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Computational Study of Flow Through Truncated Plug Nozzle

K. Yashwanth Bharath[1*], J. Praveen[2], E. Akash[3], R. Arravind[4]
[1,2,3]*Student, Department of Aeronautical Engineering, Paavai Engineering College, Namakkal, India*
[4]*Professor, Department of Aeronautical Engineering, Paavai Engineering College, Namakkal, India*

***Abstract*: Conical plug nozzle and truncated conical plug nozzle are advanced rocket nozzles suitable for use as altitude compensating nozzles. The conical plug and truncated conical plug nozzles are numerically simulated to first validate with experimental data and then to compare with the experimental results.**

***Keywords*: bell shaped rocket nozzle, Aerospike nozzle, and second law of thermodynamics.**

1. Introduction

The launching cost of one kg of payload into space is about eight lakh rupees in the present market. Currently, launch vehicle uses rocket staging to transfer payloads into their paths. These launch vehicles use the industry standard bell shaped rocket nozzle. This requires having two or three additional propulsion and fuel systems for only one launch, adding production and complexity cost to the system. In the future, reducing these high expenditures will need to come about through radical innovation to eliminate staging complexity and improve nozzle thrust efficiency, making launch vehicles less expensive and more energy efficient. Such innovation may be as simple as replacing the bell nozzle with Aerospike nozzle. This was the objective of the Single Stage to Orbit project, resulting in the development of the X-33 space plane and the Linear Aerospike rocket nozzle. The major advance that was driving research into the Linear Aerospike is the ability for the nozzle to adjust it to the surrounding atmospheric pressure. Contrary to conventional bell nozzles, which have a fixed area ratio optimized for a specific altitude, the Aerospike Nozzle is able to adjust the effective area ratio between the throat and the end point of the nozzle. This adjustability reduces the need for rockets with multiple stages accompanied with additional nozzle and gimbal assemblies, reducing overall complexity. Another benefit of this adjustability is that it enables the nozzles to operate at 100% of the theoretical thrust throughout the ascent of the launch vehicle, optimizing the fuel and oxidizer efficiency. Therefore, the Linear Aerospike rocket nozzle design has demonstrated the potential to both eliminate staging and improve overall engine efficiency. Despite the performance advantages gained from using the Linear Aerospike Engine, financial and physical problems plague the design. The development of this engine cost the government well over a billion dollars, and they only performed a static test of the Linear Aerospike Engine. Meaning, future development of this engine will require significant financial investment. Additionally, engineers discovered a major issue with the operational environment of the Linear Aerospike. During the static fire testing, the extreme temperatures experienced by the major components, caused material degradation. Failures were not experienced during testing, however, these could develop into problematic failures later in the development. Ultimately the Single Stage to Orbit project discontinued due to the expense and engineering challenges. Before the industry can benefit from the efficiency and performance of the Linear Aerospike, there are several logistical barriers and engineering problems that still need to be solved. For one, the Aerospike Nozzle has never been flown on a large-scale rocket platform capable of reaching orbit. Second, the Aerospike nozzle has very high production costs and problems with heat dissipation.

2. Design Principles

The main advantage to the annular aerospike nozzle design (both full length and truncated spike) is its altitude compensation ability below or at its design altitude. More specifically, the aerospike will not suffer from the same overexpansion losses a bell nozzle suffers and can operate near optimally, giving the highest possible performance at every altitude up to its design altitude. Above the design altitude, the aerospike behaves much like a conventional bell nozzle. Figure below shows the exhaust flow along an aerospike at low altitudes, design altitude, and high altitudes for a full spike and a truncated spike. Multiple expansion and compression, or shock, waves are evident in the flow in Figure these waves lead to losses in thrust. The outer flow boundary of the aerospike is the atmosphere itself. Unique to aerospike engines operating at their design altitude, engine geometry at the throat determines the expansion ratio of the aerospike nozzle and thus the corresponding engine performance. The above geometry adopted form the Verma (2009) experimental research work. All the dimensions are modeled as per the figure 3.1 for the computational studies of the aerospike nozzle flow characteristics.

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*Corresponding author: yash2021aero@gmail.com

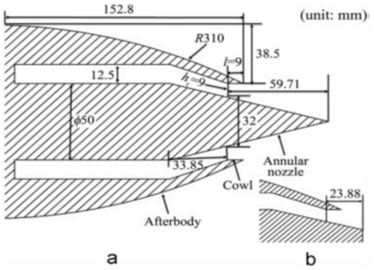

Fig. 1. Aerospike nozzle (a) Full nozzle (b) Truncated nozzle

3. Theory

As a gas is forced through a tube, the gas molecules are deflected by the walls of the tube. If the speed of the gas is much less than the speed of sound of the gas, the density of the gas remains constant and the velocity of the flow increases. However, as the speed of the flow approaches the speed of sound we must consider compressibility effects on the gas. The density of the gas varies from one location to the next. Considering flow through a tube, as shown in the figure, if the flow is very gradually compressed (area decreases) and then gradually expanded (area increases), the flow conditions return to their original values. We say that such a process is reversible. From a consideration of the second law of thermodynamics, a reversible flow maintains a constant value of entropy. Engineers call this type of flow an isentropic flow. Isentropic flows occur when the change in flow variables is small and gradual, such as the ideal flow through the nozzle shown above. The generation of sound waves is an isentropic process. A supersonic flow that is turned while the flow area increases is also isentropic. We call this an isentropic expansion because of the area increase. If a supersonic flow is turned abruptly and the flow area decreases, shock waves are generated and the flow is irreversible. The isentropic relations are no longer valid and the flow is governed by the oblique or normal shock relations. The theory understands the static test data analysis, the linear aerospike nozzle shows the out-perform the classic bell nozzle in specific impulse and thrust efficiency.

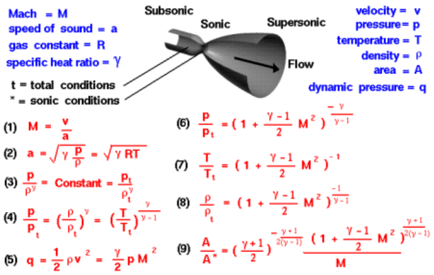

Fig. 2. Nozzle isentropic flow relations

A. Numerical simulation

A numerical simulation has been carried out to investigate the flow characteristics of aerospike nozzle with full nozzle and truncated conditions. For the analysis, a fluid domain is separated from the solid domain and discretized with nodes and cells and analyzed in the CFD solver.

4. Results and Calculations Table

Table 1
Inlet Flow property

Inlet Type	**Inlet Flow property**	**Value**
Pressure far field	Far-field gauge pressure	1277Pa
	Far-field Mach number	5.96
	Far-field static temperature	160K
	Turbulent intensity	5%
Outlet type	Inlet Flow property	Value
Pressure outlet	Outlet pressure	1277 Pa
	Bulk Total Temperature	1296.59 K

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