SCRAMJET COMBUSTOR DEVELOPMENT

Dr. Satish Kumar & Team[*]
Head, Hypersonic Propulsion Division &
Dy. Project Director, HSTDV,DRDL, Hyderabad

1. Introduction:

An airframe integrated scramjet propelled vehicle has advantages for application to several missions. In its simplest form, such a vehicle will combine the features of quick reaction, low vulnerability to counter attack and better propulsion efficiency.

The Supersonic Combustion Ramjet (SCRAMJET) engine has been recognized as the most promising air breathing propulsion system for the hypersonic flight (Mach number above 5). In recent years, the research and development of scramjet engine has promoted the study of combustion in supersonic flows. Extensive research is being carried out over the world for realizing the scramjet technology with hydrogen fuel with significant attention focused on new generations of space launchers and global fast-reaction reconnaissance missions. However, application for the scramjet concept using high heat sink and hydrogen fuels offers significantly enhanced mission potential for future military tactical missiles. Scramjet being an air-breathing engine, the performance of the missile system based on the scramjet propulsion is envisaged to enhance the payload weight and missile range.

Supersonic combustion ramjet engine for an air-breathing propulsion system has been realized and demonstrated by USA on ground and in flight. X-43 vehicle used hydrogen fuel. Hydrocarbon fuel scramjet engine is still under study and research. Mixing, ignition and flame holding in combustor, ground test facilities and numerical simulation of Scramjet engine are the critical challenges in the development of scramjet engine.

?? **Dr. B.VN. Charyulu, J.V.S. Moorthy, C. Chandrasekhar**

1.1 Scramjet engine - Technological challenges

a) Mixing, Ignition and flame holding in a scramjet combustor

Among the three critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. Such combustor shall promote sufficient mixing of the fuel and air so that the desired chemical reaction and thus heat release can occur within the residence time of the fuel-air mixture. In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely,

i) Good and rapid fuel air mixing
ii) Minimization of total pressure loss
iii) High combustion efficiency.

b) Ground test facilities for testing of Scramjet engine.

In order to carry out the experiments essentially required for the development of the scramjet engine and to clearly understand various complex areas associated with it, there is a need of scramjet test facility. Among the devices generally used to produce the test gas to simulate air entering the scramjet combustor are arc heater, ceramic storage heater and combustion burners. The scramjet ground test facilities are available in the mid Mach number range of 5 to 8. There are no steady flow test facilities in higher Mach number range since achievement of total temperatures, pressure and low pressures at exit present enormous engineering challenges. Free piston shock tunnels enable test with duration of only milliseconds at higher Mach numbers. Conventional scramjet facilities operate in the blow down mode since continuous operations implies very large power requirement for heating the air.

c) Numerical simulation of Scramjet Flow field

Ground tests and classical methods alone cannot give data with sufficient accuracy for design of hypersonic systems. Due to the closely integrated nature, component level testing will not be able to simulate accurately the complex flow field. It is difficult to simulate Reynolds number, boundary layer transition in ground test facilities. Also, the quality of air is difficult to simulate in the test facilities. Therefore there is a need to estimate the performance in the flight based on the results of ground tests. This can be accomplished only through the use of mathematical modeling of the flow, which is to be solved to first reproduce the result of the ground test and then used for predicting the flight conditions. The primary unknown on a physical plane consists of modeling turbulence and its interaction with chemistry. The issues on the numerical front consist of evolving algorithms to solve the N – S equations or their variants such that sharp gradient regions near the shocks are captured with numerical diffusion or overshoot. The prediction of wall heat transfer rate is another task to be handled both on the modeling plane and numerical experiments. One of the advantages of the mathematical model is that once it stands validated it can be used to conduct several numerical experiments on exotic ideas like with respect to enhanced mixing components with much less expense as compared to experiments. The experimental effort is not eliminated but reduced and better focused. This is in fact the current day approach to the solution to the problems of high-speed flight.

Development and realization of scramjet engine has been undertaken in USA, Russia, Japan, France, Germany and India individually as well as through joint cooperation. The urgency of realizing a hypersonic air-breathing engine has been felt by many agencies for civilian and military applications. The development of the scramjet engines poses considerable challenges and it demands multidisciplinary design, analysis, modeling, simulation and system optimization. The hardware realization and testing becomes equally complex and multidisciplinary.

DRDL is working on a program called “Hypersonic Technology Demonstrator Vehicle” (HSTDV). Technological challenge for this vehicle is to demonstrate the scramjet engine at a flight mach number of 6.5. Number of ground-based experiments have been carried out to develop the scramjet combustor and associated test facilities also have been established in DRDL. The details of test facility and tests carried out on the development of strut-based combustor, Ramp-Cavity combustor and barbotage injection of kerosene with hydrogen fuel as pilot are highlighted in the subsequent sections.

2. DEVELOPMENT OF THE KEROSENE FUELED STRUT BASED SCRAMJET COMBUSTOR

2.1 TEST FACILITY:

The setup consists of a Hydrogen burner as an on-line gas generator, an axi-symmetric convergent-divergent nozzle for accelerating the test gas to supersonic speed, a circular to rectangular transition duct. The supersonic combustor has two parts; one constant area section with backward facing step with fuel injection strut and the second one is diverging area combustor. The vitiated air is allowed to expand through an axsymmetric supersonic nozzle with 2.4 exit Mach number. The accelerated vitiated air flows through a transition duct, to provide a uniform flow at the entry of the constant area combustor, with minimum losses. The total temperature and total pressure of the vitiated airflow are measured by means of temperature sensor and pressure transducer respectively.

