Flow Field and Performance Analysis of Aerospike Nozzles with Simplified Clustered Modules

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The fundamental characteristics of simplified clustered aerospike nozzles are analyzed by the computational fluid dynamics approach. Several types of aerospike nozzles, having 6, 12 and 24 inner nozzle modules with the same area ratio and total flow rate, are examined. The interactions of the exhaust flows from the neighboring modules create shock waves, which produce high-pressure regions on the nozzle surface. The base regions of the cluster-type aerospike nozzles are not influenced by the clustering of the modules and show features similar to axisymmetric-type aerospike nozzles. The base pressure is nearly equal to the environmental pressure when the pressure ratio is low and suddenly attains a constant pressure when the pressure ratio is high. The computed results show that the number of modules influences the thrust performance, and the major reason for the decrease in thrust performance with a smaller number of modules is due to thrust loss in the ramp region.

Key Words: Aerospike Nozzle, CFD, Propulsion

Nomenclature

\[ PR: \text{ pressure ratio} \]
\[ S: \text{ distance along the nozzle surface} \]
\[ P: \text{ pressure} \]
\[ Re: \text{ Reynolds number} \]
\[ AR: \text{ area ratio} \]
\[ C_P: \text{ thrust coefficient} \]

Subscripts

e: exit
t: throat
\(a\): ambient

1. Introduction

With the aim to reduce rocket launching costs, reusable launch vehicles have been under development in the United States. Unfortunately, NASA recently decided to withdraw from the X-33 program, but much instructive knowledge was obtained from this project. The reusable launch vehicle relies solely on a single propulsion system and requires a higher thrust performance than conventional propulsion systems. Therefore, the aerospike nozzle, which has an altitude compensation capability, was to be the main propulsion device to power the vehicle into orbit. The aerospike nozzle was a candidate for the Space Shuttle propulsion system and had been vigorously studied from the early 60’s until the end of the 70’s. The technological difficulties in the development of the aerospike nozzles made it fall behind the development of the conventional bell-type nozzle, and research on the aerospike nozzle stagnated henceforth. After the aerospike nozzle was resurrected as a candidate propulsion system for reusable launch vehicles, the research on such nozzles became active again in the United States. Research also became active in Europe\(^1,2\) and Japan\(^3\)–\(^10\).

The studies on aerospike nozzles in Japan started in the mid 90’s at the National Aerospace Laboratory. Initially axisymmetric-type aerospike nozzles were investigated,\(^7\) and research then progressed to investigations of linear-type aerospike nozzles.\(^8\)–\(^10\) Many features of the aerospike nozzles were clarified. The Future European Space Transportation Investigations Program\(^1\) and Advanced Rocket Propulsion Technologies\(^2\) have also activated similar research on such nozzles in Europe.

The aerospike nozzle is comprised of a module region and an external expansion region. Aerospike nozzles are considered to have overall better performance compared to that of the conventional bell-type nozzle since the exhaust flow at the external expansion region is not bounded by a nozzle wall and can adjust itself to the environment pressure by changing the exhaust flow boundary. In addition, nozzle performance is not influenced when the nozzle is cut-off because the base pressure compensates the loss of the thrust. The authors analyzed the fundamental characteristics of axisymmetric-type aerospike nozzles and both the qualitative and quantitative aspects of the above features were confirmed.\(^3\)–\(^6\) However, the throat area inside the module of the axisymmetric-type aerospike nozzle requires forming accuracy and often faces a heat deformation problem, which leads to difficulties in designing larger-scale axisymmetric-type aerospike nozzles. Therefore, even though the deficiency exists compared to the axisymmetric-type nozzles, cluster-type aerospike nozzles are considered to be more reliable for actual flight.\(^2\)

In this study, the exit area of the modules for the axisym-
metric-type aerospike nozzles is divided into several segments assuming that each segment is a module for a clustered aerospike nozzle. The computation is considerably simplified with the above assumption since the flow simulation can be performed on a single grid system. The fundamental characteristics of the clustered aerospike nozzles are investigated based on computational results.

2. Geometry of the Aerospike Nozzle and Flow Conditions

A schematic view of the 12-module simplified clustered aerospike nozzle used in this study is shown in Fig. 1. In this study, 6, 12 and 24-module aerospike nozzles are considered, and their configurations are shown in Fig. 2(a)–(c). Each of the aerospike nozzle contours are designed under the assumption that the expansion process over the axisymmetric aerospike nozzle surface is isentropic and the nozzle contains two parts (i.e., module part and external expansion region).

The nozzle is truncated at 20% portion of the external expansion region. In this study, a 20% nozzle is used because the previous studies have confirmed that the influence of nozzle truncation to the total thrust is small. The computations are carried out inside the domain drawn by the solid line shown in Fig. 2(a)–(c), and the cyclic conditions are imposed at the circumferential boundaries. The area ratio ($AR$) of the module and whole aerospike nozzle are 1.7 and 6.5, respectively. The $AR$ of the whole aerospike nozzle is given by the circular area with a radius defined by the distance from the axis to the cowl lip ($Ae$) divided by the whole throat area in the modules ($At$). The total exit area of each module is identical so that the total flow rate and thrust produced at the module exits are the same for different configurations. Optimum expansion is achieved at a pressure ratio ($PR$) of 71 under the assumption that the flow is isentropic. The flow field and thrust characteristics, at $PR$’s from 5 to 1000, are studied. In this study, the exhaust gas is assumed to be the ideal gas. The $Re$ number is set to be $5.82 \times 10^5$ based on the length between the nozzle axis and cowl lip. The pressure is normalized by sea-level pressure.

