Optimization of Hypersonic Scramjet Triple-Ramped Inlet Configurations: Enhancing Pressure Recovery, Shock Stability and Thermal Performance

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Abstract – This study focuses on the computational and optimization-based evaluation of hypersonic triple-ramped scramjet inlets to improve pressure recovery, shock stability and thermal performance at Mach 5 and above. Computational Fluid Dynamics (CFD) simulations combined with Finite Element Analysis (FEA) are utilized, also multi-objective Non-Dominated Sorting Algorithm is used for optimizing the inlet designs. The results from the analysis indicates that the triple-ramp configuration have superior aerodynamic and thermal efficiency as compared to dual or single ramped inlets.

Key-Words *- Scramjet inlet, hypersonic flow, shock-wave boundary layer interaction, CFD, NSGA-II, FEA, SBX.*

1. INTRODUCTION

Scramjets are critical for hypersonic propulsion in flights, the engine relies heavily on effective inlet design to achieve efficient air compression, minimize aerodynamic heating and sustain operations at Mach+5 [1]. The scramjet inlet significantly influences the engine's pressure recovery, shock management and thermal load distribution. The complex interactions of shock stability and boundary layers (SBLI) [2] in hypersonic flows which requires advanced aerodynamic optimization strategies. Triple-ramped inlets are characterized by staged compression via oblique shocks but the shock-induced flow separation, instability and severe thermal stresses are the challenges that designers face while designing these complex machines. Previous studies have showed us that there is a necessity for compressive optimization frameworks. This research presents a multi-objective optimization strategy for triple-ramped inlets, leveraging CFD , FEA and NSGA-II algorithms to simultaneously maximize the pressure recovery, enhance shock stability and minimize thermal loading.

2. METHODOLOGY

2.1 Computational Fluid Dynamics modeling

The inlet geometries are designed and sketched using Ansys and SolidWorks software. The computational mesh is prioritized for the critical flow regions, ensuring resolution that can accurately capture the oblique shocks and SBLI phenomenon. The SST k-ω turbulence model is used for accurate representation of boundary layer dynamics. Hypersonic inlet boundary conditions (Mach +5, static pressure of 101325 Pa , temperature of 300k) were applied and the density-based solver in Ansys Fluent computed the aerothermodynamic performance over the geometry. A triangular mash method with 0.5cm element size.

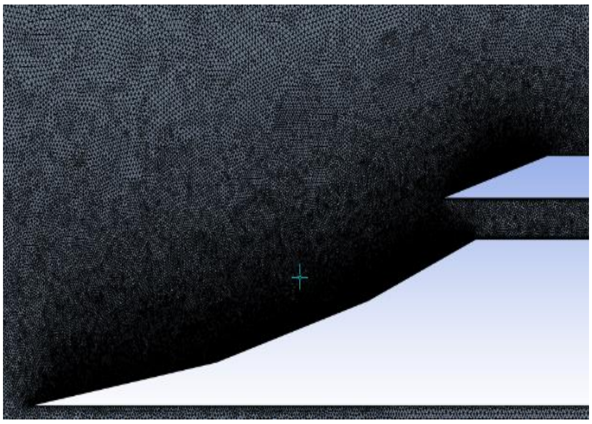

Fig-1:- Mesh topology with an inflation of 4 layers is added near the ramp and cowl tip.

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2.2 Optimization Framework

The NSGA-II algorithm optimized the triple-ramped inlet geometries based on the three objectives: maximize pressure recovery, optimal shock stability and minimal thermal loading. Objective functions considered ramp angles and lengths within specified design bounds [3]. Simulated Binary Crossover(SBX) [4] was implemented within the Distributed Evolutionary Algorithms in Python (DEAP) framework facilitated the rapid convergence to pareto-optimal solutions, highlighting the trade-offs among the objectives. The SBX is particularly suited for the real coded genetic algorithms efficiently by handling continuous design variables. The SBX methods involves selecting the pairs of solutions(parents) and then generating offsprings by simulating the effect of binary cross-over on real coded genes. This technique helps the offspring to stay in design space and maintain genetic diversity, which is crucial for complex design landscapes. The SBX operator that we used in this study has a crossover probability of 0.9 and distribution index of 20, which enabled precise control over the search intensity and convergence behaviour.

