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OPTIMIZATION OF COWL AND RAMP ANGLES FOR SUPERSONIC INTAKE IN RAMJET ENGINE

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Abstract: Supersonic inlet diffusers are pivotal in air-breathing engine performance, particularly within ramjet engines renowned for their simplicity and high-speed capabilities, valuable in aircraft and missile propulsion. The efficiency of a ramjet engine hinges significantly on supersonic inlet diffuser performance. Tasked with slowing and compressing incoming supersonic air (Mach 3 to 5) into subsonic air (Mach 0.3 to 0.4) for combustion, the diffuser profoundly affects engine performance. Improvement in supersonic inlet diffuser performance is achievable through suitable cowl and ramp geometry design. This study focuses on determining optimal cowl and ramp angles for the supersonic inlet diffuser. Numerical analysis yields pressure recovery and outlet Mach numbers at varying cowl angles (110°, 120°, 130°, and 140°), first ramp angles (30°, 40°, and 50°), and second ramp angles (210°, 220°, and 230°).

Keywords: cowl angle, Ramjet engine, ramp angles, pressure recovery, mach number.

I. INTRODUCTION

Computational tools aided in preliminary design and analysis, generating a database of intake designs for optimization. Tailored CFD models predicted both on and off-design performance, guiding efficient design iterations. Designs were refined considering subsonic diffusers, bleeding systems, viscous effects, and variable-geometry intakes to enhance intake performance[1]. The variable geometry scheme effectively addressed performance contradictions, stabilizing inlet operation across diverse speeds[2]. In a numerical study, a RANS solver with a k-w turbulence model was employed to examine a two-dimensional mixed compression supersonic air intake. The investigation explored varying cowl deflections, both with and without back pressure. These results suggested cowl deflection as a viable alternative to bleeding, providing insights into intake design optimization and performance enhancement[3]. The intake's primary function was to deliver air to the engine with minimal pressure loss, transitioning it to subsonic speeds before reaching the compressor. Effective inlets facilitated high-angle maneuvers and high-speed slides without disrupting compressor flow. Disruptive flow was quantified using numerical indices representing density, velocity, and viscous force. Shock wave formation and step development varied with supersonic Mach numbers, analyzed using analytical software[4]. A Mach 4 axisymmetric supersonic intake SR-71 scaled model. It assessed static and total pressure measurements within the duct and employed the color schlieren technique to observe shock effects on external flow[5]. Ramjet propulsion was favored for supersonic and hypersonic vehicles due to its simple, rotating part-free design. Despite its simplicity, the flow physics within the engine duct were complex, transitioning between supersonic and subsonic regimes. Finally, the low-fidelity model's effectiveness was demonstrated across a range of ramjet flow paths tailored for high-supersonic cruise vehicles[6].

A computational study investigated flow physics within a mixed compression air intake at a design Mach number of 2.2, using RANS equations and k-ω turbulence model in ANSYS. Arrays of AJs with varying hole counts and equal spacing were tested, maintaining constant injection pressure. Results showed improved performance with proper AJ spacing, facilitating vortex mixing with freestream flow and controlling shock-induced separation[7]. CFD simulations were conducted with rhoCentralFoam of OpenFOAM, modeling 2-dimensional, steady, compressible flow across Mach numbers ranging from 5 to 6.5, at varying angles of attack and a flight altitude of 26 km. Results indicated up to a 20% improvement in compression ratio (static pressure and temperature) and a 16.7% increase in captured mass flow[8]. Sensitivity analyses determined a minimum mesh size of 300k and k-ω SST turbulence model settings for optimal accuracy and computation time[9]. Advanced inlet design methods leveraged high-fidelity computational fluid dynamics and machine learning technologies, such as deep learning, to automate feature extraction and establish fast prediction models. By combining performance intelligent prediction models with multi-objective intelligent evolution algorithms, optimal inlet designs were achieved[10].