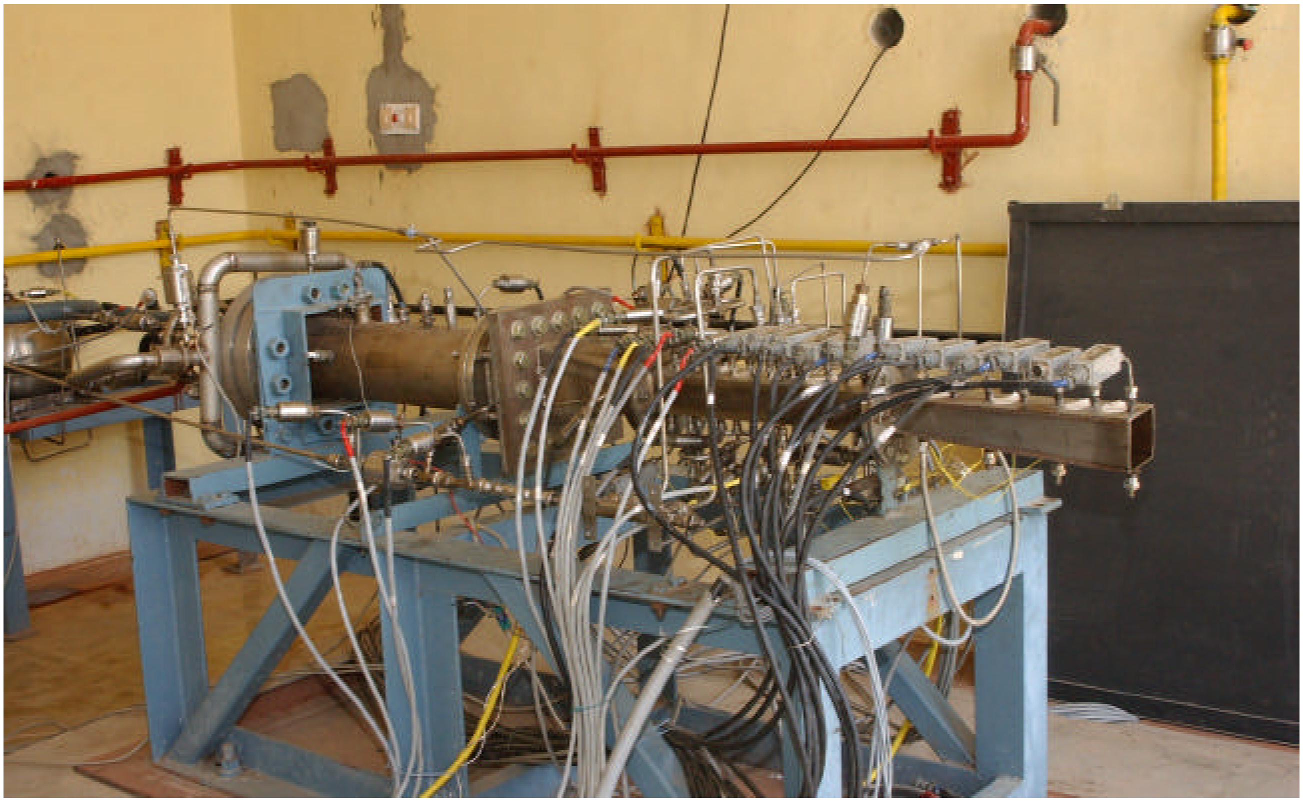


Fig 1: Scramjet Combustor Mounted on the test facility

2.2. TEST CONDITIONS

1) FLIGHT MACH NO : 6.5
2) ALTITUDE SIMULATED : 35KM
3) COMBUSTOR ENTRY MACH NO : 2.4
4) BURNER STAGNATION TEMPERATURE : 1500 K
5) AIR FLOW RATE (TOTAL) : 1 kg/s
6) FUEL FLOW RATE
KEROSENE FUEL :22 gm/s (? = 0.40).
7) TEST DURATION : 25 s

2.2.1 EXPERIMENTAL SET-UP:

The Experimental setup consists of the following parts:

1. Burner

2. Transition Duct
3. Supersonic nozzle
4. Constant Area combustor with injector
5. Diverging Combustor
6. Feed System

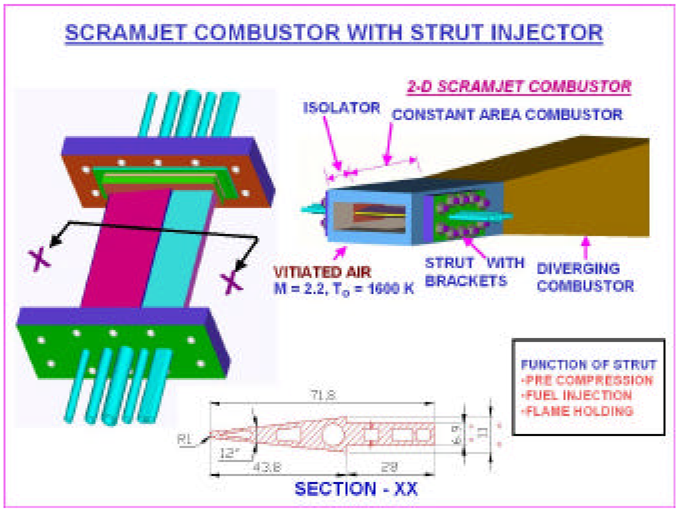


Fig 2: Strut injector

The air heater produces the vitiated air at required temperature by burning hydrogen. The oxygen is replenished by adding additional oxygen. The vitiated air is then expanded through a supersonic nozzle. The accelerated vitiated air enters the combustor which consists of two parts, constant area and diverging area combustor. In the constant area combustor, a backward-facing step on both the top and bottom wall surfaces is provided. Strut is essentially a fuel feed element and it also acts as a pre-compression system for the incoming air stream. The backward facing step plane and the leading edge of the fuel injection strut are aligned. The fuel injection strut has a blunt leading edge of 1mm radius; a compression part with a half-wedge angle of 6^0 followed by a step of 2 mm on both sides and finally a constant area section. Figure 2 shows the strut configuration and its assembly. The thickness in the step plane of the strut is 11 mm. Six numbers of fuel injectors of f 0.4 mm are located at 8 mm downstream of the strut step in the constant area section, with three fuel injectors on either side of the constant area section. The strut is placed along the flow direction with the blunt leading edge. In the constant area combustor on the top surface of the combustor, pressure transducers are mounted on the top surface for measuring wall static pressure and temperature sensors are mounted on the bottom wall for measuring wall static pressure and temperature in the combustor. The semi divergence angle of divergent combustor is 3.2^0

