Parametric Analysis of a Dual Combustion Ramjet Engine

G. Jims John Wessley, Shilpa Pradeep

Abstract: ***The Dual Combustion Ramjet (DCR) engine is capable of economically generating thrust at both supersonic and hypersonic velocities with reasonable safety so as to make them potential alternatives for rocket engines used during atmospheric stage of flight. A preliminary analysis of a DCR engine at various velocities, altitude and equivalence ratios are performed and the results are presented in this paper. The paper presents the variation of thrust, specific impulse and overall efficiency at various inputs of Mach varying from 3 to 7, Equivalence ratio 0.3 to 1, altitudes 20,000 feet to 50,000 feet and inlet diameter from 200mm to 400mm. The thrust increases with increase in Mach number of the flow and inlet area and decreases with increase in altitude and equivalence ratio. The specific impulse of the engine decreases with equivalence ratio for low Mach numbers and increases for higher Mach numbers. It is also found from the analysis that the engine is capable of producing a thrust of 14.25 kN with an overall efficiency of 44% while operating at Mach 7 with an equivalent ratio of 0.3 at an altitude of 15, 240 m (50,000 ft). The results are encouraging and substantiate the claim that these engines can play a major role in the future propulsion and space exploration.***

Keywords: Ramjet, dual combustion, supersonic, equivalence ratio, thrust

I. INTRODUCTION

An ardent search to develop air breathing engines for vehicles flying at hypersonic speeds has led to the evolution of Dual combustion Ramjet (DCR) engines, which basically combines both the ramjet and scramjet engine principles. A conventional scram jet engine requires a basic engine to reach the scramjet operation speed, say around Mach 5, which adds weight and complexity to the propulsion system. A DCR engine encompasses a subsonic ramjet that works as a pre-burner in the subsonic range along with a supersonic scram combustor.A blend of this technology is expected to make possible flights ranging from Mach 10 to 12, while the efficiency of a Ramjet engine decreases around Mach 5 and hence it cannot be used above Mach 6. Since, the DCR engines combine the advantages of ramjet and scramjet engines, there is a huge scope for research to understand and analyse the working and performance of these engines.

Aqheel and Sayeed [1], proposed an inlet design for a Scramjet engine in order to lower the starting Mach number, so that the need for an additional propulsion system can be eliminated. They modeled a scramjet engine using GAMBIT and analysis was performed in FLUENT with different designed models. The results indicate that a typical design with four ramps yielded better results than the other designs and also it was found that a DCR model with starting Mach number of 4 was feasible. The work of Susmit and Gaurav [2], provides a detailed insight into the development of scramjets, their engineering considerations, experimentation and the operation in dual modes etc., It is evident from the study that, the transition points between the modes are influenced by the type of fuel, injector configuration, inflow temperature and amount of fuel sprayed. Results show that the dual-mode operation of the scramjet engines maximizes the thrust and hence, such engines can be used as a substitute for rocket engines in the atmospheric stage of flight.

Gounko and Shumsky [3],discussed the possibility of using a diverging dual-combustion chamber in order to reduce the flight starting Mach number. The analysis of the performance characteristics of a dual-combustion ramjet with a two-dimensional air-intake were performed in the range of Mach 3 to 7. The results show that with the diverging combustion chamber it is possible to begin the ramjet operation from flight Mach numbers 2 or 3. Clinton Humphrey [4], performed the design and fabrication of a ramjet engine inlet, which was installed as an integral part on the ramjet engine. It was observed that the use of double ramp to slow the air flow resulted in higher pressure recovery and hence better combustion characteristics of the combustor. Byun et al [5], conducted a fundamental analysis on a DCR model based on gas dynamics and thermodynamic theories in order to study the operation characteristics and major design parameters. The study proposed the relationship between air inlets, gas generator, and supersonic combustor and also determined the geometry of the gas generator and supersonic combustor. The works of Billig et al [6], elaborates the new techniques required to design the Integral-Rocket-Dual Combustion Ramjet (IRDCR) engine cycle and evaluate its performance for a particular family of inlet designs and for various Mach numbers.The sensitivity of engine performance to inlet operating characteristics is discussed in terms of maximum thrust and engine efficiency. The results indicate that IRDCR performance characteristics are found to be intermediate to those of conventional ramjets and scramjets with some of the advantages of each.