SUPIN was a computational tool designed for crafting and evaluating external-compression supersonic inlets for aircraft cruising at speeds ranging from Mach 1.6 to 2.0. The tool assessed aerodynamic performance by examining flow rates, total pressure recovery, and drag, leveraging a combination of analytic, empirical, and numerical methods for rapid analysis[11]. Two key design modifications were introduced: a small cowl offset violating the shock-on-lip condition, and an internal wedge angle forcing a strong oblique shock. The optimization problem was formulated using axiomatic design theory with design parameters, including Oswatitsch ramp angle triplets and cowl internal wedge angle[12]. Designing and evaluating a supersonic intake system for a four-intake symmetric cross or X configuration missile. It operated within a freestream Mach number range of 1.8-2.5, an angle-of-attack range of $0° \leq AoA \leq 10°$, and a low altitude condition of 5-10 km. Internal geometric factors and upstream flow conditions were studied to enhance compression performance, with results indicating improved total pressure recovery (TPR) and mass flow ratio (MFR)[13]. The isolator design featured cowl convergence angles ranging from 0° to 16° and included a blockage adjustor at the exit. Nano-tracer Planar Laser Scattering (NPLS) technique and pressure measurement were used for flow visualization and characterization. Results revealed distinct flow structures such as supersonic boundary layer, separation flow, shock waves, Mach disk, and slip lines. Favorable contraction ratios provided moderate starting performance, while excessive or deficient contraction angles resulted in harder starting due to pressure rise and severe separation. Pressure profiles indicated optimal pressure endurance with an 8° cowl convergence angle, and flow deceleration to sonic occurred as blockage ratio approached choking the isolator[14].

A theoretical and analytical study examined a two-dimensional, external compression, supersonic intake at Mach 2.8. Two and three ramp configurations were analyzed using MATLAB for theoretical calculations and CATIA for geometry creation. ANSYS Fluent conducted analytical simulations, assessing overall performance in terms of Mach number and pressure recovery post-normal shock[15]. Two blunted cowl leading edge geometries were explored, with forward-shifted blunt edges improving mass capture and combustion stability while reducing shock wave boundary layer interaction[16]. Implementing ramjet engines could reduce missile weight by nearly 90%, but posed challenges such as mismatched air supply and demand. Unlike aircraft, adjustable intake and nozzle geometries were generally avoided in missile design for cost-efficiency. This report investigated intake design factors and proposed a design tested through computational fluid dynamics simulations in ANSYS Fluent, focusing on total pressure recovery and mass flow rate characteristics across Mach numbers, angles of attack, and sideslips[17]. CFD tools were applied for designing and analyzing high-speed air-breathing systems, solving 3D Navier-Stokes equations with an SST-k-ω turbulence model. End-to-end simulations of hypersonic vehicles provided aerodynamics and propulsion parameters, matching experimental data for intake performance and evaluating intake starting and unstarting characteristics through unsteady RANS simulations[18]. Increasing cowl angle led to higher flow distortion and reduced total pressure recovery, while decreasing incident shock strength reduced separation region size[19]. The ideal supersonic intake was designed using Theta-Beta-Mach relations and CAD software. Optimization involved varying cowl deflection angles and maximizing pressure recovery with intake bleed, guided by shock reflections; different bleed diameters were tested[20].

