Numerical investigation of flow separation behavior in an over-expanded annular conical aerospike nozzle

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Abstract A three-part numerical investigation has been conducted in order to identify the flow separation behavior—the progression of the shock structure, the flow separation pattern with an increase in the nozzle pressure ratio (NPR), the prediction of the separation data on the nozzle wall, and the influence of the gas density effect on the flow separation behavior are included. The computational results reveal that the annular conical aerospike nozzle is dominated by shock/shock and shock/boundary layer interactions at all calculated NPRs, and the shock physics and associated flow separation behavior are quite complex. An abnormal flow separation behavior as well as a transition process from no flow separation at highly over-expanded conditions to a restricted shock separation and finally to a free shock separation even at the design condition can be observed. The complex shock physics has further influence on the separation data on both the spike and cowl walls, and separation criteria suggested by literatures developed from separation data in conical or bell-type rocket nozzles fail at the prediction of flow separation behavior in the present asymmetric supersonic nozzle. Correlation of flow separation with the gas density is distinct for highly over-expanded conditions. Decreasing the gas density or reducing mass flow results in a smaller adverse pressure gradient across the separation shock or a weaker shock system, and this is strongly coupled with the flow separation behavior. The computational results agree well with the experimental data in both shock physics and static wall pressure distribution at the specific NPRs, indicating that the computational methodology here is advisable to accurately predict the flow physics.

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1. Introduction

The flow separation in supersonic convergent–divergent nozzles is a basic fluid-dynamics phenomenon that occurs at a certain nozzle pressure ratio (NPR), resulting in the presence of shock waves and shock/boundary layer interactions inside nozzles. It has been the subject of various experimental and
numerical studies in the past. Today, with the renewed interest in supersonic flights and space vehicles, the subject has become increasingly important, especially for aerospace applications for rockets, missiles, supersonic aircraft, etc. There has been a widespread desire to investigate features with shock/boundary layer interactions in highly over-expanded rocket nozzles, since these interactions are responsible for acoustic, vibrate-acoustic, thermal, and mechanical-induced loads that act on the structure. Conventional bell-type nozzles suffer from the above interactions with reduced engine performance at low-altitude highly over-expanded conditions due to fixed geometries. Based on the above background, different types of nozzle concept with altitude-adapting capabilities have been developed and tested on the ground in the past, and the aerospike nozzle is included as a strong contender for the propulsion system of reusable spacecraft. In the recent years, a renewed interest in the aerospike nozzle flowfield has been generated for both rocket and aeronautic applications. However, while flow separation in over-expanded planar or bell ideal and optimized contour nozzles has been widely investigated to elucidate the phenomenon of boundary layer separation and shock interactions, aerospike nozzles have received little attention in the frame of this study. Verma\textsuperscript{4} and Kapilavai et al.\textsuperscript{7} presented pioneering work upon flow separation behavior in aerospike nozzles that operated at NPRs below 10, and both of the two studies indicated that the presence of flow phenomenon was associated with nozzle flow separation, and unsteady shock oscillation induced by the interaction of the shock/boundary layer seen in conventional supersonic nozzles with diverging sections could also be expected in aerospike nozzles at off-design operating NPRs. In spite of few rare studies on this subject, understanding of the flow separation behavior as well as fundamental knowledge of supersonic flow physics in the presence of shock wave propagation, shock reflection at walls, and shock/shock and shock/boundary layer interactions in such a convergent-divergent nozzle are still needed.

Studies of flow separation in supersonic nozzles dated back to the 1960s with the first work of Arens and Spiegler\textsuperscript{8}, who published the first approach to include the Mach number influence in the theoretical prediction of free shock separation. Schmucker\textsuperscript{9} continued the research through the later years in the 1970s, and based on a simplified boundary layer integral approach, Schmucker proposed the famous purely empirical criterion for free shock separation (FSS) which is still widely used to date. From several experimental studies, performed on either full-scale\textsuperscript{10} or subscale\textsuperscript{11–13} optimized nozzles, and corroborated by different numerical simulations\textsuperscript{14–18}, the presence of two distinct flow separation patterns, namely FSS and restricted shock separation (RSS), is demonstrated. A transition in the separation pattern from FSS to RSS and vice-versa might occur, which was firstly observed in the early 1970s by Nave and Coffey.\textsuperscript{10} At the initial state of start-up or when a supersonic nozzle operates at low NPRs, the flow mostly resides in an FSS state\textsuperscript{19}, as shown in Fig. 1. A single incipient separation of the flow along the interior surface of the nozzle is triggered by an adverse pressure gradient between the regions of isentropic expansion and subsonic entrainment. The shock that originates from the incipient separation line interacts with a reflected shock; this shock emanates from the triple-point which is the location where the Mach disk, internal and reflected shocks coincide. In the FSS state, a separation region forms which encompasses a series of compression/expansion waves, and this separated flow fails to reattach back to the wall at low NPRs due to the lack of outward radial momentum as a free supersonic annular jet. A recirculating subsonic region forms between the separated free annular jet and the nozzle wall, which entrains ambient air along the nozzle wall and adapts the static wall pressure to the ambient condition. The RSS state refers to the canonical shock/boundary layer interaction which is present in many high-speed devices. For example, RSS is known to occur in thrust optimized parabola nozzles of engines like Vulcain, space shuttle main engine (SSME), or J-2S during the start-up process. RSS is characterized by a small separation region or bubble which exists immediately downstream from the shock wave, in which the mean flow circulates and separates or tilts away from the wall before

Fig. 1  Illustration of the internal shock structure in a thrust optimized parabolic nozzle during an FSS state.\textsuperscript{20}
the flow reattaches and continues down the length of the nozzle as an attached boundary layer. Depending on the nozzle contour and expansion ratio, more than one bubble may be present, as shown in Fig. 2. Upon further increases in the NPR, the RSS flow regime will translate downstream and the enclosed separation bubble opens up to the ambient environment when passing over the nozzle lip. When the last annular separation bubble downstream from the incipient separation shock opens up, the flow structure then switches to an FSS state due to the presence of a single separation shock with an associated separated flow region downstream.

