Effects of secondary injection on the performance of over-expanded single expansion ramp nozzle

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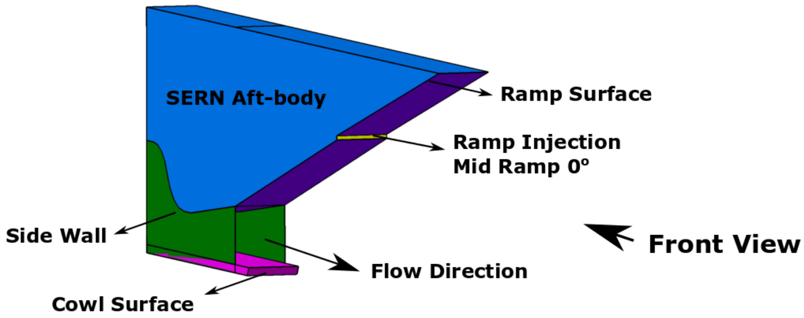
Abstract. Scramjets with Single expansion ramp nozzle (SERN) is one of the most promising candidates for an airframe integrated hypersonic vehicle propulsion system. So, studying the performance of the SERN at various flight conditions is very important to improve the overall performance of the propulsion system. The main problem with a SERN is, it tends to exhibit poor performance characteristics at the over-expanded or off-design operating conditions. So, to improve the performance of the SERN at off-design conditions, the present numerical study focuses on using various secondary injection techniques on the cowl and ramp surfaces. The freestream Mach number considered for the current study is 3, and the corresponding nozzle pressure ratio (NPR) for the SERN is 20. The effects of injection pressure, location, and angle on the axial thrust force and normal force are parametrically studied. It is found that the introduction of secondary injection significantly affects the pressure distribution over the cowl and ramp surface. This change in pressure distribution directly reflects on the magnitude of the normal force and axial thrust force generated by the SERN. The secondary injection also influences the shock pattern of the main nozzle flow.

1. Introduction

In recent years, a lot of private companies involved in the development of rocket launching systems. In order to keep the launching costs at bay, these private companies are investing in research and development of the systems like a single stage to orbit or 100% reusable multi-staging launching system. This renewed interest in developing highly efficient airframe integrated, compact, and reliable propulsion systems. The exhaust nozzle design is the most critical parameter that has to be considered for designing such a system. The SERN (Single Expansion Ramp Nozzle) is one such system that can be easily integrated into the airframe of the launch vehicle easily [1]. SERNs are designed to give optimum performance in only one design Mach number [4] but, the general mission requirements expect the SERN to operate at various operating conditions. In a typical hypersonic vehicle flight profile, the nozzle pressure ratio varies somewhere between 2 bar and 600 bar [2]. It is not possible to extract optimum performances in all those pressure ranges unless otherwise, SERN has a variable geometry throat or some active or passive controls [5,6]. Primarily if a SERN is operated at well below its design optimum pressure ratio, it generates high nose-up pitching moment due to the overexpanded flow at the SERN ramp surface [7,8]. For eliminating this, various techniques such as external burning [9,3] variable exit geometry [10,11] and secondary injection [12, 13] are tried. In this study, the secondary injection is used either at the cowl or ramp surface to improve the SERN performance operating at off-design operating conditions. The free-stream Mach number considered for the current study is three, and the optimum design Mach number of the SERN is 4.4.

2. Numerical model

The base SERN model for this study is a slightly modified version of the model used by carboni and slyne [1]. The three-dimensional view of this model is shown in figure 1a. The schematic view of the model with detailed dimensions and injection positions are shown in figure 1b. In the schematic diagram, H_t represents the height of the throat, X_{ramp} is the position of ramp injection calculated from the starting point of the ramp (where $X_{ramp} = 0$). CD dotted line represents the exit plane of the SERN.