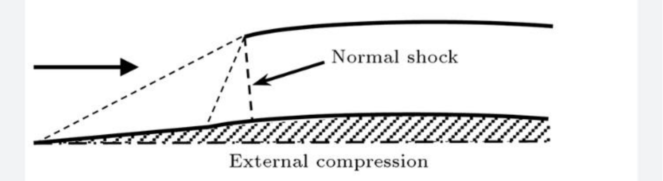


Fig.1: Internal compression of supersonic inlet

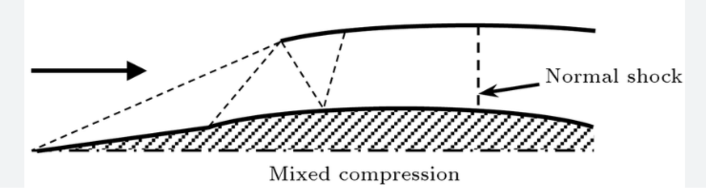


Fig.2: External compression of supersonic inlet

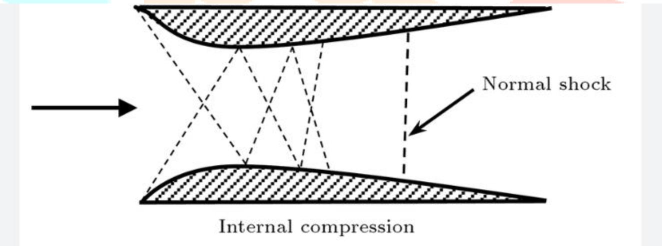


Fig.3: Mixed compression of supersonic inlet

II. METHODS

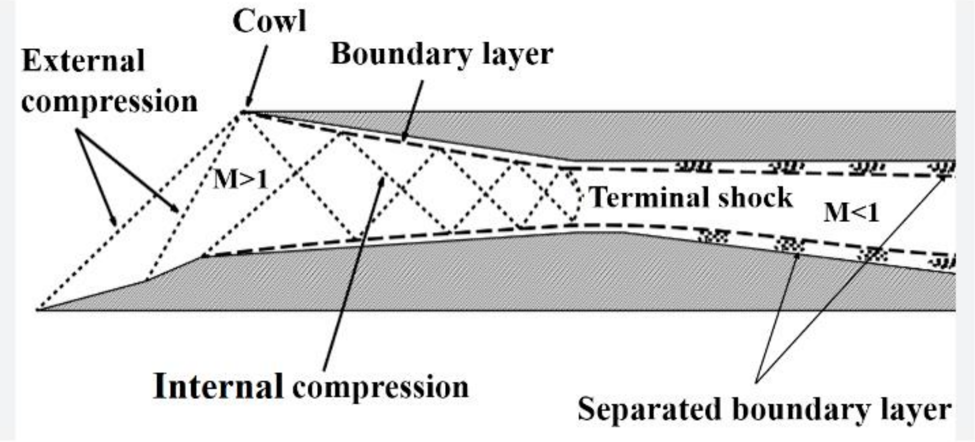
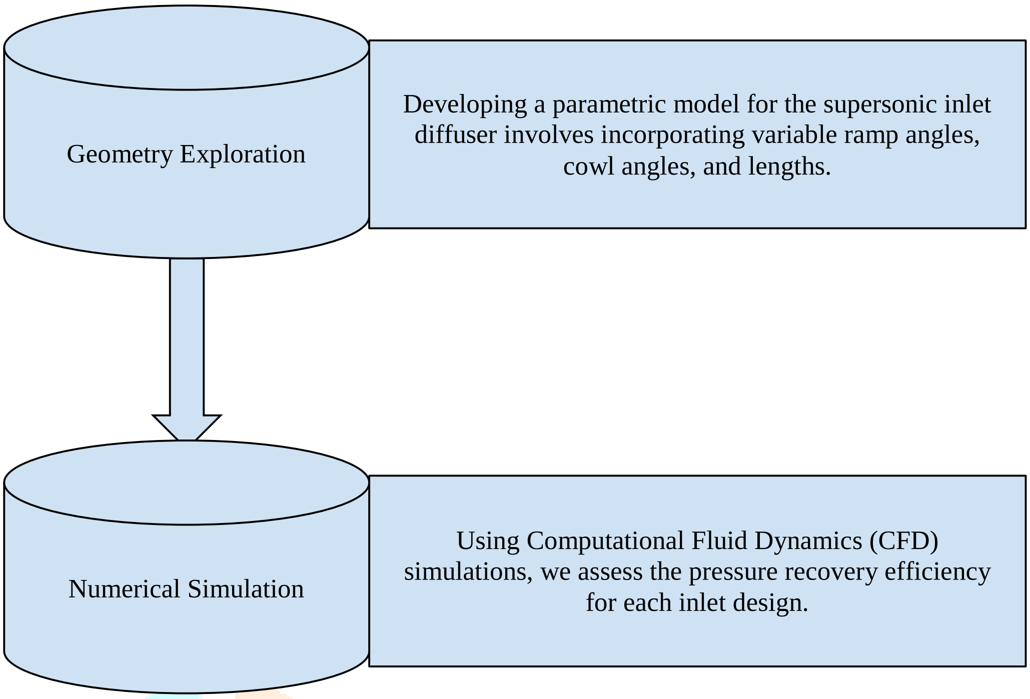


Fig.4: Mixed compression of supersonic inlet

Mixed compression supersonic inlet converts supersonic flow into subsonic flow through external and internal compressor as shown in the fig.4.



