Conceptual design of independently configurable Mach 6.8 hydrogen fuelled dual mode scramjet propulsion system

Qasim Manzoor
Dept. of Aerospace, CAE
National University of Sciences & Technology,
Sector H-12 Islamabad, Pakistan

Ali Sarosh
Dept. of Aerospace, CAE
National University of Sciences & Technology,
Sector H-12 Islamabad, Pakistan

Abstract*— In this research conceptual design of an independently configurable dual-mode scramjet propulsion system is proposed for integration to a Hypersonic Cruise Vehicle (HCV). The propulsion unit does not require the vehicle forebody to provide the initial external compression, thus alleviating the dependence on the vehicle geometry to sustain Scramjet operation on an HCV. The Propulsion system is designed to propel the Booster Stage of a derivative of HTSM 6811 vehicle, which is a Hypersonic Cruiser. The Scramjet system is designed at the design-point conditions of stage separation, for a Mixed External-Internal compression system with optimal non-isentropic external compression surface. The Mixed External-Internal Compression system is then integrated to a constant-area isolator, constant pressure burner and a Single Expansion Ramp Nozzle (SERN). One-Dimensional Aerothermodynamic method of Stream Thrust Analysis (STA) is used to calculate the performance of the Scramjet engine and ascertain the Aerothermodynamic properties of flow at each station. The propulsion system design is independent of the vehicle forebody and can be integrated to any Mach 6.8 operating HCV. Engine/vehicle integration is based on the relative position of scramjet engine with respect to SERN. This approach allows the airflow and resulting thrust at the combustor exit to increase as the propulsion module is moved aft and the distance between the body and the forebody shock increases.

***Keywords*—scramjet;dual-mode;stream thrust analysis;independently configurable**

I. INTRODUCTION

A scramjet propulsion system is a hypersonic airbreathing engine in which heat addition due to combustion of fuel and air, occurs in the flow which is supersonic relative to the engine [1]. Unlike a ramjet engine, the airflow in a pure scramjet engine remains supersonic throughout the combustion process and does not require a physical choking mechanism rather it relies on thermal occlusion to provide the necessary choking. Modern scramjet engines are able to seamlessly transition between ramjet and scramjet operation to incorporate flight at lower Mach numbers as well. Scramjets are designed to operate in the hypersonic flight regime, beyond the domain of ordinary turbojet engines, and fill the gap between the high efficiency of turbojets and the high speed of rocket engines. Successful scramjet design is dependent on careful integration of engine to airframe [2],[3] because the vehicle contributes significantly to compression and expansion component performance. An independently configurable scramjet engine would provide propulsion to any vehicle operating at the design Mach for the engine.

In this paper, a scramjet propulsion system is designed to fulfill the propulsion requirements for the booster stage of HTSM 6811 which is originally a rocket ramjet propelled vehicle [4]. The propulsion system has its own forebody compression ramp and SERN which can be integrated to the hypersonic cruise vehicle at an appropriate location. The forebody is designed to cover a wide range of operating conditions, for this reason the selection and optimization of hypersonic forebodies is a critical research area and many methods can be used for this purpose[5]. In this study, the ramp is evolved using the cycle static temperature ratio and comparing it against a suitable value of burner entry Mach number [6]. The ramp angle which gives a reasonable Burner entry Mach number is selected and the corresponding cycle static temperature ratio is chosen as the design cycle static temperature ratio ψ [1]. Stream thrust analysis is performed at the selected value of ψ to calculate the performance and various aerothermodynamic parameters at each station [1],[7]. Isolator length is determined by calculating the shock distances [8] at design point and burner length is fixed by calculating the required mixing length [1] and incorporating Rayleigh effect [8] to model the heat addition process in the burner assuming zero-shear mixing layer [9],[10]. SERN is designed using the method of characteristics which resolves hyperbolic PDEs into ordinary differential equations [11], [12] and allows the Prandtl Meyer fans in the expansion component to be resolved and Mach numbers in this component to be calculated with reasonable accuracy. Engine integration to the vehicle is done by the method specified by Curran [13]. This method allows a dual-mode scramjet propulsion system to be designed independent of the vehicle geometry and then integrated to provide propulsion at the design Mach of 6.8 even for vehicles which are not primarily designed for scramjet propulsion systems.