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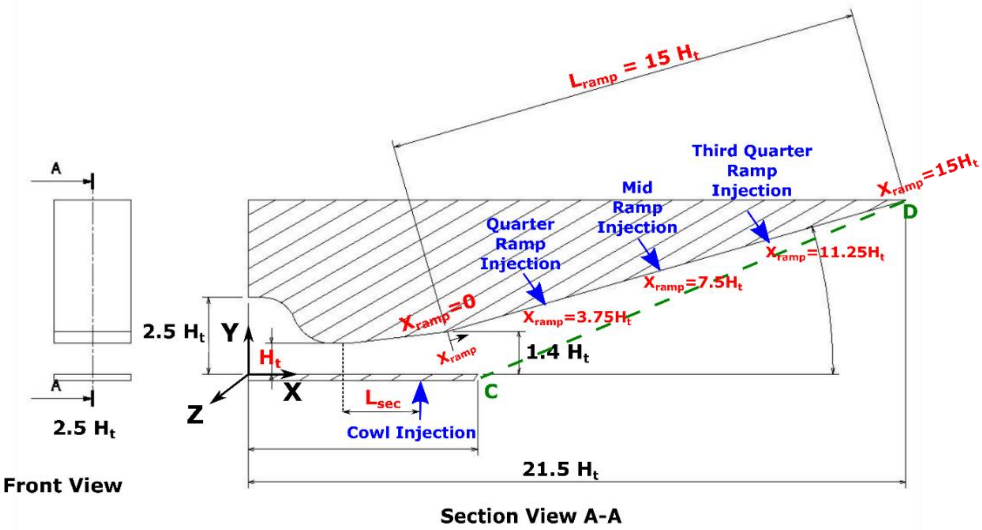


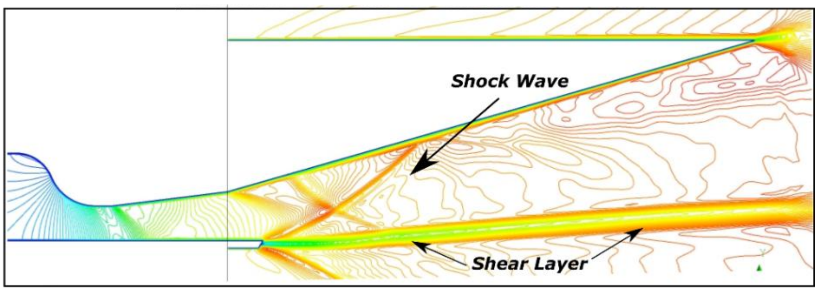
b)

Figure 1. SERN configuration with injection location a) photographic view of the SERN b) schematic diagram with injection location.

L_{sec} indicates the location of the cowl injection from the throat ($L_{sec} = 0$). The SERN flow flows in the positive X direction. The width of the SERN in the Z direction is constant throughout the length of the SERN. A 3D domain model is constructed using ANSYS design modeler, and an unstructured mesh is generated using ANSYS meshing tool. ANSYS CFX solver is used to perform the computations. The inlet boundary is specified with total pressure; the opening boundary is specified with static pressure. To reduce the computation time and cost XY plane is considered as symmetry boundary. The walls of SERN is specified as no-slip adiabatic walls. As specified in the study of Lva and Xua [13] RNG k-ε turbulence model is used. The reference pressure temperature is considered as 1 atm and 288 K, respectively. The residual target achieved in all the simulations is 10-6.

3. Results and discussion

Before studying the effects of secondary injection on the main SERN flow, understanding the flow-physics is extremely important. So the flow physics of the SERN with cowl and Ramp injection is discussed in the first part of this section, and the second part discusses the effects of secondary injection on the performance of the SERN.