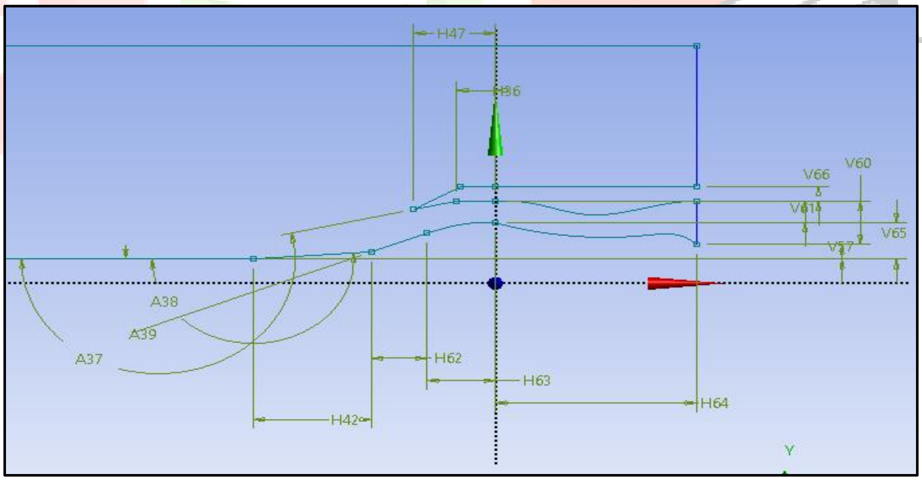
Developing a parametric model for the supersonic inlet diffuser involves incorporating variable ramp angles, cowl angles, and lengths.

Using Computational Fluid Dynamics (CFD) simulations, we assess the pressure recovery efficiency for each inlet design.

Fig.5: Graphical representation of methodology

III. Numerical Setup:

Figure 4 illustrates the supersonic inlet diffuser designed in ANSYS Fluent, comprising 96453 nodes and 95302 elements. For all eight cases, the inlet received a pressure of 8724 Pa at Mach number 4, with variations in cowl Angle (□1), first Ramp Angle (□1), and second Ramp Angle (□2) as detailed in Table 1.



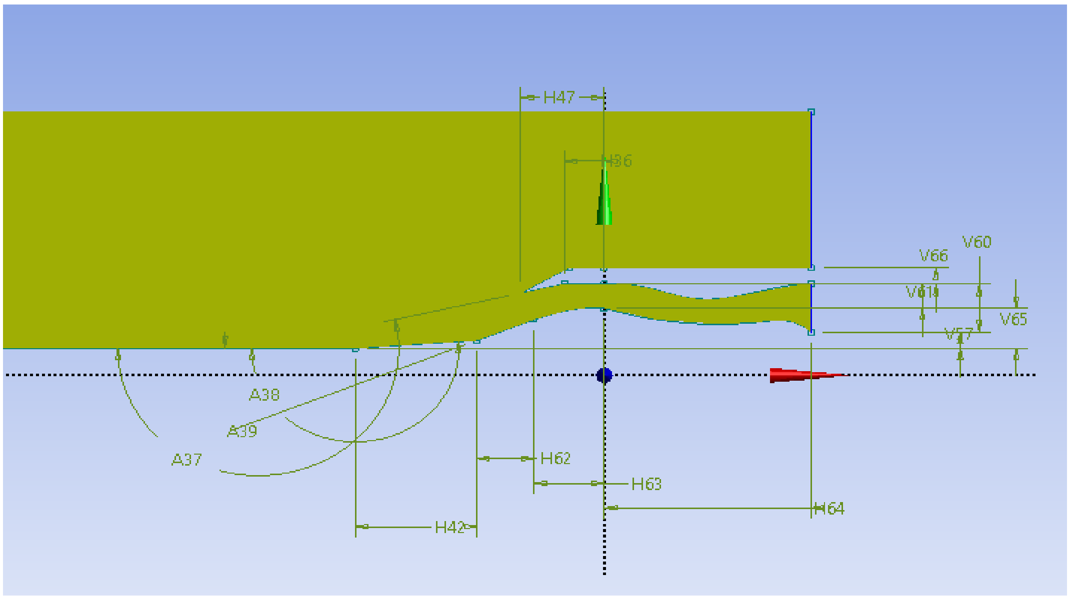


Fig.6: 2-D Sketch and geometry of Supersonic Inlet Diffuser

Table.1: Supersonic Inlet Diffuser Inlet Conditions

S.No	Inlet Static Pressure (P_1) (Pascals)	Free Stream Mach Number (M_∞)	Cowl Angle (⍰$_1$) (Degrees)	Fist Ramp Angle (⍰$_1$) (Degrees)	Second Ramp Angle (⍰$_2$) (Degrees)
1	8724	4	12	3	21
2	8724	4	13	3	21
3	8724	4	14	3	21
4	8724	4	13	4	21
5	8724	4	13	5	21
6	8724	4	13	4	22
7	8724	4	13	4	23

IV. Results:

The outlet mach number and outlet pressure distributions are obtained at constant inlet static pressure of 8724 pa and free stream mach number of 4 for different cowl angle(12^0, 13^0, and 14^0), first ramp angles(3^0,4^0, and 5^0) and second ramp angles(21^0, 22^0, and 23^0). Numerical analysis was performed for different combination of cowl and ramp angles as
shown in the table:1.

