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Impact of Cowl Deflections on Scramjet Intake Aerodynamics with Shock-on-Lip Condition

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ABSTRACT

The design of the Scramjet intake has a greater effect on the overall performance of the engine than any other component. By adjusting the leading edge's sharpness, length, and deflection, air compression can be maximized. To enhance overall pressure recovery, a shock-on-lip condition is frequently applied to a standard supersonic inlet. The design of a two-ramp mixed compression intake for freestream Mach numbers 5.5 to 7 is examined in this paper, taking into account the shock-on-lip condition in all analyses. Using inviscid numerical models, the effects of the various deflections of the cowl are investigated. Due to the shock-on-lip effect, the captured mass flow rate decreases linearly as the isolator area and height decrease with increasing Mach number. As the Mach number increases, stronger shocks result in higher pressure and temperature ratios. Additionally, the total pressure recovery, which decreases with increasing Mach number, is positively influenced by the angle at which the cowl is deflected. Due to the significant increase in isolator height brought on by the low Mach number shockwave crossing point, shock-on-lip was still present and the results for Mach 5.5 were less than ideal.

Keywords: Scramjet intake, aerodynamics, shock-on-lip, mixed-compression, OpenFOAM, CFD

I. INTRODUCTION

Hypersonic vehicles, capable of exceeding five times the speed of sound, are leading the way in revolutionizing space exploration, extending military capabilities, and advancing commercial flight. The pursuit of hypersonic flight in the atmosphere has driven generations of aerodynamicists, scientists, and engineers. Typically, scramjets comprise a converging inlet, an isolator, a combustion chamber, and a diverging nozzle (as shown in Figure 1). The supersonic velocity of the air produces multiple shock waves that cause a sudden increase in pressure and temperature when the air is compressed at the inlet. Fuel is then burned in the combustion chamber, generating thrust through supersonic combustion, and the exhaust exits through the diverging nozzle. Unlike a conventional jet engine, which compresses air through the compressor, a ramjet uses the forward motion of the aircraft to create air pressure for burning fuel, while the air moves at a subsonic speed. The primary purpose of a

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scramjet is to convert the high-velocity airstream into pressure energy (Urzay, 2018). Unlike conventional ramjets, which decelerate the air to subsonic speeds for combustion, a scramjet maintains a constant supersonic speed throughout the engine and combustor, resulting in greater engine performance and mass flow.

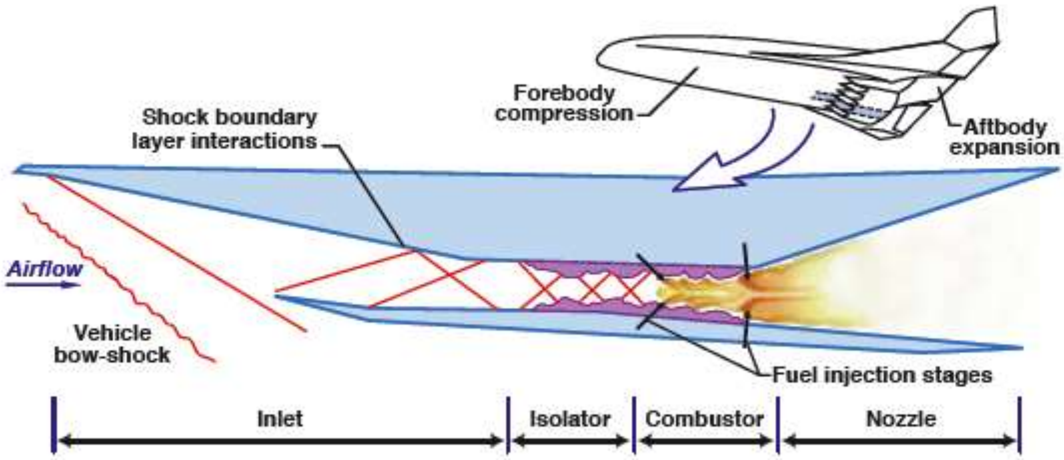


Figure 1 Scramjet Components

The objective of the Scramjet intake is to transform the kinetic energy of the air flow into a static pressure increase, causing the flow to decelerate at lower velocities. This staged compression process involves passing through a sequence of oblique shocks created by ramps at the intake. To achieve an efficient Scramjet engine, the captured air at high Mach numbers must undergo considerable compression (Bansal, 2018). The compression process is characterized by two essential features: Capability, which refers to the extent of compression achieved by the inlet, and efficiency, which is measured by the stagnation pressure ratio between the inlet and the inlet exit to the combustor. The compression ratio between the inlet and the inlet exit to the combustor determines the amount of compression achieved by the inlet. The stagnation pressure ratio between the inlet and the inlet exit to the combustor, on the other hand, measures the efficiency of the compression process.