II. METHODOLOGY

In conventional scramjets the vehicle forebody provides the external compression, but in the case of the vehicle under study the original forebody ramp of the vehicle does not provide enough compression to ensure efficient scramjet operation while satisfying the shock-on-lip condition. So a different approach was applied in which a forebody ramp for the scramjet engine was designed. The shock originating from the vehicle forebody would not be incident on the lip in this case rather the shock originating from the engine's own ramp would satisfy the shock-on-lip condition. The freestream conditions for the vehicle are the stage separation conditions for the HTSM 6811 vehicle i.e. Mach 6.8 at 35km altitude. But the effective freestream conditions for the engine are the downstream conditions after the oblique shock originating from the 2.5° vehicle forebody ramp

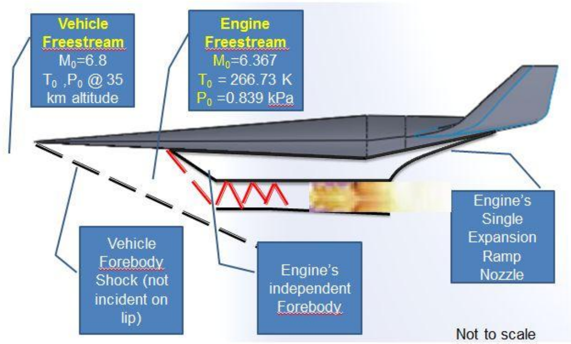

Fig. 1. HCV for Scramjet Integration (Independently Configurable)

The ramp angle is calculated by evaluating the cycle static temperature ratio and burner entry Mach number for a range of ramp angles and the ramp angle giving a suitable burner entry Mach number is selected. After the ramp angle has been selected, Stream Thrust Analysis is performed for the ψ corresponding to the selected ramp angle to calculate aerothermodynamic parameters of the flow and to determine the performance of the engine. Fig. 2 gives the reference station numbers used during the stream thrust analysis:

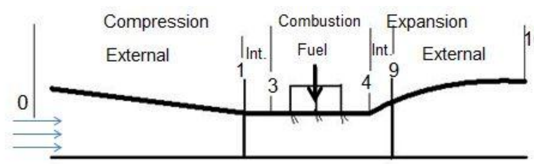

Fig. 2. Scramjet Reference Station Numbers

The geometry i.e. lengths and areas of the various subcomponents of the scramjet engine are then calculated. For the isolator length, shock distance for the reflected shock inside the inlet is calculated for the selected ramp angle at design condition. The combustor length is calculated by multiplying the mixing length by 1.5 where the mixing length L_m is given by:

$$L_m = \frac{u_c b^2}{16\, D_{FA}} \tag{1}$$

- Here D_{FA} is a proportionality constant called molecular diffusivity
- u_c mean velocity of incoming air fuel mixture
- b is inlet fuel jet dimension

D_{FA} is given by Fick's law[14], and can be estimated by the formulation.

$$Sc = \frac{\mu}{\rho D_{FA}} \tag{2}$$

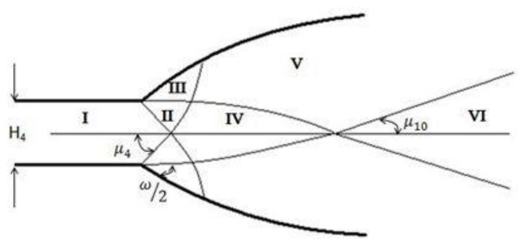

Fig. 3. Schematic Diagram of the Ideal Exhaust Nozzle

The SERN is designed using the method specified by Heiser[1], where the Mach numbers for each zone in the figure are calculated and the flow turning angles necessary to obtain the Mach numbers are calculated with accuracy by solving the Prandtl Meyer fans that will exist in the expansion component and their interaction with each other.