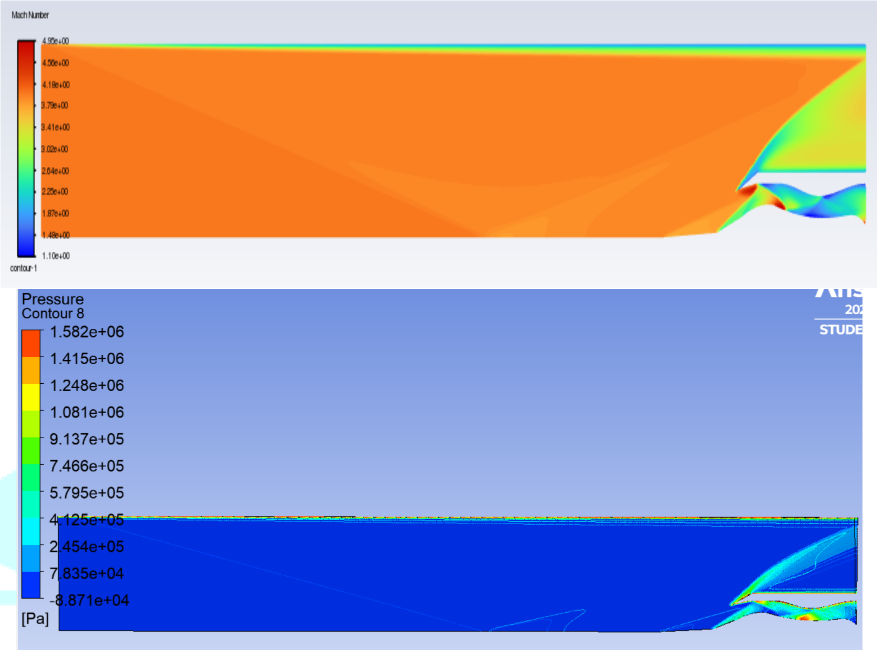


Fig.7:Mach number and pressure distribution in supersonic inlet diffuser for $\square_1=12^0$, $\square_1=3^0$,$\square_2=21^0$

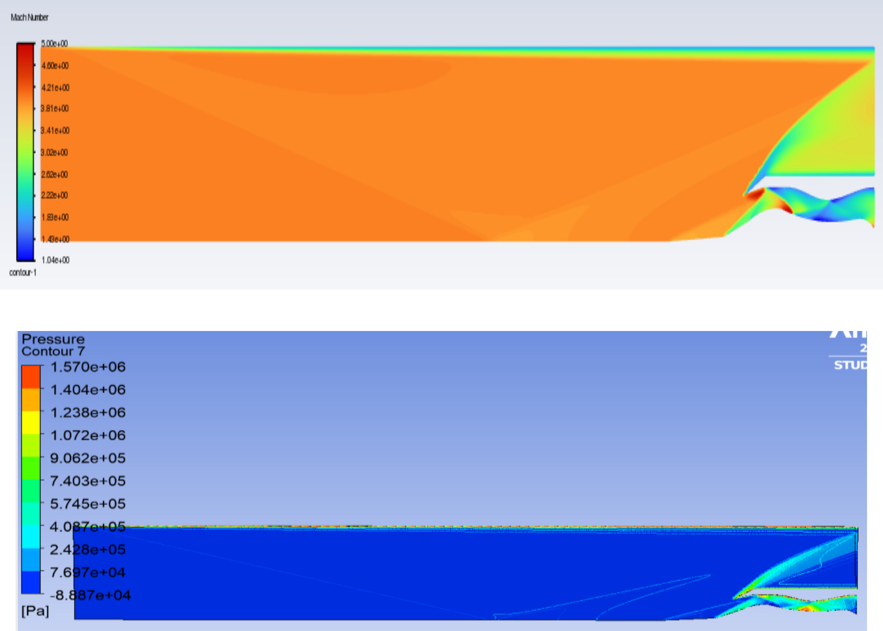


Fig.8: Mach number and pressure distribution in supersonic inlet diffuser for $\square_1=13^0$, $\square_1=3^0$,$\square_2=21^0$