Wadwankar et al [7], modeled individual components of a dual combustion ramjet engine (intake, isolator, ram diffuser and combustor, scram combustor and nozzle) using Simulink and also analyzed the performance of the assembly using integrated model. The stability, dynamic behaviour and steady state performance of the engine at various equivalence ratios, Mach 7 and at an altitude of 27.5 km were assessed. It is observed that the overall equivalence ratio of near to 0.8

Revised Manuscript Received on December 22, 2018.

G. Jims John Wessley, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamilnadu, India (E-Mail: jims_john@karunya.edu)

Shilpa Pradeep, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamilnadu, India.(E-mail: pradeepshilpa650@gmail.com)

and improved ram intake total pressure recovery have major influence on the performance of the DCR engine. Jong ho Choi et al [8], carried out component based propulsion modeling and simulation of a dual combustion ramjet engine. The subsonic and supersonic intake was modeled using Taylor-Maccoll with a cone angle of 25°. The gas generator transfers a pre-combusted gas into supersonic combustor which was created using Lumped model, and analyzed using quasi 1-D model. Jianguo Tan [9], investigated the performance of a full-size DCR engine in the Mach 4 to 6 and altitude 17 to 25 km through direct-connected experiments and numerical simulations. The results show that the thrust increases with increasing equivalence ratio. It is inferred that the thrust increment was 8.1 kN for a Mach of 4 and equivalence ratio 0.9. The thrust increment was found to be 3.15 kN for Mach 6 and at equivalence ratio 1.0. The equivalence ratio affects the combustion efficiency and the specific impulse with the same trend. The maximum combustion efficiency as found to be 0.91 at Mach 4 and 0.89 at Mach 6. Also, the maximum specific impulse is 13.3 kNs/kg at Mach 4 and 7.96 kNs/kg at Mach 6.

It is observed from the above literatures that the modeling of a complete DCR engine for various parameters of Mach, altitude and equivalence ratio is not available. Hence, this study aims at performing the preliminary analysis of a dual combustion ramjet engine at various inputs of Mach, altitude, equivalence ratio and inlet area on thrust, specific impulse and overall efficiency.

II. DUAL COMBUSTION RAMJET ENGINE

In a DCR engine, free stream air enters at supersonic speed through both the Ram intake and Scram intake. At the ram intake, the inlet flow undergoes subsonic diffusion after passing through 2 oblique and one normal shock assisted by the central cone. The central cone angle considered in the present analysis is 20°. The flow is thus decelerated to subsonic velocity before entering the subsonic combustor. In the subsonic combustor fuel is fed and partial combustion takes place producing a stream of hot gas. Meanwhile, the Scram intake flow passes through an isolator which is a diverging passage with a region of separated flow and supporting an oblique shock wave train through which the flow further decelerates but remains supersonic as it enters the supersonic combustor. The hot gaseous fuel leaving the subsonic combustor and the air coming from the isolator are mixed in the supersonic combustor. This gaseous fuel- air mixture after combustion is then allowed to expand through a diverging nozzle at supersonic velocity to obtain the required thrust from the engine. The components of the DCR engine with the state points are shown in Figure 1.

