

Numerical Simulation and Visualization of Plug Truncation Effects on Supersonic Turbulent Flow in a Conical Aerospike Nozzle

O. Anwar Bég^{1,*}, C. Okuzu², Tasveer A. Bég³, M.M. Bhatti^{4,5}, S. Kuharat¹, Henry J. Leonard¹, Ali Kadir¹ and W.S. Jouri¹

¹Multi-Physical Engineering Sciences Group, Mechanical Engineering Department, Corrosion and Coatings Lab, Room 3-08, SEE Building, University of Salford, Manchester, M54WT, UK.

²Formerly, Aeronautical Engineering Programme, SEE Building, Salford University, Manchester, M54WT, UK.

³Engineering Mechanics Research, Israfil House, Dickenson Rd., Manchester, M13, UK.

⁴Department of Physics, College of Science, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea.

⁵Material Science Innovation and Modelling (MaSIM) Research Focus Area, North-West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa.

Abstract: Truncation of aerospike plug nozzles in high-speed propulsion has become widely adopted to reduce structural length and cooling demands. However, it introduces a low-pressure base region and wake losses which can offset performance gains. To explore possible improvements to this mode of propulsion, we present a numerical assessment of truncated conical aerospike nozzles at four plug-length ratios (40%, 50%, 62.5% and 75%) operating at nozzle pressure ratios (NPR) = 8.0 and 13.3. Two-dimensional axisymmetric Reynolds-averaged Navier–Stokes turbulent gas dynamic simulations were performed for supersonic gas dynamics in ANSYS Fluent using a density-based solver with the SST $k-\omega$ turbulence model. Grid independence was established prior to the parametric study. Flow characteristics were quantified i.e. Mach number contours, static pressure fields, base pressure recovery trends, and net axial thrust/thrust coefficient comparisons. Results show that base pressure recovery increases with plug length; however, thrust does not improve monotonically with truncation ratio. Across both NPR conditions, the 50% truncated configuration delivered the highest net axial thrust (4556.82 N at NPR = 8.0; 5204.34 N at NPR = 13.3), indicating an optimum compromise between wake/base losses and expansion effectiveness. A simple idealised thrust estimate was used as a consistency check; as expected, CFD predicts lower effective performance due to base/wake losses and viscous/shock effects. The novelties of the present study include a generalization of the plug-length ratios (40%, 50%, 62.5% and 75%), operating at nozzle pressure ratios (NPR = 8.0 and 13.3), inclusion of a sophisticated turbulence model, and the extensive visualization of multiple scenarios to capture key gas dynamic characteristics, which provide a detailed insight into modern supersonic aerospace propulsion.

Keywords: Aerospike rocket nozzle gas dynamics; Mach contours; Nozzle pressure ratio (NPR), SST $k-\omega$ turbulence model; Base pressure recovery, ANSYS FLUENT; Wake losses.

1. INTRODUCTION

The evolution of rocket propulsion technology has been driven by the need to enhance efficiency and adaptability across varying atmospheric conditions. Traditional bell nozzles, while highly effective at specific altitudes, experience considerable efficiency losses when subjected to the dynamic pressure changes encountered during ascent [1]. As a rocket moves through the atmosphere, the exhaust plume's behaviour shifts, often resulting in thrust losses due to over-expansion or under-expansion. This limitation has

spurred interest in alternative nozzle designs capable of maintaining optimal performance across a range of altitudes.

The linear aerospike nozzle as shown in Fig. (1), first conceptualized in the 1960s, addresses this challenge by introducing a design that inherently compensates for altitude variations. This is a kind of altitude-compensating rocket engine featuring a V-shaped or flat tapered ramp with combustion chambers arranged along its sides, allowing for high efficiency across varying altitudes. A modern version was developed by Rocketdyne (now Boeing) in the 1990s [1] and this is a versatile linear aerospike design enabling the use of lower-cost modular combustors which can be combined in varying configurations

*Address correspondence to this author at Multi-Physical Engineering Sciences Group, Mechanical Engineering Department, Corrosion and Coatings Lab, Room 3-08, SEE Building, University of Salford, Manchester, M54WT, UK; E-mails: O.A.Beg@salford.ac.uk; gortoab@gmail.com

depending on the application. Unlike conventional bell nozzles, which rely on fixed geometry, the aerospike utilizes a central plug or spike to direct exhaust gases outward. This configuration allows the surrounding atmospheric pressure to shape the exhaust plume, providing natural altitude compensation. Consequently, the aerospike nozzle can deliver consistent thrust efficiency from sea level to space, making it particularly

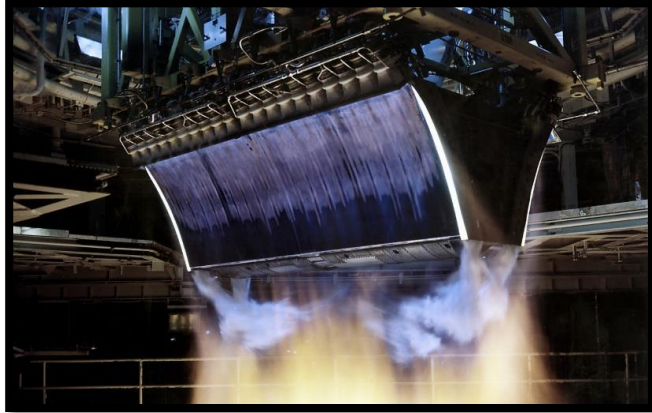


Figure 1: Linear Aerospike nozzle- courtesy NASA.

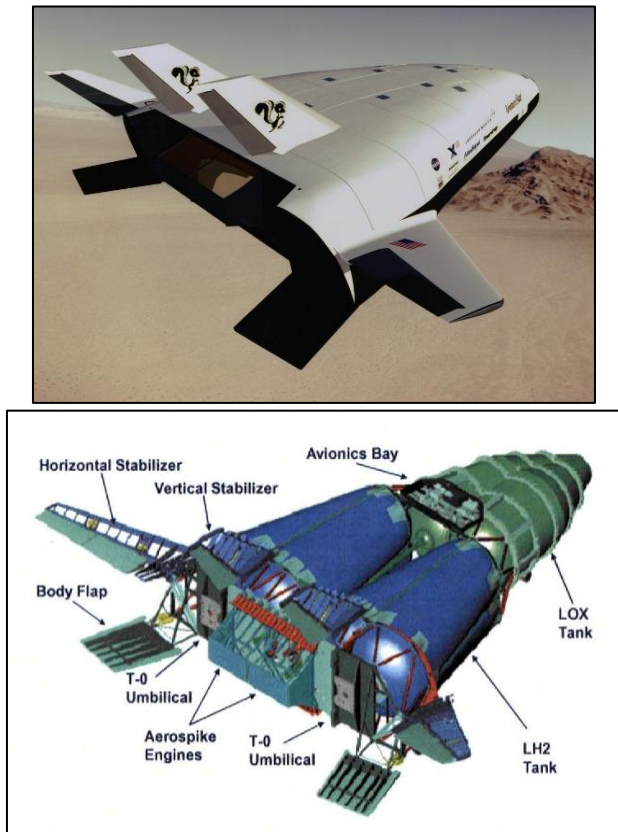


Figure 2: VentureStar reusable launch vehicle propulsion system (left)- courtesy NASA Marshall Flight Space Centre, Huntsville, Alabama and X33 design- courtesy NASA Kennedy Space Centre, Florida, USA (right) [2].

attractive for high-performance aerospace applications, such as single-stage-to-orbit (SSTO) missions. A modern variant of the aerospike nozzle has been deployed in the proposed VentureStar reusable launch vehicle propulsion system, and X33 designs, which are distinct from the NASA space shuttle (utilizing conventional nozzle engines wherein maximum efficiency at only a specific altitude was possible) as shown in Fig. (2).



Figure 3: Conical Aerospike- Courtesy NASA Dryden Flight Research Centre.

Since its inception, the aerospike nozzle has undergone numerous design iterations, reflecting advancements in both theoretical understanding and practical engineering. Early designs focused on linear configurations, where combustion chambers are aligned along a central axis to create a wedge-shaped exhaust plume. Over time, these designs evolved to include truncated and toroidal configurations, each offering unique advantages in terms of weight, adaptability, and fuel efficiency. Aerospike nozzles have been explored extensively by organizations such as NASA and Lockheed Martin, which have leveraged computational fluid dynamics (CFD) and other simulation tools to optimize these designs for modern aerospace requirements. An important development has been the *conical aerospike* (Fig. 3). This variant is also known as the annular aerospike or conical plug nozzle and achieves better propulsion efficiency across a wide range of altitudes by implementing a central, cone-shaped "spike" to guide exhaust gases. It deploys ambient air pressure as a "virtual wall," allowing the exhaust plume to automatically expand or contract as the rocket ascends. The versatility and adaptability of all aerospike nozzles make them a promising alternative to traditional bell nozzles, particularly as the aerospace industry moves towards reusable launch systems and more efficient propulsion methods. The

exploration of aerospike technology continues to provide insights into the future of rocket nozzle design, where performance across diverse atmospheric conditions is critical. This section provides a historical context for aerospike nozzle development, highlighting the significant designs that have shaped current understanding and paving the way for future innovations in propulsion technology. Aerospike (plug) nozzles are a well-established approach to altitude-compensating expansion, since the exhaust plume is bounded externally by the ambient pressure rather than by a fixed bell contour. This feature can reduce off-design losses associated with conventional nozzles during ascent, motivating sustained interest in *plug-based concepts* for high-performance launch propulsion and compact nozzle packaging. Important studies have been communicated in this regard by Verma [3] who considered freestream effects for conical aerospike nozzles. His experiments demonstrated that a 4% decrement in performance arises due to freestream flow at Mach number of 2. He also observed that internal nozzle over-expansion shocks, plug surface shocks, and cowl lip expansion fans dominate the flow and base pressure characteristics, with freestream effects delaying base-wake closure. However, contoured plugs produced a dramatic enhancement in base pressure characteristics compared to straight conical plugs under these conditions. Computational methodologies have also been applied to optimize aerospike nozzle performance. Korte *et al.* [4] used a nonlinear computational fluid dynamics code to calculate the aerodynamic thrust, and a three-dimensional finite-element model is used to determine the structural response and weight in aerospike propulsion. However, practical implementation of full-length aerospikes is constrained by structural length, thermal loading, and cooling complexity, which has driven the widespread adoption of truncated plug geometries as a compromise between performance and manufacturability. Important studies in this regard include Hagemann *et al.* [5] who used a numerical method based on the method of characteristics to investigate plug nozzle effects. They observed that at low altitudes (high ambient pressure), the external air forces the exhaust against the plugs surface, effectively "squeezing" it to match the ambient conditions. As altitude increases and pressure drops, the exhaust expands naturally, mimicking a larger nozzle without physical reconfiguration. They further compared their computations with Schlieren imaging and wall pressure

