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Research Article

# Investigation on Scramjet Performance Parameters at Various Mach Numbers and Inlet Forebody Ramps

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## ABSTRACT

Scramjet is a hypersonic vehicle, and its performance majorly depends on upstream subcomponents and the amount of fuel consumed. The engine thrust is produced using divergent nozzle but it will have a large pressure thrust component as well. A triple ramp scramjet engine will escalate the pressure and temperature of the approaching air to a higher-level which further approach to the combustion chamber and nozzle, results in high momentum and pressure thrust. The scramjet engine performance parameters are investigated for two different triple ramps at various Mach number ranging from lower supersonic to hypersonic speeds, and also at various equivalence ratios. It also helps in understanding the start and unstarts conditions of the engine and the relative variations in the performance. Two different forebody triple ramps are studied to understand the variations in their scramjet performance. Study of hydrogen-based triple ramp scramjet at various equivalence ratios will result in understanding the significant variations in thrust generation and also the other related performance parameters. The performance parameters focused in this research work are thrust, propulsive efficiency, specific impulse, specific thrust, and specific fuel consumptions.

**Keywords:** Specific impulse; Specific thrust; Specific fuel consumption; Inlet ramp; Propulsive efficiency

## INTRODUCTION

The future air breathing engine for hypersonic flight is Scramjet. As there is no need to carry oxidizer onboard, its specific impulse is higher than any non-air breathing chemical propulsion system. Scramjet has no turbo machines and its working principle follows the thermodynamic brayton cycle. Initially it needs external assistance to start at supersonic velocity but unlike ramjet engine, the combustion takes place at supersonic speeds. The working principle of scramjet engine includes compression, combustion and expansion processes.

In the scramjet engine the compression process to achieve a considerable rise in pressure and temperature of the air it uses the weak oblique shocks generated from the forebody ramps exposed at supersonic velocities. The inlet design of scramjet decides the compression efficiency, amount of the air capturing and the combustion stability. The engine was tested at Mach 6 with inlet air mass flow rate of 0.36 kg/s, and it is observed that the temperature rise across the inlet is found to be twice of the ambient and the pressure is 100 times the ambient [1]. The number of ramps determines the flow field structure through the inlet and also affects the overall compression ratio and the efficiency of the inlet. For an inlet upstream Mach number ranging from 5 to 10, the pressure rise is 15 to 115 times the ambient condition at the inlet, which is due to the upstream Mach number and the ramp angle [2]. Based on the inlet conditions having temperature well above 1000 K and pressure typically above 50 kPa and requires around 250 mm combustor length [2].

The rise in the inlet temperature decides the combustor exit temperature for an equivalence ratio. The inlet configuration chosen for a scramjet is dominating feature for entire configuration of engine. When a scramjet is designed to propel at Mach 10 and 30 km altitude producing specific thrust of 1000 N, the corresponding fuel air ratio would be 0.039 and combustion efficiency will reach up to is 90% [3]. The specific impulse of 2662 seconds was also found with propulsive efficiency of 92.8% and overall efficiency of 64.2% for a triple ramp scramjet engine. The pressure ratio and temperature ratio have the decisive effect on the performance of a scramjet engine. With the continuous increase of the air fuel ratio, there will be increase in specific thrust as well as specific impulse, and specific fuel consumption will decrease [3].

Scramjet engine with a combustion process at constant area, constant pressure, and constant Mach number can have lower values of maximum pressure and temperature compared with constant area combustion process [4]. A Scramjet engine travelling with flight mach number 4.0 to 8.0 will have 60% thrust factor if the combustion is stoichiometric, and 70% thrust factor if two stage injections with thin strut are used in the combustor [5]. High compression may also lead to additional system constraints on

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the inlet such as the need for variable geometry or boundary layer bleed, and may lead to large losses and external drag [6]. At Mach 8, the pressure in the combustor is 350 times the ambient when analyzed for various equivalence ratios [7].

Scramjet with inlet forebody having two, three and four ramps are studied previously considering the external compression and mixed compression designs. It is found that the inlet with three ramps yield better result than other inlet designs [8]. To start a scramjet at Mach 3.5, fuel of lower calorific value and lower ignition temperature has to be used for complete combustion [9]. This also results in adopting the gaseous fuel in combustion of scramjet engine than any liquid fuel. Recent research also shown the preheated kerosene is also used to have complete combustion at higher rate [9].

## THEORY

In this research paper, a numerical approach for scramjet engine performance is carried out which quantifies the various performance parameters at different Mach numbers, combustion equivalence ratios, and forebody ramp angles. The variation in performance parameters explains the engine start and unstarts condition, and also the significant preliminary design constrains. Along the length of scramjet engine, the flow property variations are discussed as shown in Figure 1.

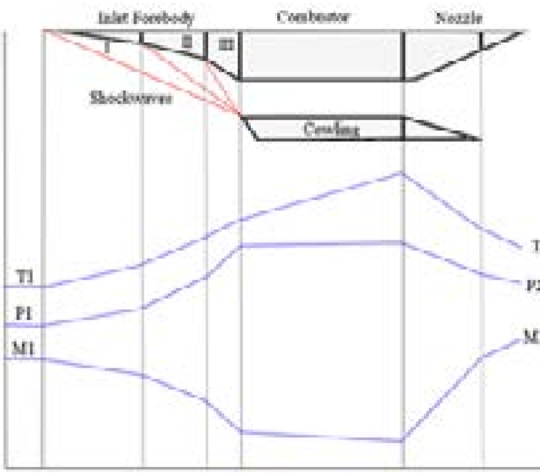


**Figure 1:** Variations in flow parameters along the scramjet engine.

The scramjet engine has four major components-inlet forebody, combustor, nozzle and cowling. The flow parameters-pressure, temperature and mach number are used together to quantify the performance parameters of the engine. The variation of these flow parameters are such that, the pressure and temperature will increase till the combustor section and further decreases in nozzle whereas, the Mach number decreases till the combustion zone and increases to hypersonic speeds in the nozzle.

The scramjet engine considered has only external compression inlet in which a forebody having three ramps will produce three weak oblique shock waves. The flow across these oblique shocks gets compressed maintaining the supersonic velocities of relatively lower magnitudes deduced using isentropic oblique shock wave relations. The combustion process is analyzed at constant pressure, without considering the acoustics interference, shock wave interactions, and reflections due to fuel injection wedge (strut) in the combustor. The high pressure and temperature air approaching combustor is mixed with hydrogen fuel at certain equivalence ratio and combusted. In this study, the fuel injection is throttled at various equivalence ratios and respective adiabatic flame temperatures are determined. The flame temperatures are deduced considering only the major species and steady state approximations. For the expansion of gases, a divergent nozzle is used to accelerate the flow at hypersonic velocities. In this type of air breathing engine, the thrust force will have large pressure thrust component as well. The impact of various inlet ramp angles and Mach numbers on the individual engine component performance and overall performance parameters of the engine are analytically studied in this research paper.

### Scramjet inlet

The inlet of scramjet is designed considering compression process is isentropic, fluid is compressible and inviscid, steady flow, interaction between shock waves and boundary layer are neglected, and no shock reflections are considered.

Two different set of inlet forebody having triple ramp are selected which creates three individual weak oblique shock waves terminating at cowling tip. The flow properties across the shock wave decides the operating condition of the supersonic inlet based on various upstream Mach numbers ranging from 1.8 to 10. It is also found that, for low supersonic speeds across the three oblique shock waves the downstream flow doesn't remain supersonic as the adverse pressure gradient across the shock waves diminishes the flow velocity which is considered to be unstart condition of the engine.

### Scramjet combustor

The hydrogen fuel undergoes rapid combustion with air compared to other hydrocarbon fuel and also hydrogen fuel has large calorific value to molecular weight ratio compared to other fuels available. The Combustion temperature and fuel mass flow rate are determined using adiabatic flame temperature relations and the steady flow energy equations for various flight Mach numbers and φ in Figure 2.

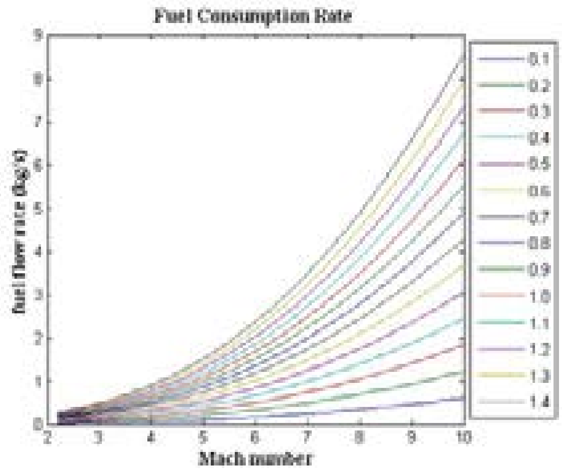


**Figure 2:** Fuel flow rate in the combustor at different equivalence ratio

The above describes the fuel flow rate in the combustor for both the types of inlet ramps. The combustion temperature is varying from 689 K to 2786 K for the equivalence ratios and Mach number considered. With increase in the equivalence ratio, the air fuel mixture becomes rich which increases the combustion temperature, but beyond equivalence ratio 1.2 the combustion temperature decreases significantly. Also the flow being supersonic, the combustion process will have incomplete combustion for higher equivalence ratio. The type-1 inlet, the amount of fuel required is comparatively more than the type-2 inlet for the complete Mach number range. It is also observed that, with increase in the inlet upstream Mach number the fuel requirement also increases exponentially. The fuel injected for the range of Mach number varies from 0.021 to 8.57 kg/s for type-1 inlet and from 0.02 to 7.47 kg/s for type-2 inlet engine.