The aim of this research is to assess the aerodynamic properties of a scramjet intake that has double ramps in order to determine the optimal cowl geometry that can achieve the highest overall mass flow rate, pressure recovery, and ideal temperature and static pressure ratios at a designated design Mach number. The focus of this study is on modeling the 2D aerodynamics of a scramjet intake while also taking into account cowl deflections that adhere to the shock-on-lip condition for different Mach numbers.

Zhang et al. (2018) stated that the shock-on-lip (SOL) condition is typically used to maximize the total pressure recovery of a typical supersonic intake during the cruise stage. This approach allows for maximum mass flow to enter the intake, but its effectiveness is dependent on the upstream Mach number for the shock angle and is not optimal in non-optimized environments. On the other hand, Khan et al. (2019) noted that mixed compression inlets are preferred due to their benefits, such as reduced entropy increase, ease of production, simplicity, and absence of complex flows, making them the leading candidate for 2-D planar inlets. Fry (2004) reported that scramjets operate in the Mach 4 to Mach 15 range. Chandran et al. (2017) used computational fluid dynamics (CFD) models to study the impact of cowl angle on shock wave-boundary layer interactions in scramjet intakes. Their study revealed that increasing the cowl's angle of attack can reduce boundary layer separation, preventing pressure loss and intake instability.

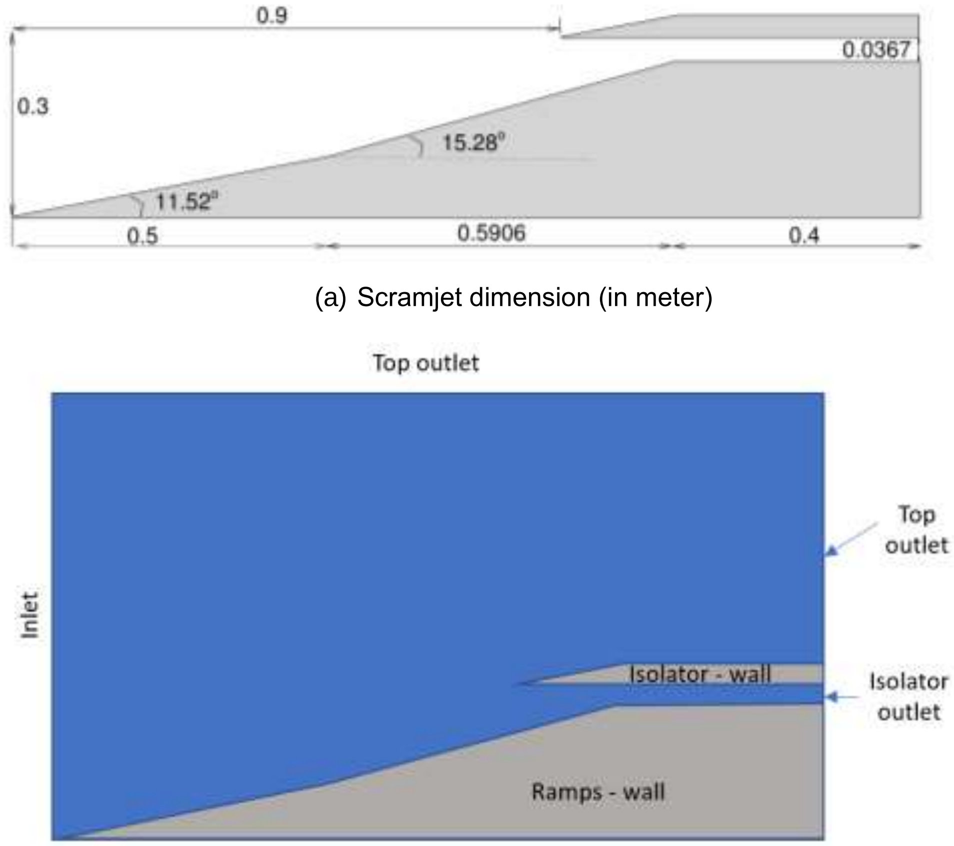
Smart (1999, 2012) found that compression ratios between 50 and 100 were most efficient for various Mach numbers. Das et al. (2016) showed that an increase in cowl deflection angle improved the flow field in the internal duct near the throat and a slight displacement of the cowl tip to the right could reduce the intensity and location of the reflected shock on the ramp, improving downstream flow and performance. They observed the surface flow pattern using oil flow visualization and found that increasing the cowl angle reduced the separation zone, improving flow behavior and performance compared to ideal flow behavior. Even with a cowl angle of 0 degrees, significant size separation bubbles were observed on the side wall.