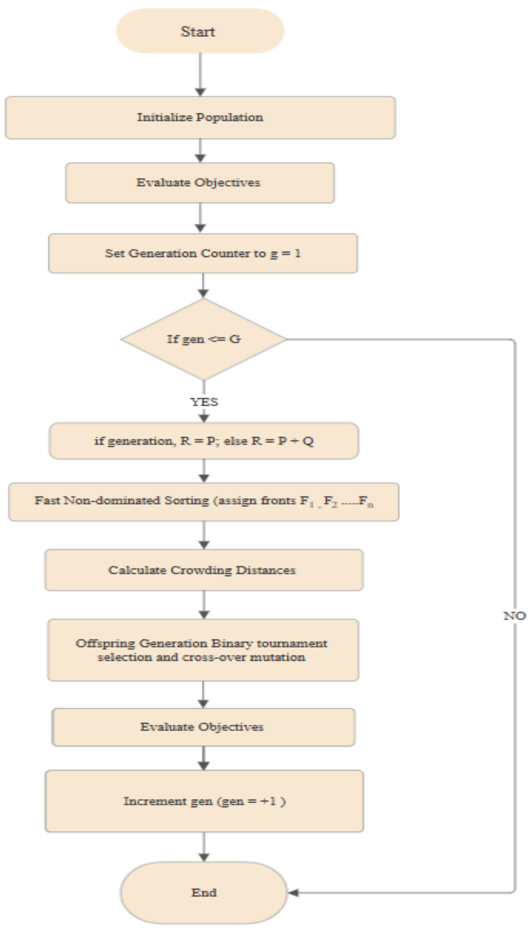
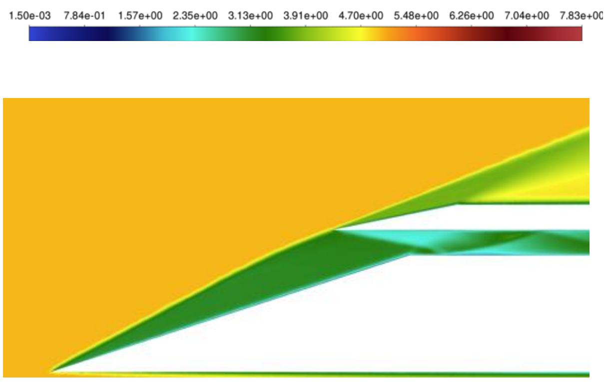


Fig-2:- Flow chart of NSGA-II algorithm

3. RESULTS AND DISCUSSIONS

The CFD simulations for single, dual and triple ramped inlet configurations revealed critical differences:

- **Mach Number and Velocity Contour:** triple-ramped inlets showed a gradual deceleration and superior shock alignment, significantly reducing total pressure loss. as compared dual or single-ramp geometries.
- **Pressure Distribute :** Triple-ramp configuration has achieved a higher and smoother pressure recovery up to (2.8MPa), whereas single and dual ramps configurations showed a sharp pressure gradient and instability.
- **Shock Stability :** Enhanced shock stability was observed in triple-ramp configurations, reducing inlet unstart and boundary-layer separation.
  Thermal analysis highlighted that there is an increase in but a manageable thermal load in triple-ramp inlets, which highlight the importance of thermal management support close to terminal inlet ramp regions and isolator.



(a)

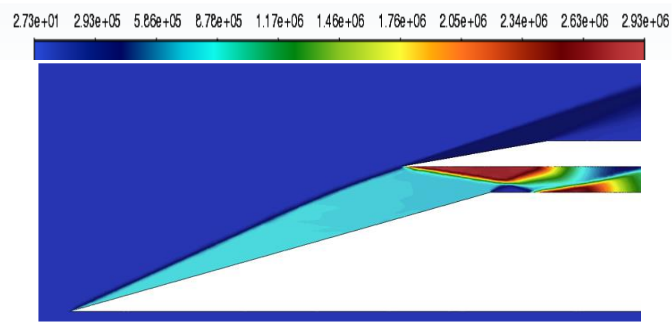
(b)