In the past, many researchers from different groups in Europe, USA, and Japan have distinguished these flow separation behaviors in rocket nozzles and have identified a transition phenomenon between the two separation regimes during the start-up or shut-down process. In a typical rocket engine, the combustion chamber pressure rises from the ambient pressure to the steady-state operating condition, and flow separation occurs when the chamber pressure is relatively low, so as to yield a static wall pressure much lower than the ambient one in some locations of the nozzle divergent. During the start-up process, the nozzle flow is popularly dominated by the FSS structure, and then when the combustion chamber pressure rises over a certain critical value, the FSS regime is replaced by the RSS regime. The identification of this transition is important for nozzles applications in rocket engines or supersonic aircraft, as it is directly attributed to the largest lateral loads seen during their operations.

Previous studies on this subject have also shown that these flow separation behaviors in rocket nozzles and nozzle performance in two classic aerospike nozzle concepts, the conical annular and linear with low-angle plug configurations, truncated and full length with or without freestream effects were also considered. For an over-expanded annular conical aerospike nozzle, it was observed that the over-expansion shock from the internal nozzle, the over-expansion shock on the spike surface, and the expansion fan from the cowl lip of the internal nozzle dominated the overall flowfield development. Increasing the NPR changes the angles of these shocks as the internal nozzle operates from the over-expanded to the under-expanded condition. This produces three different types of flow separation conditions on the spike. The paper gave an idea of the flowfield once the shock moved out of the internal nozzle, while the flow features when the shock structure resided within the internal nozzle section at lower NPRs were not available. However, complex shock physics and flow features can be expected in this spectrum of NPRs as indicated by present numerical studies.
dominated by shock/shock and shock/boundary layer interactions at all off-design NPRs. Depending on shock interaction with the boundary layer on the plug wall, the nozzle exhibited both fully separated and reattached boundary layer regimes. However, it should be noted that the shrouded plug nozzle whose shroud or cowl extends over a considerable portion offers both aerodynamic and structural characteristics with respect to a more conventional aerospike nozzle. These results and comments indicate that a coupled research effort between experiment and numerical simulation is needed to fully understand the shock physics in aerospike nozzles for the complete spectrum of nozzle pressure ratios.

The current work attempts to reproduce and to expand the experimental studies of Verma. The aim of the paper is to numerically study in detail the flow separation behavior at sea-level as well as imposed high-altitude simulation conditions without freestream flow, for the purpose of providing an insightful understanding of the shock physics and characteristics of shock/shock and shock/boundary layer interactions at various operating conditions, from highly over-expanded conditions to the designed point of the nozzle, in particular, the shock-induced flow separation behavior and its evolution process with the change of NPR. A comparison of the separation data against a series of separation criterions forms literature is conducted to address their applicability for the prediction of flow separation behavior in such an asymmetric supersonic nozzle. Additionally, a comparison of flow separation behavior at sea-level conditions against the imposed high-altitude simulation conditions is to demonstrate the gas density effect on afore-mentioned flow characteristics in present aerospike nozzles; in particular, its effect on the flow separation behavior in highly over-expanded conditions has been studied when more complex shock/boundary layer interactions can be expected.

2. Numerical analysis

2.1. Experimental details and modeling

The experimental work performed on the present aerospike nozzle was carried out in a 0.5-m base flow facility, a special purpose blow-down-type tunnel, detailed in Ref. The salient features relevant to this study are shown in Fig. 3, in which the 15° half-angle θ annular conical aerospike nozzle model with a design Mach number of 2.0 was mounted on the central cylindrical inner body. The afterbody contour was designed based on the recommendations given in Ref. To obtain the steady pressure distribution on the spike, up to 12 pressure points with a pitch of 4.0 mm were installed at axial locations along a single line on the spike surface. The nozzle exit radius r_e is 25 mm, the annular gap at the throat section h_i is 9 mm, and the length of the spike or plug L is 59.71 mm. The aerospike nozzle area ratio is defined as the ratio of the area at the spike end A_s to the annular throat area A_t. The length of the cowl, measured as the distance from the throat section to the cowl lip, l is fixed as 9.0 mm, resulting in an area ratio of the inner nozzle e_i = 1.19.

In the present case, a modified experimental annular conical aerospike nozzle model is used, resulting in an annular axisymmetric nozzle configuration, as seen in Fig. 3, where the flow phenomena of primary interests takes place. The modified section to house the plug nozzle is not included in the axisymmetric computations; this strut is unlikely to have major effect on the nozzle flowfield as it is located in the upstream subsonic convergent section of the nozzle. A straight annular tube similar to the one in the experiments is utilized in the present numerical model to provide an area-constant expansion region until the subsonic streams reach the beginning of the nozzle convergence.

2.2. Flow conditions

The computational flow conditions reproduce and extend on the experimental conditions, that is, NPR covers a wide range of 1.60–9.87, corresponding to the unchoked subsonic condition to a slightly under-expanded condition. In the experiments, NPRs were conducted as 2.10 ≤ NPR ≤ 5.75 for the full-length spike analysis. As indicated in Section 2.1, the presence of the cowl results in an additional diverging section of the shock interacting with the boundary layer on the upstream spike and cowl surface at low NPRs, where the main flow phenomena were unable to be captured by the schlieren images in the experiments. The present NPRs design will provide a complete flow expansion spectrum for such a supersonic nozzle configuration.

Three environment back pressure, p_b, or ambient pressure, p_a, conditions are designed to conduct the gas density effect analysis, as shown in Table 1. In Table 1, p_ON is the total pressure at the nozzle inlet. Comparisons are made between a sea-level case and two imposed high-altitude simulation cases with
back pressure values of 50% and 25% of the sea-level ambient pressure condition, respectively. The NPRs conducted are identical for all three cases. The objective of the simulation is to assess the impact of the low ambient pressure environment, resulting in low nozzle total pressure and then low gas density for the NPR mimic on the shock structures and flow separation characteristics. In the present study, the Reynolds number is based on the hydraulic diameter defined as the incipient separation location ranged from $1.59 \times 10^6$ to $34.93 \times 10^6$, corresponding to a fully turbulent boundary layer.

### 2.3. Numerical procedure

The numerical study has been conducted using a finite-volume unsteady Reynolds-averaged Navier–Stokes (RANS) solver. The two-equation shear stress transport (SST) model of Menter et al. is used here to describe the turbulence. Previous successful efforts to compute the internal nozzle separated flow using RANS-type models by Hunter, Xiao et al., and Carlson indicate that the SST model provides a reasonable prediction of flow separation just downstream from the shock caused by the shock/boundary layer interaction inside the nozzle, and therefore the best capture of the shock location and pressure distribution against the experiment. In present study, all computations are made using the axisymmetric assumption with a primary motive of a fast and efficient means of obtaining insight into the relevant shock structure and flow separation behavior at various operating conditions. Later, when the computational results are compared with the experimental data, it will be shown that the axisymmetric assumption is accurate for the prediction of salient shock physics as well as static wall pressure.