Kubota et al. (2006) discovered that even a slight bending of the cowl can have a positive impact on the initial performance of a ramp-compression intake operating at Mach 4. To enhance performance, a two-ramp design can be used to achieve mixed compression, which is preferable over a single ramp at the temperature ratio of the bow shock under design conditions, despite the similar intensities of the bow and external shocks. When the cowl deflection angle is increased, the capture area decreases, leading to a reduction in mass flow rate. The compression ratios increase in proportion to the Mach number for a given cowl deflection angle due to the increased strength of the shock wave. The compression ratios are directly proportional to the level of shock resistance.

The optimal use of kinetic energy occurs at intermediate Mach levels, close to the design point, as noted by Babu et al. (2016). However, the natural deflection of the cowl can have a detrimental effect on performance. Babu et al. (2016) also found that increasing the cowl angle at Mach values below the design point can enhance kinetic energy efficiency. In the simulation of scramjet intakes, Siqueira et al. (2020, 2022) discovered that the use of an isolator with a 20 mm height produced fewer shock waves compared to using one with a 15 mm height. Increasing the isolator height led to a reduction in static pressure along the isolator. In a recent numerical investigation, Yao et al. (2021) studied a full-scale scramjet at altitudes of 28 to 40 km and Mach numbers of 7 to 10, demonstrating that the increase in dynamic pressure results in a nearly linear increase in viscous drag.

II. METHODOLOGY

The current investigation utilized the dimensions and parameters established in Babu et al.'s (2016) work as a basis for designing the Scramjet Intake. To ensure the maximum capture area and the shortest possible intake length, the shock-on-lip condition was chosen as the design criterion. The Scramjet model consists of two ramps or two exterior shocks and one cowl shock or one interior shock, with the first ramp having a length of 0.5 m and an angle of 11.52° and the second ramp having a length of 0.5906 m and an angle of 15.28°. These ramp angles were determined geometrically and using gas dynamic relations to fulfill the shock-on-lip and cowl shock cancellation conditions.



(a) Scramjet dimension (in meter)

(b) CFD boundary conditions

Figure 2 Scramjet Geometry and CFD boundary conditions

The isolator, which is the horizontal area between the cowl and the inner body following the expansion area, is intended to be 0.4 m long. The intake's geometric parameters and shape are illustrated in Figure 2. A two-dimensional, compressible flow computational fluid dynamic analysis was performed on the scramjet intake for this study.

To construct the mesh for the computational fluid dynamics (CFD) analysis, the hexahedral dominant cell was utilized with the cfMesh mesh generator. As shown in Figure 3, the mesh consisted of approximately 2,800,000 cell elements for the 2D simulation. To accurately capture the shocks, a high-resolution mesh was created near the wall boundaries of the ramp, isolator, and cowl. The RANS CFD analyses were performed using OpenFOAM, based on the rhocentraFOAM compressible flow solver in steady state. The boundary conditions are presented in Figure 2 and summarized in Table 1.