### Scramjet nozzle

The isentropic nozzle is designed divergent to achieve hypersonic conditions at exit from the inlet supersonic conditions. As the approaching flow is already supersonic, the nozzle will accelerate the flow further to hypersonic velocities. The divergent angle is not sufficient for a given length of nozzle to expand, hence the flow will be expanding partially to the ambient conditions, hence, both pressure and momentum thrust components are determined. The area ratio between the nozzle exit areas to the inlet capture area of 2.18 is considered in the engine performance analysis. The velocity ratio (vehicle approaching velocity to the nozzle exit velocity) for the complete range of Mach number is found varying from 0.2794 to 0.7370 for type-1 inlet and 0.2772 to 0.7375 for type-2 inlet, which further used to determine the propulsive efficiency of the engine. It is observed that, for higher inlet upstream Mach numbers, the velocity ratio is small as compared to the lower inlet upstream Mach numbers. The propulsive efficiency ranging from 44.62 to 84.86 % and 43.5 to 85 % is obtained for the scramjet engine with type 1 and type 2 inlets. The propulsive efficiency is found to be more at lower vehicle Mach numbers and less at higher vehicle Mach numbers as the vehicle velocity is close enough to nozzle jet velocity.

## RESULTS

The performance characteristics considered in the research work are thrust, specific fuel consumption, specific impulse and specific thrust which are obtained using the following.

The specific fuel consumption is a very important performance parameter which quantifies the amount of fuel required onboard for the complete range of vehicle at the calculated thrust. It is found that at lower Mach number, the specific fuel consumption is more than at higher Mach number. The growth in specific fuel consumption is even more as the equivalence ratio increases in the combustion process. Among the two types of inlets, the specific fuel consumption is less for type-2 inlet than type-1 inlet as shown below. At lower flight mach number, the compression in the intake of the scramjet is determined to be small; hence the thrust production is less compared to the thrust at higher flight mach number and also the fuel consumption increases to reach maximum combustion temperature.

## DISCUSSION

Specific impulse is the ratio of amount thrust produced by consuming a unit amount of fuel. As the thrust production is more at higher flight mach number than at lower Mach number, the specific impulse is more at higher Mach number. For lower equivalence ratio the fuel consumption is less which further increases the specific impulse. It is observed that the specific impulse is high for type-2 inlet than type-1 inlet due to less fuel consumption rate and more thrust production in Figure 3.

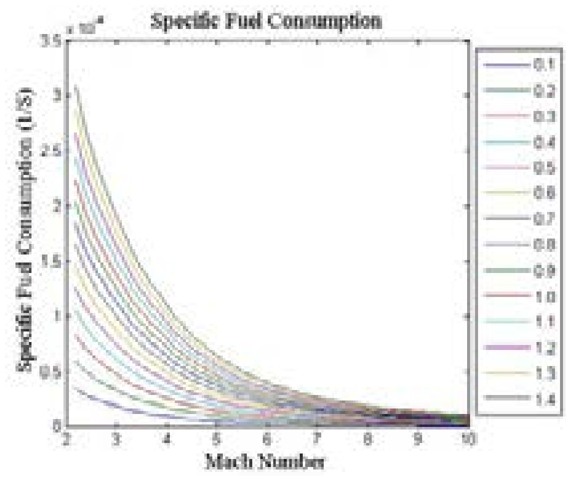


**Figure 3:** Variation of Specific Fuel consumption with Mach number.

In the analysis of scramjet engine for different forebody design, the thrust force is found to be increasing exponentially with vehicle mach number at various equivalence ratios. The specific fuel consumption is found decreasing for higher upstream mach number for the engine whereas the specific impulse and specific thrust increase exponentially with increasing flight mach number.

## CONCLUSION

In the numerical investigation of scramjet engine performance parameters, the design of a triple ramp scramjet engine considering the performance parameters at preliminary levels are focused and two types of triple ramp inlets are analyzed. Across the inlet, the flow parameters behind the three oblique shock waves are comprehended for flight mach number varying from 1.8 to 10 mach. The engine start and unstart conditions are also determined based on inlet downstream conditions. The combustion parameters are quantified considering only the major product species for different equivalence ratios (0.1 to 1.4). Across the diverging nozzle, the pressure thrust and momentum thrust components together are determined. With increase in forebody ramp the shock angle increase too, leading to adverse pressure variation across the shock and low flow velocity. This results in low specific fuel consumption and the thrust. As the forebody ramp angles are progressive, the flow relatively becomes slower.

It is found that, among the two types of triple ramp fore bodies, ramps having higher angle are recommended for having relatively better specific impulse and specific thrust than the ramps with smaller angles. The equivalence ratio of 0.5 to 0.8 gives sufficient increase in the combustor temperature for the complete Mach number range. The specified inlet ramps are no longer supersonic if the upstream Mach number is 2.1 and less.

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