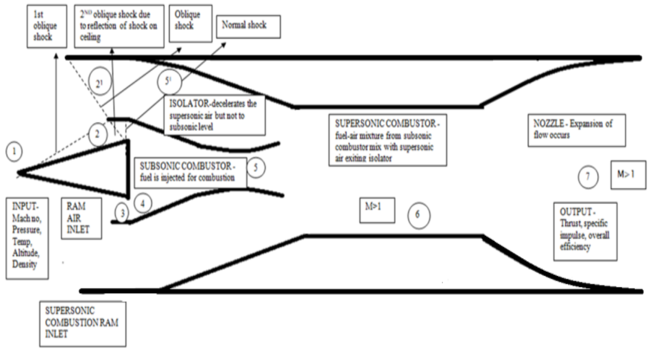

Fig. 1 Schematic diagram of the DCR engine in the present analysis

1 – Free stream region
2'– Region after oblique shock in scram inlet
2 – Region after first oblique shock in ram inlet
3 – Region after second oblique shock in ram inlet
4 – Region after normal shock in ram inlet / subsonic combustor entry
5' – Isolator exit / supersonic combustor entry
6 – Supersonic combustor
7 – Nozzle
5 – Subsonic Combustor

III. PARAMETRIC ANALYSIS

This section presents the methodology of designing the DCR engine and its parameters. The design of ram inlet is based on the equations of supersonic flow and oblique shocks. The supersonic flow is decelerated to subsonic velocity by a series of shocks. The air properties like Mach, Pressure ratio and density ratio after the first oblique shock wave are obtained by the following equations. The Mach number of the flow after the shocks is found out by using the equation 1 & 2.

$$M_{n,1} = M_1 \sin\beta \tag{1}$$

$$M_{n,2}{}^2 = \frac{1+\frac{\gamma-1}{2}M_{n,1}{}^2}{\gamma M_{n,1}{}^2-\frac{\gamma-1}{2}} \tag{2}$$

The important properties like pressure ratio and density ratio is obtained by the equations 3 & 4.

$$\frac{P_2}{P_1} = 1+\frac{2\gamma}{\gamma+1}(M_{n,1}{}^2 - 1) \tag{3}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_{n,1}{}^2}{2+(\gamma-1)M_{n,1}{}^2} \tag{4}$$

Mach number and temperature ratio after the oblique shock is found as,

$$M_2 = \frac{M_{n,2}}{\sin(\beta-\theta)} \tag{5}$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{\rho_1}{\rho_2} \tag{6}$$

The parameters after the second oblique shock reflected from the ceiling are obtained by the same set of equations. For the thirdand final shock, same set of equations are repeated with the wave angle β in the normal direction. After the final shock, the flow is subsonic and the final values of pressure, temperature and Mach number of air entering the subsonic combustion chamber is obtained. The inlet performance of the engine can be defined by inlet total pressure recovery. A higher pressure recovery indicates a better performing inlet. It is calculated by the relation,

$$\eta_{pr} = \frac{P_{04}}{P_{01}} \tag{7}$$

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

The ratio of Scram inlet area to ram inlet area is given by the relation,

$$\frac{A_1}{A_4} = \frac{M_4\sqrt{1+\frac{\gamma-1}{2}{M_4}^2\frac{P_4}{P_{04}}}\,P_{04}}{M_1\sqrt{1+\frac{\gamma-1}{2}{M_1}^2\frac{P_1}{P_{01}}}\,P_{01}} \quad (8)$$

In the subsonic combustion chamber, air leaving from the ram diffuser is mixed with fuel and partial combustion takes place.The fuel used in the analysis is Kerosene. The flow properties downstream the combustion chamber is obtained using Rayleigh and energy relations that is expressed by,

$$T_{05}=\frac{\eta_{gc}\times m_f\times Q_{LHV}+m_{a-sub}\times Cp_a\times T_{04}}{(m_f+m_{a-sub})\times Cpg} \quad (9)$$

At the supersonic inlet, due to the effect of ramp an oblique shock is produced and the air is decelerated to some extent. The air properties after this oblique shock are calculated using the same set of equations used in ram inlet calculations. Air then passes through a short duct between the inlet and the combustor known as isolator. The isolator is a constant area duct that maintains normal or oblique shock trains. Isolator exit Mach number is given by the relation,

$$M_{5^1}=\left[\frac{\gamma^2\times {M_{2^1}}^2\times\left(1+\frac{\gamma-1}{2}\times {M_{2^1}}^2\right)}{\left(1+\gamma {M_{2^1}}^2-\frac{P_{5^1}}{P_{2^1}}\right)^2}-\frac{\gamma-1}{2}\right]^{-0.5} \quad (10)$$