The compression capacity of the inlet is defined by the ratios of static temperature and pressure in the inlet. The degree of entropy produced by the inlet is evaluated by examining the total pressure recovery. This metric is the ratio of the total pressure at the isolator exit to the total pressure in the free stream, indicating how much greater the free stream pressure is than the isolator exit pressure. A higher-pressure recovery factor results in a higher exit Mach number, even without a change in the compression ratio, making it a useful predictor of the amount of drag that will be generated.

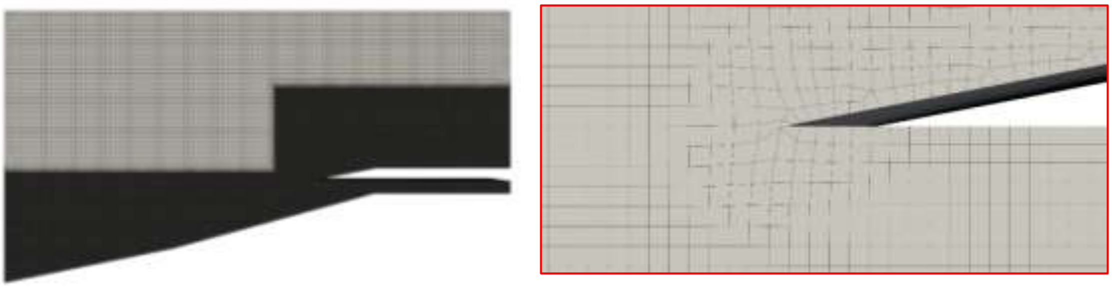


Figure 3 Mesh topology

Table 1 Boundary conditions

Location	Boundary Type	Boundary Details			Value
		Pressure	Velocity	Temperature	
Inlet	Patch	Fixed Value	Fixed Value	Fixed Value	p=2188 Pa U=1834.2 m/s T=219.3 K
Isolator Outlet	Patch	Wave Transmissive	Zero Gradient	Zero Gradient	
Top	Patch	Zero Gradient	Supersonic Freestream	Inlet Outlet	
Cowl	Wall	Zero Gradient	Slip	Zero Gradient	
Ramps	Wall	Zero Gradient	Slip	Zero Gradient	

III. RESULTS AND DISCUSSIONS

This research examines various cases, involving multiple cowl deflections (θ_c = 0°,3°,6°) and Mach numbers (M = 5.5, 6.0, 6.5, 7.0), while utilizing ramps that were designed by Babu et al. (2016). The angles of the first and second ramps were designed to ensure that the shocks formed at the compression corners strike the cowl tip precisely. As the shock angle changes with the upstream Mach number, it is essential to determine the intersection point between the shockwave and each Mach number to determine the location of the scramjet cowl and whether the shock-on-lip condition is satisfied. Figure 3 illustrates the geometry of the cowl that meets the shock on lip condition. A higher Mach number will place the cowl closer to the ramp, resulting in a decrease in the isolator height. Maintaining the shock on lip condition while increasing the degree of cowl deflection will result in an increase in isolator heights.

This study explores multiple scenarios, including varying cowl deflections, using the ramps from Babu et al.'s (2016) work. Specifically, θ_c = 0°, 3°, and 6°, and Mach flight numbers of M = 5.5, 6.0, 6.5, and 7.0 were evaluated. The first and second ramps were designed in Babu et al.'s work to optimize the shock waves generated at the compression corners, ensuring they hit the cowl tip precisely. The shock angle is known to shift in response to upstream Mach numbers, and off-design Mach numbers will not satisfy the shock on lip condition, leading to performance penalties. Therefore, it is essential to identify the intersection between the shockwave and each Mach number to determine the location of the scramjet cowl and if it satisfies the shock-on-lip condition. Figure 3 illustrates the cowl geometry that meets this condition, and a higher Mach number moves the cowl closer to the ramp, decreasing the isolator height. The isolator height increases in proportion to the degree of cowl deflection while maintaining the shock on lip condition.

Figure 4 depicts the impact of cowl deflection on the performance of the scramjet inlet at various Mach numbers, assuming a constant angle of attack and shock on lip condition. As the cowl deflection angle increases, the isolator height and capture area also increase, resulting in a rise in the mass flow rate, while a decrease in Mach number demonstrates a linear decrease in mass flow rate. In a particular cowl deflection angle, an increase in Mach number leads to an increase in static pressure ratio due to a stronger shock, whereas a wider isolator and higher isolator height, caused by increased cowl deflection, weaken the isolator shocks, resulting in a decrease in static pressure ratio.