![Fig. 1. Schematic view of a simplified clustered aerospike nozzle.](image1)

![Fig. 2. Configurations of the aerospike nozzles.](image2)
3. Numerical Method

The governing equations are three-dimensional Navier-Stokes equations. The convective terms are evaluated by the SHUS\textsuperscript{12}) scheme, which is a family of AUSM-type schemes. High-order space accuracy is obtained using the MUSCL, using the primitive variable interpolation. The viscous terms are evaluated by central differencing and the eddy viscosity is modeled by the Baldwin-Lomax turbulence model\textsuperscript{13}) with Degani-Schiff correction\textsuperscript{14}) implemented. Only the steady-state solutions are considered, and the LU-ADI factorization time integration algorithm\textsuperscript{15}) is used. The computational code used in the present study has been used for a wide variety of flow fields and validated in the past.\textsuperscript{16,17}) Although there are no experimental data for the same configured clustered aerospike nozzle available for the comparison, the code has been used for the cone-type aerospike nozzle flow fields and showed good agreement with the experiment.\textsuperscript{3}) Different grids are individually used for each type of nozzle. The computational grid consists of 151 nodes in the streamwise direction and 101 nodes from the spike surface to the outer boundary of the computational domain. The computations are carried out inside the domain drawn by the solid line as shown in Fig. 2, and 105 nodes are distributed in the circumferential direction. Figure 3 shows the computational grid near the nozzle surface for the 12-module aerospike nozzle as an example.

4. Computed Results

4.1. Streamwise flow field and pressure distributions on the nozzle surface

The fundamental characteristics of the flow field and pressure distributions are similar for the 6, 12 and 24-module aerospike nozzles. Therefore, only the 12-module aerospike nozzle under $PR = 71$ (which is a designed point) is considered for the discussion.

The Mach number contour plots on the cross section of the exhaust flow near the nozzle surface is shown in Fig. 4. Under-expansion occurs inside the modules for the current $PR$ and the exhaust flows from each of the modules expand toward the circumferential direction. Interactions of the exhaust flows occur at the intermodular area and the mixing layer develops downstream from the interaction point. Strong oblique shockwaves toward the module centerline appear from the interaction point and consequently interact with each other near the tip region of the ramp.

The pressure contour plots and the pressure distributions on the module centerline and intermodular symmetry line are shown in Fig. 5(a) and (b), respectively. The horizontal axis of Fig. 5(b) shows the distance along the nozzle surface. $S = 0.0$ indicates the module exit and $S = 1.245$ indicates the center of the base.

The discussions on the intermodular symmetry line are carried out first. From Fig. 5(a), the exhaust flow expands in the circumferential direction and creates low-pressure regions at the upper-stream regions of the intermodular area. This low-pressure region appears at $S = 0.0 - 0.1$ (\textcircled{C}) plots) in Fig. 5(b). However, the interactions of the exhaust flows take place downstream of the intermodular area and the high-pressure region behind the oblique shock waves appears in Fig. 5(a). This high-pressure peak appears at $S = 0.35$ (\textcircled{C}) plots) in Fig. 5(b). After the pressure reaches its peak at $S = 0.35$, the flow expands along the nozzle surface until it reaches the base region.

The following discussions are carried out for the region on the module centerline (\textbf{■} plots) in Fig. 5(b). The present aerospike nozzles are designed so that the expansion fan emanates from the cowl-lip of the module. The pressure becomes nearly constant at upper-stream portions from where the initial expansion fan impinges on the ramp surface at $S = 0.2$. After the initial expansion fan reaches the ramp at $S = 0.2$, the exhaust flow expands along the nozzle surface ($S = 0.2 - 0.33$). The sudden pressure rise at $S = 0.33 - 0.5$ is due to the oblique shock wave interactions. Downstream of the interaction point, the exhaust flow again expands along the nozzle surface until it reaches the base region.

From the above discussions, there exists a clear difference between the pressure distributions on the module centerline and intermodular symmetry line at the ramp region. However, the difference does not exist in the base region ($S = 0.73 - 1.25$) from Fig. 5(b). This indicates that the effect of clustering at the base region is small and an axisymmetric
base flow exists at the base region. Previous studies\textsuperscript{3–6)} showed that the base region of axisymmetric-type aerospike nozzles (no modules) is influenced by the ambient pressure when the \( PR \) is low and becomes independent from the ambient pressure when the \( PR \) is high. There will be further discussions to analyze whether the present clustered aerospike nozzles show the same trend as the axisymmetric-type aerospike nozzle.

