Design optimization of single expansion ramp nozzle using computational method

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Abstract. The project is about the computational study of Single Expansion Ramp Nozzle (SERN). A comparison is carried out for four different cowls of length 2h with initial arc radii of 0mm, 10mm, 20mm and 30mm. The ramp and the cowl are angled. The study elaborates the effect of arc (0mm, 10mm, 20mm and 30mm) in the cowl on the performance of the SERN. The CFD procedure is validated by comparing with experimental results. The optimum design is obtained by analyzing the computational result.

1. Introduction
A nozzle is designed to control the characteristics of a fluid flow and to increase the kinetic energy of the flowing medium at the expense of its pressure and internal energy. SERN is a kind of physical linear expansion nozzle shown in figure 1, where the gas pressure transfers work only on one side. Generally, SCRAMJET engines make use of SERNs because of weight reduction at large expansion ratios or the additional lift at under expansion. Khandai et al [1] carried out experiments at different ramp angles (18°, 20° and 22°) and cowl lengths (0h, 1h, 2h, 3h, 4h) for Nozzle Pressure Ratios (NPR) 2 to 6 and the effect was analysed. Thus, it can be inferred that the effect of changing the ramp angle is negligible at low supersonic speeds and it is also found that the SERN with 20 degrees ramp angle performs better than SERNs with ramp angles of 18° and 22°. SERN with ramp angle 20° & 4h cowl has better performance than the other configurations. Zheng Lv et al [2] carried out computational analysis of SERN. Various similar researches have been referred as in Lokesh Silwal et al [3], Meijun Zhu et al [4] and Riehmer et al [5] on CFD and numerical studies of SERN. To generate the nozzle contour, the method of characteristics is used to calculate the inviscid flow field and the boundary layer thickness is corrected by applying the reference temperature method. The results of the CFD approach show that the initial arc radius on the ramp slightly influences the axial thrust coefficient and that the variation in the length and initial expansion angle of the cowl affect the axial thrust coefficient. The nozzle designed by truncating an ideal nozzle is also investigated for comparison to verify the superiority of this new method. Now through this paper, it is intended to study the effect of initial arc radius in the cowl on the axial thrust of a SERN with a straight ramp.

2. Computational procedure
The commercial CFD software, CFX is used for the simulation of the nozzle. And the appropriate governing equations such as continuity, momentum and energy equation are used. The computational data and the experimental data is compared to validate the numerical method and turbulence model.
The experiment is done with a SERN with ramp angle of 10 degrees and no cowl. The centerline pressure along the jet is measured using the Pitot connected with pressure scanner. The experiment and simulation are carried out for an inlet absolute pressure of 7 bars. A rectangular domain is chosen as the converging section is rectangular. The domain dimensions are chosen such that the jet merges into ambience within the domain. The isometric view and cut section of the computational domain is shown in figure 2 and figure 3.

To capture the effects of the jet and the shock cell phenomenon accurately, sphere of influence is used close to the jet to increase the mesh density at that area. To capture the boundary layer effects, inflation is used near the wall. Fine cells are present near the wall as shown in figure 5. Front view and cut section view of the mesh is shown in figure 4 and 5.
The centerline pressure from both experiment and CFD is obtained. They are plotted together and the difference between them is found to be within 15%. So, the CFD procedure is validated and the error is found to be within limits. The comparison graph is shown in figure 6.

### 3. Results and Discussion

The Mach contours of 10 degree model (0mm and 10mm) are shown in figure 7 and 8. In 10 degree 10mm model, it is identified that the sonic speed is achieved at the throat. Till the midpoint of the Ramp and the end of the cowl, the Mach number increases from 1.29 to 2.58. Suddenly due to the influence of shock waves, the pressure is getting increased and the Mach number decreases to 0.641. There are four points at the exit of SERN at which the pressure and Mach number change abruptly.

In 10 degree 20mm model shown in figure 9, the properties are same as 10 degree 10mm model. But the values of Mach number are slightly different from the model with arc of radius 10mm. It is identified that the sonic speed is achieved at the throat. Till the midpoint of the Ramp and the end of the cowl, the Mach number increases from 1.303 to 2.606. Suddenly due to the influence of shock waves, the pressure is getting increased and the Mach number decreases to 0.6514. There are four points at the exit of SERN at which the pressure and Mach number change abruptly.
The Mach contours of 10 degree model (30mm and 0mm) are shown in figure 10 and 7. In 10 degree 30mm model, it is identified that the sonic speed is achieved at the throat. Till the midpoint of the Ramp and the end of the cowl, the Mach number increases from 1.29 to 2.58. Suddenly due to the influence of shock waves, the pressure is getting increased and the Mach number decreases to 0.646. There are four points at the exit of SERN at which the pressure and Mach number change abruptly.

In 10 degree 0mm model, it is identified that the sonic speed is achieved at the throat. Till the midpoint of the Ramp and the end of the cowl, the Mach number increases from 1.28 to 2.565. Suddenly due to the influence of shock waves, the pressure is getting increased and the Mach number decreases to 0.6414. There are four points at the exit of SERN at which the pressure and Mach number change abruptly.

The distribution of static pressure along the cowl of length 2h is plotted for different models and shown in figure 11. It can be seen that the static pressure keeps decreasing along the cowl only until certain location. The flow is accelerated until the appearance of first shock cell. This location shifts upstream with increasing arc radius. This can be seen from the plot shown in figure 12 and from the data in the table 1. But the minimum pressure along the cowl is least for 30mm case and increases with decrease in arc radius.

![Figure 7. Mach contour ramp and cowl angle of 10deg with initial arc radius 0mm at the cowl.](image1)

![Figure 8. Mach contour ramp and cowl angle of 10deg with initial arc radius 10mm at the cowl.](image2)

![Figure 9. Mach contour ramp and cowl angle of 10deg with initial arc radius 20mm at the cowl.](image3)

![Figure 10. Mach contour ramp and cowl angle of 10deg with initial arc radius 30mm at the cowl.](image4)
Table 1. Location and value of minimum pressure along the cowl for various models.

| Arc radius (mm) | Minimum value of static pressure along the cowl \( p/p_{\text{abs}} \) | Location of minimum pressure along the cowl \( x/2h \) |
|----------------|-------------------------------------------------|--------------------------------------------------|
| 0              | 0.1131                                          | 0.5406                                           |
| 10             | 0.1126                                          | 0.5205                                           |
| 20             | 0.1062                                          | 0.5005                                           |
| 30             | 0.0979                                          | 0.4905                                           |

Minimum pressure values are shown in figure 13. From the figure, it is analyzed that minimum pressure is the proof for better acceleration. This leads to increase in thrust which can be seen table 2 showing thrust values obtained from CFD.

![Figure 11. Pressure along the cowl.](image)

![Figure 12. Location of minimum pressure values.](image)
This is due to the difference between sudden expansion at a sharp point and gradual expansion by introducing an arc. Gradual expansion leads to better flow acceleration and thrust performance.

Table 2. Thrust variation in different models.

| Arc radius (mm) | Thrust (N) | Percentage increase in thrust when compared to model without arc |
|-----------------|------------|-----------------------------------------------------------------|
| 0               | 54.031     | -                                                               |
| 10              | 54.082     | 0.0950                                                          |
| 20              | 54.258     | 0.4201                                                          |
| 30              | 54.273     | 0.4478                                                          |

4. Conclusion
The effect of initial arc radius in the cowl on the thrust performance of SERN is studied with the help of CFD procedure which is validated by comparison with experimental data. The following observations are made

- The minimum pressure along the cowl decreases with increase in arc radius.
- The location of this minimum pressure shifts upstream with increase in arc radius.
- Thrust for model with arc of radius 30mm is 0.44% more than the model without arc in cowl.
- All these effects reduce in magnitude when we keep increasing the arc radius.

5. References
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