When the cowl deflects, two internal compression shocks are generated by the cowl leading edge and point of cowl deflection, which interact with the expansion fan before reaching the isolator wall. At higher Mach numbers, the stagnation pressure ratio and total pressure recovery decrease, whereas increasing the cowl deflection angle causes these values to increase. At Mach 5.5, the mass flow rate is lower than at Mach 6.0, indicating a linear decline in the Mach number increment. However, increasing cowl deflection at any Mach number leads to a decrease in mass flow rate, as demonstrated by the graph. The ratio of static pressure and temperature to Mach number is directly proportional, resulting in an increase in static pressure as Mach number increases. However, increasing cowl deflection at Mach 5.5 leads to an increase in both static pressure and static temperature. The stagnation pressure ratio behaves similarly to the mass flow rate and shows the lowest value at Mach 5.5 compared to other cases.

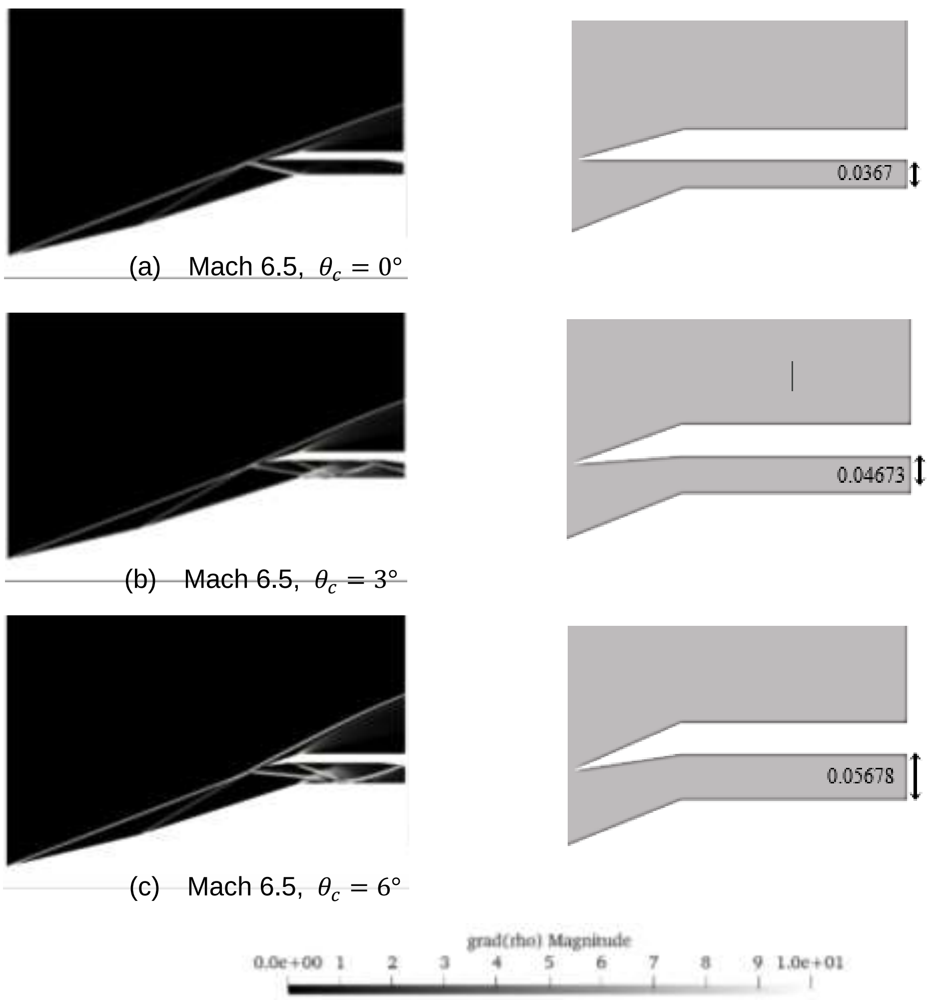
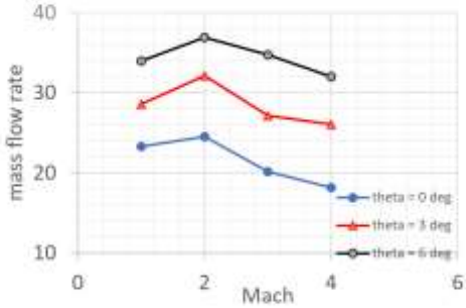
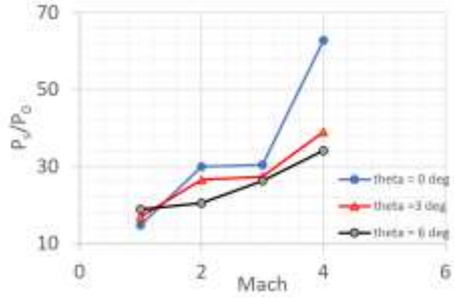