2.3 FUEL INJECTION SCHEME:

Pilot hydrogen is introduced to increase the temperature of the test gas. Kerosene was injected after 3sec. The pilot hydrogen was withdrawn after 3.7sec. The kerosene injection was continued. Fuel (aviation kerosene) is injected normal to the airflow. The fuel gets atomized, vaporized and mixes with the airflow. The rise in wall static pressure and wall temperature indicate the supersonic combustion in the scramjet combustor.

2.4 HYDROGEN BURNER

The burner has performed satisfactorily. The measured values of burner stagnation pressure and temperature were found to be steady throughout the test duration, and values were as expected. The temperature of the burner was 1430K and stagnating pressure was 14.5bar. The air, Hydrogen and Oxygen mass flow rates were steady through out the test duration.

The following table (T 1) brings out the performance of the Burner and Nozzle. It can be observed that the Burner and nozzle have performed satisfactorily. The nozzle exit Mach number was calculated to be 2.4.

TABLE 1

S.No	Parameter	Theoretical	Actual
1	Burner Stagnation pressure	15.00 Bar	14.50 Bar
2	Burner Stagnation temperature	1500.00 K	1430.0 K
3	Nozzle Exit static pressure	1.00 Bar	1.04 Bar
4	Combustor Inlet static pressure	1.00 Bar	1.03 Bar
5	Equivalence Ratio – combustor	0.40	0.398

The following table (T2) depicts the mass flow rates during the experiments.

TABLE 2

S.No	Parameter	Hot reacting flow	
		Expected	**Actual**
1	Air (Kg/s)	0.750	0.6200
2	Hydrogen (Kg/s)	0.020	0.021
3	Oxygen (Kg/s)	0.230	0.237
4	Fuel (gm/s)	25.0	22.00
5	Coolant (gm/s)	400.0	440.0

2.4.1 SUPERSONIC DIFFUSION FLAME

The supersonic diffusion flame could be seen in three phases. As shown in Plate 1, when the pilot Hydrogen was alone injected, because of the transparent flame, supersonic diamond pattern was observed. As shown in Plate 2 With Kerosene injection the flame could be sustained and supersonic flame was observed. After hydrogen pilot was withdrawn, supersonic flame could be observed with kerosene fuel alone. The flame appeared to be continuous during major part of reacting flow. Also there was an increase in the wall pressure as indicated by the wall pressure distribution.