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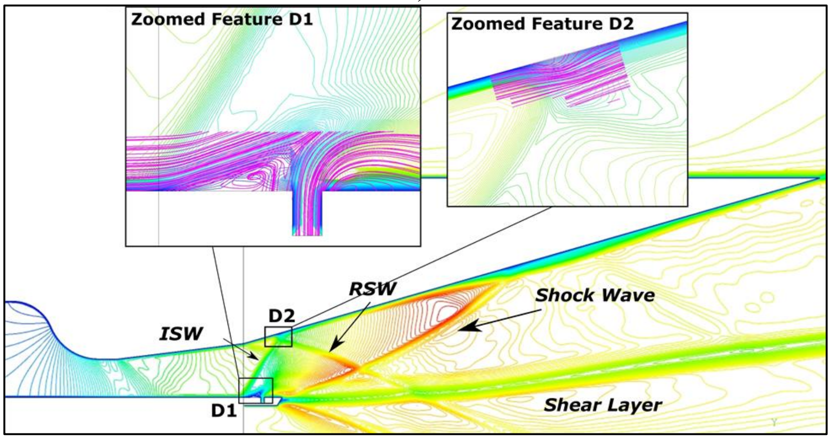

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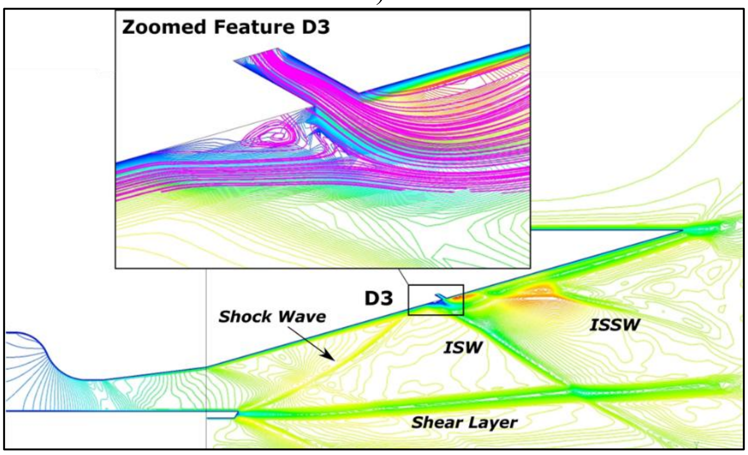


c)

Figure 2. Flow features of the SERN a) no injection b) cowl injection c) ramp injection.