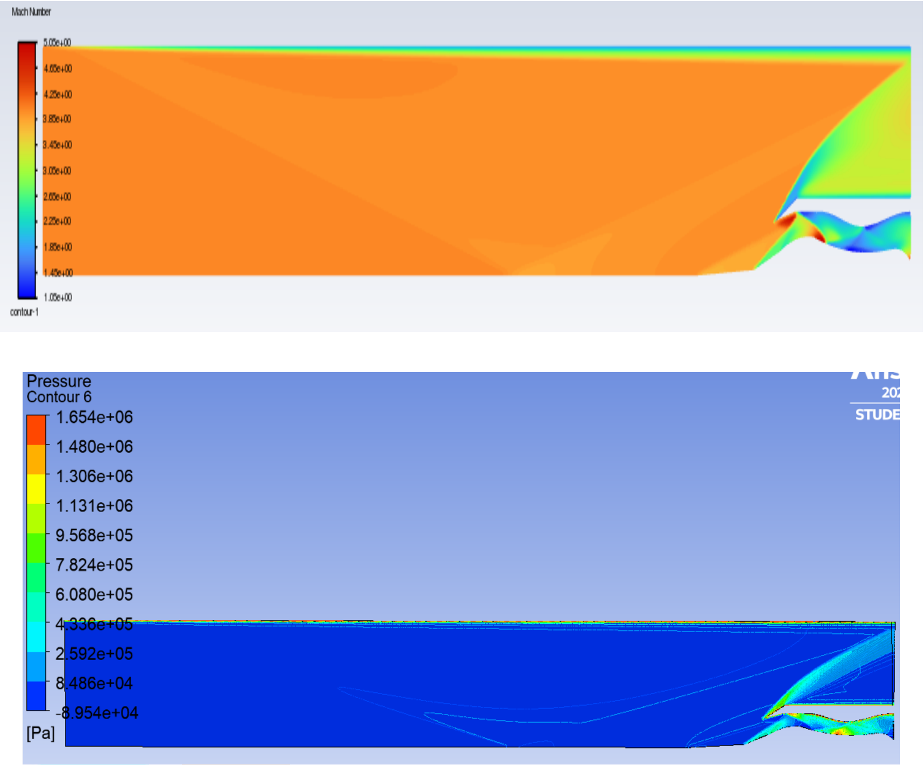
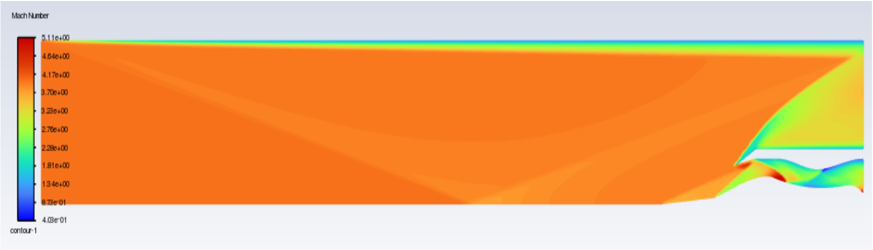


Fig.9: Mach number and pressure distribution in supersonic inlet diffuser for $\square_1=14^0$, $\square_1=3^0$,$\square_2=21^0$

Fig.10: Mach number and pressure distribution in supersonic inlet diffuser for $\square_1=13^0$, $\square_1=4^0$,$\square_2=21^0$



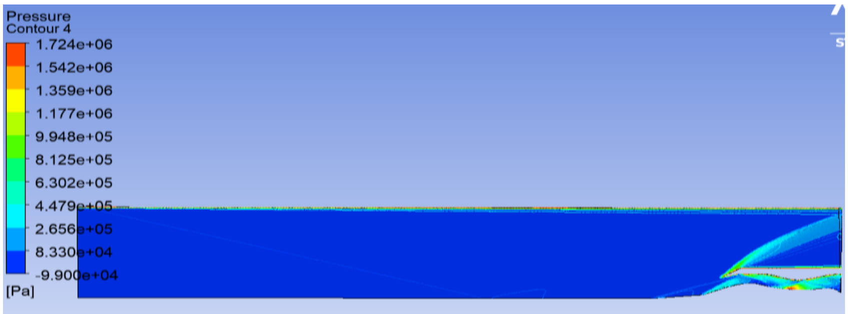


Fig.11: Mach number and pressure distribution in supersonic inlet diffuser for 1=13^0, 1=5^0 ,2=21^0