Isolator area is given by,

$$A_{5^1}=\frac{1}{\gamma {M_{7^1}}^2}\left[\frac{1+\gamma {M_{2^1}}^2}{\frac{P_{5^1}}{P_{2^1}}}-1\right] \quad (11)$$

The inputs to the scram combustor are the outlet conditions from the isolator (air flow) and the ram combustor nozzle (fuel flow).The flow properties of the fuel–air mixture in the scram combustor are calculated by an averaging process.The nozzle used in dual combustion ramjet engine is a divergent nozzle. Nozzle exit Mach is calculated by,

$$M_7=\sqrt{\left[\left[\frac{\left(1+\frac{\gamma-1}{2}{M_6}^2\right)^{\frac{\gamma}{\gamma-1}}}{\frac{P_7}{P_6}}\right]^{\frac{\gamma-1}{\gamma}}-1\right]\times\frac{2}{\gamma-1}} \quad (12)$$

The cycle performance is obtained by evaluating the thrust generated, specific impulse and the overall efficiency. The thrust force developed by the is expressed by the relation,

$$T = (m_7V_7 - m_1V_1) + (P_7 - P_1)\,A_7 \quad (13)$$

The specific impulse is defined as thrust-to-air mass flow rate,

$$I_{sp} = \frac{T}{m_f g} \quad (14)$$

The overall efficiency is given by the relation,

$$\eta_0 = \frac{V_1}{Q_{LHV}\frac{m_f}{T}} \quad (15)$$

A Matlab program based on the equations as above is written to estimate the output conditions of the engine at various input parameters. The methodology of estimation used in the Matlab coding is shown in Figure 2.