measurements noting that plug nozzles mitigate the problems associated with conventional nozzles where the flow is constrained by internal walls, since the plug nozzle guides the exhaust along an inner central body (plug), allowing the outer boundary to remain open to ambient pressure. Truncation fundamentally changes the thrust balance by introducing a base region downstream of the truncated plug. The resulting wake can exhibit open- or closed-wake behaviour depending on operating condition, and the associated base pressure can either contribute to or penalise net thrust. Experimental investigations of Verma [3] have further shown for annular conical aerospike nozzles that the internal overexpansion shock system, the spike-surface shock, and the expansion fan from the cowl lip strongly govern the developing flow field and base-wake closure, and that *base pressure is particularly sensitive to shock motion and its interaction with the inner shear layer*. Nair *et al.* [6] deployed ANSYS FLUENT CFD software to simulate turbulent gas dynamics in a truncated conical plug nozzle, noting that wake structure and base pressure recovery remain key sensitivity drivers, and that flow-control concepts such as base bleed can recover base pressure and improve performance in short truncation cases. Sullivan [7] also used ANSYS software with a k-epsilon turbulence model to simulate film cooling and transpiration cooling in an aerospike nozzle configuration, again noting that truncation sensitivity and plug-length effects are critical factors in regulating efficiency. He also showed that transpiration cooling provides superior cooling efficiency with minimal performance loss and that secondary fluid injection at the throat can be beneficial to maintaining pressure recovery. Despite the available experimental and numerical literature, consistent performance ranking of truncation level remains non-trivial because (i) increasing plug length generally improves base pressure recovery, while (ii) changes in local expansion effectiveness and wake losses can offset gains in a non-monotonic manner as noted in [5], [6]. In addition, compressible plume development can involve shock-shear-layer interactions and, depending on operating regime, shock-related unsteadiness phenomena that influence separated regions and may affect thrust sensitivity. These aspects have been identified by Verma *et al.* [8] and also Dutton and Carroll [9]. Accordingly, a controlled parametric comparison using a unified numerical (CFD) framework is valuable for identifying practical truncation ratios that provide a favourable trade-off between thrust performance and geometric simplification.

In this study, a two-dimensional axisymmetric CFD simulation is conducted for truncated conical aerospike nozzles at four plug-length ratios (40%, 50%, 62.5% and 75%) operating at two nozzle pressure ratios, $NPR = 8.0$ and $NPR = 13.3$. These configurations have not yet been fully explored in any previous study on aerospike nozzle gas dynamics. The computations are performed in ANSYS Fluent [10, 11, 12] using a density-based implicit solver with the SST $k-\omega$ turbulence model, supported by a grid-independence study. Performance is quantified using Mach number contours, base pressure recovery trends, selected static pressure contours, and net axial thrust comparisons. The SST $k-\omega$ model is selected due to its established performance for adverse-pressure-gradient and separated flows within an engineering RANS framework, as noted by Menter [13], and the numerical methodology follows standard finite-volume CFD best practice for compressible flow verification [14]. The present work aims to identify an optimum truncation level and provide flowfield-based interpretation of the observed performance trends under both NPR conditions using a detailed CFD analysis.

2. GAS DYNAMICS, NOZZLE PRESSURE RATIO AND PLUG TRUNCATION

The flow through rocket nozzles, especially aerospike nozzles, involves high-speed compressible gas dynamics. The accurate representation of such flows requires solving the conservation laws of fluid dynamics in a compressible form which are the mass and momentum conservation, typically coupled with an equation of state. These governing equations form the mathematical basis for both theoretical analysis and computational fluid dynamics (CFD) simulations used in this project.

2.1. Gas Dynamic Flow Equations

Continuity Equation (Conservation of Mass)

For a compressible fluid, the conservation of mass is expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (1)$$

Momentum Conservation Equations

The full 3-D compressible Navier-Stokes eqns. are:

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \nabla \vec{v} \right) = -\nabla P + \rho \vec{g} + \mu \nabla^2 \vec{v} \quad (2)$$

Here $\vec{V}$ is velocity vector, ρ is the fluid density (kg/m^3), P is the static pressure (Pa), μ is dynamic viscosity (Pa.s). For 2-dimensional axisymmetric plug nozzle aerospike flow, (u, v) are velocity components (m/s) in the axial (x) and transverse (y) directions, respectively, x is the axial coordinate, and y is the transverse coordinate.

2.2. SST $k-\omega$ Turbulence Model

The CFD software used in this study, ANSYS Fluent, solves these governing equations using the finite volume method (FVM) on a structured mesh. For high-speed compressible flows, a density-based solver is selected, which is more stable for handling shock waves, expansion fans, and high Mach number regimes, especially in truncated geometries. In the simulations, turbulence closure is achieved using the SST (*shear stress transport*) $k-\omega$ model, and numerical schemes such as second-order upwind discretization are employed for higher accuracy in regions of steep gradients. This turbulence model [15] has enhanced capabilities in predicting separation and reattachment relative to the conventional $K-\varepsilon$ (k -epsilon) and the standard $K-\omega$ (k -omega) models. The SST model is an improvement of the standard $K-\omega$ model which blends aspects of the $K-\varepsilon$ model. The SST $K-\omega$ model reduces the sensitivity to free-stream conditions inherent in the standard model by considering the transport of turbulence shear stress. The SST $K-\omega$ model obtains turbulence specific energy (k) and the specific dissipation rate (ω) from the transport equations given in Eqn. (3) and Eqn. (4), where G_k is the turbulence kinetic energy generated due to mean velocity gradients, G_ω is the generation of ω , Γ_k and Γ_ω denote the effective diffusivity of k and ω , Y_k and Y_ω indicate the dissipation of both k and ω due to turbulence, S_k and S_ω are user defined source terms and finally, G_b and $G_{\omega b}$ account for buoyancy terms.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k + G_b \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega + G_{\omega b} \quad (4)$$

The effective diffusivities are defined as $\Gamma_k = \mu \frac{\mu_t}{\sigma_k}$ and $\Gamma_\omega = \mu \frac{\mu_t}{\sigma_\omega}$ where σ_k and σ_ω are the associated turbulent Prandtl numbers. Combining turbulence specific energy and dissipation rate we have the turbulent viscosity, $\mu_t = a^* \frac{\rho k}{\omega}$. The a^* term causes a low Reynolds number correction by damping the turbulent viscosity and is calculated by using the following equation:

$$a^* = a_{\infty}^* \left(\frac{a_0^* + Re_t / R_k}{1 + Re_t / R_k} \right) \quad (5)$$

Here $Re_t = \frac{\rho k}{\mu \omega}$, $R_k = 6$, $a_0^* = \frac{\beta_i}{3}$, $\beta_i = 0.072$. For the $K - \omega$ SST model, a blending function is implemented between the $K - \varepsilon$ and $K - \omega$ models which limits the turbulent viscosity. This is done so that the turbulent shear stress transportation can be sustained smoothly between the freestream and the wall bound flow. The modified turbulent viscosity is given as:

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left[\frac{1}{a^*}, \frac{SF_2}{a_1 \omega} \right]} \quad (6)$$

Further details of this model are given in Miller *et al.* [15].

2.3. Nozzle Pressure Ratio (NPR) Significance

The nozzle pressure ratio (NPR), defined as the ratio between the *stagnation pressure upstream of the nozzle throat and the ambient atmospheric pressure*, plays a central role in determining the behaviour and efficiency of high-speed flows in rocket nozzles. It is defined mathematically as:

$$\text{NPR} = \frac{P_0}{P_a} \quad (7)$$

Here P_0 is *upstream stagnation pressure (Pa)* and P_a is *ambient atmospheric pressure (Pa)*. This parameter governs how the exhaust plume expands, whether shocks or expansion waves form, and how closely the flow approximates ideal isentropic conditions. In the context of aerospike nozzles, particularly truncated configurations, NPR dictates the expansion pattern of the exhaust and the flow structure near the base. At lower NPR values, typically below 5, the ambient pressure is sufficiently high to interfere with the exhaust flow, resulting in shock formation and wake instability. These conditions often lead to open wake regimes where the base pressure is low, and the nozzle experiences significant thrust losses due to the presence of a recirculating wake behind the truncated plug. As NPR increases, the ambient pressure becomes less influential, allowing the plume to expand more freely and transition into a closed wake regime. In this state, the *recirculation zone behind the truncated base is enclosed by shear layers*, and the flow becomes less sensitive to atmospheric effects, leading to more stable and efficient operation. Experimental and numerical studies have demonstrated this behaviour clearly, as noted by Verma [3], who observed a distinct transition in flow behaviour around $\text{NPR} \approx 5.5$, where base pressure ratios began to stabilize,

indicating the onset of a closed wake. Similar findings by Nair *et al.* [6] via CFD simulations of a 40% truncated plug nozzle confirmed that NPR critically influences shock patterns, pressure gradients, and base thrust characteristics.

In the current study, two NPR values i.e. 8 and 13.3, are selected to represent different stages of a launch trajectory. $\text{NPR} = 8$ corresponds to *moderate altitude conditions* where the flow is still strongly influenced by the atmosphere, leading to possible shock-shock interactions, reattachment phenomena, and base pressure variations. $\text{NPR} = 13.3$, on the other hand, simulates *near-vacuum or high-altitude conditions*, where the ambient pressure is minimal, and the flow achieves near-isentropic expansion. These two operating points are strategically chosen to capture the contrast between the transitional and near-optimal performance regimes of truncated aerospike nozzles. Understanding the influence of NPR is therefore essential not only for interpreting CFD results but also for framing the conditions under which aerospike nozzles offer advantages over conventional bell nozzles. It forms a theoretical and practical foundation for the design decisions in aerospike rocket nozzle propulsion systems and provides a robust context for analysing truncation effects on base pressure recovery, thrust coefficient, and wake behaviour.

2.4. Plug Truncation Theory

The concept of plug truncation arises from the need to balance aerodynamic efficiency with structural feasibility in the design of aerospike nozzles. A full-length aerospike, while theoretically ideal in terms of pressure recovery and altitude compensation, is rarely practical for actual launch systems. Its extended geometry imposes significant penalties in terms of mass, cooling requirements, and integration complexity. As a result, truncating the spike i.e., removing a portion of the aft section of the plug, has become a widely studied and implemented strategy to retain many of the nozzle's benefits while reducing its physical and manufacturing burden. An example of truncation of the nozzle is shown in Fig. (4) relative to an untruncated 100% aerospike configuration.