Fig. 4 shows the nozzle numerical model, including the detailed grid distribution in the nozzle region where the flow phenomena of primary interest take place. The computational domain includes the domain inside the nozzle and an ambient region around the outer surface. The domain extends $15D$ (where $D$ is nozzle exit diameter) upstream from the throat, more than $40D$ downstream, and $10D$ in the direction perpendicular to the axis. In terms of grid structure, multi-block structured grids have been used in this calculation and are shown in Fig. 4(b). Only every second grid line in each direction is displayed for clarity. For the nozzle region, grid density is higher in the divergent part of the nozzle to improve the resolution for capturing shocks. In addition, the grid is clustered along the cowl and spike walls to resolve the boundary layers, for a Reynolds number based on an order of $10^6$, and the first grid point from either the spike or the cowl wall gives a $y^+ < 1$. A detailed discussion of the grid convergence study is reported in the next section.

Fixed total conditions have been employed for the outer-face boundary, outlet upstream, outlet lateralface, and outlet downstream, the total pressure is set to the ambient pressure, and the boundary condition is designed in such a way that the supersonic plume may go out of the boundary, while the ambient air may come into the boundary due to the possible plume entrainment effect. The total pressure and the total temperature at the nozzle inlet are specified to be

### Table 1

<table>
<thead>
<tr>
<th>Ambient pressure conditions</th>
<th>Case No.</th>
<th>NPR</th>
<th>$p_{ON}$ (kPa)</th>
<th>$p_a$ (Pa)</th>
<th>Mass flow rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea-level atmosphere</td>
<td>1-1</td>
<td>1.60</td>
<td>9.87</td>
<td>162.12–1000.09</td>
<td>103125</td>
</tr>
<tr>
<td>50% of sea-level ambient pressure</td>
<td>1-2</td>
<td>1.60</td>
<td>9.87</td>
<td>81.06–500.04</td>
<td>50662.5</td>
</tr>
<tr>
<td>25% of sea-level ambient pressure</td>
<td>1-4</td>
<td>1.60</td>
<td>9.87</td>
<td>40.53–250.02</td>
<td>25331.25</td>
</tr>
</tbody>
</table>

Fig. 4 Illustrations of the nozzle numerical model: (a) overall computational domain, both inside and outside the nozzle, and (b) a close-up view of mesh topology in vicinity of the nozzle region.
\( p_{ON} = \text{NPR} \times p_a \) and \( T_{ON} = T_a \), respectively. For all cases, the stagnation and the ambient temperature, \( T_{ON} \) and \( T_a \), in the computations are fixed as 300 K, and pure gaseous nitrogen is simulated as the nozzle jet while a perfect gas with the properties of air is treated as the ambient fluid. A no-slip, adiabatic condition is specified for the solid walls, and a symmetric condition is imposed on the nozzle axisline. In addition, the upstream turbulence intensity is prescribed at the nozzle inlet boundary based on the located hydraulic diameter.

Preconditioning is employed for accelerating the calculation at low subsonic NPRs. However, the computed shock structures show the flow to assume a steady state in contrast to the experiment, in which a 1500-Hz peak in frequency can be seen in the region of separation. This is particularly true when RANS-type time-averaged models are utilized to compute an internal nozzle flow with random unsteadiness or distinct acoustic tones. For the present study, all the computations are conducted with an RANS-type modeling method in the primary interest of salient shock structure and flow separation characteristics development as the NPR is increased from low to high values in such an asymmetric supersonic nozzle.

### 2.4. Grid convergence

In order to establish the fidelity of the numerical database, we have conducted a grid convergence study on the nozzle, and a series of three computational meshes has been run. As it is important to accurately capture the salient shock structures and their interaction with the boundary layer which drives the flow separation behavior. We begin the discussions by comparing the computational flow patterns and the static wall pressure profiles at specific NPRs with the data taken from experiments at similar NPRs for the grid convergence study. In the experiments, when increasing the NPR values, the internal nozzle operates from the over-expanded to the under-expanded condition, three types of flow separation patterns can be observed at \( \text{NPR} = 2.10, 2.57, 3.82 \), respectively. The comparisons in this section are all for the above three NPR conditions. Schlieren images have been used in the experiments to help in identifying the first gradients of density, which can exhibit the shock patterns in the flowfield. To make a direct comparison of the computational flowfield with the experimental results, the computational results also use the numerical schlieren pictures contoured by the plots of the absolute values of the first gradients of density at the grid nodes.

The shock-induced flow separation patterns for various mesh resolutions are displayed in Fig. 5, in which the numerical schlieren pictures listed from the first to the third row show the results based on the coarse (Mesh A), medium (Mesh B), and fine grid (Mesh C) cases, respectively. For all the three meshes, the three types of flow separation patterns at specific NPRs are well reproduced, and the numerical results are in very good agreement since the shock structures are very close to each other.

The pressure distributions along the nozzle spike and the cowl wall have also been compared for the three meshes. Fig. 6 shows the static wall pressure \( p_w \) profiles normalized by the ambient pressure, \( p_a \), at the three specific NPRs of 2.10, 2.57, and 3.82, respectively. Again, the plots are really similar for the three meshes, but a slight shift is observed between the coarse grid and the two finer grids. In addition, it is shown that the results for the medium and fine meshes

![Fig. 5](image-url) Comparison of shock-induced flow separation patterns for various mesh resolutions.
collapse almost perfectly. It is noteworthy that the shock structures and location as well as the separation point are well predicted whatever mesh is considered. As a consequence, the so-called fine grid mesh is used in the present study, as the shock pattern captured is more elaborate as the grid is refined in the nozzle flow region, especially in highly over-expanded conditions when more complex shock/boundary layer interaction can be expected.