Figure 4 (Left) Visualization of shock waves (colored by the gradient of density) for the scramjet intake at Mach 6.0 and (Right) isolator heights.

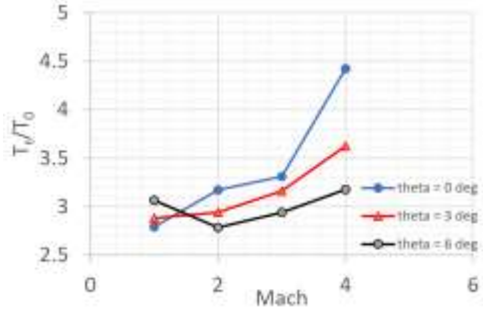
In Figure 5, the impact of cowl deflection angle and Mach number on the static pressure distribution along a line that intersects the scramjet intake from inlet to isolator exit is shown. At Mach 6.5 and 0 cowl deflection angle, the pressure remains stable due to the shock cancellation mechanism proposed by Babu et al. (2016) for their on-design scramjet intake. However, in other cases, the pressure oscillates as a result of shockwaves within the isolator. Observations of pressure gradients along the length of the scramjet intake have been made, and simulation results show a clear correlation between cowl deflection angle and pressure. Pressure values increase wherever the shock wave travels through, especially when external shocks contact the cowl lip, and the cowl shock hits the isolator wall. The pressure distribution graph reveals that pressure increases as Mach number increases but decreases as cowl deflection angle increases.



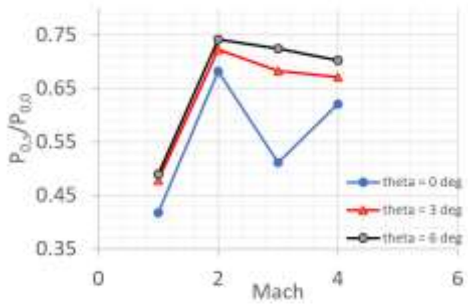
(a) Mass flow rate



(b) Static Pressure



(c) Temperature



(d) Stagnation Pressure ratio

Figure 5 Effect of cowl deflection for varying Mach number

(a) Mach 6.5, $\theta_c = 0°$

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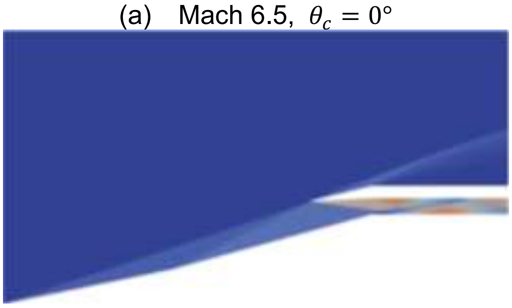
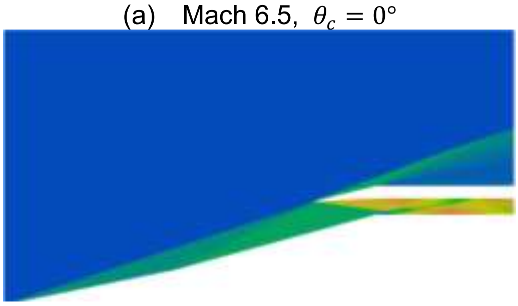
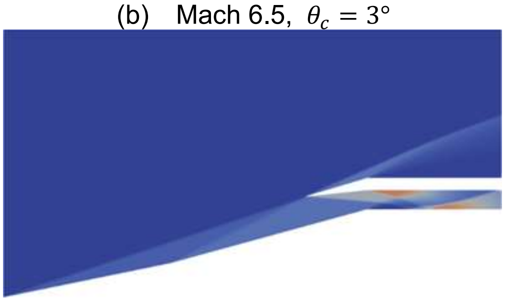