(c)

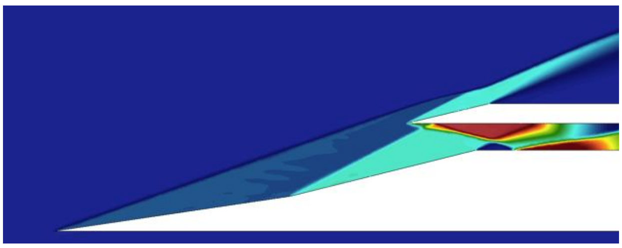
Fig-3:- Mach Number contour of (a) single, (b) dual and (c) triple-ramped inlet in Mach+5 flow regime.

3.1 Detailed comparative analysis

A comparative study between the single, dual and triple ramp inlets have revealed specific performance benefits of each configuration. Single-ramp although it is simpler, exhibited a flow separation and less effective shock management, limiting their operational range. Dual-ramp configurations have a slight improvement upon shock alignment but still faces challenges with a significant pressure gradient leading to potential instabilities. The triple-ramp inlet configuration provided a much superior results as compared to the single or dual ramp like better shock stability, smoother flow transitions and reduced thermal stress due to an even distribution of aerodynamic heating.



(a)



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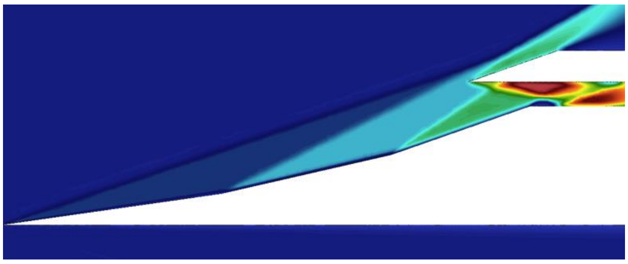

(c)

Fig-4:- Pressure contour of (a) single, (b) dual and (c) triple-ramped inlet in Mach+5 flow regime.

Inlet Configuration	P_{inlet} (Pa)	P_{exit} (Pa)	Total Pressure Recovery
Single Ramp	51,281,070	46,830,072	0.9135 (91.35%)
Dual Ramp	51,485,851	49,177,850	0.9552 (95.52%)
Triple Ramp	50,855,912	49,184,760	0.9671 (96.71%)

Table -1: Total Pressure recovery

The above table highlights the total pressure recovery values derived from single, double and triple-ramped inlet configurations by dividing the mass-weighted average total pressure at the exit of the inlet by the freestream exit total pressure. The trends shows that the total pressure recovery could be expected with the number of ramps: the single ramp achieves a recovery of 91.35% , Dual ramp increases this to 95.52% while the triple-ramp case achieves 96.75%, This progression reflects that the effectiveness of staged compression in multi ramps systems, where a sequence of weaker shocks results in a lower entropy generation and reduced stagnation pressure loss. Higher total pressure recovery translates to improved inlet efficiency and more favourable downstream conditions for combustor performance in hypersonic propulsion systems.

The pressure contour plots provided a valuable insight into the thermal performance of the hypersonic inlet configurations. High-pressure regions observed in these contours , particularly at the shock impingement points and ramp bends/ intersections experiences an increased aerothermodynamic heating [2]. By analysing the distribution and intensity of pressure along the inlet surface we identified potential thermal hotspots and extreme thermal loads. This qualitative correlation between pressure fields and heat transfer will enable designers to select proper materials that can withstand such thermal loads.

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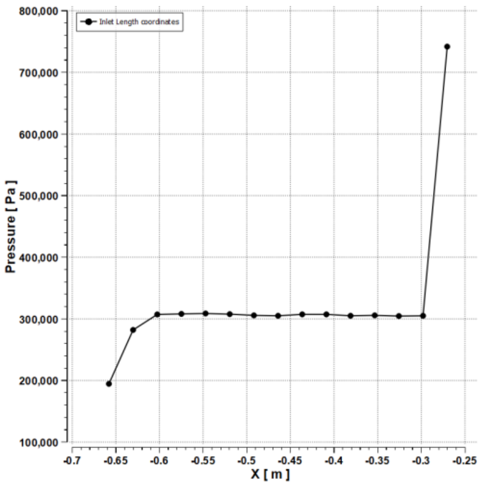
3.1.2 Pressure distribution study

