Three Dimensional Computational Flow Simulation of Truncated Aerospike Nozzle Considering Different Plug Lengths

Gorle Swathi, Chaganti Satya Sandeep*, Mandapudi Snigdha, Gudikandula Sravanthi and Dussa Govardhan

Department of Aeronautical Engineering, Institute of Aeronautical Engineering, Hyderabad – 500043, Telangana, India; swathig2591@gmail.com, chsatyasandeep@gmail.com, snigdha.mandapudi@gmail.com, sravanthig83@yahoo.com, sravanthig83@yahoo.com

Abstract

Propulsive systems for planetary landing and ascent needs mass reduction since the cost of delivering the required propellant and structural mass is very high. Aerospike nozzle has demonstrated a significant potential advantage for purely in-space applications. This paper mainly concentrates on the CFD analysis of aerospike nozzle for 100%, 75%, 50% and 25% plug length with the CFD analysis at cases considering multiple altitudes representing ideal, under-expansion and over-expansion conditions of the flow had been carried out. ANSYS CFX was used to simulate the flow at these different conditions. The visualisation obtained through the CFD simulation was used to compare the performance of different spike lengths at different above mentioned operation conditions. A deduction had been made that at overexpansion condition the spike nozzle is efficient of producing five percent more thrust and the loss of the thrust is proportional to the truncation.

Keywords: Aerospike Nozzle, CFD Analysis, Different Spike Plug Lengths

1. Introduction

It is a known fact that with the increase in the altitude of the launch vehicle the ambient pressure decreases. A nozzle generating same thrust for the entire trajectory will obviously lead to less efficient performance. An aerospike nozzle being a variable diameter nozzle compensates this problem by adjusting thrust produced in the entire trajectory. Since the variation of the exit diameter of a spike nozzle is in our control we can vary the diameter according to the variation of the ambient pressure during the entire trajectory. This gives an advantage to spike nozzle making it an aerodynamically efficient, altitude compensating nozzle. These characteristics made aerospike nozzles to be the used in Single Stage to Orbit (SSTO). The design of the aerospike has shown its efficiency for suitingle single stage orbit flight. The spike nozzle has proved 85-90 % efficient in overall performance than bell shaped nozzle, at the low altitude because the atmospheric pressure restrict the expansion of the exhaust gas. At sea level high ambient pressure forces the exhaust to remain close to the center body maintaining high efficiency whereas at the optimum altitude the exhaust plume is column shaped producing maximum efficiency. Another added advantage of the spike nozzle is its size when compared with the bell nozzle, spike nozzle has proved in giving an optimum performance for the given length. At high altitudes the exhaust plume is bound by shock waves that force it to remain column shaped for high efficiency. The plug nozzles have proved to be efficient among the micro
sized nozzles as well. J. M. Pearl and his team investigated a study on 3D linear plug micro nozzles with Reynold number varied from 80-820 and the nozzle depths of 90-360 micro meters. They found that the 3D plug nozzle outperformed the 3D 30 degree linear walled nozzle in both 2D and the 3D simulation for the range of Reynolds numbers. Figure 1 clearly shows different flow conditions which is under expansion overexpansion and ideal flow with a schematic diagram of an aerospike. The smaller modular combustion chambers used in spike engine are less expensive thrusters which adds economic efficiency and enable manoeuvring with efficient thrust vectoring and reduced base drag of the rocket.

Figure 1. Schematic of aerospike nozzle and comparison of aerospike nozzle with bell nozzle for different flow conditions.

2. Aerospike Nozzle Design and Grid Generation

An aerospike nozzle with ethanol-oxygen in 1:21 ratio has been considered for the design. Chamber pressure of 2067857 N/m² with a design altitude of 3657.6 meters and an optimum thrust of 4443.9 Newton's has been considered. Specific impulse of the motor is assumed as 235 seconds with mass flow rate of 3.25 Kg/Sec. Coming to the throat of the nozzle the throat angle was designed at 57.16 degrees with the throat area of 1.438 X 10⁻³ m² and throat radius to 0.045 m. The exhaust area, exhaust radius and the exhaust Mach number were designed to 7.04 X 10⁻⁶ m², 0.0478 m and 2.084 respectively. For 100% case the plug length has been taken to 0.1275 m while for 75% case the length has been taken to 0.0942 m with the base radius of 0.00463 m. For the case of 50% the plug length of 0.06286 m with the base radius of 0.0115 m has been considered meanwhile for the case of 25% a plug length of 0.03143 m with a base radius of 0.02091 m has been considered.

ICEM CFD meshing module in ANSYS was used for the generation of the grid. Figure 2 shows the schematic of the meshed model. Each of these four cases of the aerospike nozzle has been simulated to four different flow conditions which are detailed in Table 1.

Figure 2. Grid generation in ICEM CFD.

| Case | P_exit (KPa) | P_atm (KPa) | Ratio (P_atm/P_exit) | P_total (KPa) | NPR (P_total/P_atm) |
|------|-------------|-------------|---------------------|--------------|---------------------|
| 1    | 148.51      | 59.404      | 0.400               | 500.877      | 8.432               |
| 2    | 148.51      | 101.297     | 0.682               | 500.877      | 4.945               |
| 3    | 148.51      | 148.51      | 1.000               | 500.877      | 3.373               |
| 4    | 148.51      | 222.765     | 1.500               | 500.877      | 2.248               |

Table 1. Conditions simulated for the different dimensions of the aerospike nozzle

3. Results and Discussions

Figure 3. Temperature distribution for different percentages of plug lengths in an aerospike nozzle.
The exhaust flume of the spike nozzle starts from the convergent section of the nozzle. The exhaust is not bounded by the solid boundary, this makes the gases expand according to the outside atmospheric pressure, making spike nozzle an altitude compensation nozzle. For the case where the ambient pressure is greater than the exit nozzle pressure, two expansion waves one from the upper lip to the center of the base and the second at the tip of the truncated portion was observed. An oblique shock was created around the upper lip of the primary nozzle. The case with 25% truncation had more effect of shock waves when compared with other spike lengths.

For the case where the exit nozzle pressure is equal to the ambient pressure, decrease in the density of the fluid was observed at the tips of the nozzle and the truncated portion. At the tip of the truncated portion two vortices were observed due to the recirculation of the exhaust flume. Large amount of the expansion was observed for the flow moving towards the direction of the truncation. Vortices were generated at the base of the plug for the case where exhaust pressure is greater than atmospheric pressure.

4. Conclusion

An attempt to understand the behaviour of an aerospike nozzle at different altitudes had been implemented. Four cases have been simulated for four different spike lengths to understand the flow phenomena using CFX module in ANSYS. In case 3 as shown in Table 1 the exit pressure of the nozzle and the ambient atmospheric pressure have been taken equal, whereas in case 1 and case 2 the exit pressure was greater than the ambient atmospheric pressure (under expansion) and in case 4 the exit pressure of the nozzle being less than the ambient pressure (over expansion). It had been clearly observed that in case 4 when the exit pressure is less than the ambient pressure (over expansion), or the condition when the altitude is smaller than the design altitude, low value of truncation in the nozzle has shown a better performance. For the case 1 and 2 where the exit pressure is less than the greater than the ambient pressure, high truncation in the nozzle had shown a good performance. It was also concluded that the loss of thrust is proportional to the value of the truncation. Comparison of the generated data with a conventional convergent divergent nozzle has shown that aerospike nozzle was 5% more efficient when the exit pressure of the nozzle was less than the ambient pressure. This 5% efficiency proved to add a lot of advantage to launch vehicles.

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