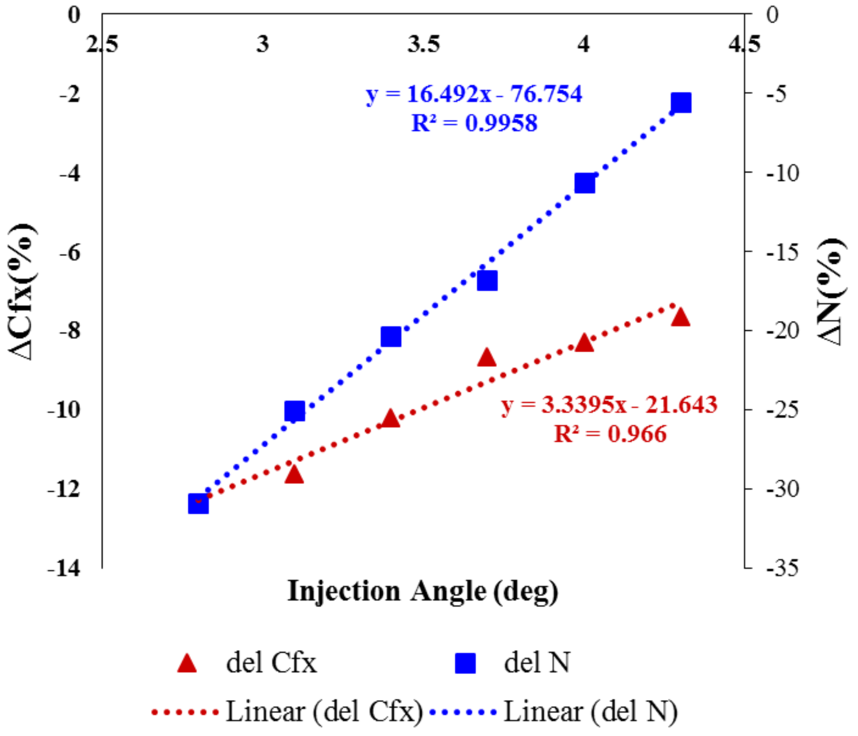
3.1. *Flow feature of SERN*

For the operating Mach number of 3, the main nozzle of the SERN has an NPR of 20. It is the highly over-expanded case for this configuration. The flow feature of this configuration without any injection is shown in figure 2a. From the figure, it can be observed that at the start of the ramp surface, an expansion fan is positioned, and it accelerates the flow Mach number locally. Since the flow is already over-expanded due to the adverse pressure gradient, a mild shock wave is induced at the downstream location of the expansion fan. Due to the interaction between the shear layer originating from the cowl lip and the internal supersonic flow, a cowl lip induced shock is generated and intersects the ramp surface near to the quarter ramp point. This cowl lip shock is again reflected back into the flow, but it is not clearly visible in the picture due to its mild strength. After the intersection point, the flow continues to expand in supersonic velocities. The over-expansion over the ramp surface induces normal vertical force, which creates a continuous noise up pitching moment. This significantly affects the stability of the airplane. So, to reduce the effect of overexpansion on the ramp surface, secondary injection is introduced in the SERN cowl and ramp surface. Figures 2b and c show one such system.

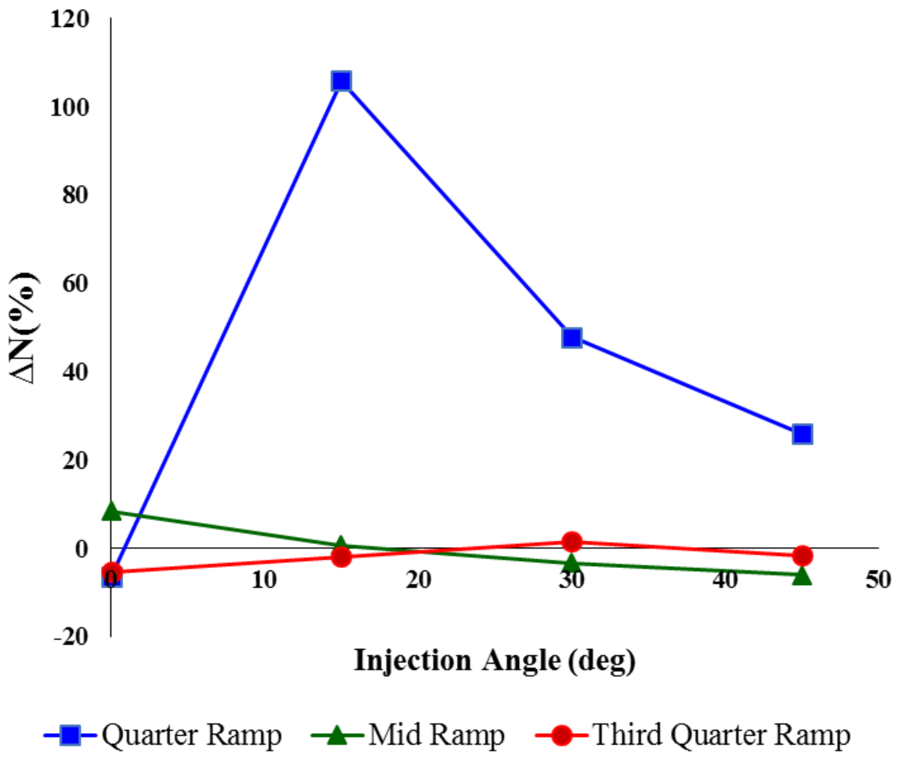
Figure 2b shows the flow features of the SERN flow field with the secondary injection at the cowl surface. When the injection is provided at the cowl surface, the injection flow obstructs the oncoming supersonic SERN flow. This induces an oblique shock just ahead of the injection port. Due to this, an adverse pressure gradient is generated at the downstream of the shock near to the cowl surface. This induces the flow separation in the region between the shock wave and the injection port. It is clearly captured in the zoomed feature D1 in figure 2b. The oblique shock generated due to the introduction of the injection port is intersecting the ramp surface at the D2 region and reflected (reflected shock wave RSW) back into the main SERN flow. In this D2 region, also due to adverse pressure gradient, a small flow separation region is seen, and it is shown in zoomed feature D2 in figure 2b. Similar to the non-injection case in this case also a shock is induced at the cowl lip due to the flow interaction between the SERN flow and free streamflow. Because of the induced shock (ISW), the surface pressure at the ramp pressure significantly increases; this results in overall reduction vertical normal force magnitude. Similar to the previous case, the flow feature of the ramp injection configuration is shown in figure 2c. In this case, also the injection of the secondary fluid at the ramp surface induces a shock wave (ISW) at the upstream location of the injection port. This shock wave intersects and cuts through the shear layer. The region between the induced shock wave and the injection port has a flow separation region due to the adverse pressure gradient created by the shock wave. One more flow separation region is also observed at the downstream of the injection port; this separated flow immediately attaches to the surface of the ramp. At the reattachment point of this separated flow, a secondary incident shock wave is generated, and this can be seen in figure 2c. In figure 2c, the zoomed feature D3 shows the upstream separation region clearly. In this case, the ISW and ISSW significantly increase the average pressure over the ramp surface.