3. Results and discussion

3.1. Comparison with experiments and validation

Computational results for the three specific NPRs of 2.10, 2.57, and 3.82 have been compared to the data taken from the experiments for the same NPR conditions. The comparisons of flow separation patterns and static wall pressure profiles are shown in Fig. 7. In Fig. 7, Plug-Num and Plug-Exp represent numerical calculation and experiment of plug. The photographs on the second row show the experimental schlieren images, while the ones on the first row show the computational results at the same NPRs. For the three NPRs, three different types of flow separation patterns as well as basic flow characteristics that can be observed are the external jet boundary developing from the cowl lip, over-expansion shocks formed on both the cowl and spike surfaces, and the interaction between them. The computational schlieren clearly replicates these salient flow features. However, an RSS characteristic, separated wake being reattached because of the Coanda effect, is also captured in the computation at NPR = 2.10 while an FSS condition was reported by

![Fig. 6](image-url)  
Static wall pressure profiles of the spike and the cowl for various mesh resolutions.

![Fig. 7](image-url)  
Comparison of static wall pressure distributions and shock-induced flow separation physics between numerical calculations and wind tunnel experiments with no freestream by Verma, Case 1-1, $p_a = 101325$ Pa.
Verma. The numerical schlieren shows the presence of wake reattachment on the spike surface which cannot be distinguished in the experimental schlieren image, and a detailed analysis on the shock physics can be found in a later section. In addition, the experiments used both vertical and horizontal configurations of the knife edge in the schlieren setup. The vertical knife edge helped to identify horizontal gradients, whereas the horizontal knife edge helped to identify the vertical gradients. Note that the upper and lower halves of the experimental flow schlieren exhibit an axisymmetric nature of the shock pattern which indicates that the axisymmetric computational methodology here is advisable to accurately predict the flow physics.

In terms of static wall pressure distribution, as shown in numerical schlieren images on the top row, the static wall pressure distributions along the spike surface are compared. All three plots show good agreement with the experimental results in both shock location and pressure distribution. However, the shock location is under-predicted for all the three NPRs and the miss-prediction expands as the NPR changes from low to high values. This discrepancy may contribute to miss-mimicking the experimental condition. In the experiments, the ambient pressure $p_a$ was measured on the afterbody, 15-mm upstream from the cowl lip, by varying the jet stagnation pressure $p_{st}$ to vary the NPR, and the local ambient pressure $p_a$ decreased with each increase in $p_{st}$ because of the jet entrainment effect. Thus, the NPR defined as the ratio of the upstream total pressure to the ambient pressure, is therefore different for the experiments and the present numerical simulations. Overall, the computational results agree well with the experimental data in both shock physics and static wall pressure distribution, and the characteristics described by both the simulations and the experiments are indicative of the flow physics that are observed at the three NPRs.

3.2. Flow separation and shock structure progression in the nozzle

To understand the details of the flow separation behavior as well as the shock structure motion in the nozzle, computations when the NPR is increased from low to high values are conducted and the numerical schlieren images of shock structures constructed from computational results are summarized in Fig. 8. In this section, the numerical schlieren pictures are also contoured by the plots of the absolute values of the first gradients of density at the grid nodes, and additionally, static wall pressure distribution plots along the cowl and spike surfaces are superimposed on the schlieren pictures in order to help understand the flow physics.

We begin the discussion with NPRs ranging from 1.60 to 1.90 when the shock structure resides within the cowl, but was not captured in the experiments. A prominent feature that can be found in the computational schlieren is that a fully separated shear layer emerges from the throat of the cowl-side, and the shear layer as well as the spike surface forms an aerodynamic diverging passage downstream from the throat region. This phenomenon is absent in an over-expanded conventional nor the similar shrouded plug nozzle reported by Kapilavai et al. Fig. 9 gives a line diagram of the nozzle throat design, in which the aerospike nozzle considered presently has a sharp change in the slope at the throat on the cowl-side, and a turning angle up to 20.37° makes the nozzle inlet total pressure here not high enough to expand the jet to form a wall-bounded flow on the cowl surface by Prandtl–Mayer expansion. As the NPR increases, the separated shear layer moves toward the cowl surface and the flow in the above aerodynamic diverging passage exhibits a multitude of shock structures. Detailed flow physics is seen more clearly in Fig. 10.

For the NPR $= 1.60$ shown in Fig. 8(a), note that the static wall pressure at the throat region is over 0.528 times of the nozzle inlet total pressure, and the flow near the throat region is still unchoked, so no shock structure is captured in the flow field at this NPR condition. When the flow negotiates the throat region, it goes back to a subsonic wall-bounded flow condition on the spike surface. As the NPR increases to 1.80, the throat region starts to choke as shown in Fig. 8(b) and Fig. 10(a), respectively. The shock exhibits an apparent asymmetric structure like a normal shocklet structure on the spike surface, which is similar to what can be discerned in a transonic diffuser at low NPRs while a serial of expansion and compression waves or shocks appears on the cowl-side flow region. As shown in Fig. 10(a), the flow is compressed immediately by the separated shear layer just after an expansion to Mach number 1.24 through an expansion fan at the sharp corner, and then again expands to an over-expansion shock downstream. The expansion fan that emerges from the over-expansion shock foot over-expands the jet finally to a normal shocklet in the diverging section. As the NPR increases to a slightly higher value of 1.90 as shown in Fig. 8(c) and Fig. 10(b), the normal shocklets coalesce in a single normal shock downstream and occupy the entire cross section. However, the shock is still not strong enough to induce the spike wall boundary separation. In this NPR case, the compression waves induced by the separated shear layer now coalesce in an oblique compression shock which travels across the entire stream without the interception of the over-expansion shock observed in the case of NPR $= 1.80$. This oblique compression shock is incident on the spike surface and the reflected shock from the spike surface hits the normal shock downstream. Another feature that can be noticed is the presence of weak expansion and compression waves in the aft region of the normal shock, which seem to be a manifestation of the natural convergent–divergent passage formed downstream from the normal shock, and evidence can also be found from the wavy plots of the static wall pressure distribution along the spike surface.

The separated shear layer finally reattaches on the cowl surface when the NPR is about 1.96, and the flow undergoes shock-induced flow separation on both the cowl and spike surfaces when the NPR increases to 2.00, as shown in Fig. 11(a). A close-up view of the computational result can be found in Fig. 10(c). At this point, the shock structure consists of oblique shocks starting from both the spike and cowl surfaces, and these two oblique shocks occupy the downstream normal shock where their interaction makes the normal shock of the spike-side flow region to curve. The flow along the spike surface separates and reattaches in a short distance forming a small recirculation bubble while the flow is fully separated over the entire length of the cowl just aft of the oblique shock.