III. RESULTS

Iterative calculations for ψ and the burner entry Mach number for a range of ramp angles from 0.5 to 25 degrees yields the following plot:

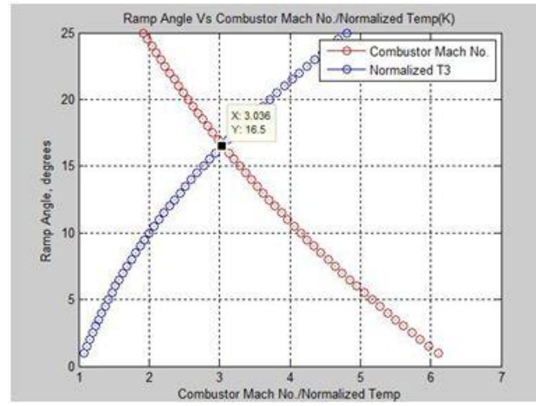

Fig. 4. Ramp Angle vs. Combustor Mach No. / ψ

Selecting the ψ at the point of intersection corresponding to a ramp angle of 16.5, stream thrust analysis is performed for constant pressure burner configuration at the engine freestream conditions. The results obtained from the STA are:

Table I. STA Results @ ψ=3.036

Parameters	Stations			
	Station 0	***Station 3***	***Station 4***	***Station 10***
M_i	6.367	3.05	1.58	3.32
V_i (m/s)	2039.72	1725.3	1617	2544.9
T_i (K)	266.73	809.78	2916.3	1637.5
P_i / P_0	1	32.65	32.65	1
A_i / A_0	1	0.109	0.434	0.506
Sa_i (Ns/kg)	2077.5	1861.06	2138	2731

The performance measures calculated from the results of the STA are:

Table II. Performance Measures of Engine

Performance Measure	Value
Specific Thrust	579.32 Ns/kg
Overall Efficiency	0.34
Propulsive Efficiency	0.9435
Thermal Efficiency	0.358
I_{sp}	2027.52 s

The lower Mach limit of scramjet operation for the dual mode scramjet engine is determined to be M_0=3.78 using the relation:

$$M_0 > \sqrt{\frac{2}{\gamma_c - 1}\left\{\left(\frac{\gamma_c + 1}{2}\right)\frac{T_3}{T_0} - 1\right\}} \qquad (3)$$

Forebody ramp geometry along with Isolator Length and Burner Length are calculated using MATLAB code which generates the geometry in Fig. 5.

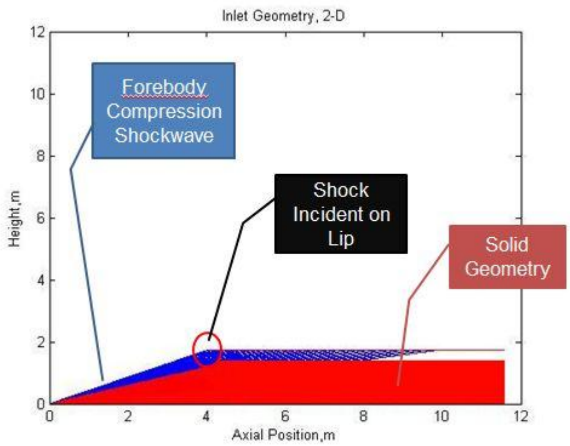

Fig. 5. Inverted Scramjet Geometry (Forebody, Isolator, Burner)

The important geometric parameters obtained from the MATLAB code and Fig. 5. Are listed in Table III

Table III. Component Geometry Parameters

Parameter	Value
Isolator Height	0.389 m
Isolator Length	0.517 m
Burner Length	6.41 m
Burner Area Ratio A_4/A_3	3.95

The height of isolator is calculated from the area of the inlet which is determined from the mass flow rate at the inlet, where the width of the inlet is 17.3 m. The mass flow rate is determined to be 690.46 kg/s from the specific thrust value for an installed vehicle thrust of 400kN.

The results obtained from the SERN calculations by applying the method of characteristics to solve the Prandtl Meyer expansion fans is given in Table IV:

Table IV. SERN Characteristics

Parameter	Value
$\omega/2$	26.22°
M_{III}	2.364
L_{II}	0.94m
μ_{III}	25.018°
L_{IV}	2.437m
H_{10}/H_4	7.23

After the geometry parameters are calculated a 2-Dimensional model of the scramjet engine in generated and is given in Fig. 6