3.2. Effect of secondary injection on the thrust coefficient and normal force

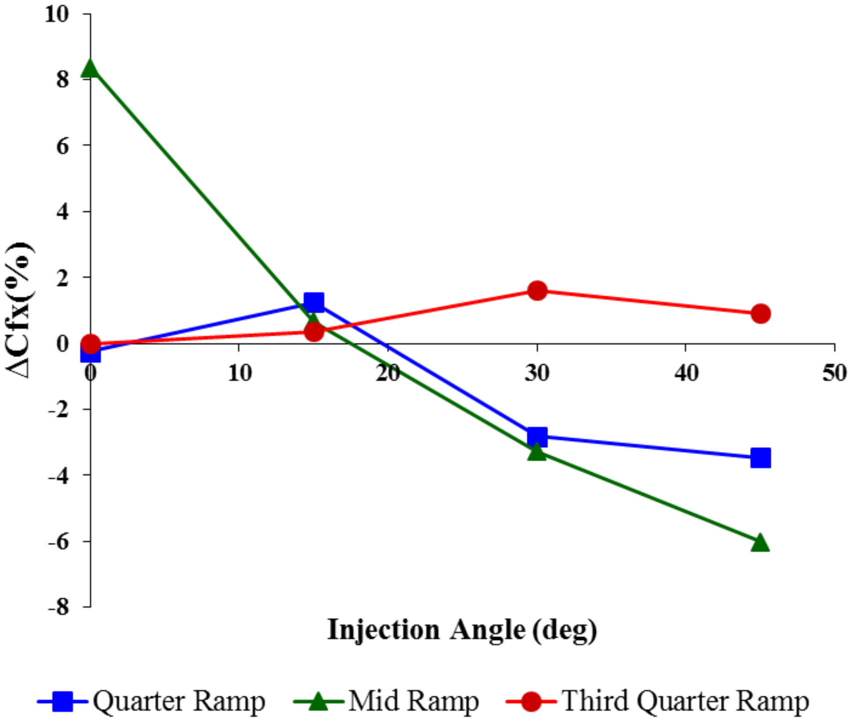
In this section, the effect of cowl injection on the thrust coefficient and normal force is discussed first, and it was followed by the effect of ramp injection on the performance of the SERN. The change in thrust coefficient (ΔC_{fx}) and normal force (ΔN) are calculated using **equation 1 in which X is the performance parameter**, and both of these parameters are shown in figure 3. The cowl injection is positioned at $L/H_t = 2.75$ is the closest to the throat, and the cowl injection at L/H_t 4.3 is the farthest. By observing the thrust coefficient plot of cowl injection figure 3a, irrespective of the injection position, the cowl injection produces a loss in the thrust coefficient. If the injection port is positioned closer to the throat, it creates maximum thrust coefficient loss, and if the injection port positioned at the moved to farthest location produces the lowest loss in the thrust coefficient. The variation is also linear in nature with respect to the position of the injection port from the throat. The linear curve fit drawn using the ΔC_{fx} values has an R^2 value of 0.9958. In the same graph, the normal force reduction ΔN is also shown. The reduction of normal force also varies linearly with the position of the injection port from the throat. The linear curve fit for this case has an R^2 value of 0.966. The maximum normal force reduction of 25% is achieved in the case of $L/H_t = 2.75$, but at the same time, it is essential to note that the loss of thrust coefficient is more than 12%.