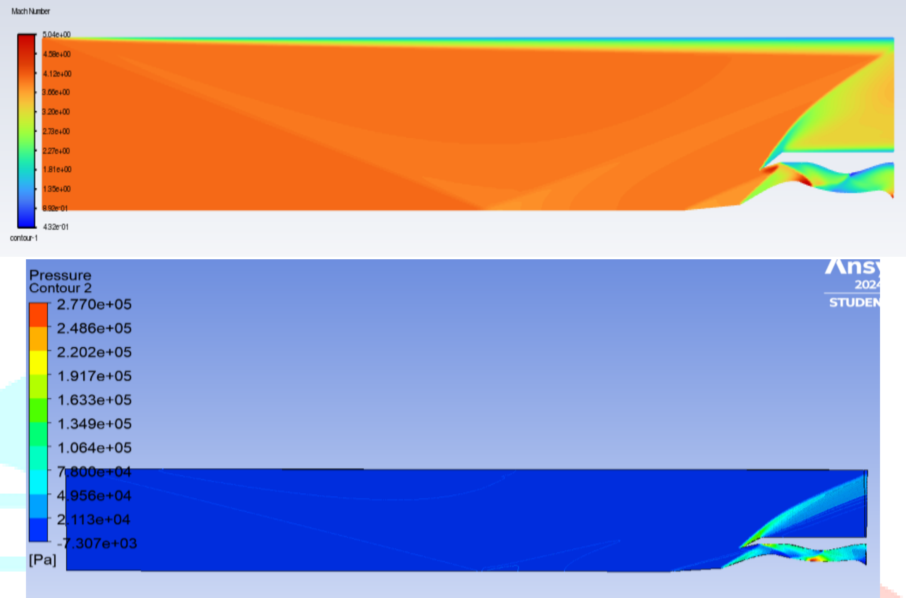


Fig.12:Mach number and pressure distribution in supersonic inlet diffuser for 1=13^0, 1=4^0 ,2=22^0

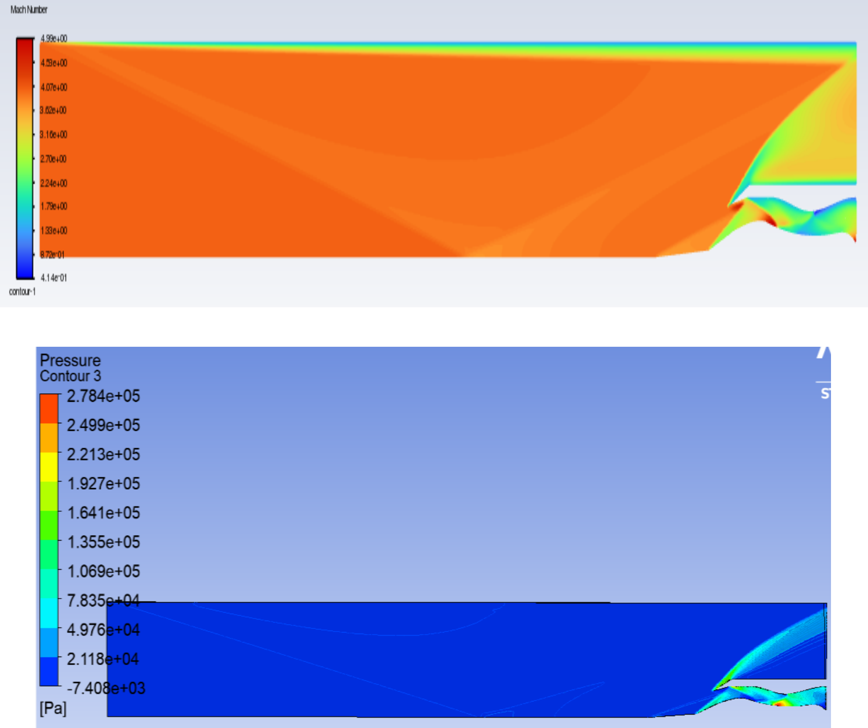


Fig.13: Mach number and pressure distribution in supersonic inlet diffuser for 1=13^0, 1=4^0 ,2=23^0

V. Discussion:

Outlet mach number, outlet stagnation pressure, were plotted against cowl angle, first and second ramp angles as shown in the figures 14, 15.

