Study of full and truncated aerospike nozzles on performances at different working conditions

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Abstract. Aerospike nozzles have been a spinoff the plug nozzle alternative for propulsion systems that require adaptation for outside pressure variations. Their capacity to adapt their aerodynamics without the need of moving parts makes them very interesting for space launching vehicles. Conventional Laval nozzles have to trade-off performance as they cross the atmosphere from sea level to their maximum altitude. In this study, the flow simulation is carried out for full and truncated nozzle. Three cases for the truncated length are chosen: 40%, 50% and 60% plug in different working conditions. In over-expansion conditions, with the increase of plug truncation a loss of thrust is observed, compared with the under-expansion conditions, were the nozzle truncation has a negligible effect. CFD analysis shows which plug truncation is giving the optimum performances and how great is the influence of altitude and temperature on this type of propulsion system.

1. Introduction
In the aerospace industry, supersonic nozzles have many applications [1], and depending on the application, different geometrical configurations are preferred. Adjustment of contour, area ratio and length to match the varying altitude conditions, factor in typical rocket nozzle optimization studies [2]. Nozzle at sea level leads to a thrust loss due to difference between ambient pressure and wall pressure, meaning that the rocket has to carry with it a mass that is not useful for propulsion. In the case of an aerospike nozzle, the "bell" profile is turned inside out; the flow is not completely constrained by the nozzle walls, being adjusted by a system of naturally occurring shockwaves on the outer surface. Nozzle expansion is controlled by the ambient pressure, so the flow at the nozzle exit changes with the altitude [3].

At high altitudes, the aerospike nozzle is able to expand the engine exhaust to a larger effective nozzle area ratio. Better performances can be obtained comparative with the bell nozzles, especially for over-expanded conditions. Also, on over-expansion conditions, the losses will not be the same as in the case of bell nozzle; can even operate near optimal [2]. In under-expanded conditions, for the design conditions, this type of nozzle behaves as an ideal nozzle. Aerospike nozzles are often referred to an altitude compensating nozzle due to its capability of maintaining efficiency with the change of altitude [4].

An aerospace nozzle has 90% overall better performance than the conventional bell shaped nozzle [5] [2]. A vehicle using an aerospike nozzle also saves 25-30% more fuel at low altitudes [2] [4]. At low altitudes, the efficiency is much higher due to atmospheric pressure which restricts the expansion of the exhaust gas.
Improvement of this type of nozzle over the conventional bell nozzle is obtained at altitudes lower that the design altitudes [6], at higher altitudes the operating performances are similar. The most important part in the design of an aerospike is the spike contour and the nozzle angle, which varies with the operating conditions [7]. These nozzles allow the exhaust gases to expand freely, with Prandtl – Meyer expansion fan. Expansion process originates at the cowl-lip, a point on the outer edge of the annulus, [2].

When the full length nozzle is truncated, the geometry will have a flat base on the truncation area. In this area, a recirculation area develops. Flow physics for truncated and full nozzle differ depending on exit and ambient conditions [7]. These nozzles allow the exhaust gases to expand freely, with Prandtl – Meyer expansion fan. Expansion process originates at the cowl-lip, a point on the outer edge of the annulus, [2].

2. Problem setup

2.1. Mathematical model and geometry

The main part that helps to increase the nozzle performances is the central body, whose design represents the primary focus on this study. In the specialty literature, are defined a number of methods used to develop the contour of an aerospike nozzle. In this paper, the contour shape is designed using the methods of characteristics. For defining the expansion wave, Prandtl –Meyer function was used. This function relates the Mach number and Prandtl –Meyer angle, and describes the angle through which a flow, at a given initial and final Mach number can turn isentropically [1]. Prandtl – Meyer expansion fan consists of a region is defined at an infinite number of expansion waves or Mach lines. The Mach angle is given by:

\[ \mu = \arcsin \left( \frac{1}{M} \right) \]

\[ u(M) = \sqrt{\frac{y+1}{y-1}} \tan^{-1} \left( \frac{y+1}{y-1} \left( M^2 - 1 \right) - \tan^{-1} \sqrt{\left( M^2 - 1 \right)} \right) \]  