y = 16.492x - 76.754
R² = 0.9958
y = 3.3395x - 21.643
R² = 0.966
ΔCfx(%)
ΔN(%)
Injection Angle (deg)
del Cfx
del N
Linear (del Cfx)
Linear (del N)

a)


ΔN(%)
Injection Angle (deg)
Quarter Ramp
Mid Ramp
Third Quarter Ramp

b)



c)

Figure 3. Performance plots of SERN with secondary injections a) normal force and thrust co-efficient for cowl injection configuration b) change in normal force for ramp injection configuration c) change in thrust co-efficient for ramp injection configuration.

Thrust coefficient reduction and normal force reduction for the ramp injection case is shown in figure 3b and c. The thrust coefficient varies significantly depending on the location of the injection port. For a mid-ramp injection, the thrust coefficient increases up to 8% if the injection angle is 0°, and at the same location for the 15% injection angle case, the thrust coefficient increment is just 1%. For the other 2 cases of injection angles (30° and 45°), the thrust coefficient experiences a reduction of 2%. In the quarter ramp injection case, the thrust coefficient increases for the injection angle of 15°, and for all the other configurations, the thrust coefficient reduces. For the third quarter ramp injection case, all the injection angle increases the thrust coefficient, but the increment achieved is below 2%. By comparing these parameters, the 0° mid-ramp injection has the maximum augmentation of the thrust coefficient, which is equal to 8%. This happens because when the injection is introduced at 0° angle at the mid-ramp location, it provides very minimal disturbance to the flow and also enriches the low-pressure region of the ramp surface with a fresh flow of high energy fluid. In the case of normal force reduction achieved in the 0° injection provided at either of the quarter ramps, mid-ramp and third quarter injection is 5%. Especially the injection provided at the quarter ramp significantly augments the normal force (except 0° injection angle), it is highly undesirable. The other two injection positions do not provide significant variation in the normal force reduction. Specifically, the third quarter injection does not have a significant effect on the normal force. It happens because the aftermath of the injection does not fully felt by the ramp surface. Because the length of the ramp surface after the third quarter injection is too short, so the flow does not have a sufficient amount of resting time over the ramp surface.

$$\Delta X = \frac{X_{with} - X_{no}}{X_{no}} \times 100\% \tag{1}$$

Conclusion

SERN exhibits poor flight performance at the off-design operating condition. Especially while operating at an over-expanded condition due to the overexpanded flow at the ramp surface, a nose-up pitching moment is generated. In this study, to reduce this, various secondary injections are used at various locations on either of the cowl surface or ramp surface. In cowl injection, a normal force reduction achieved is more than 30%, but it comes with the expense of a 12% thrust coefficient. If the injection port is moved closer to the throat, normal force reduction achieved is also high. In the case of ramp injection, the maximum normal force reduction of 5% is achieved in the case of 0° quarter ramp and 0° third quarter ramp injection with almost zero loss in thrust coefficient. So in order to improve the performance of the SERN, both of these injections can be used together, and an optimum configuration can be found. But that is the scope for future study.

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