As the NPR increases from 2.00 to a slightly higher value, the shock structure in the mean flow starts to move out of the cowl which can be captured by the experimental schlieren images. Increasing the NPR from 2.10 to 3.82 changes the angles of the oblique shocks on both the cowl and spike surfaces and their interaction at the internal nozzle operates from
the over-expanded to the under-expanded condition. As indicated by Verma \textsuperscript{4}, this produces different shock structures as well as shock-induced flow separation behaviors on both the cowl and spike surfaces, which can be classified into three types. Firstly, in the low NPR = 2.10 case, the numerical schlieren shows a shock/boundary layer interaction similar to that seen in planar supersonic nozzles.\textsuperscript{12,43} The shock structure exhibits a Mach reflection,\textsuperscript{44} and oblique shocks starting from both the spike and cowl surfaces anchor a normal Mach stem in the mean flow. The flow along the spike surface separates and reattaches again in a short distance forming a small recirculation bubble, and evidence can be found in figures illustrated in a later section, which are contoured by the static wall pressure distribution and axial value of wall shear stress plots along the spike surface, thus exhibiting a restricted shock flow separation, RSS, condition. However, Verma has reported an FSS characteristic for this NPR case in Ref.\textsuperscript{4}, and this discrepancy may be produced by the undistinguishable wake reattachment in the experimental schlieren image. At this point, the flow separation behavior is not a classical RSS condition, while the mechanism of the wake reattachment is more likely the Coanda effect.\textsuperscript{45,46} The asymmetric flow passage leads to a radial momentum toward the spike-side flow region and the separated shear layer is very close to the spike surface, so the lower pressure in the separation zone works like an extra suction force, in addition to that of the original Coanda effect on the supersonic jet side, ensuring the separated wake to adhere to the wall.

At an intermediate value between 2.57 and 3.12, a second shock structure can be discerned. The length of the normal portion of the normal shock decreases with the increase of the NPR, because the strength of the oblique shock on the cowl surface weakens while the interaction between the oblique shock on the spike surface and the normal shock forms a lambda shock pattern on the spike. Detailed flow physics of such a \(\lambda\)-shock pattern for an NPR of 2.57 is seen more clearly in Fig. 11(f). The flow then reattaches which increases the local static wall pressure above ambient, as shown in Fig. 11(c)–(d). For NPR = 3.82, a third flow condition is produced when the internal nozzle starts to operate in a little under-expanded condition shown in Fig. 11(e). The expansion fan emerges from the cowl lip and over-expands the flow along the spike surface, resulting in the forming of an oblique over-expansion shock, which hits the free shear layer from the cowl lip and induces an expansion fan at the intersection point. The shock pattern on the spike surface that encloses a recirculation bubble indicates that the nozzle is still in the RSS regime. Another feature that can be discerned from the schlieren is that the internal shock originating from the sharp corner of the throat impinges on the spike surface upstream from the separation shock, forming a region of compression that induces a pressure bump shown in Fig. 11(e).
At higher NPRs, the expansion fan impinges further downstream causing the over-expansion shock as well as the flow reattachment point to move downstream. At NPR = 5.22, the over-expansion shock starts to induce a free shock separation condition on the spike, as shown in the axial wall shear stress plots in later section. The length of the separation bubble just covers the entire portion of the spike downstream from the incident separation point; detailed analysis on this flow condition is followed in a later section.

For NPRs above 5.22 through 8.40, the free shock separation is the mode of separation on the spike surface. Increasing the NPR to 5.75 continues to weaken the separation shock on the spike while strengthening the internal shock as well as the expansion fan from the cowl lip, and the region of compression induced by the impingement of the internal shock now produces a distinct pressure bump, as shown in Fig. 12(a). Additionally, an important phenomenon in these NPR cases that should not be neglected is the motion of the separated shear layer away from the spike surface. This behavior indicates a higher pressure in the separation zone to push the shear layer towards the mean flow. The mechanism of the phenomenon may be interpreted by the impinging jet effect. The spike considered here has a simple conical configuration where the annular jet that expands from the end of the spike has an impinging angle of 30°. Even at present the NPR is slightly below the design point, and the separation bubble is enclosed by the annular main flow producing a higher local pressure up to 1.7 times of the ambient pressure as shown in Fig. 13(c). However, this impinging region will not be present if the spike has been contoured.

At NPR’s above 7.75, a new type of shock structure is produced when the internal nozzle starts to operate in a highly under-expanded condition in which an interception shock is generated at the cowl lip while a reflected shock emerges from the spike surface where the internal shock originating from the sharp corner of the throat impinges, as shown in Fig. 12(b). Increasing the NPR to the design point continues to strengthen these shocks. A stronger expansion fan coming from the cowl lip over-expands the flow along the spike surface and leads to the free shock separation formation even in the case of the designed condition shown in Fig. 12(c). For NPR’s above 9.87 shown in Fig. 12(d), the pressure on the spike surface is high enough and no flow separation can be captured.

It is important to note here that unlike a contoured spike configuration in a conventional aerospike nozzle, in which the nozzle achieves expansion to the ambient condition by means of a centered expansion fan generated at the cowl lip and terminated at the spike end at the design condition, the expansion fan hits at shorter distances on the spike, and as a consequence, a series of expansion/compression waves continues till the spike end. In the present case, the non-uniform flow exhausting from the internal nozzle in addition to the conical configuration of the spike surface makes the spike geometry incapable of canceling out all the impinging waves. Firstly, the flow at the exit of the internal nozzle is not uniform, due to the asymmetric expansion fans coming from the nozzle throat and the following compression shock generated by the sharp change in slope at the throat section. Secondly, when the internal nozzle starts to operate in under-expanded conditions, additional asymmetric expansion fans and interception shock are generated from the cowl lip. Finally, the asymmetric flow passage in addition to that impinging jet effect induces a higher back pressure. The result of these phenomena is the formation of stronger compression shock and sustaining over-expansion of the flow along the spike surface to a shock-induced flow separation even at the design condition.
3.3. Static wall pressure and axial wall shear stress profiles

The numerical schlieren images of shock structures constructed from computational results obtain additional shock physics and associated flow separation behavior at various NPR’s against the experimental methodology. In particular, the presence of a restricted shock separation regime at low and moderate NPR’s while a free shock separation regime at high NPR conditions is recognized. In order to further confirm these flow characteristics, the static wall pressure as well as the axial wall shear stress distribution on the spike is instructive. The plot of the axial wall shear stress on the spike can clearly show the separation as well as the reattachment point induced by the incident and separation shocks by that the value decreasing to below zero indicates that the boundary separates at the present point while increasing to above zero indicates that the boundary reattaches again. Fig. 13 shows the plots of the predicted static wall pressure and the axial wall shear.
stress distribution on the spike. As the nozzle exhibits a multitude of shock structures and associated flow separation regimes at various NPR’s, the figures show a progression of NPRs for the entire range. The throat is located at $X/L = 0$, while the static wall pressure, the axial wall shear stress, and the $X$ coordinate have been normalized by the ambient pressure, the maximum value of the axial wall shear stress, and the spike length, respectively.

The plots in Fig. 13(a) and (b) correspond to that of no flow separation regime for NPR’s below 1.96, and the flow expands from a subsonic condition at an NPR of 1.60 to a normal shock condition at an NPR of 1.90. Looking at the plot with an NPR of 1.90 for the spike, we notice a bump in the static wall pressure at $X/L = 0.09$, for which as in our earlier discussion, this pressure increase is induced by the normal shock which is not strong enough to induce the flow boundary separation, and it is also evident in the axial wall shear stress distribution that the value stays above and beyond zero along the entire spike as shown in Fig. 13(b). Another feature that can be discerned in the pressure distribution is the pressure adaptation to the ambient condition, in which the spike is enclosed by the annular jet and induces a back pressure higher than that in the ambient condition, and then the static wall pressure increases above and beyond the ambient pressure just aft in the throat region monotonically. This scenario is absent in a conventional bell-type nozzle during transonic conditions.

Fig. 13(c) shows the static wall pressure distribution in the restricted shock separation regime for NPR = 2.00, 2.10, 2.57, 3.12, 3.82. It is evident from the axial wall shear stress plots that the nozzle really exhibits an RSS regime at these NPRs, and in fact the details of the flow pattern cannot be recognized by the experimental methodology. More than five types of shock structures are captured at these NPRs, however, only the moderate NPR = 2.57, 3.12, exhibit a conventional RSS regime while the lower, NPR = 2.00, 2.10, and higher, NPR = 3.82, NPRs are not classical RSS conditions as seen earlier. In case of the conventional RSS regime, the shock exhibits a $\lambda$ structure and the pressure rises after the first leg of the $\lambda$-shock and then forms a plateau which ends when the reflected shock, the second leg of the $\lambda$-shock, hits the recirculation bubble. Immediately after this, the pressure increases till the reattachment point and then monotonically decreases as the flow expands downstream from reattachment. However, using the present case of NPR = 3.82 as an example, the expansion fan emerging from the cowl lip over-expands the flow along the spike surface and results in forming of a single

![Shock structure motion as the NPR is increased from 5.75 to 9.87 at the sea-level atmospheric conditions, Case 1-1, $p_a = 101325$ Pa.](image.png)
Numerical investigation of flow separation behavior in an over-expanded annular conical aerospike nozzle

Fig. 13  Streamwise distribution of the static wall pressure and the axial wall shear stress along the spike surface for different NPRs in the sea-level atmospheric conditions, Case 1-1, $p_a = 101325$ Pa.
oblique over-expansion shock; the pressure rises after the separation shock ($X/L = 0.4$) and continues to increase till the reattachment point ($X/L = 0.66$), and then decreases downstream from reattachment, while no plateau can be discerned along the recirculation bubble.

Fig. 13(e) shows the static wall pressure distribution progression during the flow separation pattern transition regime for NPRs of 4.29–6.25 when the shock structure transforms from the restricted shock separation regime to the free shock separation regime. The transition happens at an NPR of 5.22 as seen earlier, and is also evident in the axial wall shear stress plots shown in Fig. 13(f). In contrast to flow separation transition phenomena in a bell-type nozzle, there is no distinct step change in the evolution of the static wall pressure on the spike. This difference is not entirely clear but is consistent with our computation upon the grid density effect study later. Examination of the static wall pressure plots shows a region of compression (seen as a hump) starting from $X/L$ of 0.26–0.27. The hump grows up with increasing the nozzle pressure ratio while its starting point has slight excursion. In addition, the static wall pressure profile shows similar evolution as the one for a classical RSS condition that the pressure rises after the separation shock and then forms a plateau which ends in a distance, and immediately after this, the pressure increases till $p_{sep}/p_a$ is over 1.5. Moreover, this scenario indicates a different free shock separation behavior from the one in a conventional axisymmetric bell-type nozzle.

In the final figures of the series, Fig. 13(g) and (h), these NPR’s shown exhibit that the flow condition on the spike transforms from the free shock separation at NPRs of 1.60–8.40 to full expansion at an NPR of 9.87 although the static wall pressure at the end of the spike surface is still below that in the ambient condition. The plots of the axial wall shear stress show clearly the progression of the separation point. The region of compression on the spike now shows a distinct static wall pressure plot hump. By using both the static wall pressure non-dimensionalized with respect to the ambient condition and the axial wall shear stress profile, the fact that the expansion fan coming from the cowl lip over-expands the flow along the spike surface and leads to the free shock separation mechanism even in the case of the designed condition can be clearly recognized.

### 3.4. Prediction of the flow separation behavior

As flow separation may lead to performance losses and undesired high nozzle structural loads, accurate separation criterion is crucial. A series of separation criterion has been developed with increasing knowledge and availability of experimental data. However, most of the historical data are predominantly for conical or bell-type nozzles with an axisymmetric configuration, and thereby applicability on the present asymmetric nozzle needs to be validated. Fig. 14 plots the separation data ($p_{sep}/p_a$ or $p_{sep}/p_{ON}$) as a function of the corresponding wall separation Mach number, $Ma_{sep}$, or the NPR, on the spike surface as well as the cowl wall, where the wall separation Mach number is based on the isentropic ratio of $p_{ON}/p_{sep}$. Three separation criteria are plotted for comparison: the well-known Schmucker criterion, the separation criterion (2) for turbulent nozzle flows suggested by Stark et al., and the separation criterion (3) suggested by Ge et al. recently based on flow separation data in asymmetric ramp nozzles.

\[
\frac{p_{sep}}{p_a} = (1.88 Ma_{sep} - 1)^{-0.64}
\]  
\[
\frac{p_{sep}}{p_a} = \frac{1}{Ma_{sep}}
\]  
\[
\frac{p_{sep}}{p_a} = -1.76 \left(0.47 Ma_{sep}^{0.45} - 1\right)
\]