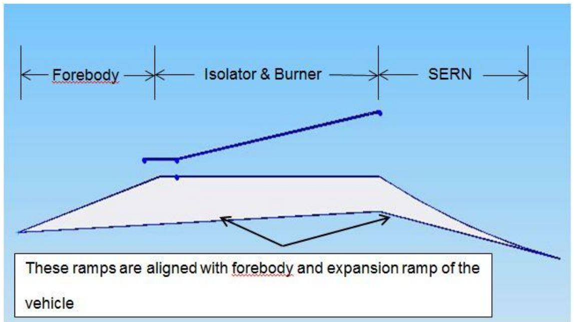

Fig. 6. 2-Dimensional model of Scramjet

Finally the engine is integrated to the vehicle at in such a way that the start of the forebody compression ramp lies at an x/L=0.5 and the start of the SERN lies at an axial location of x/L=0.647

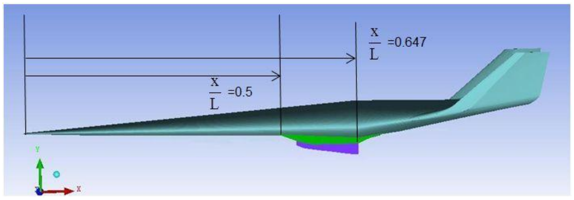

Fig. 7. Scramjet integrated with vehicle

IV. CONCLUSION

The scramjet engine designed by following the above method is fully configurable to the vehicle for which it was designed and the dimensions of the engine are compatible with those of the booster stage of the HTSM 6811. The forebody ramp of the designed scramjet can be integrated with the ramp of the vehicle forebody and the SERN, with a turning angle of 26.2^o, can be adjusted to conform to the 11^o ramp at the exhaust of the HTSM 6811 by means of isentropic expansion which will give the surface of the SERN. The engine length is $1/5^{th}$ of the total vehicle length which is typical for scramjet engines [13]. The scramjet engine can be integrated to the vehicle at the aftmost location before the exhaust ramp of the original vehicle starts for the reason that this location will allow the airflow and resulting thrust at the combustor exit to be the highest along with the added benefit of increasing the distance between the vehicle forebody shock and the inlet of the engine.

V. REFERENCES

[1] W. H. Heiser and D. T. Pratt, *Hypersonic airbreathing propulsion*: AIAA, 1994.

[2] R. Hallion, "The Hypersonic Revolution Vol. I: From Max Valier to Project PRIME (1924-1967)," *Air Force History and Museums Program, Bolling, AFB, DC,* 1998.

[3] R. Hallion, "The Hypersonic Revolution: Eight Case Studies in the History of Hypersonic Technology, Vol. 2, Special Staff Office, Aeronautical Systems Div., Wright-Patterson AFB, OH, 1987, pp. 893-923."

[4] D. Jacob, G. Sachs, and S. Wagner, "Basic research and technologies for two-stage-to-orbit vehicles," ed: Weinheim: Wiley-VCH, 2005.

[5] A. Sarosh, C. Shi-Ming, and D. Yun-Feng, "A difference-fractional FOM decision method for down-selection of hypersonic compression system configurations," *Aerospace Science and Technology,* vol. 27, pp. 147-155, 2013.

[6] G. C. Oates, *Aerothermodynamics of gas turbine and rocket propulsion*: Aiaa, 1997.

[7] E. T. Curran and R. R. Craig, "The use of stream thrust concepts for the approximate evaluation of hypersonic ramjet engine performance," DTIC Document1973.

[8] A. H. Shapiro, "The dynamics and thermodynamics of compressible fluid flow," *New York: Ronald Press, 1953-54,* vol. 1, 1953.

[9] A. Sarosh, D. Y. Feng, and M. Adnan, "An Aerothermodynamic Design Approach for Scramjet Combustors and Comparative Performance of Low-Efficiency Systems," *Applied Mechanics and Materials,* vol. 110, pp. 4652-4660, 2012.

[10] O. Planché and W. Reynolds, "Heat release effects on mixing in supersonic reacting free shear-layers," *AIAA Paper*, 1992.

[11] G. Emanuel, "Gasdynamics: theory and applications," *New York, American Institute of Aeronautics and Astronautics, Inc., 1986, 460 p.,* vol. 1, 1986.

[12] G. J. Harloff, H. Lai, and E. Nelson, *Two-dimensional Viscous Flow Computations of Hypersonic Scramjet Nozzle Flowfields at Design and Off Design Conditions*: National Aeronautics and Space Administration, 1988.

[13] E. Curran and S. Murthy, *Scramjet propulsion* vol. 189: AIAA, 2000.

[14] R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport phenomena*: John Wiley & Sons, 2007.