4.2. Base pressure characteristics on the pressure ratios

Figure 6 shows the averaged base pressure for the 6, 12 and 24 cluster-type and axisymmetric-type aerospike nozzles versus various pressure ratios. This figure is plotted under the assumption that the vehicles’ chamber pressure is constant during ascent and five times higher than atmospheric pressure at sea level. The dotted line shows the ambient pressure \( (Pa) \), which decreases as the pressure ratio or altitude becomes higher.

At low altitudes (e.g., low-pressure ratio), the base pressure linearly decreases as the ambient pressure decreases. This indicates that the base region is influenced by the external environment and its pressure is quantitatively equal to the environment pressure. The pressure thrust produced by the base is small at low altitudes.

On the other hand, at high altitudes (e.g., high-pressure ratio), the base pressure of each nozzle becomes constant despite the variation in altitude. As the altitude increases, the environment pressure decreases and the difference between the base pressure and environment pressure increases. Therefore, the base pressure thrust increases.

There is an abrupt transition in the flow characteristics in the base region during the vehicle’s ascent. The base starts to produce thrust only after this transition. Both the clustered and axisymmetric-type aerospike nozzles have the same base pressure characteristics. This indicates that the effect of clustering on the base region is small. The base pressure of the clustered aerospike nozzle has a higher pressure level compared to that of the axisymmetric-type aerospike nozzle. This is caused by compression due to the exhaust flow interactions on the nozzle surface.

4.3. Proportions of the thrust

The thrust component for each of the nozzles under \( PR = 500 \) is shown in Fig. 7. This \( PR \) is selected as an example where a steady-state flow field is obtained and contributions of each component can be readily observed. The total thrust is computed as the sum of the momentum and pressure

\[ T = T_m + T_p \]

Fig. 6. Base pressure characteristics.

Fig. 5. Pressure distributions for the 12-module aerospike nozzle.
thrust produced at the module exit and the pressure thrust produced at the ramp and base region. The thrust component of the axisymmetric-type aerospike nozzle is also plotted for comparison. The total module exit area for each type of aerospike nozzle is designed to be identical. Therefore, the momentum thrust and pressure thrust produced at the module exit becomes almost the same. A slight thrust difference for the momentum thrust and pressure thrust is observed since the grid becomes coarser as the number of modules decreases. However, the difference is within 2% of the total thrust and can be ignored in terms of discussion. Although the number of modules is different, the base pressure thrust becomes almost the same for all configurations. It is clear from Fig. 7 that, as the number of modules decreases, the pressure thrust at the ramp region decreases significantly compared to the axisymmetric-type aerospike nozzles. This is the main reason for thrust loss due to clustering when making a comparison with axisymmetric-type aerospike nozzles.

The pressure difference between cluster-type aerospike nozzles and axisymmetric-type aerospike nozzles is shown in Fig. 8. The solid line shows where the pressure levels between the two coincide with each other. The upper-stream region of the solid line indicates where the cluster-type aerospike nozzles have lower pressure compared to that of the axisymmetric-type aerospike nozzles. The results show that as the number of modules decreases, the lower pressure regions around the intermodular area increase as compared to the axisymmetric-type aerospike nozzle. It is clear that the lower pressure in the upper-stream regions (mainly in the intermodular region) is the main reason for the thrust decrease when clustering.

5. Thrust Performance for the Clustered Aerospike Nozzle

The relation of the thrust coefficient to the pressure ratio is shown in Fig. 9. The solid line denotes the ideal thrust co-
efficient and the dashed line denotes the theoretical thrust coefficient of the bell nozzle with the same area ratio as the present aerospike nozzle. Note that a theoretical value is obtained under the optimal isentropic condition. The results for the axisymmetric aerospike nozzle are also plotted for comparison. In the low-pressure ratio regions, the bell nozzle does not produce as much thrust as any of the aerospike nozzles. This is the reason for the higher performance of the aerospike nozzle at low-pressure ratios (lower altitudes). Qualitatively, the thrust coefficients of each of the aerospike nozzles show the same trend with the ideal thrust coefficient, which indicates that the aerospike nozzle operates at nearly peak thrust efficiency over a wider range of pressure ratios than the classical bell nozzle. It is clear from Fig. 8 that, as the number of modules decreases, the distance between the modules increases and allows the exhaust flow to expand towards the broader intermodular area. This leads to wider lower pressure distributions compared to that of the axisymmetric-type aerospike nozzles. As a result, the performance of the clustered aerospike nozzle decreases as the module number decreases (Fig. 9).

6. Conclusion

The flow structure and performance of 6, 12 and 24-module aerospike nozzles were numerically investigated. A clear difference between the pressure distributions on the module centerline and intermodular symmetry line exist at the ramp region. However, the base pressure was found to be insensitive to the clustering of the module. The characteristics of the base region become indistinguishable from the axisymmetric-type aerospike nozzle. The base region is influenced by the ambient pressure when the pressure ratio is low and becomes independent of the ambient pressure when the pressure ratio is high. When the number of modules decreases, large low-pressure regions are created upstream of the ramp at intermodular areas and the performance of the aerospike nozzle decreases.

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References