Looking at the plots of separation data on the spike wall shown in Fig. 14(a) and (b), the data affected by the region of compression, the over-expansion by the expansion fan generated at the cowl lip, and the enclosed back pressure environment by the annular jet for $NPR \geq 3.82$ when the internal nozzle starts to operate in an under-expanded condition are clearly pointed out in the plots. A region covers nozzle pressure ratios of 3.12–3.82, corresponding to the wall separation Mach number of 1.65–1.80, and divides the data-set into two regions. The data show a strong variation and are bounded below by all the three separation criteria for $NPR \leq 3.12$ and above by the criteria for $NPR \geq 3.82$. At first sight, an important separation behavior transformation seems to happen in between as discussed earlier. The data of Schmucker and Stark criteria show below $NPR \leq 3.12$ a trend which seems to be a sight parallel shift and reproduces the separation pressure with a reasonable accuracy for this NPR regime, while failing at the prediction for the $NPR \geq 3.82$. The separation criterion (3) suggested by Ge et al. fails to reproduce the separation pressure data for both of the two regions. This is a significant hint that the asymmetric nozzle configuration may affect the flow separation behavior in the present aerospike nozzle and induce the miss-prediction by the separation criterion developed from separation data in conical or bell-type rocket nozzles.

Some interesting effects are also pointed out in the plots of separation data on the cowl wall shown in Fig. 14(c) and (d). For NPR’s between 2.00 and 2.57, the flow separation on the cowl wall is always in the FSS regime as seen earlier. However, with the interception effect of the oblique compression shock induced by the separated shear layer at the sharp corner, the flow separation on the cowl surface exhibits abnormal free shock separation behavior. The separation pressure, $p_{sep}$, show an opposite trend as a function of NPR that increasing the NPR strengthens the upstream oblique compression shock, leading to a higher local static wall pressure and total pressure loss, and then to a lower wall separation Mach number, $Ma_{sep}$. Again, all the three separation criteria fail to reproduce the separation data on the cowl wall.

### 3.5. Gas density effect

The above discussion gives a detailed view of the shock physics and flow separation behavior as the NPR is increased from low to high values for the sea-level condition. Now, we compare the gas density effect on the above-mentioned flow characteristics at specific NPRs for the three ambient pressure conditions. Recent studies on a thrust-optimized parabolic nozzle have reported significant variations in results when comparing data from tests conducted in sea-level atmosphere...
with those inside a high-altitude chamber. The series of pictures illustrated in Fig. 15 shows the predicted shock patterns at the three different ambient pressure conditions for NPR = 2.00, 2.10, and 2.57, when more complex shock/boundary layer interaction is expected for these highly over-expanded conditions. It is noteworthy here that the results of shock-induced flow separation structures and location as well as the static wall pressure profiles variations with the three different ambient pressure conditions show a similar tendency as those for NPR = 2.57. As a consequence, the results for higher NPRs are not included in the paper. Pictures are also contoured with the same levels by the data constructed from the computational results with the absolute values of the first gradients of density at the grid nodes. At first sight, the shock structure is somewhat less distinct in the high-altitude simulations, indicating a weaker shock system for lower density flows.

Looking at the pictures on the left of Fig. 15(a), (d), and (g) from top to bottom for an NPR of 2.00, we note that the predicted shock patterns and associated flow separation on both the spike and cowl surfaces in the two high-altitude simulations exhibit distinct differences in contrast to the sea-level condition, suggesting a strong gas density effect at this NPR condition. As discussed earlier, this particular NPR of 2.00 lies in the shock transition from a normal shock to Mach reflection on the spike surface while the separation point jumps from the throat’s sharp corner to the downstream cowl extension. For flows in the high-altitude simulations, the shock structure generates a $\lambda$ pattern enclosing a smaller recirculation zone at the spike. The oblique compression shock starting from the throat’s sharp corner is weak now and hits on the first foot of the lambda shock; the separation shock is modified in the vicinity of the wall by the intersection between these shocks.

In terms of cowl side, decreasing the ambient pressure pushes the separation point on the cowl surface back to the throat’s sharp corner, and it freezes exactly when the ambient pressure increases from 25% to 50% at high-altitude simulation conditions, suggesting that a higher inlet total pressure is needed to push the separation point to jump downstream into the cowl extension for lower density flow. This phenomenon is similar to the gas density effect on the sneak transition process in dual-bell nozzles, and recent studies on a subscale dual-bell nozzle have reported that the separation point for tests inside a high-altitude simulation chamber moves into the region of wall inflection much earlier and stays there for a much longer time. This delays the process of transition and hence increases the NPR of dual-bell transition as $p_{\text{ON}}$ is

![Fig. 14](image-url) Comparison of separation data plots on the spike and cowl surfaces at the sea-level atmospheric conditions, Case 1-1, $p_a = 101325$ Pa as a function of $Ma_{sep}$ and NPR, respectively.
decreased for tests inside the high-altitude simulation chamber. For results at higher nozzle pressure ratios of 2.10 and 2.57 shown in the middle and right list of Fig. 15, the comparison between the predicted shock patterns at the three ambient conditions shows a close one at these higher NPRs. One difference between the three results is that the separation point shows a distinct excursion upstream on both the spike and cowl surfaces as the ambient pressure decreases. The other feature that can be discerned is a smaller excursion of the separation point at a higher NPR of 2.57 than that observed for an NPR of 2.10. This suggests that the gas density effect may be weakening at a higher Mach number flow regime, when the flow Reynolds number increases with the increase of nozzle pressure ratio as well as flow Mach number, and the Reynolds number has been reported to have a significant influence on the shock/boundary layer interaction.54

Fig. 16(a)–(c) plot the streamwise distribution of the non-dimensional mean static wall pressure for the three NPRs at different ambient conditions. Again, the plot of the axial wall shear stress along the spike is used here to interpret the excursion behavior of the separation shock as shown in Fig. 16(d)–(f). It may be noted that approximately similar values of the static wall pressure are being experienced irrespective of the simulated ambient pressure conditions except in two regions. One difference is that the lowest pressure value just before the separation shows an increase with a decrease in the ambient pressure. Therefore, a lower pressure rise is needed for the static wall pressure adaptation to the ambient condition, resulting in a weaker separation shock for the lower-density flow, as shown in the predicted shock patterns. The second difference is the absent wavy plots of the static wall pressure distribution for the two high-altitude simulation cases. This suggests that, for lower gas density, the weak expansion and compression waves in the aft region of the main normal shock are also weakened by the separation shock and even disappear for extremely low ambient pressure conditions. A distinct decrease of the axial wall shear stress with a decrease in the ambient pressure is shown in the axial wall shear stress plots,
Fig. 16 (d)-(f). The excursion upstream from the separation point location, the reduction in the lateral extent of the separation zone, and the weaker influence on the above two features with a decrease in the ambient pressure are shown clearly in the pictures.

Fig. 17 shows the variation of the streamwise distribution of the non-dimensional mean static wall pressure and the axial wall shear stress along the cowl surface. Because the length of the cowl, \( l_c \), is smaller compared with that of the spike, the gas density effect is more distinct for the separation behavior on the cowl surface. It can be noted that the static wall pressure distribution shows a larger discrepancy in the separation region, while with a decrease in the ambient pressure, the rate of pressure rise across the separation shock decreases.
gradually. This feature is less distinct with the increase of the NPR shown in Fig. 17(c). The phenomenon that the location of the incipient separation point excurses back to the throat’s sharp corner and freezes exactly even with large changes in the ambient pressure (transition from the 25% to the 50% ambient pressure case) is shown clearly in the axial wall shear stress plots, Fig. 17(d)–(f).

To investigate the reason behind the observed discrepancies, Fig. 18 shows a comparison of the static wall pressure gradient near the separation shock region for the three ambient conditions at NPR = 2.10, 2.57. Here the static wall pressure gradient, \( \frac{dp}{dx} \), is non-dimensional (the static wall pressure, \( p_w \), is non-dimensionalized with respect to the ambient pressure, \( p_b \)) and the \( X \) co-ordinate is normalized by the annular gap at the throat section \( h_t \). The separation point locates between \( X/h_t \) of 0.5–1.0 and 1.0–1.5 for NPR = 2.10, 2.57, respectively. It can be seen that approximately similar values of \( \frac{dp}{dx} \) are being experienced outside the separation region irrespective of the simulated gas density. However, as the ambient pressure increases, the value of \( \frac{dp}{dx} \) shows a decrease with a decrease in gas density across the separation shock. Studies on bell-type nozzles have also indicated that a distinct excursion of the incipient separation point occurs when the adverse pressure gradient across the separation shock is smaller. This suggests that \( \frac{dp}{dx} \) is larger for higher gas density and vice versa, indicating a stronger shock system for higher density flow.

During a low-altitude mode with NPR = 2.00, the shock patterns and associated flow separation behavior strongly signify the compression shock and the separated shear layer starting from the throat’s sharp corner. As discussed earlier, once the throat region has reached the supersonic regime, the wall inflection at the sharp corner that controls separation occurs over a wide range of NPRs because a large pressure gradient prevalent at the corner allows only a small movement of the separation point with large changes in the NPR. In particular, the gas density effect delays this process because of lower \( \frac{dp}{dx} \). Additional calculations and experimental tests on high-altitude simulation are needed to get deeper insight into the aerodynamic mechanism behind the observed gas density effect.

4. Summary and conclusions

(1) The computational results agree well with the experimental data in both shock physics and static wall pressure distribution, indicating that the axisymmetric computational methodology here is advisable to accurately predict the flow physics. The progressively increased excursion in the plots of static wall pressure distribution with an increase in the NPR may contribute to slightly miss-mimicking the experimental condition because of the jet entrainment effect.

(2) The annular conical aerospike nozzle is observed to be dominated by shock/shock and shock/boundary layer interactions at all calculated NPRs, and the shock physics and associated flow separation behavior are quite complex. Increasing the NPR changes the operating condition of the internal nozzle as well as the basic flow physics such as the expansion fans, the separated shear layer, and the over-expansion shock on both the spike and cowl surfaces. As the internal nozzle operates from the highly over-expanded to the over-expanded condition and then to the under-expanded condition, the flow condition on the spike exhibits a normal shock structure with no flow separation for NPR < 2.0, a multitude of shock structure transitions with the restricted shock separation for 2.0 \( \leq \) NPR \( \leq \) 5.22, and an oblique over-expansion shock with the free shock separation for 5.22 \( < \) NPR \( \leq \) 8.40 regimes. This shock and separation transitions are absent in optimized bell-type nozzles nor the reported shrouded plug nozzle, and the identification of these three regimes helps in further investigation on the unsteady fluid dynamics and related side loads generation. The computational results provide additional flow characteristics against the experimental data; in particular, the shock/shock and shock/boundary layer interactions with the restricted shock separation at highly over-expanded conditions and the free shock separation behavior at higher NPRs than those at design conditions are excluded in the experimental study.
Numerical investigation of flow separation behavior in an over-expanded annular conical aerospike nozzle

(3) The separation data show that a strong variation for the spike, a region that covers NPR of 3.12–3.82, corresponding to the wall separation Mach numbers of 1.65–1.80, divides the data-set into two regions. All the three separation criterias fail to reproduce the separation data of the spike for the NPR $\geq 3.82$, when the internal nozzle starts to operate in under-expanded conditions. On the other hand, the flow separation structure on the cowl surface is always in the FSS regime. However, with the interception effect of the oblique compression shock induced by the separated shear layer at the sharp corner, the separation pressure, $p_{sep}$, shows an opposite trend as a function of the NPR in contrast to that in over-expanded conventional bell-type rocket nozzles. We conclude that the separation criteria developed from separation data in conical or bell-type rocket nozzles may be inapplicable for the prediction of flow separation behavior in the present asymmetric supersonic nozzle.

(4) A strong gas density effect has been found at the highly over-expanded condition with NPR = 2.00, when the wall inflection at the sharp corner that controls separation occurs over a wide range of NPRs during this flow regime. However, for results at higher NPRs, the comparison between the predicted shock patterns at the three ambient conditions shows a close one for these higher NPRs regime. This suggests that the gas density effect is going to weaken at a higher Mach number flow regime when the flow Reynolds number increases with an increase of the NPR as well as the flow Mach number. The adverse pressure gradient across the separation shock, $dp/dx$, is larger for higher gas density and vice versa, indicating a stronger shock system for higher density flow, which may contribute to the observed gas density effect. These results emphasize that the flow separation behavior tests in such an aerospike nozzle inside a high-altitude test facility should be carefully interpreted; in particular, Reynolds number effects are needed to be concerned when comparing results from the sea-level conditions.

References

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