From a theoretical standpoint, the full-length plug enables exhaust gases to expand in an isentropic nature along the contoured surface, continuously transferring axial momentum to the vehicle. This flow remains attached along the spike's length, providing a controlled expansion that adapts passively to ambient

pressure changes. Truncation interrupts this surface prematurely, introducing a planar or nearly flat base that is exposed to the exhaust wake. This geometric

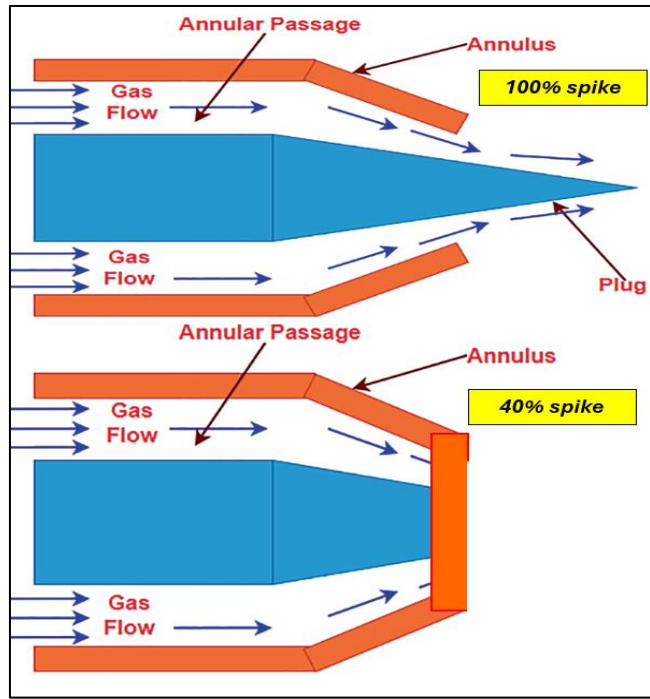


Figure 4: Example of a truncation.

modification replaces a potentially high-pressure, momentum-contributing spike region with a low-pressure, non-contributing wake zone. The *principal aerodynamic consequence of truncation is a reduction in the thrust coefficient*, primarily due to the formation of a separated flow region or base wake behind the truncated edge. In this region, the gas no longer impinges on the nozzle surface to contribute to thrust. Instead, it recirculates and mixes, generating a zone of low static pressure which exerts a net drag on the base. This phenomenon is commonly referred to as base drag, and its magnitude is strongly dependent on the nozzle pressure ratio and the degree of truncation. Analytically, the loss in thrust, ΔF , can be related to the reduction in pressure over the truncated area. If P_b denotes the base pressure and A_b the base area, the missing thrust component due to truncation is given by:

$$\Delta F = (P_0 - P_b)A_b \quad (8)$$

Here P_0 is the stagnation pressure. This expression emphasizes that lower base pressures (typical in the open wake regime) result in greater thrust penalties. In some configurations, this loss can account for up to 15% of total nozzle thrust, depending on the truncation

length and ambient conditions. However, truncation is not entirely detrimental. The mass and volume saved by removing a portion of the plug are significant, especially for launch systems where payload capacity is tightly constrained. Furthermore, as several studies have shown, most of the useful thrust generated by a plug nozzle originates within the first 30–40% of the spike's length. The remaining length contributes marginally to thrust but adds disproportionately to the structural weight and cooling surface area. Consequently, truncation beyond this region—at lengths such as 50%, 62.5%, or even 75% of the full spike—is often justified by a favourable trade-off between performance and practicality. In this study, four truncation levels (40%, 50%, 62.5%, and 75%) are evaluated using ANSYS FLUENT CFD to quantify the gas dynamics penalties and assess exactly how wake dynamics and base pressure recovery evolve with increasing truncation. Theoretical expectations suggest that as truncation increases, the base area grows, and pressure losses become more pronounced. Nevertheless, the specific impact depends on NPR and flow stability in the base region and CFD simulation is a very useful tool to explore these aspects. These simulations will provide insight into how far the spike can be truncated before the aerodynamic cost outweighs the structural benefit.

3. GEOMETRIC MODEL AND SETUP

3.1. Geometry and Truncation Configurations Designed

A conical aerospike (plug) nozzle geometry was modelled in two-dimensional axisymmetric form to enable efficient parametric evaluation while retaining the dominant compressible flow features relevant to plug nozzles (shock formation, external expansion, and base-wake development). The source geometry is adapted from Verma [3] and features the annular nozzle, cowl, afterbody etc, as depicted in Fig. (5). Four geometrical cases were developed in SOLIDWORKS and are shown in Fig. (6). The baseline configuration corresponds to a full-length plug, from which four truncated geometries are generated by removing the downstream portion of the spike to yield plug-length ratios of 40%, 50%, 62.5% and 75% of the original spike length. The truncation plane defines a circular base surface normal to the axis of symmetry, forming the base region where wake closure and base pressure recovery are assessed, in accordance with earlier investigations, for example Nair *et al.* [6].

4. ANSYS FLUENT SIMULATION, GRID INDEPENDENCE AND VALIDATION

4.1. Computational Framework

All simulations were performed in ANSYS Fluent using a two-dimensional axisymmetric finite-volume formulation for steady, compressible turbulent flow. The working fluid was treated as an ideal gas. A density-based implicit solver was employed due to the presence of high-Mach-number acceleration and shock structures, which are characteristic of aerospike nozzle flows and are commonly addressed using compressible density-based formulations within the finite-volume method (FVM)-based ANSYS FLUENT solver framework [15,17]. No-slip, adiabatic wall conditions were applied on the nozzle and plug surfaces, and axisymmetry was enforced along the centreline.

4.2. Mesh Generation Strategy

Structured quadrilateral meshes were generated with targeted refinement in regions expected to contain strong gradients, including the throat, near-wall plug region, and the base/wake zone downstream of the truncation plane. Boundary-layer refinement (inflation) was applied along solid surfaces to improve near-wall resolution and to capture shear-layer development and potential separation/recirculation features. A representative mesh distribution is shown in Fig. (8), illustrating the local refinement strategy employed across the computational domain.

4.3. Grid-independence Study

A grid-independence assessment was conducted prior to the parametric truncation study to ensure that key solution outputs were not sensitive to mesh resolution. Three progressively refined meshes were tested with approximate cell counts of 1.14×10^5 (coarse), 1.46×10^5 (medium) and 1.91×10^5 (fine). Grid sensitivity was evaluated using two monitored quantities: exit velocity and maximum pressure (consistent with the values reported in Table 1). The comparison was performed for both a full-length (0%) reference configuration and a representative 40% truncated configuration.

Table 1: Grid-independence Assessment for the Full-length (0%) and 40% Truncated Configurations: Mesh Size, Total Cell Count, Maximum Static Pressure, and Nozzle Exit Velocity

Geometry	Mesh Option	Cells	Max Pressure [Pa]	Exit Velocity [m/s]
Full Length	1	113,915	3,512,962	1207.63
	2	145,690	3,512,456	1207.76
	3	191,004	3,512,147	1207.41
Truncation 40%	1	113,711	3,513,952	1208.43
	2	145,685	3,514,457	1207.36
	3	191,114	3,513,458	1207.52

The results (Table 1 and Fig. 9) show minimal variation in monitored quantities between the medium

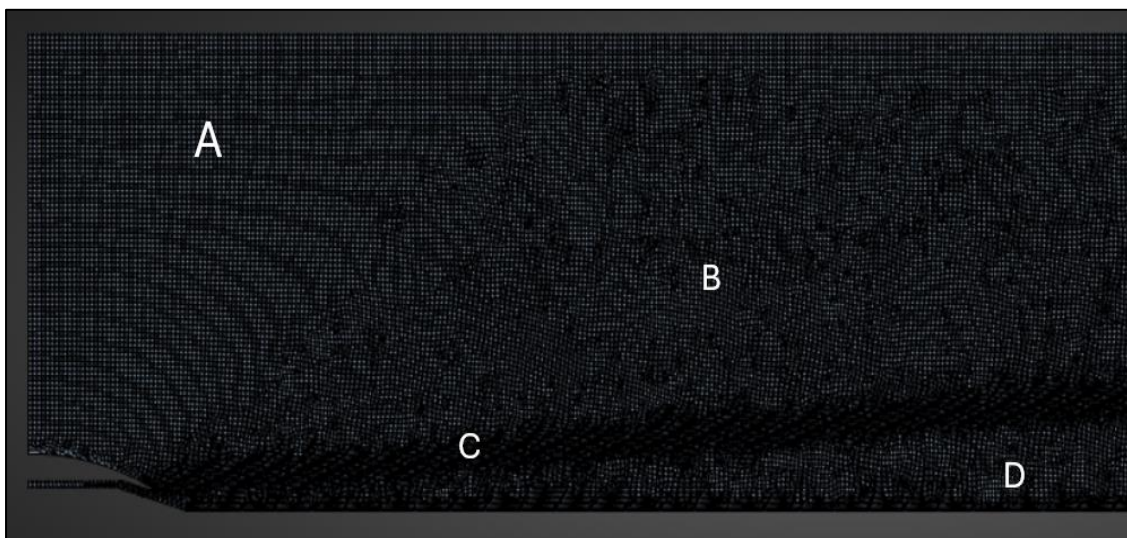


Figure 8: Computational mesh for the axisymmetric truncated aerospike nozzle domain showing local refinement regions: (A) upstream/inlet region, (B) expansion/plume region, (C) near-wall refinement along the plug/nozzle surfaces, and (D) base-wake refinement downstream of the truncation plane.

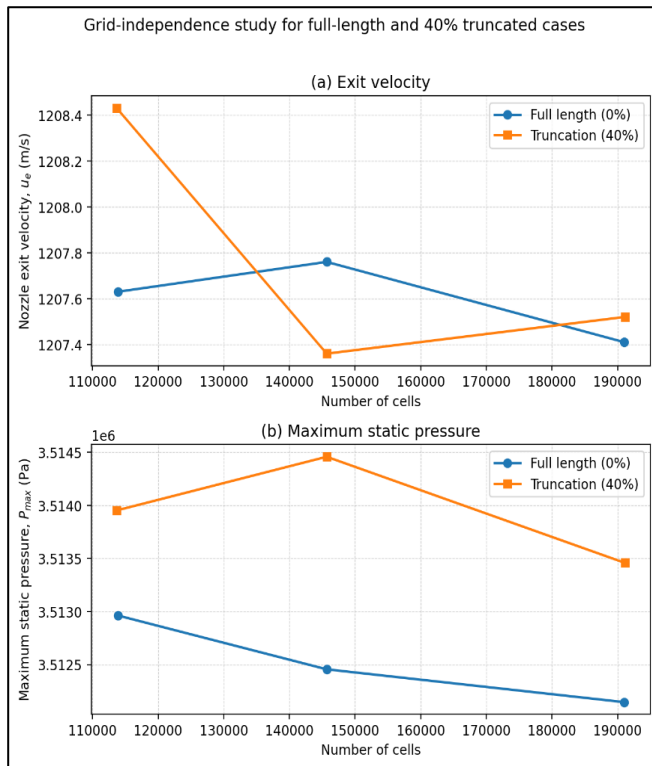


Figure 9: Grid-independence trends for the full-length (0%) and 40% truncated cases showing variation of (a) nozzle exit velocity and (b) maximum static pressure with total cell count.

and fine meshes, indicating that the solution is effectively mesh independent within this refinement range. Based on this outcome, the fine mesh ($\sim 1.91 \times 10^5$ cells) was adopted for all truncation configurations to ensure consistent resolution across cases while maintaining feasible computational cost. This approach is consistent with best practice in CFD verification for nozzle flows where base-wake behaviour and shear-layer development can be sensitive to near-wall and wake-region resolution [18].