The pressure distribution across the inlet length coordinate is shown above for 3 types of inlet configurations reveals that the progressive impact on the ramp staging on compression behavior [5]. The single ramp inlet shows a basic compression profile with one major rise in pressure followed by a sharp unsteady spike near the isolator entry point which indicates a weaker shock control. The dual ramp inlet exhibits a more balanced distribution of pressure in two stages enhances the pressure recovery and maintains a stable flow. The triple ramp indicates the highest-pressure recovery reaching *2.8 MPa-* through a well distributed oblique shock and pressure transitions which is smoother as compared to single and dual ramp geometries. It highlights the effectiveness of the triple-ramp system is managing the shock interaction and optimization is compression for high-speed applications. [2]

(a)



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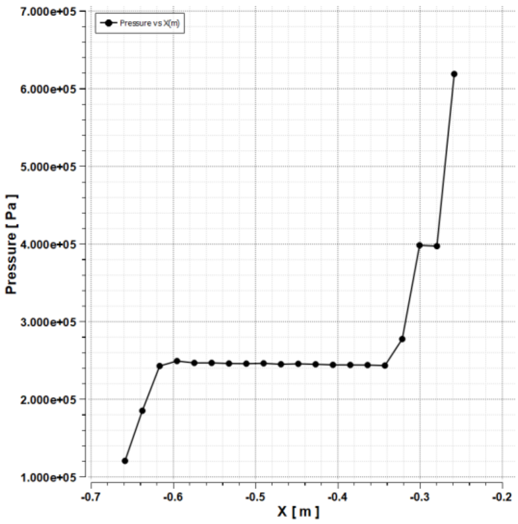

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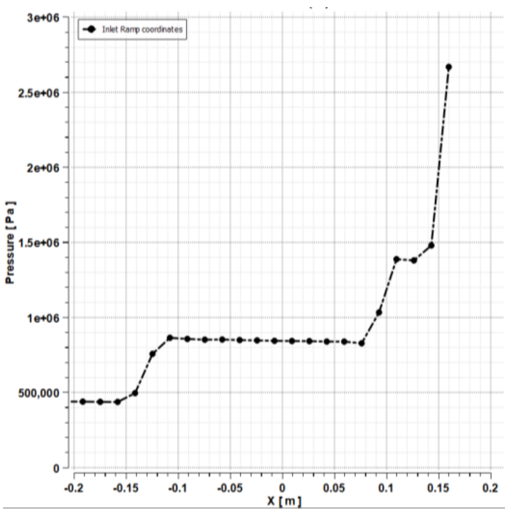

Fig-5: Pressure distribution of single-ramp (a), dual-ramp(b) and triple-ramp(c) system in a Mach >5 flow regime

Sl.no	Feature	Single Ramp	Dual Ramp	Triple Ramp
1	Initial Pressure Rise	One sharp jump	Two-stage rise	Multi-stage rise
2	Plateau Uniformity	Good	Moderate	Very smooth
3	Final Pressure Level (approx.)	~0.75 MPa	~0.62 MPa	~2.8 MPa
4	Shock-Induced Compressi on	Low	Moderate	High
5	Stability Near Exit	Spike (instability)	Controlled rise	Well-managed train

Table -2: Inlet Compression Behavior Comparison of different scramjet configurations

4.CONCLUSIONS

The integrated CFD and NSGA-II optimization framework has effectively balanced aerothermodynamic efficiency, shock -stability and thermal performance, establishing the triple-ramp inlet configuration as a promising approach for hypersonic propulsion systems. Future research could explore curvature and active flow control strategies to further optimize the performance and operational robustness.

5. FUTURE SCOPE

Future studies should explore the real -gas effects and three-dimensional flow phenomena, using higher fidelity simulations like Large Eddy Simulations (LES) to capture transitional flows Experimental validations are also recommended to complement the computational fluid dynamic simulation findings. Additionally, exploring the adaptive curvature profiles and active morphing techniques could provide significant improvements in shock-boundary layer interactions control and thermal management.

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