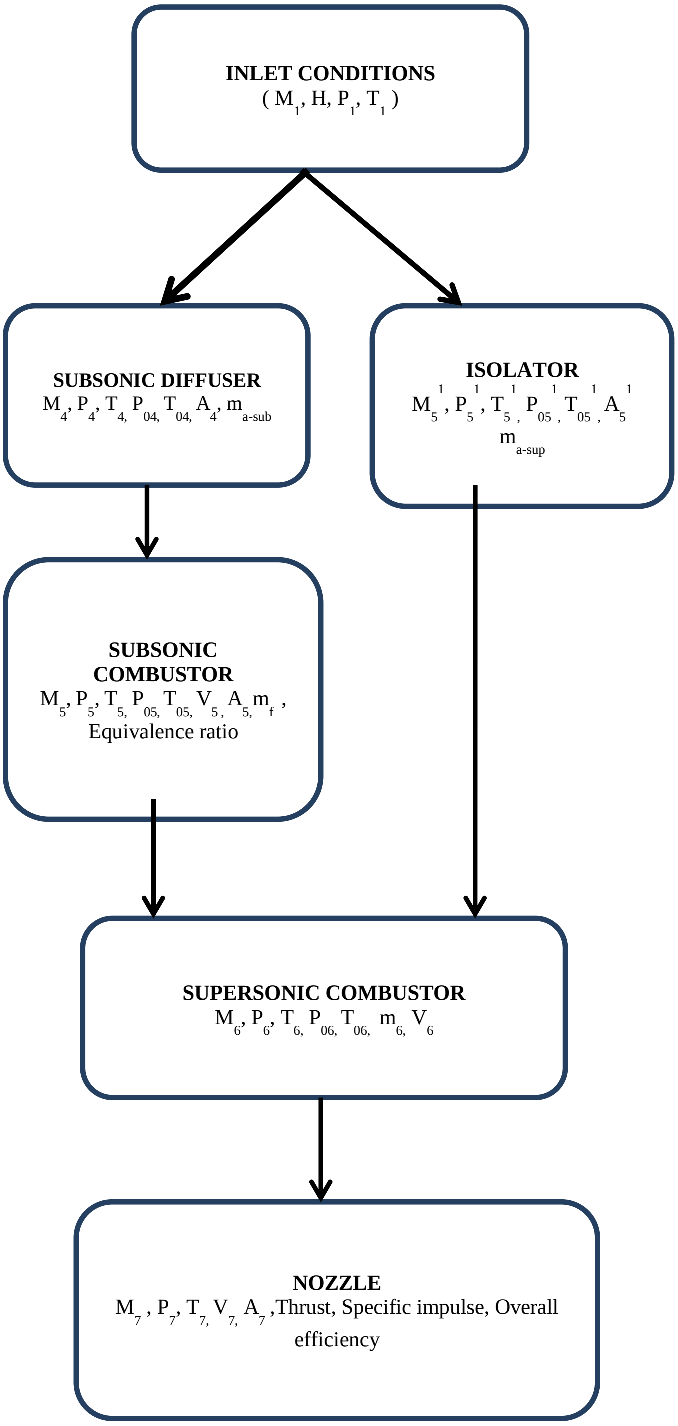

Fig. 2 Methodology of estimation used in the Matlab programming

IV. RESULTS AND DISCUSSIONS

The preliminary analysis of the dual combustion ramjet engine is performed and the results are obtained. The inlet pressure recovery of the engine at various Mach numbers is shown in Figure 3.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

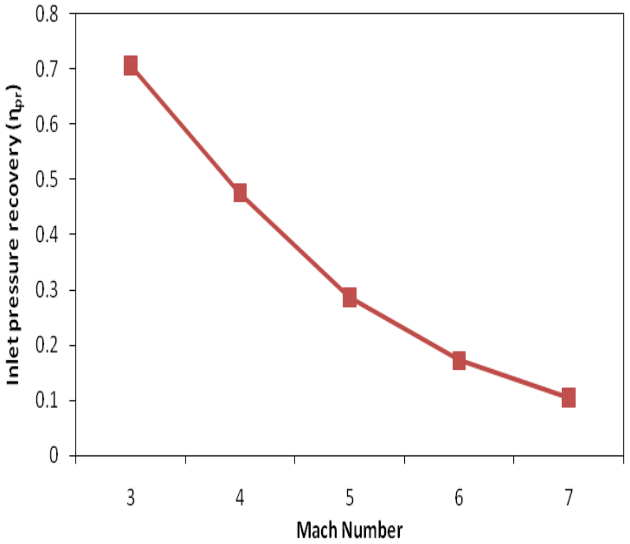

Fig. 3 Variation of inlet pressure recovery at various Mach number

It is clear from the figure that, as the Mach number increases, the inlet pressure recovery decreases and hence the maximum pressure recovery is obtained at less Mach number. The change in area ratio for different Mach numbers is shown in Figure 4. It is seen that the area ratio increases as Mach increases. Therefore it is clear that for operation at higher Mach numbers the area of scram inlet needs to be more than ram inlet.

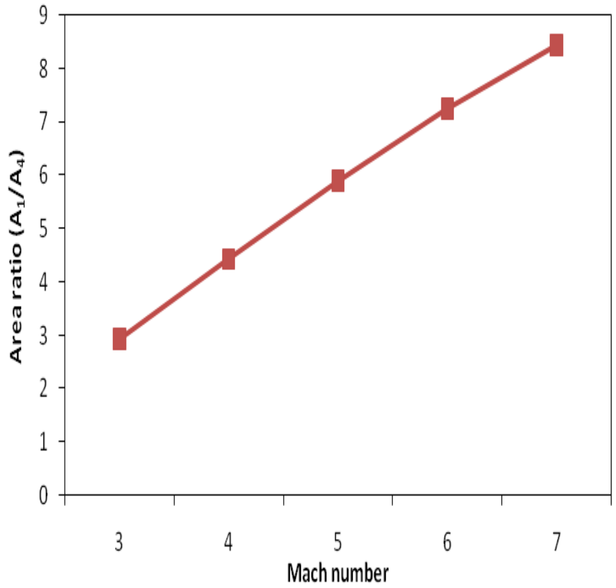

Fig. 4 Variation of Area Ratio at various Mach number

Figure 5 shows the amount of thrust generated by the engine at various Mach numbers. It is inferred that with increase in Mach number, the thrust generated also increases. For instance at constant equivalence ratio of 0.3 and altitude 6096 m (20,000 feet), the thrust produced at Mach 3 is 35.9 kN. The maximum thrust generated by the engine at Mach 7 is found to be is 54 KN.