4.4. Boundary Conditions and Operating Cases

A pressure inlet boundary condition was applied at the inlet plane with prescribed stagnation conditions, while the outlet was specified as a pressure outlet. The ambient pressure was adjusted to impose the required nozzle pressure ratios $NPR = P_0/P_a$, with simulations conducted at $NPR = 8.0$ and $NPR = 13.3$. The operating pressure was set to 0 Pa in ANSYS FLUENT; *all reported pressures are absolute unless stated otherwise*. Axisymmetric conditions were applied along the centreline, and all solid boundaries were treated as no-slip, adiabatic walls. Consistent boundary condition definitions were maintained across truncation cases to ensure that observed changes in flow structure and

performance arose from geometric effects rather than numerical inconsistency.

4.5. Discretisation, Turbulence Modelling and Convergence Criteria

Turbulence closure was provided by the SST $k-\omega$ model, which is selected for its established capability in flows with adverse pressure gradients, separation tendencies, and shock–turbulence interaction [15]. Second-order spatial discretisation was applied to improve accuracy in capturing steep gradients and shock features. Convergence was enforced using residual targets of 10^{-6} for the governing equations, together with monitoring of exit quantities (including exit velocity and pressure) to ensure stabilisation of the solution. Each case was considered converged when residuals met the prescribed tolerance and monitored quantities exhibited negligible variation with further iterations.

4.6. Simulation Matrix and Workflow

A total of eight CFD cases were simulated, covering all combinations of four truncation ratios (40%, 50%, 62.5% and 75%) and two NPR values (8.0 and 13.3). They are shown in Table 2.

Table 2: Simulation Matrix for Truncated Aerospike Nozzle Configurations and Operating Conditions

Case	Truncation Level	NPR	Ambient Pressure (Pa)
1	40%	8.0	500,000
2	40%	13.3	300,000
3	50%	8.0	500,000
4	50%	13.3	300,000
5	62.5%	8.0	500,000
6	62.5%	13.3	300,000
7	75%	8.0	500,000
8	75%	13.3	300,000

All cases were solved using the same numerical settings and mesh strategy to enable direct comparative assessment. Post-processing focused on Mach number and pressure fields, base pressure recovery characteristics, and performance metrics including net axial thrust and thrust coefficient, allowing truncation configurations to be ranked consistently under both operating conditions.

4.7. Validation

To provide confidence in the numerical setup, a validation case was conducted against published conical plug (aerospike) wall-pressure measurements reported by Verma [3] for an annular conical plug nozzle under no-freestream conditions. The validation simulation reproduced the same nozzle pressure ratio by setting the operating pressure to $P_a = 101325$ Pa and specifying the inlet total pressure such that $NPR = P_0/P_a$. For the present validation run, $NPR = 5.75$ was imposed, corresponding to an absolute inlet total pressure $P_0 = 5.75 P_a$. The outlet was prescribed with zero gauge-pressure (i.e., $P = P_a$ in absolute terms). The primary comparison metric was the *streamwise wall static pressure ratio* $\frac{p_w}{p_0}$ along the plug/nozzle wall. Wall static pressure data were exported from ANSYS Fluent using XY-plots along the relevant wall boundary and converted to a nondimensional form using

$$\frac{p_w}{p_0} = \frac{p_{w,abs}}{p_0} = \frac{p_{w,gauge} + P_a}{p_0} \quad (10)$$

The streamwise coordinate was expressed as a normalised curvilinear distance s/L , where s denotes the *cumulative distance along the wall from the start of the plug/nozzle wall* and L is the total sampled wall length.

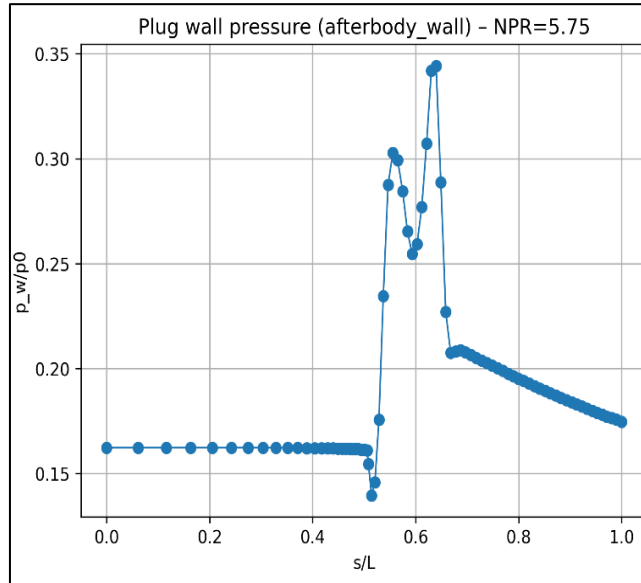


Figure 10: ANSYS FLUENT wall-pressure ratio plotted in same non-dimensional form as Verma [3] for qualitative comparison. (solid blue line-Verma [3], blue dots - ANSYS FLUENT).

Figure (10) compares the present ANSYS FLUENT solutions for p_w/p_0 as a function of s/L for the

validation NPR. The solution captures the expected qualitative features described in the experimental study of Verma [3], including: (i) *an initially low-pressure region downstream of the lip, followed by (ii) a pronounced pressure rise associated with the internal compression/shock system and onset of separation/reattachment behaviour, and (iii) recovery toward the downstream region.* As a simple quantitative indicator, the location of the sharp pressure rise (taken as the maximum gradient in p_w/p_0) was extracted and reported as s/L for direct comparison and repeatability. The computed wall-pressure ratio p_w/p_{0i} exhibits the same qualitative trend reported by Verma [3] for $NPR = 5.75$, including an initial decrease followed by a recompression ‘hump’ over the mid-plug region, providing confidence in the present ANSYS FLUENT modelling for the parametric truncation study.

5. NUMERICAL RESULTS VISUALIZATION AND DISCUSSION

Extensive CFD simulations were conducted to examine the effects of NPR and truncation percentage on gas dynamic characteristics. We consider the simulations in groups for each NPR value.

5.1. Flow Field Characteristics at $NPR = 8.0$

5.1.1. Mach Contours

Figure (11) presents Mach number contours for the truncated aerospike configurations at $NPR = 8.0$. Across all truncation levels, the flow accelerates through the annular throat and expands along the plug surface, forming a high-Mach core adjacent to the spike and a shear layer that bounds the external plume. Downstream of the truncation plane, a separated base region forms and interacts with the expanding jet, producing a *recirculating wake whose size and closure behaviour vary with truncation level.* These trends are consistent with prior observations that truncated plug nozzles exhibit wake-driven sensitivity governed by shear-layer development and the interaction of expansion waves with the base region, as elaborated in for example, Gorle *et al.* [18]. At the shortest plug length (40%), the base region is more pronounced, and the near-base flow exhibits stronger separated behaviour, indicating increased wake-related losses. As the truncation level increases (50–75%), the external expansion along the plug becomes more developed and the base region is comparatively reduced, indicating improved base pressure recovery and a less severe separated wake. The 75% truncated nozzle (Fig. 11d) exhibits the highest exit Mach

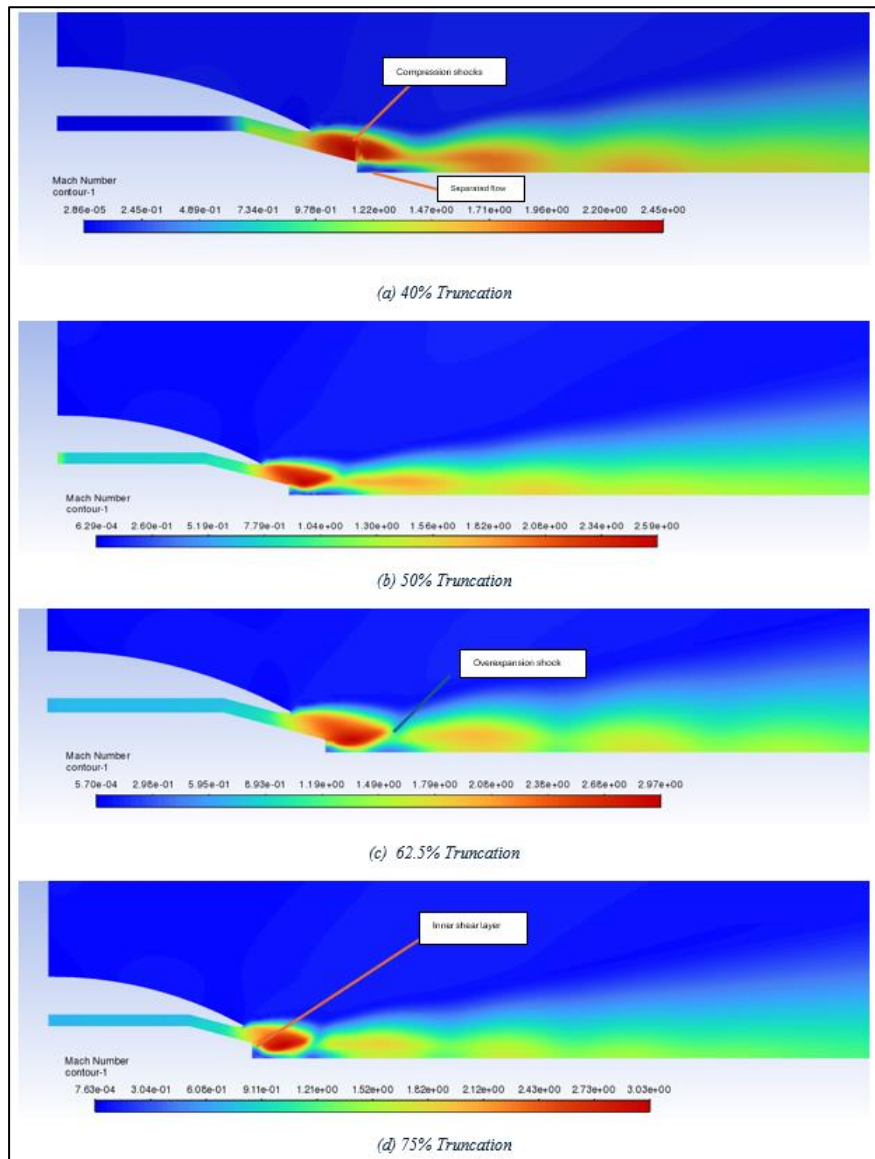


Figure 11: Mach number contours for truncated conical aerospike nozzles at $NPR = 8.0$: (a) 40% truncation, (b) 50% truncation, (c) 62.5% truncation, and (d) 75% truncation.

number. This suggests nearly ideal expansion conditions with minimal flow detachment and strong directional jet alignment. The contour shows a narrow, high-speed jet core and well-distributed pressure contours across the spike, leading to high exit velocity and improved thrust coefficient. Although some wake remains behind the plug, it is reduced in size and strength, indicating a shift toward a closed wake behavior, similar to the full-length configuration. This case likely offers comparable aerodynamic efficiency to the full-length spike with substantially lower structural complexity. However, the flow field comparison suggests that improvements in base recovery do not necessarily translate into monotonic thrust gains, since the effective expansion process and local shock/expansion interactions also influence net

performance. These trends concur with many previous studies including Verma [3] and Nair *et al.* [6]. The 75% configuration (Fig. 11d) yields the highest observed Mach number of 3.45, as with the 40% truncation case, but with dramatically improved wake control. The longer plug allows for smoother expansion and delays separation, minimizing flow distortion downstream. The result is a narrow, high-speed jet, with minimal pressure losses at the base. This performance is approaching that of the full-length plug and suggests that truncation up to 75% may preserve aerodynamic efficiency while achieving significant mass and volume reductions. The full-length reference contour at $NPR = 8.0$ is provided in Fig. (12) for qualitative comparison with truncated cases.

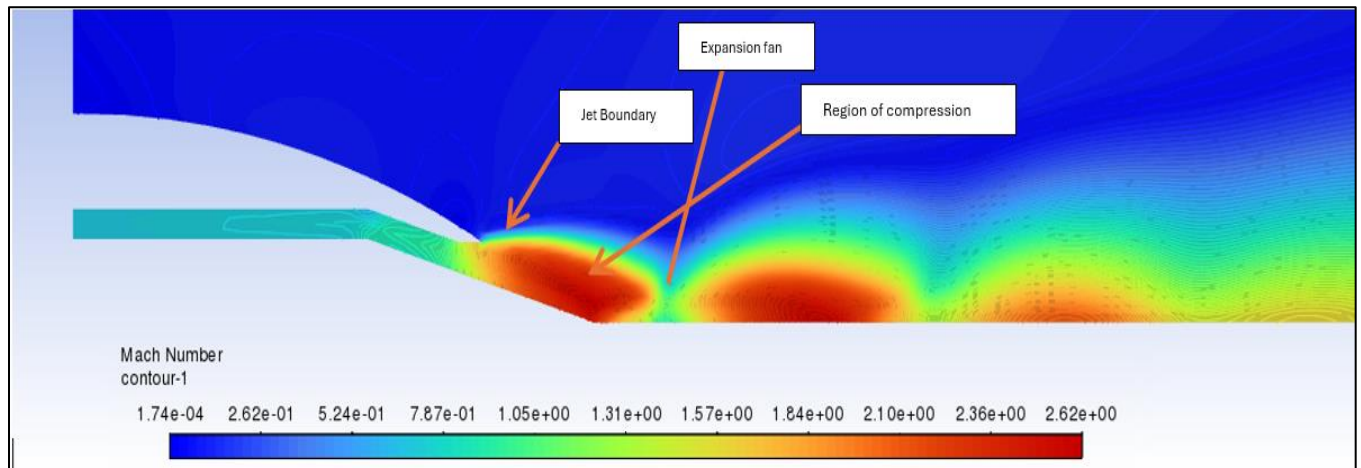


Figure 12: Mach number contour for the full-length (0% truncation) conical aerospike nozzle at $NPR = 8.0$.

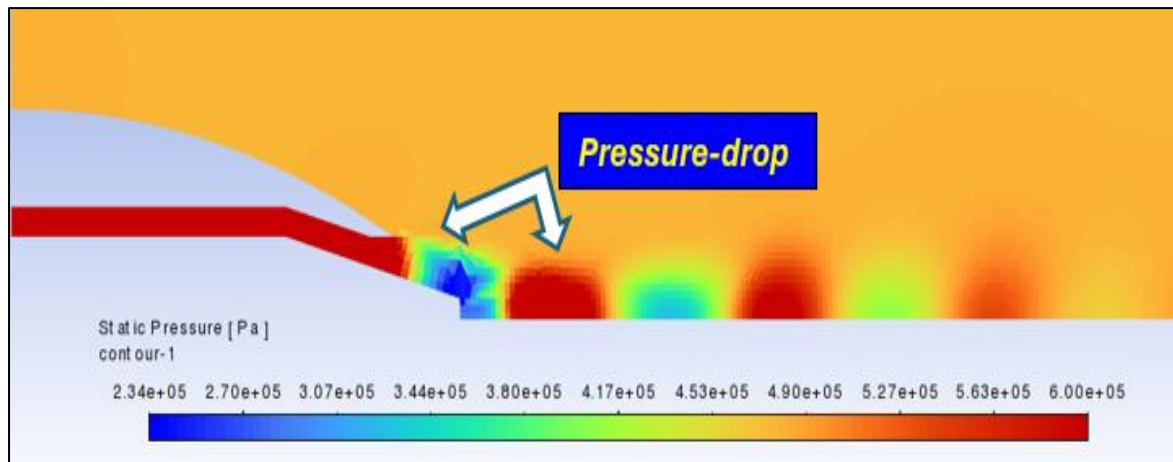


Figure 13: Pressure contours for the 40% truncation conical aerospike nozzle at $NPR = 8.0$.

5.1.2. Static Pressure Contours

Now we address static pressure distributions for selected truncated nozzle configurations under a nozzle pressure ratio (NPR) of 8. The focus is on evaluating base pressure behaviour, shock structures, and the impact of truncation on pressure recovery. While only the 40% and 50% truncation levels are discussed in detail due to post-processing constraints, the trends observed are representative of the aerodynamic phenomena across all configurations.

As shown in Fig. (13), the 40% truncated nozzle exhibits a prominent low-pressure region at the base of the plug. This is visualized in dark blue, with static pressures falling as low as $\sim 2.34 \times 10^5$ Pa, significantly below the freestream value of 5.0×10^5 Pa. This pressure drop is a direct result of the flow separation and recirculation that forms immediately behind the truncation edge. The sharp geometry change at the

base causes the flow to detach, forming a broad wake that induces adverse pressure gradients and hinders thrust production. Downstream of this base wake, the contour reveals alternating bands of higher pressure (in orange/red contours), corresponding to recompression regions where the flow adjusts to the ambient pressure. These shock regions are likely trailing shocks or oblique recompression waves. The wide spread of low-pressure zones confirms that the 40% configuration operates in an open wake regime, with unstable flow and poor pressure recovery at the base—both contributing to thrust losses. Fig. (14) depicts the pressure contours for the 50% truncated nozzle and evidently there are signs of improved flow stability and partial pressure recovery at the base. While the wake remains visible, the low-pressure region is narrower and better confined to the base zone compared to the 40% case. This suggests a reduction in flow separation severity and the early stages of wake reattachment.

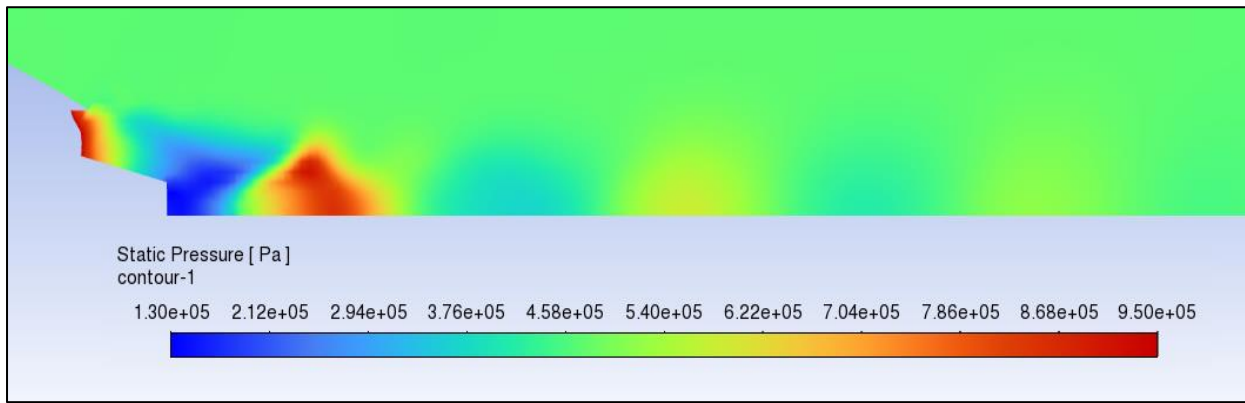


Figure 14: Pressure contours for the 50% truncation conical aerospike nozzle at $NPR = 8.0$.

The base pressure is still significantly lower than ambient, but the pressure rise across the recompression zones is more organized and symmetric. This indicates a stronger, more collimated jet, and suggests that the 50% configuration may represent a transitional point between the unstable behaviour of short plugs and the recovery observed in longer ones. Overall, the pressure distribution implies improved aerodynamic performance and thrust recovery potential over the 40% truncation.

5.2. Flow Field Characteristics at $NPR = 13.3$

In this case we restrict attention to only Mach contour capturing. Fig (15) shows the corresponding Mach contours for $NPR = 13.3$. Relative to $NPR = 8.0$, a higher level of expansion is observed, with a larger high-Mach region downstream of the throat and along the plug surface. The shear layer persists further downstream and the external plume exhibits a stronger expansion structure, as expected for increased pressure ratio operation. Truncation continues to introduce a base region and wake, but the higher NPR tends to promote more robust jet development and modified wake topology, affecting the interaction between the inner shear-layer and the base region [1, 3, 18]. Among the truncated configurations, the 50% case exhibits a balanced plume development with a comparatively stable downstream structure, while the shorter truncation (40%) shows a more pronounced near-base separated region. For longer truncations (62.5–75%), the base region appears reduced; however, the *plume/expansion structure indicates that performance ranking remains governed by a trade-off between base pressure recovery and overall expansion effectiveness rather than by base behaviour alone* [2, 19]. At 62.5% truncation (Fig. 15c), the plug is long enough to support a well-developed expansion process

while still achieving substantial structural simplification. The exit Mach number of 3.44 matches that of the longest truncated design. The shear layer remains controlled, and the base wake is compressed, reducing pressure loss. Flow uniformity at the exit improves significantly compared to shorter truncation levels. This configuration represents a strong balance between thrust performance and geometric efficiency. The full-length scenario (untruncated) at $NPR = 13.3$ is shown in Fig. (16) as a baseline reference.

5.3. Performance Trends and Optimum Truncation Level

5.3.1. Net Axial Thrust

Figure (17) shows the variation of net axial thrust with truncation level for $NPR = 8.0$ and $NPR = 13.3$. For both operating conditions, the 50% truncation provides the highest thrust, yielding 4556.82 N at $NPR = 8.0$ and 5204.34 N at $NPR = 13.3$ (Table 3). The 40% truncation produces lower thrust, consistent with reduced expansion surface area and stronger wake-related losses. Beyond 50% truncation, thrust decreases markedly for both NPRs, with the 75% case producing the lowest thrust (2692.32 N at $NPR = 8.0$; 2687.72 N at $NPR = 13.3$). This indicates that *thrust does not increase monotonically with plug length*; instead, an optimum is obtained when improved expansion is not outweighed by truncation-related base/wake and flow-structure penalties.

5.3.2. Base Pressure Recovery

The effect of truncation level on base pressure is shown in Fig. (18). Base pressure clearly increases with truncation level for both NPR values, rising from approximately 1.88 MPa at 40% to 2.31 MPa at 75% aerospike truncations (Table 3).

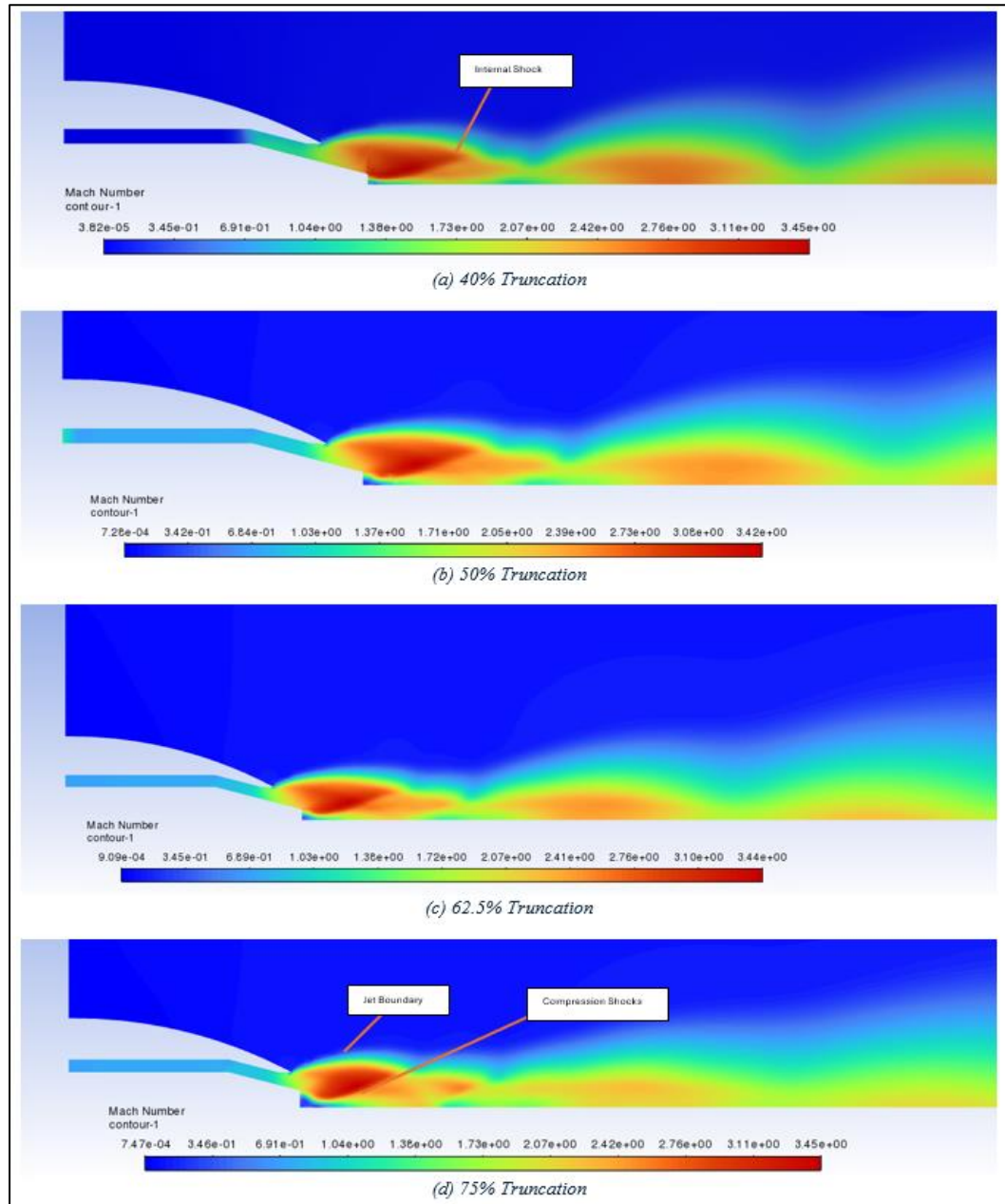


Figure 15: Mach number contours for truncated conical aerospike nozzles at $NPR = 13.3$: (a) 40% truncation, (b) 50% truncation, (c) 62.5% truncation, and (d) 75% truncation.

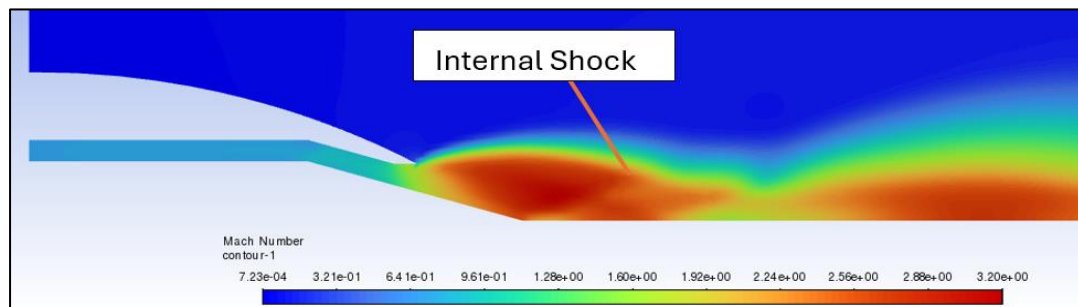


Figure 16: Mach number contours for the full-length (0% truncation) conical aerospike nozzle at $NPR = 13.3$.

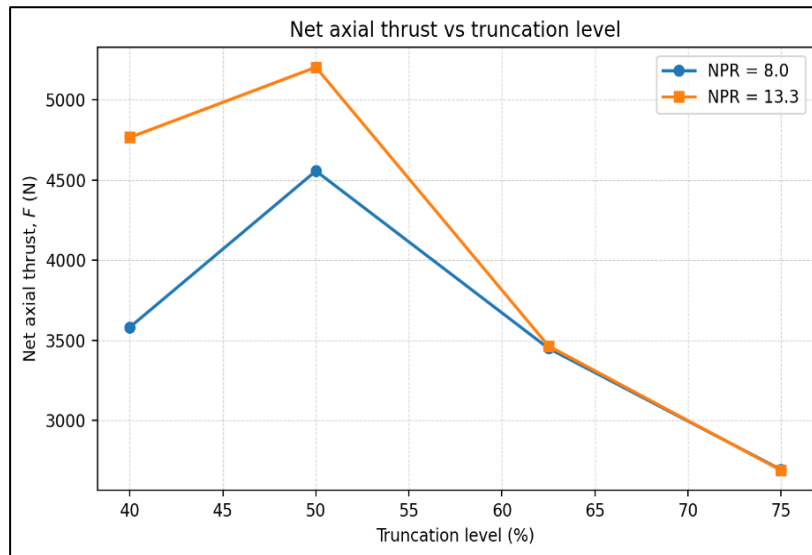


Figure 17: Net axial thrust variation with truncation level for $NPR = 8.0$ and $NPR = 13.3$.

Table 3: ANSYS FLUENT CFD Results (P_b , F , P_e , u_e) for Truncation Levels of 40–75% at $NPR = 8.0$ and $NPR = 13.3$

Case No.	Truncation Level	NPR	P_b [Pa]	Axial Thrust [N]	Exit Pressure P_e [Pa]	Exit Velocity U [m/s]
1	40%	8	1878636.1	3581.5333	420659.83	851.99132
2	50%	8	2015472.5	4556.8223	381980.21	883.79699
3	62.50%	8	2189038.2	3449.8483	340768.66	912.53487
4	75%	8	2306011	2692.3162	368357.4	879.23026
5	40%	13.3	1868806.9	4766.4819	274601.59	833.92251
6	50%	13.3	2014821.5	5204.3425	253935.5	874.40136
7	62.50%	13.3	2189180.2	3464.818	247474.73	896.55251
8	75%	13.3	2306111.6	2687.7169	266801.32	866.98646

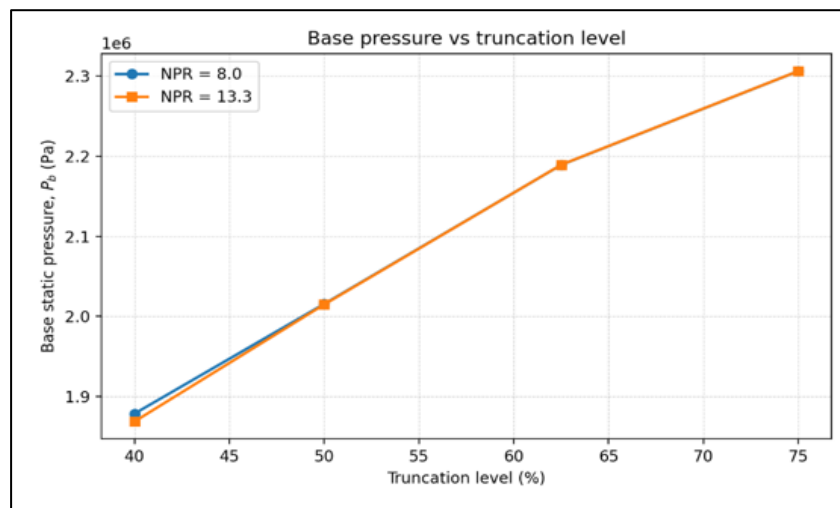


Figure 18: Base static pressure variation with truncation level for $NPR = 8.0$ and $NPR = 13.3$.

This trend indicates improved wake pressure recovery as the plug length increases, consistent with a more developed shear layer and reduced recirculation losses in the base region. However, higher base pressure alone does not guarantee higher net thrust, highlighting that thrust performance is controlled by the *combined contribution of base pressure recovery and overall plume expansion effectiveness*.

5.3.3. Exit Velocity and Exit Pressure Behaviour

Figures (19 and 20) show the trends in exit velocity and exit static pressure with truncation level. Exit velocity increases from 40% to 62.5% truncation for both NPR values, reaching a maximum at 62.5%

(912.53 m/s at $NPR = 8.0$; 896.55 m/s at $NPR = 13.3$), before decreasing slightly at 75%. Exit pressure decreases from 40% to 62.5%, indicating progressively more complete expansion, followed by a modest increase at 75%. This behaviour suggests that truncation levels beyond 62.5% may begin to introduce local flow recompression and/or reduced jet coherence near the trailing section of the plug. Importantly, the configuration with the highest exit velocity (62.5%) does not produce the highest thrust, reinforcing that optimum performance arises from a balance between expansion quality and losses associated with base-wake interaction and shock/expansion structure.

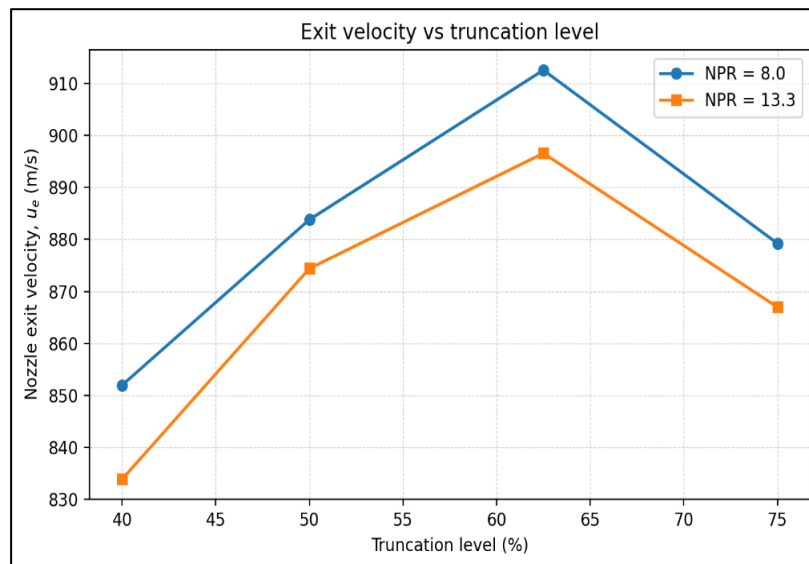


Figure 19: Area-averaged exit velocity variation with truncation level for $NPR = 8.0$ and $NPR = 13.3$.

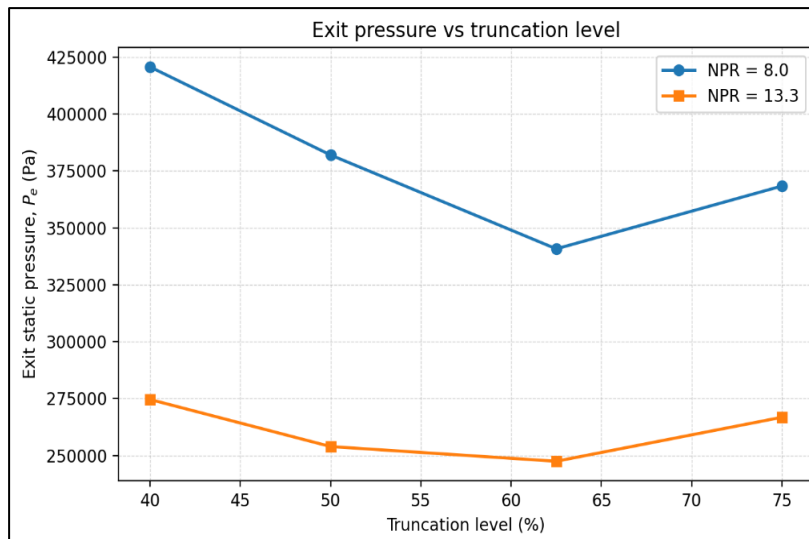


Figure 20: Area-averaged exit static pressure variation with truncation level for $NPR = 8.0$ and $NPR = 13.3$.

5.3.4. Optimum Truncation Selection

Considering the combined trends in thrust, base pressure recovery and exit conditions (Table 3), the 50% truncation configuration is identified as the optimum within the range studied for both $NPR = 8.0$ and $NPR = 13.3$. While longer plugs (62.5–75%) improve base pressure recovery and can enhance exit acceleration, the overall net thrust is reduced, implying that the additional plug length introduces losses that outweigh the benefits of increased expansion. Fig. (21) gives a histogram comparing all simulation cases with different truncation levels.

Inspection of Fig. (21) reveals that the 50% truncation case is the most balanced and efficient configuration. It delivers several distinct advantages:

- The highest thrust output across NPR conditions,
- Strong base pressure recovery
- High exit velocity
- Effective wake control without the drawbacks of overextension.

This truncation level offers a favourable trade-off between geometric simplification and aerodynamic performance, making it an ideal candidate for optimizing future plug nozzle designs in altitude-compensating rocket propulsion systems.

6. CONCLUSIONS

Two-dimensional axisymmetric supersonic flow simulations have been conducted with ANSYS FLUENT software to quantify the influence of plug truncation on the flowfield and performance of a conical aerospike nozzle for rocket propulsion. Four truncation ratios (40%, 50%, 62.5% and 75%) were assessed at two operating conditions ($NPR = 8.0$ and 13.3) using consistent meshing and solver settings. The Mach number contours at both NPR conditions, together with the full-length reference cases (untruncated), have identified intricate flow characteristics (Mach contours, pressure distributions, velocity fields) which impact on the propulsion performance i.e. thrust, base pressure recovery etc. Mesh independence and validation with previous experimental studies have been included. The main findings of the current study can be crystallized as follows:

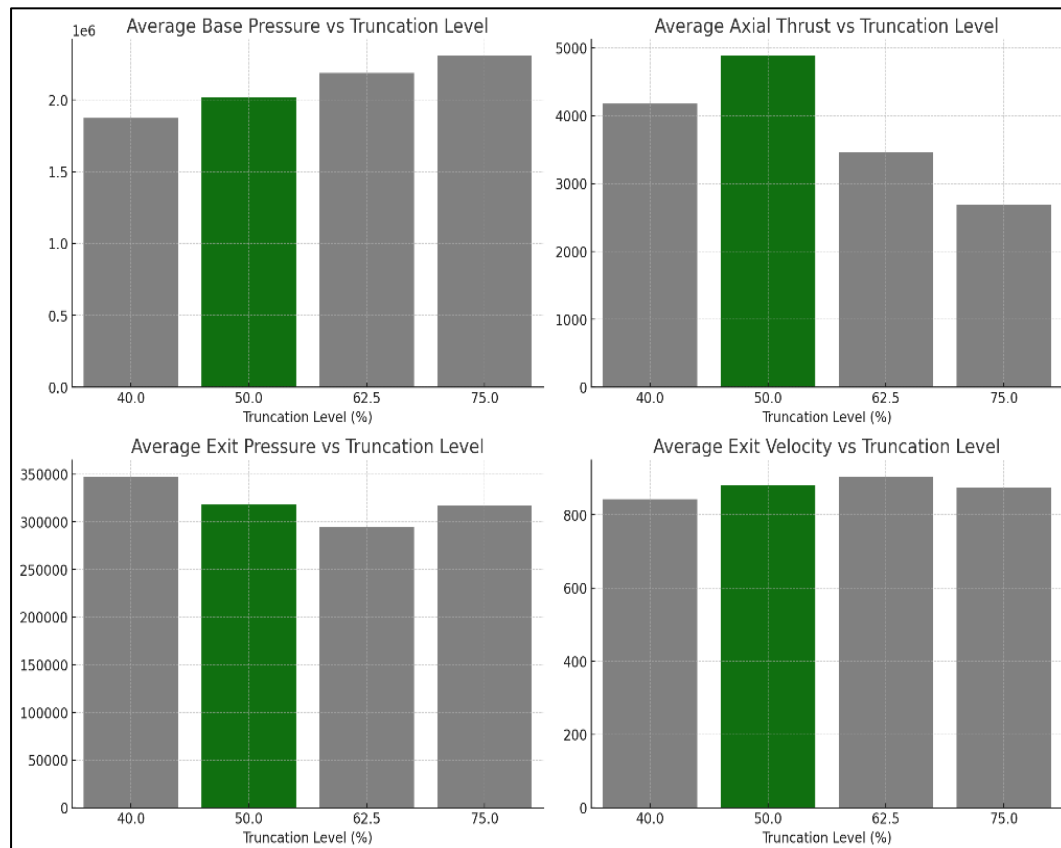


Figure 21: Summary of propulsion performance for different truncation level aerospike configurations simulated.

- I. Aerospike truncation modifies the post-tip shear-layer development and the size/closure behaviour of the base recirculation region, which directly affects base pressure recovery and net thrust.
 - II. Across both NPR values, the results demonstrate that thrust does not increase monotonically with increasing plug length. The 50% truncation produced the highest net axial thrust at both operating conditions, achieving 4556.82 N at NPR = 8.0 and 5204.34 N at NPR = 13.3. The shortest configuration (40%) delivered lower thrust, consistent with reduced effective expansion surface area and stronger base/wake penalties. Beyond 50% truncation, thrust decreased substantially, with the 75% case producing the lowest thrust values at both NPRs. This confirms the presence of an optimum truncation level where the benefits of additional expansion surface are not outweighed by changes in shock/expansion structure and wake-related losses.
 - III. Truncating the aerospike plug alters both the geometry and the flow structure within the nozzle. While it offers structural and thermal advantages, the aerodynamic implications vary significantly with truncation length. The simulation results clearly show that truncation introduces base flow separation, reduces surface area for expansion, and affects shock structure, all of which influence nozzle performance.
 - ii. At lower truncation levels (e.g., 40%), the plug is too short to allow complete expansion. This causes strong wake formation and pressure deficits behind the base, leading to reduced thrust and poor base pressure recovery. At the opposite end, longer plugs (75%) allow for improved base pressure but fail to maintain peak thrust due to increased drag and less effective momentum transfer.
 - iii. Base pressure recovery increased steadily with truncation level for both NPR values, rising from approximately 1.88 MPa (40%) to 2.31 MPa (75%), consistent with improved wake pressure recovery as the plug length increases. However, direct comparison of thrust and base-pressure trends shows that higher base pressure alone does not guarantee higher thrust; overall performance is governed by the combined contributions of base pressure recovery, plume expansion effectiveness along the plug, and local recompression/shock interactions. Exit-plane trends further support this trade-off.
 - iiii. The maximum exit velocity occurred at 62.5% truncation for both NPR conditions reaching 912.53 m/s (NPR = 8.0) and 896.55 m/s (NPR = 13.3), while exit static pressure decreased from 40% to 62.5% before increasing slightly at 75%. Very significant is the observation that the configuration with the highest exit velocity (62.5%) did not yield the highest thrust, reinforcing that optimum performance arises from a balance between expansion quality and truncation-induced base/wake penalties rather than from any single metric.
 - iiv. Overall, within the truncation range studied (40–75%), the CFD results identify 50% truncation as the most favourable configuration for net thrust at both NPR = 8.0 and NPR = 13.3, providing a practical compromise between geometric simplification and propulsion performance.
- While the present simulations have revealed some complex flow structures directly impact propulsion performance, a number of simplifications have been made. The present work is restricted to truncated aerospike nozzles under steady-state, isothermal conditions. A number of robust pathways are available for refining the present work:
- i. *Transient and Unsteady Flow Analysis:* Future work should explore time-dependent simulations to capture wake oscillations, vortex shedding, and dynamic pressure fluctuations — especially at lower NPRs.
 - ii. *Base Bleed and Flow Control Techniques:* Inspired by Nair *et al.* [6] and Merryman *et al.* [20] incorporating base bleed strategies may recover lost base pressure in short truncation designs and further enhance thrust.
 - iii. *Thermo-structural effects and Wall Heat Transfer:* This study assumed adiabatic walls. Including heat transfer and thermal protection system (TPS) modelling could assess thermoelastic structural material response via flow-structure interaction (FSI) and cooling requirements. High temperature corrosion may also be addressed [21] which can include erosion via ablation on the propulsion nozzle walls using a discrete phase model (DPM) in ANSYS FLUENT.

- iv. *3D Geometry Modelling*: While 2D axisymmetric results are efficient and informative, and provide a very good stepping stone, real-world rocket engines require full 3D analysis which would refine performance predictions, although it is more costly.
- v. *Optimization Techniques*: Using tools such as genetic algorithms or surrogate modelling could optimize spike contour and truncation level simultaneously for even greater performance.
- vi. *Experimental Validation*: While corroboration with Verma's experiments [3] has been included, building a scaled physical model in a thermal supersonic wind tunnel or hot-fire testing would provide further crucial data for validating CFD models and calibrating more complex simulations.
- vii. *Turbulence characteristics computation*. Although turbulent simulations were conducted using the SST $k-\omega$, detailed visuals of turbulence kinetic energy, eddy dissipation, turbulent Prandtl number etc, were not included. These will be communicated soon and compared with other turbulence models including LES (large eddy simulation) [22, 23]. LES offers the advantage in ANSYS FLUENT that eddies with a wide range of length and time scales can be accommodated without the need for direct numerical simulation (DNS). The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of turbulence kinetic energy.
- viii. Additionally radiative heat transfer and non-Newtonian gel propellants may be considered using a variety of rheological models such as the Jeffreys viscoelastic model [24] and second grade differential model [25].

Efforts in these directions are underway and will be reported imminently.

NOMENCLATURE

Roman

- A — Area (m^2)
- A_t — Throat area (m^2)
- C_f — Thrust coefficient (—)
- F — Axial thrust (N)
- L — Full-length aero-spike plug length (m)
- L_t — Truncated plug length (m)

- M — Mach number (—)
- $\dot{m}$ — Mass flow rate ($\text{kg}\cdot\text{s}^{-1}$)
- NPR — Nozzle pressure ratio, P_0/P_a (—)
- P — Static pressure (Pa)
- P_0 — Stagnation (total) pressure (Pa)
- P_a — Ambient pressure (Pa)
- r — Radial coordinate (m)
- T — Static temperature (K)
- u — Velocity magnitude ($\text{m}\cdot\text{s}^{-1}$)
- γ — Ratio of specific heats (—)
- ρ — Density ($\text{kg}\cdot\text{m}^{-3}$)
- μ — Dynamic viscosity ($\text{Pa}\cdot\text{s}$)
- k — Turbulent kinetic energy ($\text{m}^2\cdot\text{s}^{-2}$)
- ω — Specific dissipation rate (s^{-1})

Subscripts

- a — Ambient condition
- b — Base region
- e — Exit condition
- t — Throat condition
- 0 — Stagnation (total) condition

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

O. Anwar Bég originated the concept, conducted material and data acquisition for high speed gas dynamics, organized and supervised the simulations, contributed to the turbulence model selection and implementation, and edited the discussion and references; **C. Okuzu** conducted the ANSYS FLUENT simulations and produced the graphs and some of the discussion; **Tasveer A. Bég** prepared the introduction and contributed to the discussion, formatting, mathematical equations, pressure effects, conclusions and references; **M.M. Bhatti** organized the layout, conducted data verification and interpretation and interpretation of the results; **S. Kuharat** collaborated on the ANSYS FLUENT simulations and the geometric figure designs; **Henry J. Leonard** advised on the commercial case studies, axial thrust dynamics,

supersonic flow conditions and also contributed to the interpretation and plug length effect aspects; **Ali Kadir** participated in the mathematical modelling, guided on the design and parametric study for plug length nozzle pressure ratio and base pressure effects and also finalized the references and case study images; **Walid S. Jouri** contributed to the aerospike case studies, pressure conditions for the simulations, material data, and design implications. The manuscript was written and revised through the contribution of all 8 authors. **All 8 authors** discussed the results, reviewed, and approved the final version of the manuscript.

REFERENCES

- [1] Flinn ED. Aerospike engine powers RLV savings. *Aerospace America*. 1996 Nov;34(11):18-19.
- [2] Letchworth G. X-33 Reusable launch vehicle demonstrator, spaceport and range. In: *AIAA Space 2011 Conference and Exposition*; 2011 Sep 27-29; Long Beach, CA, USA. AIAA 2011-7314; 2011.
- [3] Verma SB. Performance characteristics of an annular conical aerospike nozzle with freestream effect. *AIAA J Propulsion and Power*. 2009;25(3):783-791.
- [4] Korte JJ, Trexler CA, Spaid FW. Investigation of altitude compensation for aerospike nozzles. Hampton, VA: NASA Langley; 1997 Feb. NASA Technical Memorandum 19970014941.
- [5] Hagemann G, Immich H, Terhardt M. Flow phenomena in advanced rocket nozzles - The plug nozzle. In: *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*; 1998 Jul 13-15; Cleveland, USA. AIAA Paper 98-3522; 1998.
- [6] Nair PP, Suryan A, Kim HD. Computational study on flow through truncated conical plug nozzle with base bleed. *Propulsion and Power Research*. 2019;8(2):108-120.
- [7] Sullivan G. CFD and heat transfer analysis of rocket cooling techniques on an aerospike nozzle [MSc thesis]. Statesboro, GA: Georgia Southern University; 2022.
- [8] Verma SB, Stark R, Haidn O. Relation between shock unsteadiness and the origin of side-loads in a thrust optimized parabolic rocket nozzle. *Aerospace Science and Technology*. 2006;10(6):474-483.
- [9] Dutton JC, Carroll BF. A review of shock wave/boundary-layer interactions in high-speed flows. *Progress in Aerospace Sciences*. 1989;26(5):413-485.
- [10] ANSYS FLUENT Theory Manual. Version 25. New Hampshire, USA: ANSYS Inc.; 2025.
- [11] Daud HA, Li Q, Bég OA, Ghani SAA. Numerical investigations of wall-bounded turbulence. *Proc Institution of Mechanical Engineers - Part C: Journal of Mechanical Engineering Science*. 2011;225:1163-1174.
- [12] Bég OA, Kuharat S, Bég TA, Pattison J, Kadir A, Jouri WS. Two-way fluid-structure interaction hydroelastic simulation of vibrating membranes with applications in marine renewable wave power. In: *Soni A, Tripathi D, Sahariya J, Sharma KN, editors. Eco-Materials and Green Energy for a Sustainable Future*. USA: CRC Press; 2024. p. 295-329.
- [13] Menter FR. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*. 1994;32(8):1598-1605.
- [14] Versteeg HK, Malalasekera W. *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*. 2nd ed. Harlow, England: Pearson; 2007.
- [15] Miller A, Bég OA, Bég TA, Bhatti MM, Kuharat S, Kadir A. Computational fluid dynamics simulation of rotor blade aerodynamics for the Mars ingenuity helicopter. *J Computational Applied Mechanics*. 2026;57(2):296-325.
- [16] Angelino G. Approximate method for plug nozzle design. *AIAA Journal*. 1964;2(10):1834-1835.
- [17] Rao GVR. Exhaust nozzle contour for optimum thrust. *Jet Propulsion*. 1958;28(6):377-382.
- [18] Gorle S, Chaganti SS, Mandapudi S, Gudikandula S, Dussa G. Three-dimensional computational flow simulation of truncated aerospike nozzle considering different plug lengths. *Indian Journal of Science and Technology*. 2017;10(13).
- [19] Escher WJD, Kaye TG. XRS-2200 linear aerospike rocket engine. *Journal of Propulsion and Power*. 2000;16(4):620-625.
- [20] Merryman EL, et al. Supersonic drag reduction via base bleed technique. *Journal of Propulsion and Power*. 2005;21(2):240-247.
- [21] Kadir A, Bég OA, El Gendy ME, Bég TA, Shamshuddin M. Computational fluid dynamic and thermal stress analysis of coatings for high-temperature corrosion protection of aerospace gas turbine blades. *Heat Transfer*. 2019;48(6):2302-2328.
- [22] Chen H, Sun M, Xiong D, Yang Y, Wang T, Wang H. Large eddy simulation of supersonic flow in ducts with complex cross-sections. *Theoretical and Applied Mechanics Letters*. 2023;13(6):100469.
- [23] Smirnov R, Shi S, Celik I. Random flow generation technique for Large Eddy Simulations (LES) and particle-dynamics modelling. *ASME Journal of Fluids Engineering*. 2001;123:359-371.
- [24] Waqas M. Diffusion of stratification based chemically reactive Jeffrey liquid featuring mixed convection. *Surfaces and Interfaces*. 2021;23:100783.
- [25] Waqas M. Analysis of thermally radiative magnetized viscoelastic (second grade) fluid by impermeable vertical cylinder. *Waves in Random and Complex Media*. 2026;35(7):12952-12966. DOI: 10.1080/17455030.2022.2139006.

<https://doi.org/10.66000/3110-9780.2026.02.05>

© 2026 Bég *et al.*

This is an open access article licensed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>) which permits unrestricted use, distribution and reproduction in any medium, provided the work is properly cited.