional top wall static pressure distribution non-dimensionalised by the stagnation pressure of the vitiated air heater along the length of the scramjet combustor for the first test is shown in Fig. 9. The pressure rise due to oblique shocks emanated from the leading edge of the struts is clearly visible in the case of non-reacting flow. Whereas in the reacting flow, the oblique shocks have smeared out due to efficient heat release in the combustor. Efficient mixing is taking place downstream of the struts due to 'V' gutters and flow recirculation as a result of flow blockage offered by the struts to the supersonic flow. This efficient mixing of fuel/air has caused the spontaneous heat release from the upstream of the stage-II struts as seen by the rapid rise of pressure. During the intensive supersonic combustion a maximum non-dimensional wall static pressure rise of 0.355 is observed at 6.56 H_i from the combustor entry. Further it can be seen from the figure that the flow separation in the combustor is occurring at 9.3H_i from the combustor entry for the non-reacting case and at 11.2H_i for the reacting case. This manifests that the fluid flow separation is delayed in energetic flow environment.

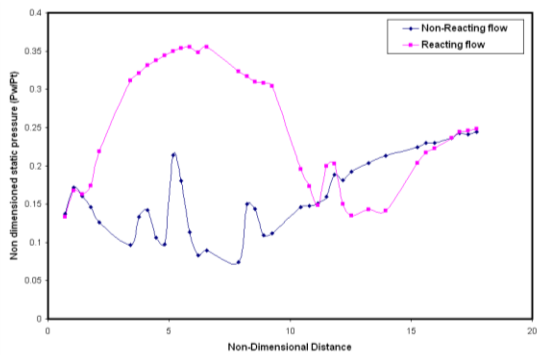


Fig. 9 Non-Dimensional top wall static pressure distribution for the first test

On the similar lines, non-dimensional top wall static pressure distribution along the length of the scramjet combustor for the second test is shown in Fig. 10. In the intense heat release region the wall static pressure rise and its location in the combustor are of the same order as seen in the first test. Considerable difference noticed in this test compared to the first test is the location of flow separation in the reacting flow. It is occurring farther downstream by 2.3H_i compared to the first test. The reason for earlier flow separation in the first test can be due to oxidation, melting and erosion of the leading edges of the struts causing increase in skin friction coefficient and hence more total pressure loss compared to un-eroded structure of the fuel injection struts. Hence, the thermo-structural integrity of the fuel injection struts in the scramjet combustor plays a vital role in extracting the optimum performance from a given combustor geometry.

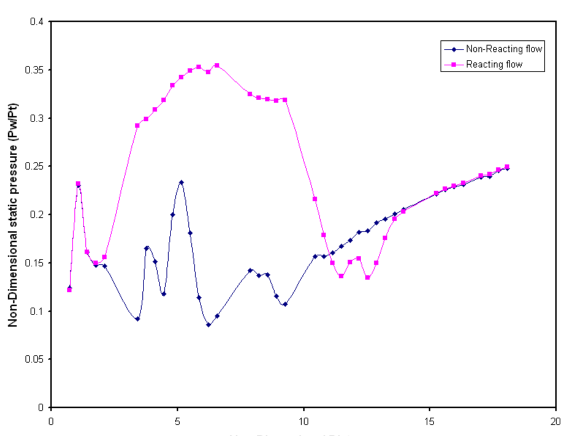


Fig.10 Non-Dimensional top wall static pressure distribution for the second test

9.5 Performance of Fuel Injection Struts made of Niobium C-103 alloy

In the first test, strut assemblies are made of Niobium C-103 material. It is observed from the heat transfer analysis of the strut that the leading edge of the strut is experiencing 1626 K temperature after 25 s, which is quite close to the allowable temperature limit i.e. 1647 K for Niobium C-103 alloy. As Niobium C-103 alloy is prone to severe oxidation, silicide coating has been applied on the struts using pack cementation process.

From the Fig. 5 it can be seen that the fuel injection process has started at around 32 s from the start of the test events and near steady mass flow rate of kerosene has been injected into the combustor for 10 s i.e., upto around 42 s. At 42 s as seen from the figure that there is a drastic rise in mass flow rate of kerosene injected into the combustor. Post test hardware visual inspection revealed that the leading edges of the stage-II struts have eroded similar to the liners of the solid rocket motors. In addition to this the EB weld joint on the bottom of the stage-II struts also eroded and opened up resulting in flooding of the fuel on the floor of the combustor bottom wall. The photograph of the strut taken after experiencing 20 s of supersonic combustion flow field in the combustor is shown in Fig. 11. This shows that the material has failed due to oxidation or hydrogen embrittlement, as the supersonic combustor flow field is highly oxidizing and contaminated with traces of hydrogen, nitrogen, carbon, carbon-dioxide, carbon-monoxide, water-vapour etc. It is concluded from the behaviour of the material in high speed and high temperature flow accompanied with oxidizing and contaminated environment that the material has to be handled carefully during every stage of the fabrication process while realizing the component. In addition, stringent quality control checks are to be incorporated in the process plan to overcome the failure issues pertaining to the quality aspects.

Fig.11 Condition of the Stage-II Niobium C-103 alloy Strut after experiencing 20 s of supersonic combustion in the combustor

9.6 Performance of Fuel Injection Struts made of W-Ni-Fe alloy

In the second test, strut assemblies employed are made of W-Ni-Fe alloy. Figure 7 exhibits the variation of kerosene mass flow rate with time injected into the scramjet combustor during this test. It can be seen that the fuel injection process has started at around 35 s from the start of the test events and near steady mass flow rate of kerosene has been injected into the combustor for 12 s i.e., upto around 47 s. At 47 s as seen from the figure that there is a drastic rise in mass flow rate of kerosene injected into the combustor. This shows that the fuel injection struts might have failed. Post-test hardware visual inspection revealed that the brazed joint of one of the struts has opened up and as a result increase in mass flow rate of kerosene injected into the combustor noticed. The most important feature to be noticed in this test is that the failed fuel injection strut was located at stage-II. Similar scenario has been noticed in the first test too. The photograph of the strut in which brazed joint has failed during the test is shown in Fig. 12. Apart from this, the leading edges of the struts were found to have eroded during the test. The photograph depicting minor/partial erosion of the leading edge of the strut in the supersonic combustion flow field environment is shown in Fig. 13. It is concluded from these tests that the struts made of W-Ni-Fe alloy possesses better thermal resistance properties compared to the struts made of C-103 alloy.

Consequently, number of tests have been carried out by employing W-Ni-Fe alloy struts after modifying the joint configuration and by using various types of thermal barrier and oxidation resistance coating. The results of all these have turned out to be lesson-learning exercises. Hence, in order to circumvent the hostile flow conditions encountered by Stage-II struts, two strategies have been devised for the future course of action. They are 1) to actively cool the fuel injection struts viz., Stage-II struts using the same quantity of the fuel as being injected into the combustor by adopting two-pass technique, 2) to locate the struts in a thermally benign flow conditions. In the case of strategy-1, struts made of Nimonic C-263 alloy shall be used. Only Stage-II struts will be fabricated using cooled two-passage configuration and the other two stages of the struts will be of un-cooled configuration. Whereas, for the strategy-2 struts are to be made of Nimonic C-263 alloy using heat sink design.

Fig.12 Condition of the Stage-II W-Ni-Fe alloy Strut in which vacuum brazed joint failed after experiencing 20 s of supersonic combustion in the combustor

Fig.13 Condition of the Stage-II W-Ni-Fe alloy Strut in which leading edge has eroded after experiencing 20 s of supersonic combustion in the combustor

10. CONCLUSIONS

The following conclusions have been derived from the results of these tests:

(1) Static tests of the strut based scramjet combustor have been carried out using kerosene fuel by employing fuel injection struts made of Niobium C-103 and W-Ni-Fe alloys in the first and second tests respectively. These tests have been carried out to identify the suitable material for the fuel injection struts of the scramjet combustor which can withstand for HSTDV scramjet engine mission duration of 20 s duration using heat sink design.

(2) Fabrication difficulties encountered during various stages of realization of the fuel injection struts made of Niobium C-103 and W-Ni-Fe alloys have been resolved. The fabrication phase with these two materials has given better insight into the handling of these materials. Various new techniques got generated while realizing the struts.

(3) Ignition and sustained combustion of kerosene fuel with vitiated air have been achieved in both the tests in the Mach 2.0 flow.

(4) In both the tests, during supersonic combustion significant rise in wall static pressure is observed compared to the corresponding non-reacting flow (only vitiated hot air flow without fuel injection) values.

(5) In both the tests, it is observed from the video recording that the exit plume is found to be erratic after the thermo-structural failure of the fuel injection struts. In the first test, splinters have started emanating from the combustor exit right from the instant of fuel injection into the scramjet combustor. This is due to melting and erosion of the leading edges of the struts caused by severe oxidation in the scramjet combustor. Contrary to this, in the second test splinters are not observed in the exit plume. This issue has been corroborated from the post-test hardware inspection of the struts.

(6) Struts made of Niobium C-103 alloy coated with silicide (anti-oxidation) failed due to oxidation or hydrogen embrittlement, as the supersonic combustion flow field is highly oxidizing and contaminated. To establish the actual cause of the failure, stringent quality control checks are to be incorporated in the manufacturing process plan. In the second test, partial erosion of the leading edges of W-Ni-Fe alloy struts is noticed. The failure of the struts is noticed in the Stage-II injection.

(7) The thermo-structural integrity of the fuel injection struts in the scramjet combustor plays a vital role in extracting the optimum performance from a given combustor geometry. In the case of Niobium C-103 alloy struts, erosion of the leading edges is found to be severe compared to W-Ni-Fe alloy struts. Hence, the total pressure loss in the former is found to be more compared to the latter. This is corroborated from the occurrence of flow separation in the reacting flow. In the first test (Niobium struts used) the flow separation is occurring earlier compared to the second test (W-Ni-Fe struts employed).

(8) Struts made of W-Ni-Fe alloy seem to be promising candidate material compared to Niobium C-103 alloy.

(9) Subsequent tests carried out by employing struts made of W-Ni-Fe alloy revealed that the powder metallurgy route to realise the W-Ni-Fe alloy plate is unable to deliver/impart consistent mechanical properties in all the directions of the plate i.e., anisotropy is prevailing. On this front, it is found that the material developed at this juncture is found to be unsuitable for the scramjet application.

(10) In order to overcome the aspect of survivability of stage-II struts in the scramjet flow field, two strategies have been proposed and they will be pursed in the near term activities.

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