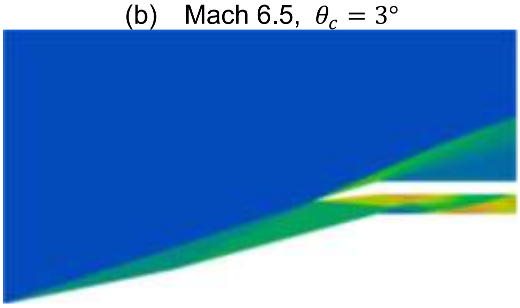
(b) Mach 6.5, $\theta_c = 3°$



(b) Mach 6.5, $\theta_c = 3°$

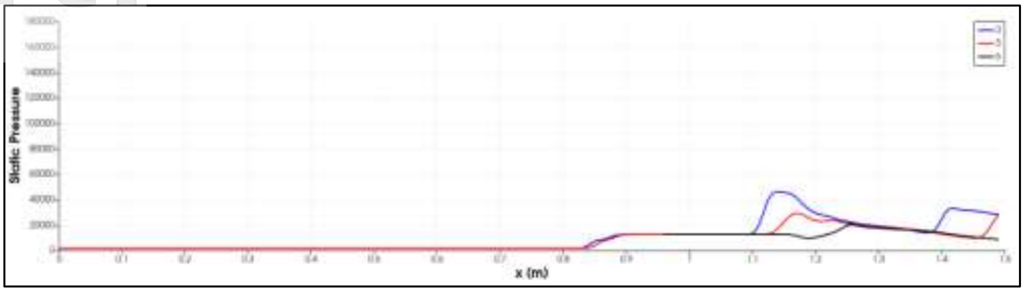


(c) Mach 6.5, $\theta_c = 6°$

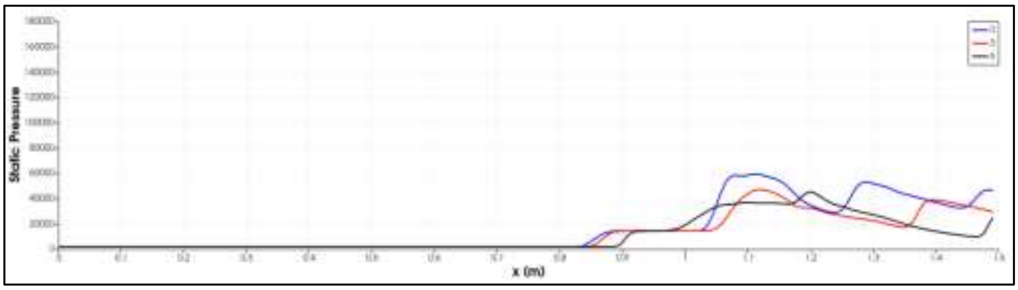


(c) Mach 6.5, $\theta_c = 6°$

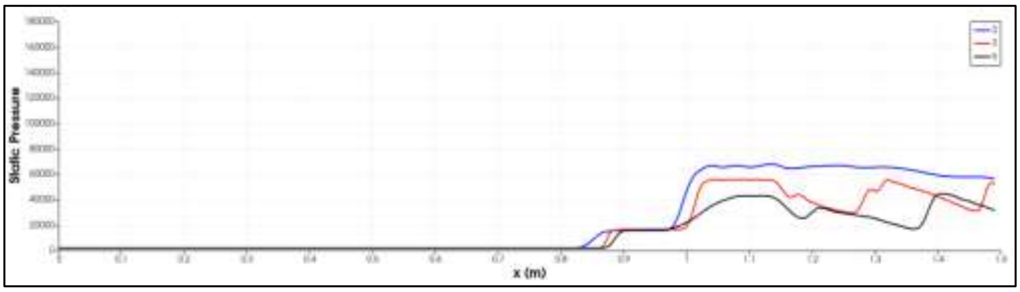
Figure 6 Pressure and Temperature



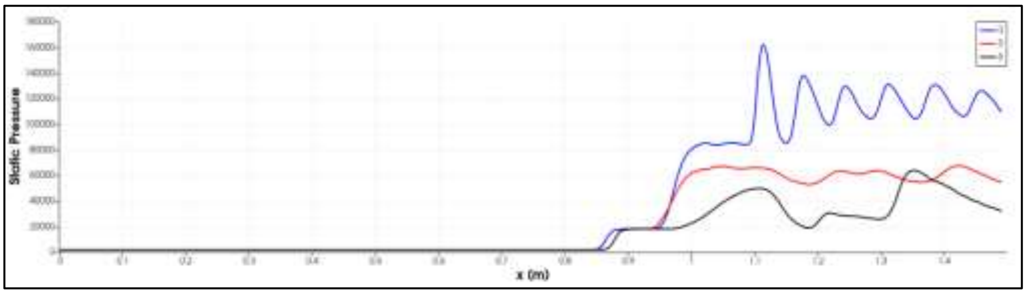
(a) Mach 5.5



(b) Mach 6.0



(c) Mach 6.5



(d) Mach 7.0

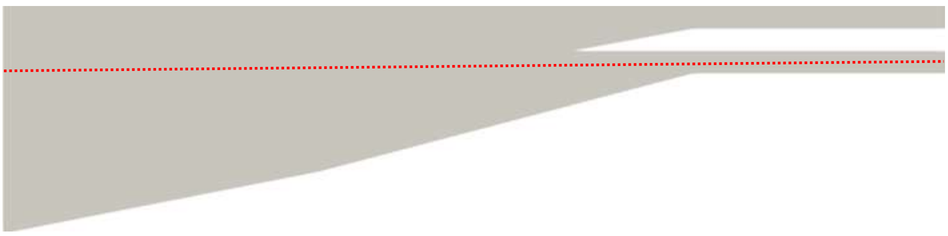


Figure 7 Pressure Distribution along scramjet intake (pressure extracted along the dotted line)

The static pressure and temperature behaviors can be observed in Figure 6, with the temperature rising on average after the throat due to the cowl reflecting some of the shockwave. Evidence suggests that a higher Mach number or shorter isolator height leads to a higher shock train frequency within the isolator. Increasing the cowl deflection angle led to a drop in both temperature and pressure, while an increase in Mach number resulted in a rise in both. The increase in temperature caused an intensification of the flow, leading to a rise in static pressure within the isolator. This effect is more pronounced with higher Mach numbers or shorter isolator heights. Increasing the height of the isolator significantly reduces the static pressure along the isolator, as shown in

Figure 7. The initial shockwave impact generates a peak in high pressure at the start of the isolator, which then drops downstream. Lowering the height of the isolator results in a higher frequency shockwave train generated within the isolator, as well as additional zones with high static pressure and temperature.

IV. CONCLUSIONS

To evaluate the performance of a mixed-compression scramjet intake at an altitude of 26 kilometers above sea level, simulations using inviscid numerical solutions were conducted. The study examined various Mach numbers and cowl deflections, with the cowl positioning being optimized for each scenario to determine the impact of shock on the lip's condition. The validity of the study was established by comparing the results with those of previous research using OpenFOAM and the rhoCentralFoam solver. The findings revealed that the results of earlier studies were accurately reproduced, with differences amounting to less than 3%. The research indicated that a Mach number of 6.0 is required to achieve the highest possible pressure recovery and capture mass flow rate. Both aspects improve with an increase in cowl deflection. The static pressure ratio and temperature ratio reach their maximum values as the Mach number increases. This is because decreasing the isolator height increases the frequency of shock trains. However, excessive isolator height resulting from cowl deflection angles negatively impacts Mach 5.5 due to poor characteristics. The large isolator affects static temperature and pressure and results in a lower frequency of shock trains within the isolator.

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