Also, with the help of the exit Mach number an important relation between the exit and throat area is given by:

\[ \frac{A_{\text{exit}}}{A_{\text{throat}}} = \sqrt{\frac{1}{M_{\text{exit}}^2} \cdot \left[ \frac{2}{y+1} \cdot \left( 1 + \frac{y+1}{2} M_{\text{exit}}^2 \right) \right]^{y+1}} \]

The geometrical parameters of the four types of nozzles are presented in table 1. For the exterior domain, the length of domain is 15 times the inlet diameter of the nozzle, 0.091 m; and a diameter of 0.036 m.

| Table 1. Geometrical features of the nozzle. |
|---------------------------------------------|
| Inlet radius [m] | 0.023 | 0.023 | 0.023 | 0.023 |
| Inlet air – radius [m] | 0.00032 | 0.00032 | 0.00032 | 0.00032 |
| Outlet – radius [m] | - | 0.00082 | 0.00061 | 0.00044 |
| Length – radius [m] | 0.00729 | 0.004625 | 0.00542 | 0.006225 |

Due to its ability to adjust the environment by altering the outer jet boundary, the aerospike nozzle delivers better performance compared to present day bell nozzle.
2.2. Spatial discretization

Figure 1a presents the geometry calculated for the full length aerospike, while figure 1b illustrates the truncated plug, at 40% from the full length geometry.

![Figure 1a: Full length aerospike.](image1)

![Figure 1b: Truncated plug 40%.](image2)

**Figure 1. Nozzle geometry.**

The grid for the geometries was realized using the commercial software ANSYS CFX, and the mesh is structured due to better convergence and higher resolution, figure 2. For all cases a number of approximate 11.8 million nodes and near 7 million elements are generated, with a finer resolution near the nozzle walls.

![Figure 2. Grid geometry.](image3)

2.3. Boundary conditions

The model is designed in the ANSYS ICEM software, and its behaviour is analyzed with the CFD software CFX. The paper will present comparison between the full and truncated models.

Computational domain and regions where the boundary conditions are set are illustrated in figure 3. Boundary conditions used:

- **INLET:** convergent nozzle
- Static Pressure: 20 bar, 15 bar
- Total Temperature: 50°C (323 K); 450°C (723 K)

- **OUTLET**: computational domain: *supersonic*
- **NOZZLE**: wall
- **EXTERIOR DOMAIN**: opening:
  - opening pressure and direction: 0 bar
  - opening temperature: 288 K

![Figure 3. Computational domain and the boundary conditions.](image)

To predict the flow field structured, k-ω SST (Shear Stress Transport) turbulence model has been used. This model was chosen because its ability to predict better flow separation [13] even with highly separated regions. SST is a two-layer, which uses the k-ω model of Wilcox in the inner region of the boundary layer and switches to k-ε model in the outer region of boundary layers [14].

### 3. Results

The flow pattern for different configurations of aerospike nozzles analyzed, and also different working conditions are compared. Full length nozzle, can affect the thrust development, due to the wake formation. To overcome this problem the truncated nozzle was analyzed for three truncation lengths (40%, 50% and 60%). At two planar sections, normal to the jet axis at distance of 2.5 and 5 times the length of 40% truncated plug. The evolution of the fluid flow was analyzed and plotted for comparison. Figure 4 presents the distribution of Mach number for a static pressure of 20 bar and with a total temperature of 723 K (323 K - figure 5). In both cases an abnormal/different behavior results in the case of the full length aerospike, performances of the nozzle are decreasing for this configuration, compared with the truncated ones. Although counterintuitive, a truncated aerospike can provide better overall aerodynamic performance. From the graphics presented below the best characteristics are obtained for a nozzle truncation of 60%. With the decrease of the temperature, the value of the Mach number, and therefore of the velocity in that area, retains largely the same shape for this configuration.
Figure 4. Evolution of Mach Number in the Z direction at a distance of 2.5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

Figure 5. Evolution of Mach Number in the Z direction at a distance of 2.5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 323K.