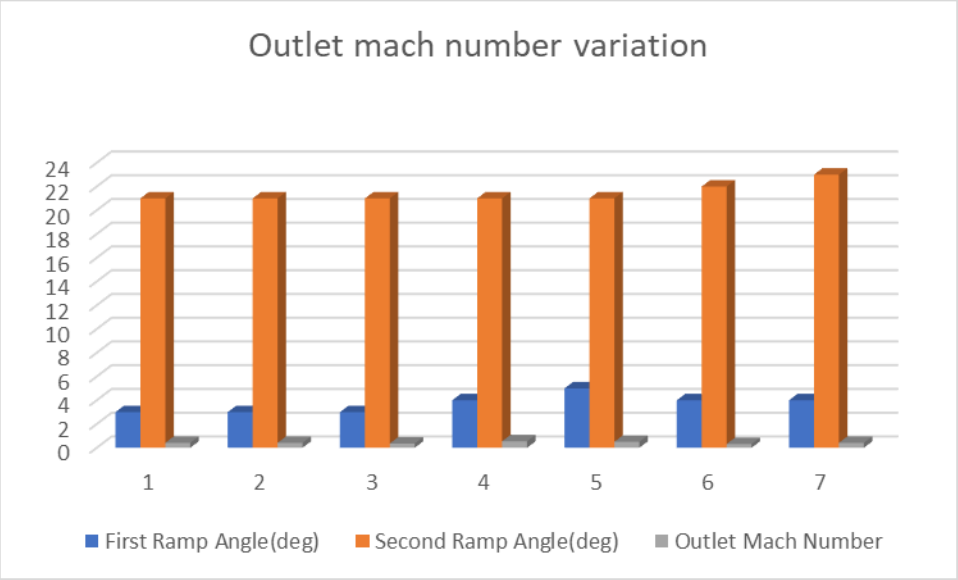


Fig.14:Outlet mach number variation at different first and second ramp angles of supersonic inlet.

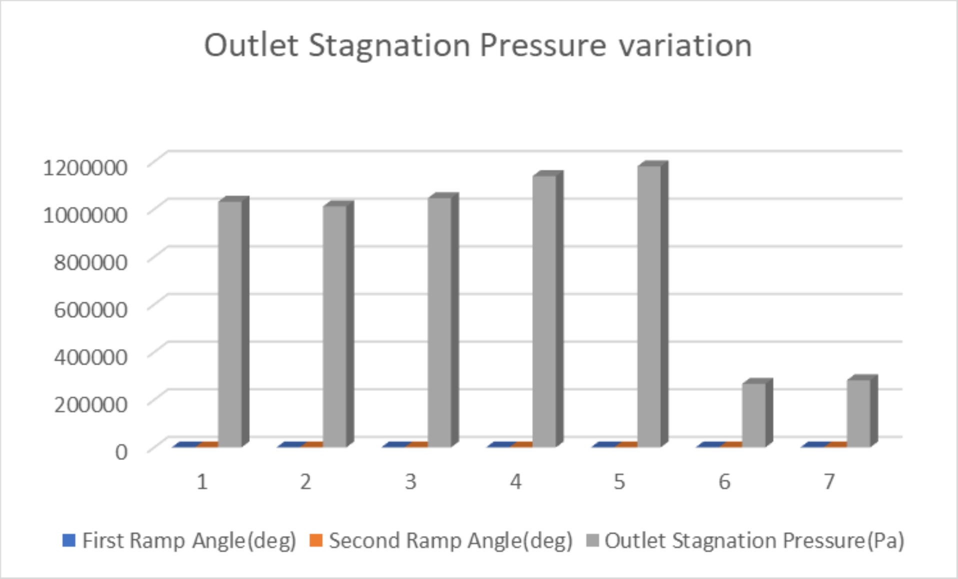


Fig.15:Outlet stagnation pressure variation at different first and second ramp angles of supersonic inlet.

VI. Conclusion:

The performance of ramjet engines is directly influenced by the effectiveness of their supersonic inlet diffusers, which, in turn, is contingent upon the geometric design of the cowl and ramp. Through numerical analysis, the supersonic inlet diffuser was examined under various conditions: cowl angles (12°, 13°, and 14°), first ramp angles (3°, 4°, and 5°), and second ramp angles (21°, 22°, and 23°), maintaining a constant inlet static pressure of 8724 Pa and a free stream Mach number of 4. Assessments of total pressure recovery, outlet Mach number, and outlet stagnation pressure were conducted across different combinations of cowl and ramp angles. Optimal results were achieved with a Mach number of 0.417 and a pressure recovery of 0.21 at a cowl angle of 13°, a first ramp angle of 4°, and a second ramp angle of 23°. These angles demonstrated superior performance, exhibiting more uniform pressure and Mach number distributions within the system.

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