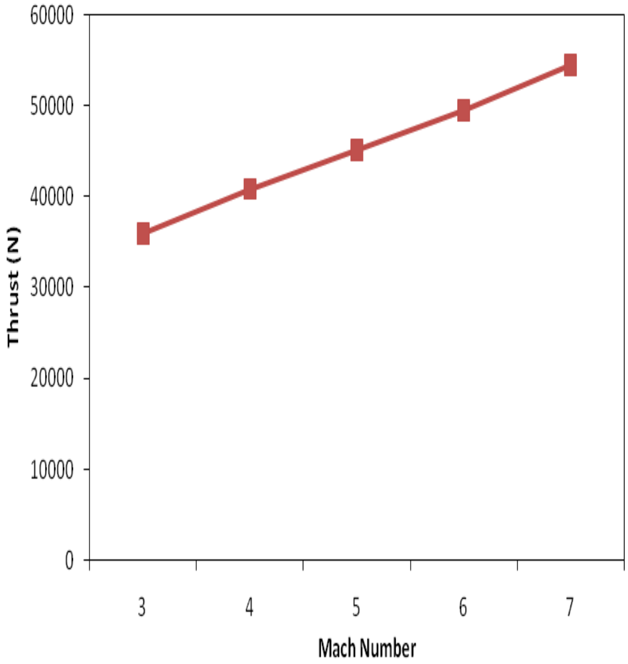

Fig. 5 Thrust produced at various Mach numbers

The change in thrust generated at different equivalence ratio is given in Figure 6. It is seen that with increase in equivalence ratio, the thrust decreases. Hence, for maximum thrust, the engine must be operated at low equivalence ratio possible. The thrust produced at an equivalence ratio of 1 and Mach 3 is found to be a minimum of9.7 kN.

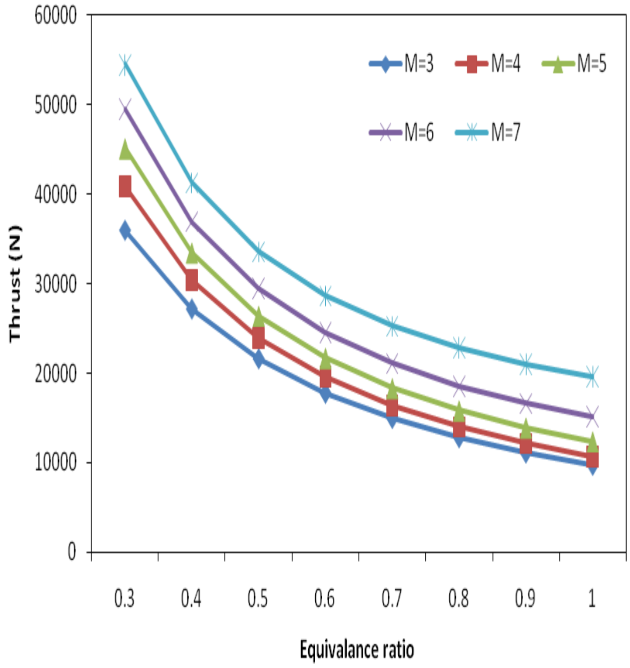

Fig. 6 Thrust produced at various Equivalence ratios

The variation of thrust generated with change in altitude is shown in Figure 7. It is observed that the thrust decreases with increase in altitude. Hence it is advisable to start the DCR engine at lower altitudes, say 6096 m (20,000 feet).