Because of the different behavior and greater performances losses obtained for the full length nozzle, this geometry this paper will be focusing on the truncated geometries only. Differences given by the change of the inlet temperature, both at 723 K and at 323 K, figure 6, show that with the increase of the temperature, the Mach number is increasing in the core region of the jet. Also for all cases the jet is symmetric towards the axis of the nozzle. This paper will only focus on the results obtained for the temperature of 723 K which will be presented in further detail. Mach number does not vary much for large variation of the truncation length. Along with the increase of the distance, from the nozzle, the value of velocity is reaching the same value, and its magnitude is decreasing.
Figure 6. Evolutions of Mach Number in the Z direction at a distance of 2.5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K / 323 K.

Figure 7. Evolutions of Mach Number in the Z direction at a distance of 5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

In figures 8 and 9 the turbulent kinetic energy is presented at different distances from the nozzle exit. Turbulent flow consist of various eddies, that have different size range. This phenomenon is attributed to the recirculation annular bubble forming at the base of the truncated nozzle, a greater the truncation leading to greater TKE generation due to shear stresses.
Figure 8. Turbulence Kinetic Energy in the Z direction at a distance of 2.5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

Figure 9. Turbulence Kinetic Energy in the Z direction at a distance of 5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

Figures 10 and 11 presents the turbulent eddy dissipation, which is also greater for the cases where there is a larger recirculation bubble - due to a greater truncation of the nozzle cone.
Figure 10. Turbulence Eddy Dissipation in the Z direction at a distance of 2.5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

Figure 11. Turbulence Eddy Dissipation in the Z direction at a distance of 5 times the length of the 40% truncated plug. Static Pressure = 20 bar, Total Temperature = 723K.

Figure 12. User Surface used to determine Mach Number.
To determine the value of the Mach number on the same location and conditions for all geometries, a user surface was used on the flow exit area, figure 12. Full length aerospike, has the Mach number with 0.1 much lower that the nozzle with a 60% truncated plug.

![Mach Number Bar Chart](image)

**Figure 13.** Mach Number obtained for different geometries. Static Pressure = 20 bar. Inlet Total Temperature = 723K.

Because in the case of 40% and 60% truncated plug, higher performances are obtained, a comparison of these geometries, for different inlet conditions is presented in figure 14. The change in pressure, leads to a consistent performance.

![Mach Number Bar Chart](image)

**Figure 14.** Mach Number obtained for two geometries: 40%, 60% truncation. Inlet Total Temperature = 723K. Static Pressure = 20 bar / 15 bar.

To determine the aerospike nozzle which leads to the higher performances, figure 15 is presented the specific force for the truncated plugs. It is seen that a 40% truncated plug leads to a higher force, the differences between the 40% and 60% is 0.0963 N.
Figure 15. Specific force for the three types of aerospike: 40%, 50%, 60%. Inlet Total temperature = 723K.

Figure 16 presents the evolution of Mach number. After the fluid flow passes the critical area, it is accelerated, leading to an increase of the velocity, also on Mach number. On this case, with a nozzle with 40% truncation plug, Mach number is reaching a value of 2.7, and a supersonic flow field. On the nozzle exit, figure 16, a subsonic recirculation area forms, due to the stagnation point that appears on that area. Fluid flow recirculation can be observed in figure 17, with the help of the velocity vectors, and also in figure 18 showing contours of total pressure. After the stagnation point adjusts to the ambient pressure, the flow is parallel with the symmetry axis. Also Mach disks are formed due to sudden changes in pressure and density. These types of disks are formed on both sides of the symmetry axis, being separated by the trailing wake.

Figure 16. Mach Number for the 40% truncated plug. Static Pressure = 20 bar. Inlet Total Temperature = 723K.
4. Conclusion
Flow structure of truncated aerospike nozzles and full length nozzles were compared, using numerical analysis with the help of ANSYS CFX. The effect of the spike length is studied using different configuration (full length, and truncated to 40%, 50, 60% of the original size). Numerical simulations were carried out for different work conditions. For the same geometries, a change on the inlet temperatures leads to a decrease of the velocity and an increase of the exit pressure. Nozzles are compared for the design temperature, and pressure. Based on the study of the performances delivered by aerospike nozzle with different truncation plugs, can be concluded that a maximum performance can be delivered by the 40% truncation plug.

5. References
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