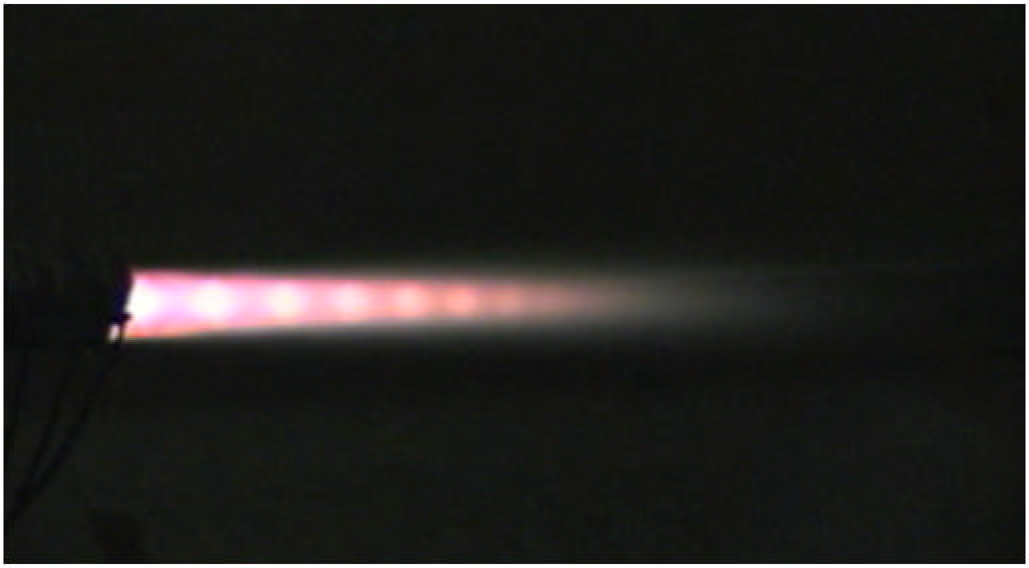


PLATE 1: Supersonic Flame during Pilot Hydrogen injection

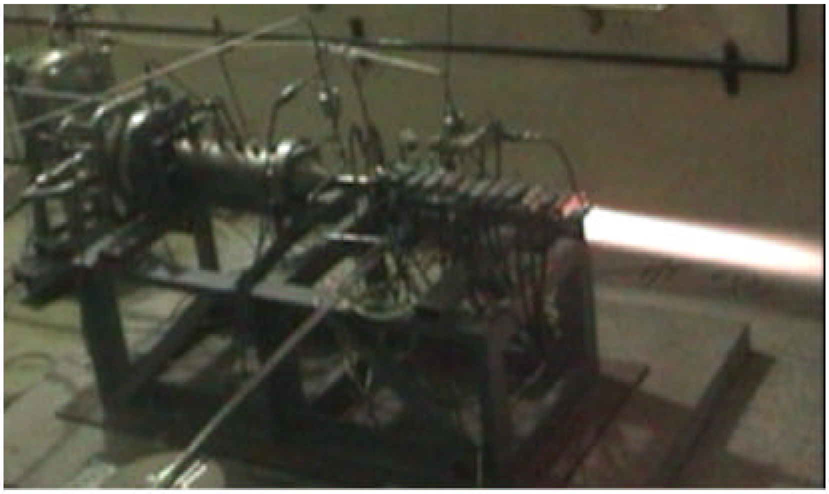


PLATE 2 : Supersonic Flame during Kerosene injection

2.4.2 COMBUSTOR WALL PRESSURES

Fig (3) Shows the static pressure distribution for the following cases

- Test gas alone. (Without fuel injection)
- With pilot Hydrogen fuel injection only.
- With pilot Hydrogen and Kerosene fuel injection.
- With Kerosene fuel injection only.

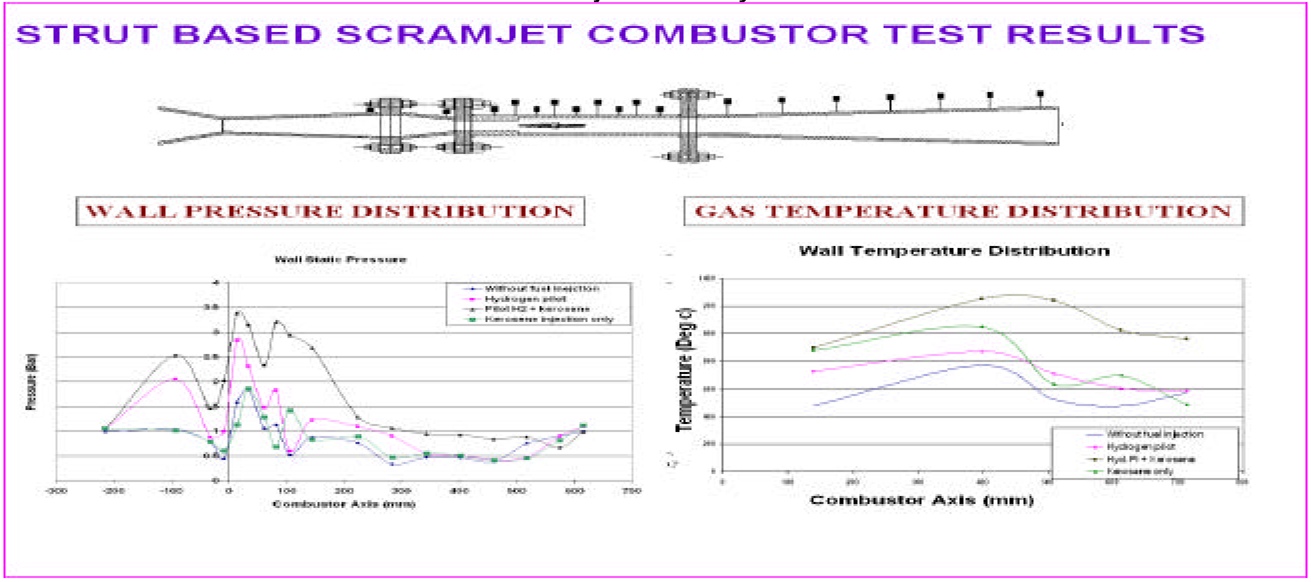


FIGURE 3: Pressure and Temperature Distribution

Wall pressure measured at combustor entry was about 1kscA as expected. From the pressure distribution it was clear that the nozzle throat was choked and the entry to combustor was supersonic (M =2.4). Also the wall static pressures were following the trend as expected in the combustor, indicating that the flow was supersonic throughout the combustor. During both hot non-reacting and hot reacting flow conditions, the flow separation occurred at the rear end of the diverging area combustor.

The following were the observations made on wall static pressure distribution

1) The maximum wall pressure was 3.14bar recorded during the injection of both kerosene and hydrogen, followed by 2.87bar for pilot hydrogen injection and 1.8bar with only kerosene injection. The base line was with out any fuel injection. The increase in wall static pressure for injection of kerosene alone (with reference to the baseline wall pressure curve) indicates the ignition and sustained combustion of kerosene even after the pilot hydrogen was withdrawn.
2) For the case of kerosene injection alone, the wall static pressure rise could be observed from combustor wall pressure measurements.
3) Upstream influence due to the injection, for the cases of the 'pilot hydrogen' injection alone and 'Pilot hydrogen and kerosene' injection has been observed.
4) The separation point was slightly upstream when there was no injection of fuel.

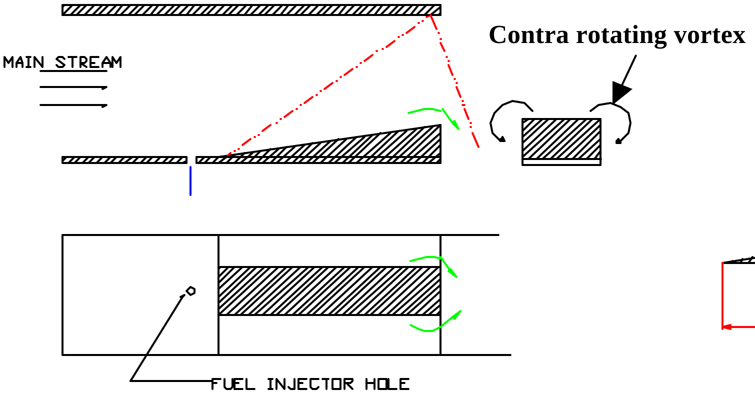
2.4.3 Temperature measurements

Thermocouples were mounted on the test section there were wall flushed temperature probe and skin temperature probes. The wall temperature distributions along the combustor for hot-reacting and hot non-reacting flow conditions are given in fig (3). There is a marked rise in temperature in all channels, between injection case and no injection case. The maximum temperature rise was observed for the case of 'pilot hydrogen and kerosene injection’. The temperature rise for ‘kerosene injection only’ was between that of the ‘pilot hydrogen & kerosene injection’ and ‘pilot hydrogen injection only’. This signifies the ignition and sustained combustion of kerosene. The maximum skin temperature of 407K was achieved near the strut region when kerosene injection was on.

3. DEVELOPMENT OF THE RAMP-CAVITY BASED SCRAMJET COMBUSTOR

3.1 Ramp injectors

One of the strategies to solve the aforesaid problems of mixing is generation of axial vortices. Axial vortices possess a better far field mixing characteristics. Also they are being propagated to a considerable distance, even with the suppressing characteristics of the supersonic core flow. Ramp injectors are considered to be a key feature to generate axial vortices. Figure 4 & 4A depicts some of the characteristics of Ramp injectors flow field. The following are the characteristics of the ramp injectors.



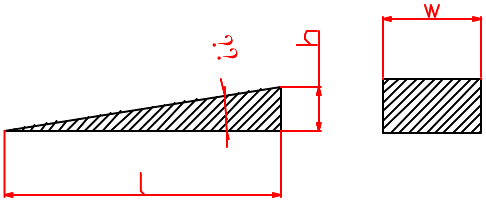


Fig4: Ramp injector Flow field :ating **Fig4A: Ramp injector geometry**

compression.

2) Pre-compression by the Ramp face produces favorable region for injection.
3) Stagnation region near the leading edge of the Ramp injector improves ignition.

4) The strength of the spillage vortices increase with increase of core flow mach no, thus retaining the performance at higher operating conditions.

3.2 Cavity Based Injection:

Generation of acoustic oscillations is also considered to be a better candidate to achieve better mixing. Unsteady shear layers generate acoustic oscillations. Wall mounted cavities generates these oscillations to aid the mixing enhancement. The Cavity parameters in figure 5. Cavities are characterized by their L/D ratio. There are three regimes of cavity behavior, categorized by the shear layer separation and its reattachment. For cavities of L/d less than 1, the shear layer reattaches way past the trailing edge of the cavity it generates transverse oscillations. These cavities are called as 'Open Cavities'. This type of oscillations aid in penetration of fuel For L/D more than 2, the separated shear layer attaches to the bottom wall of the cavity, it generates longitudinal oscillations, which aid in flame holding characteristics. The third type of cavities is square and transition cavities, where L/D is one or close to one. They exhibit a very low level of oscillations

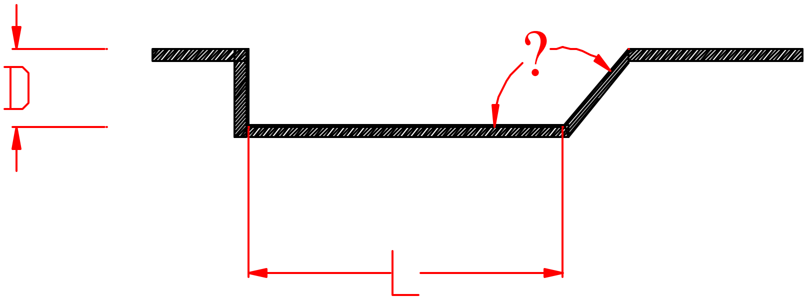


Fig5: Cavity parameters

3.3 Combination of Ramp and cavity injectors

The overall performance of ramp and cavity injectors can be improved by combining them properly. The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion. Ramps will enhance the fuel penetration in to the core and cavities will enhance the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency. Thus Ramp and cavity combination shows promising characteristics for better scramjet combustor performance.

The following table 3 shows the design criterion.

Table 3.

S.No	**Parameter**	**Criterion**
	Ramp Injector	
1	Length (L)	Evaporation length of droplets
2	Wedge angle (?1)	Compression and shock strength
3	Ramp base width (w)	Area blockage by ramp
4	Ramp Spacing (w1)	Minimum the blockage area-distribution
	Cavity Injector	
1	Length (L)	Ramp Base height
2	Cavity depth (D)	L/D ratio needed
3	Trailing edge angle (?)	Shock strength at the Trailing Edege

Considering the above design parameters a Ramp-Cavity combustor is designed and fabricated. The combustor has been tested for its performance. The details of test results are given as under.

3.4. TEST OBJECTIVES:

1. To study the flow field characteristics of Ramp-cavity based Scramjet combustor.
2. Demonstration of ignition and sustained supersonic combustion with Kerosene fuel in the two dimensional supersonic combustor with Ramp-cavity injection.

3.5 Combustor Test Facility:

The setup consists of a Hydrogen burner as an on-line gas generator, an axi-symmetric convergent-divergent nozzle for accelerating the test gas to the desired supersonic condition and a circular to rectangular transition duct. The supersonic combustor has two parts; one constant area section with backward facing step in which the ramps and cavities are located and the second one is diverging area combustor

Kerosene fuel was injected transversely upstream of the ramps through five orifices of 0.4 mm diameter through the top and the bottom walls of the combustor. Kerosene was also injected through five 0.4 mm orifices parallel to the flow through the ramp base. Pilot Hydrogen was injected to ensure the ignition and sustained combustion of kerosene fuel. The fuel injection scheme was shown in fig. (6). Wall pressures along the axial length of the Hydrogen burner, convergent- divergent nozzle, transition duct and supersonic combustor were measured with strain gage type pressure transducers. The burner stagnation temperature and the wall temperatures were measured with Tungsten-Rhenium thermocouples. Skin temperatures were also recorded during the test.

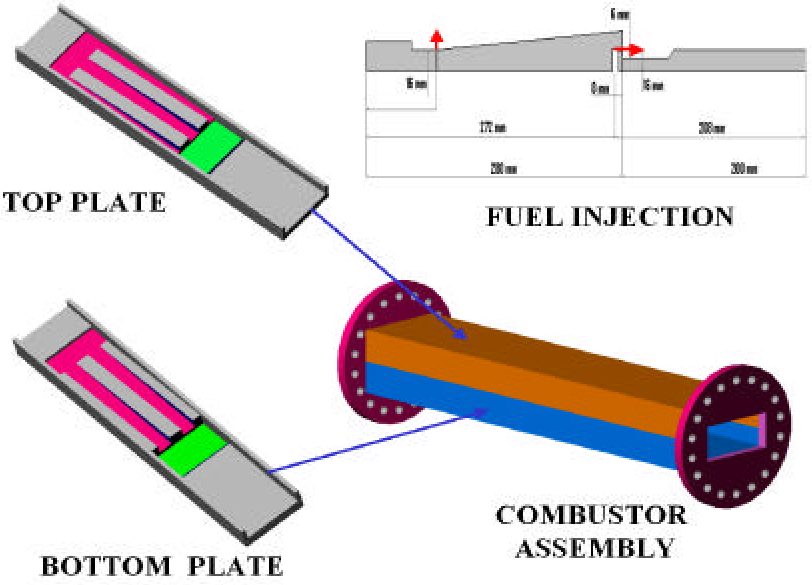


Fig 6: Ramp Cavity Based Scramjet Combustor

3.6 TEST CONDITIONS

Flight Mach No.	:	6.0
Flight altitude	:	32 km
Combustor entry Mach No.	:	2.4
Burner stagnation temp.	:	1500 K
Fuel equivalence ratio	:	0.4
Test gas flow rate	:	0.85kg/sec
Kerosene mass flow rate	:	26 gm/sec
Kerosene injector pressure	:	16.6 bar

3.7 Results and Discussion:

The following tables give details of the achieved flow conditions.

Table 4

S.No	Parameter	Theoretical	Actual
1	Burner Stagnation pressure	14.0 Bar	12.23 Bar
2	Burner Stagnation temperature	1500.0 K	1343.0 K

The following table depicts the mass flow rates during the experiments.

Table 5

S.No	Parameter	Hot reacting flow	
		Expected	Actual
1	Air (Kg/s)	0.750	0.625
2	Hydrogen (Kg/s)	0.014	0.012
3	Oxygen (Kg/s)	0.180	0.181
4	Fuel (gm/s)	24.0	26.00
5	Pilot Hydrogen flow (g/s)	2.00	1.9
6	Equivalence Ratio – combustor (kerosene)	0.40	0.467
7	Equivalence Ratio – combustor (Hydrogen)	0.1	0.1

The figure 7 shows the static pressure and the wall flushed temperature distribution along the combustor, for various instants of the test sequence. There is a marked pressure and temperature rise between the ‘without fuel injection” case to the “Kerosene injection case”. Also the maximum pressure and temperature occurred during the injection of both hydrogen and kerosene.

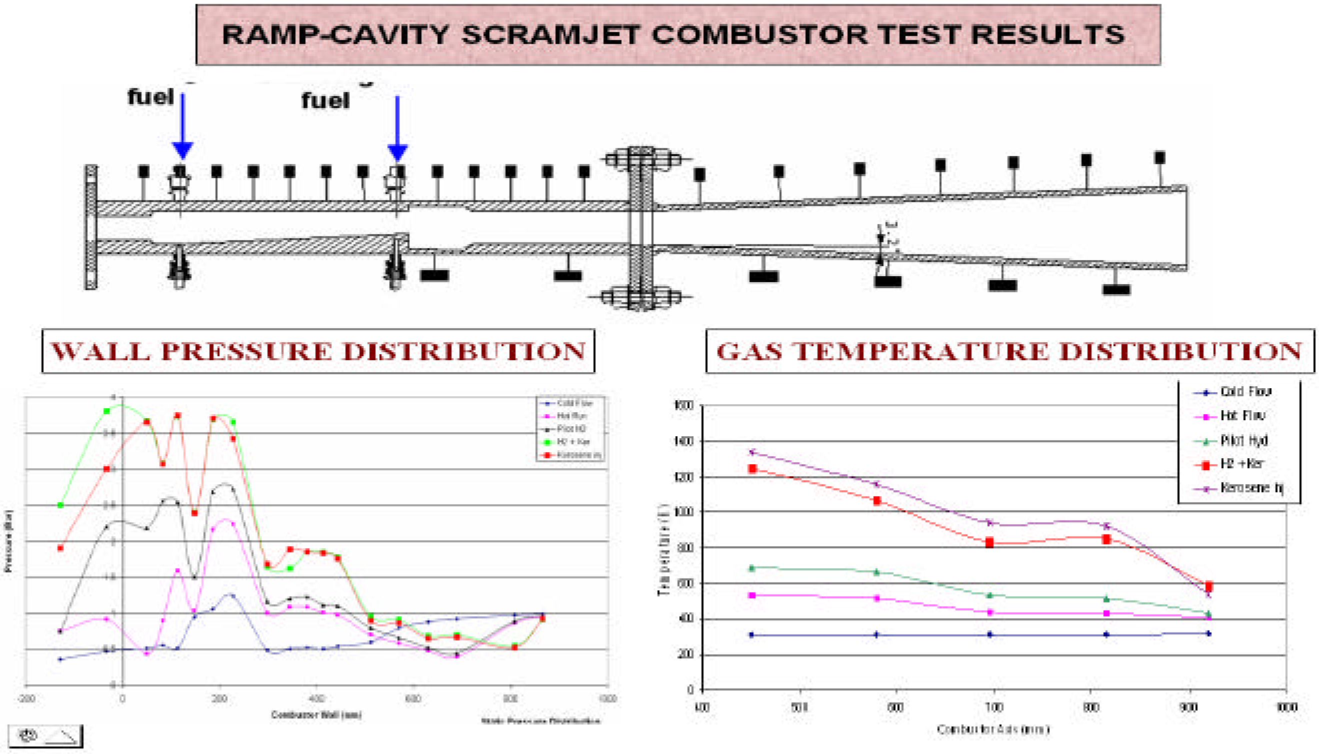


Fig 7: Pressure and temperature Distribution (ramp-Cavity combustor)

4.0 DEVELOPMENT OF BARBOTAGE INJECTION SYSTEM

Effervescent atomization is a phenomenon in which gas has to be introduced into the liquid with a very low velocity, leading to turbulent two-phase flow that can improve penetration and vaporization of the fuel jet spray. The difference in the densities of liquid and the gas, the interaction between the two phases are helping in breaking the liquid to smaller droplets and reducing the flow dimensions for the liquid which helps in injecting the liquid fuel as very fine droplets. Barbotage injection with liquid Kerosene and Hydrogen/Air has a definite advantage in terms of breakup of droplets for better mixing with the supersonic air stream and combustion enhancement. Also using hydrogen as the barbotaging gas creates favorable conditions for the kerosene combustion also.

The basic configuration of the barbotage injection unit is shown in the Fig 8. The kerosene is injected through a central tube into a mixing zone, to which the Hydrogen flows through the annular gap around the kerosene tube. In the mixing zone, gas bubbles into the liquid. Then the two-phase flow is injected into scramjet combustor through the injection orifices.

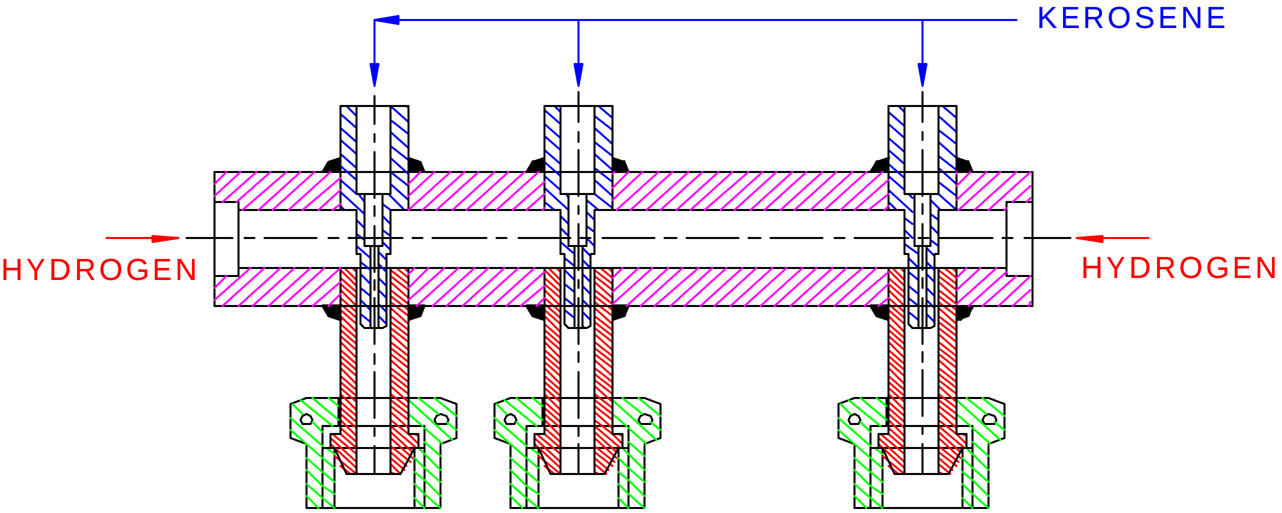


Fig 8: Barbotage system

The flow visualization studies were carried out with the above system by allowing the jets to atmosphere. Plates 3 & 4 show the difference between the pure kerosene injection and that of barbotaging. It clearly indicates the breakup of droplet to very fine diameters and increased spread angle.

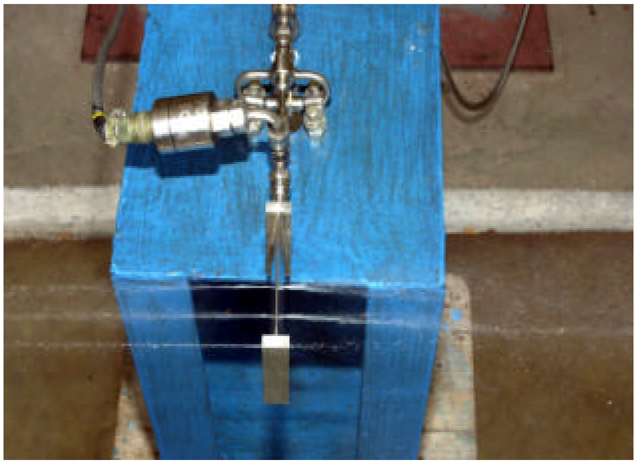


Plate 3: Kerosene injection

Plate 4: Barbotage injection

An experiment on Ramp-Cavity based combustor, with Barbotage injection system, was conducted. The following figure shows the Ramp-Cavity combustor with Barbotage injection system.

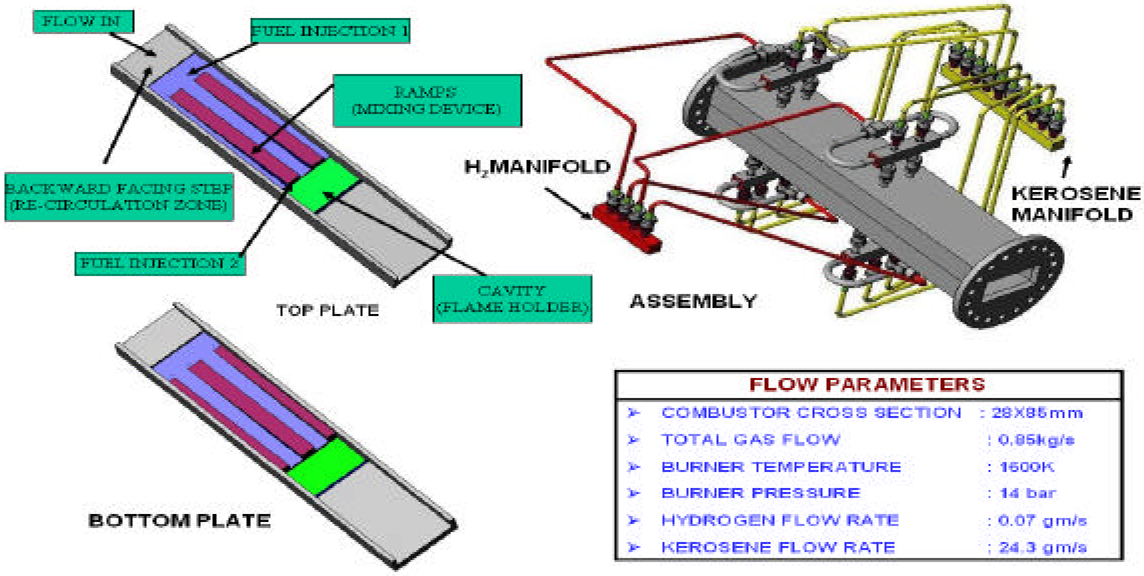


Fig9: Ramp-Cavity with Barbotage system

4.1. Results and discussion

The following figure 10 shows the wall pressure distribution and the temperature distribution of the ramp-cavity test with Barbotage injection. The kerosene injection was 26g/s for *"the kerosene injection only"* (with out barbotaging) case and 24.3gm/sec for the *Barbotage injection case*. Comparing to condition of injection of kerosene only, the Barbotage injection generated higher pressure and temperature rise, with comparable amount of fuel injected.

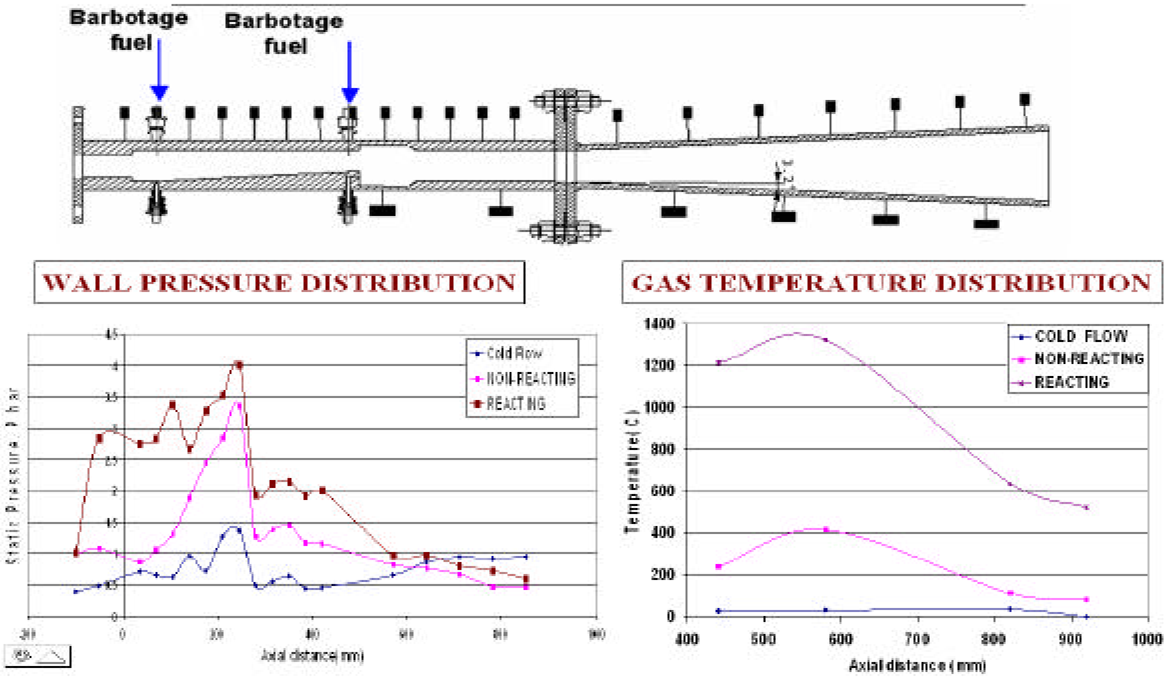


Fig 10: Pressure and Temperature distribution (Ramp-Cavity with Barbotage system

5 CONCLUSIONS

i) Ignition and sustained combustion of kerosene could be achieved with pilot hydrogen even at lower air temperatures (1430 K).

ii) The kerosene could be ignited using pilot hydrogen at a total temperature of 1343.K, which is lower than the strut configuration.

iii) The kerosene combustion was sustained at an equivalence ratio of 0.467, even after the withdrawal of pilot hydrogen.

iv) The Flame was anchored at the cavity inside the combustor.

v) The Barbotaging of kerosene produced very fine droplets and higher cone angles of injection, during the injection to the atmosphere.

vi) Barbotaging of kerosene with hydrogen produced higher-pressure and temperature rise with comparatively lesser amount of kerosene injection.

The experimental data generated on three configurations has provided a useful insight for the configuration design of full-scale combustor for Hypersonic

Technology Demonstrator Vehicle (HSTDV). The wall pressure distributions achieved during the experiment has been used for the validation of CFD codes like CFX & Fluent.

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