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

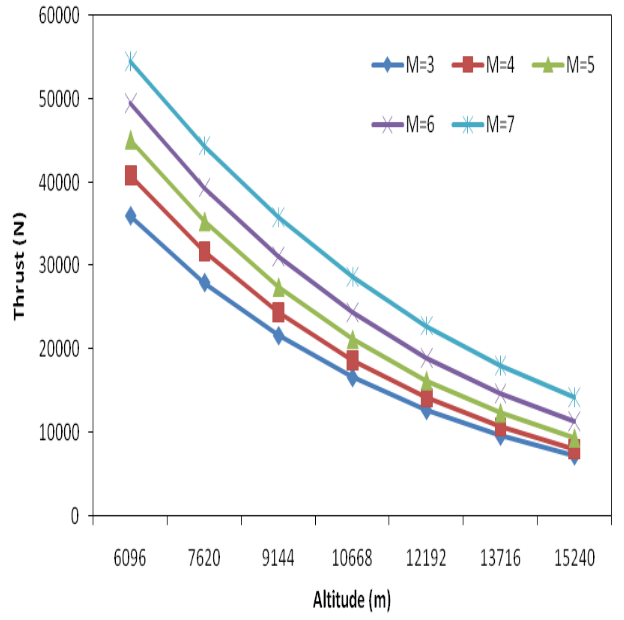

Fig. 7 Thrust produced at various altitude

Figure 8 depicts the amount of thrust generated by the engine for various scram inlet areas.

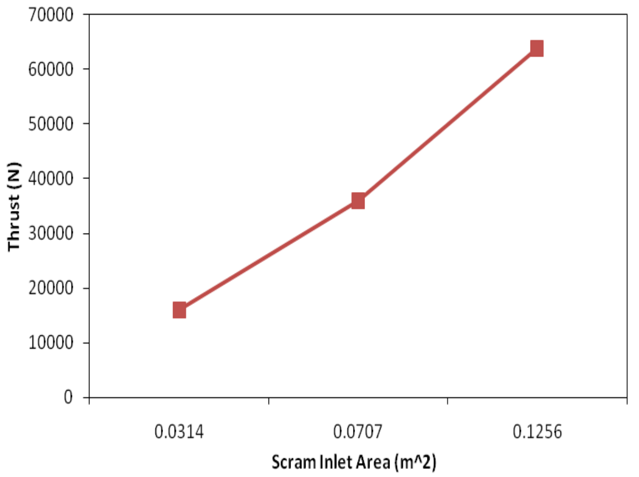

Fig. 8 Thrust generated at various scram inlet areas.

It is seen from the graph that with the increase in scram inlet area the thrust generated by the engine also decreases. The change in specific impulse with equivalence ratio is plotted in Figure 9.

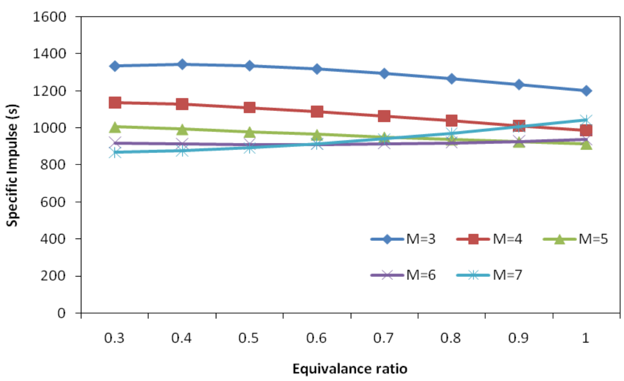

Fig. 9 Variation of specific Impulse for various Equivalence ratios

It is inferred that, when the equivalence ratio increases, the specific impulse decreases for lower Mach numbers, say Mach 3, 4 and 5, while the specific impulse increases for higher Mach numbers, above 6. Therefore it may be concluded that, for lower Mach numbers, lower equivalence ratio provides the maximum specific impulse whereas for higher Mach numbers high equivalence ratio is preferred. Mach 3 line shows highest value of specific impulse at all equivalence ratios.

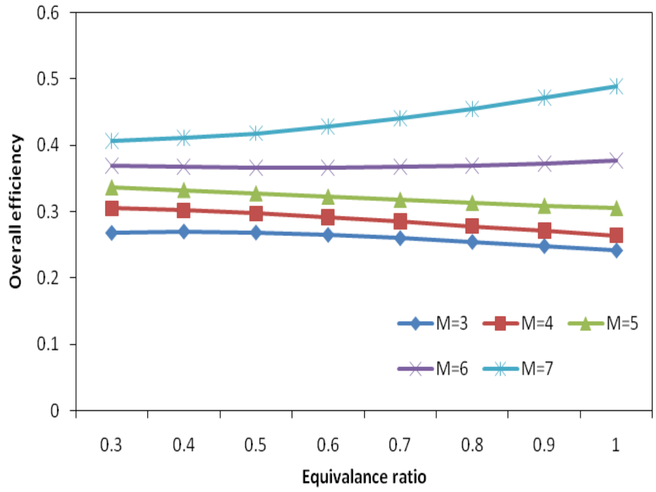

Fig. 10 Overall Efficiency of the engine at various Equivalence ratios

The overall efficiency of the engine as compared to various equivalence ratios is shown in Figure 10. It can be inferred from the figure that, at lower Mach numbers, as equivalence ratio increases, the overall efficiency decreases while, for higher Mach numbers the overall efficiency increases with increase in equivalence ratio.

V. CONCLUSIONS

The preliminary analysis of a Dual Combustion Ramjet (DCR) engine is carried out and the following conclusions have been obtained.

- The inlet pressure recovery decreases with increase in Mach number.
- The area ratio has to be increased while operating at high Mach numbers.
- The thrust generated by the engine increases with increase in Mach number at constant equivalence ratio and same altitude.
- The thrust decreases with increase in equivalence ratio for any Mach number and altitude.
- The thrust produced by the engine increases with increase in inlet area.
- The specific impulse of the engine is maximum at higher Mach numbers and higher equivalence ratios. Low Mach produces high specific values at low equivalence ratios.
- At lower Mach numbers, as equivalence ratio increases, the overall efficiency decreases while, for higher Mach numbers the overall efficiency increases with increase in equivalence ratio.

REFERENCES

1. AqheelMurtuza and G.M.Sayeed Ahmed, "Design and Analysis on Scramjet Engine Inlet", International Journal of Scientific and Research Publications, vol. 3,pp. 1-12, 2013.
2. Susmit Joshi and Gaurav Kulkarni,"Overview of Dual-mode Operation of Scramjets," International journal of Current Engineering and Technology, vol. 6, pp. 2067-2078, 2016.
3. Yu.P. Gounko and V.V. Shumsky,"Characteristics of dual-combustion ramjet,"Thermophysics and Aeromechanics, vol. 21, pp. 499-508, 1973.
4. Clinton C. Humphrey, "Design and Fabrication of a Ramjet Inlet," June 2013.
5. Jong-Ryul Byun, JoongkiAhn, Hyun-Gull Yoon, and Jin-Shik Lim, "Preliminary Performance Analysis of a Dual Combustion Ramjet Engine," Korea Promotion Engineering, vol. 5, 72-81, 2011.
6. F. S. Billig, P. J. Waltruptt and R.D. Stockbridge, "The integral-rocket dual-combustion ramjet: A new propulsion concept," Journal of Spacecraft and Rockets, vol. 17, pp. 433-444, 1980.
7. N Wadwankar, G Kandasamy, N Ananthkrishnan, VS Renganathan, Ik-Soo Park and Ki-Young Hwang, "Dual combustor ramjet engine dynamics modeling and simulation for design analysis" Journal of Aerospace Engineering, vol. 16, pp. 1-16, 2018.
8. Jong ho Choi, Iksoo Park, Hyun young Gil, and Ki young Hwang, "Analysis of Dual Combustion Ramjet Using Quasi 1D Model," Journal of the Korean Society of Propulsion Engineers, vol. 17, pp 81-88, 2013.
9. Jianguo Tan, Jiping Wu and Zhenguo Wang, "Experimental and numerical investigations on flow fields and performance of dual combustion ramjet,"Journal of Aerospace Engineering,vol. 228,pp. 920–929, 2013.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication