Introduction to Aerospike and its Aerodynamic Features

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Abstract- Aerospike nozzles are being considered in the development of the Single Stage to Orbit launching vehicles because of their prominent features and altitude compensating characteristics. The annular nozzle, also sometimes known as the plug or "altitude-compensating" nozzle, is the least employed of those discussed due to its greater complexity. The term "annular" refers to the fact that combustion occurs along a ring, or annulus, around the base of the nozzle. "Plug" refers to the centerbody that blocks the flow from what would be the center portion of a traditional nozzle. As any fluid dynamicist recognizes, the significant disadvantage of the "flat" plug is that a turbulent wake forms aft of the base at high altitudes resulting in high base drag and reduced efficiency "Altitude-compensating" is sometimes used to describe these nozzles since that is their primary advantage, a quality that will be further explored later. . However, this problem can be greatly alleviated in an improved version of the truncated spike that introduces a "base bleed," .This paper presents the aerodynamic features performance characteristics and advantades and disadvantages

Index Terms- Aerospike Nozzle, Single Stage to Orbit (SSTO), Linear Aerospike, Truncation and Rocket Nozzle

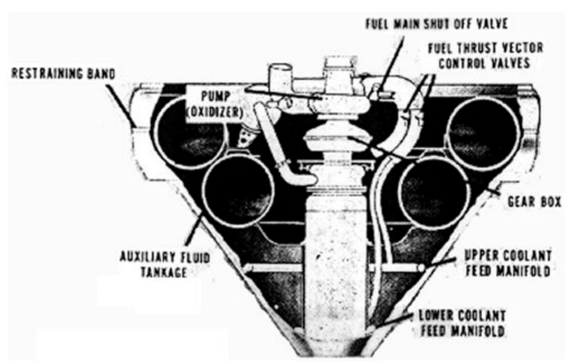
I. INTRODUCTION

Ever since jet and rocket propulsion systems have emerged, researchers have invented and implemented many types of nozzles, mainly to increase the thrust performance of nozzles in off-design working conditions. Among these various designs, features of the aerospike nozzle have attracted researchers since mid-1950s. Many theoretical studies of the aerospike nozzle have been carried out in 1960s. In early 1970s, thermal and strength problems of the aerospike nozzle and development of more efficient methods for fabrication of conventional nozzles led to a decline in research activities in this field. Development of the nozzle with the capability of producing optimum amounts of thrust in wide ranges of altitude has been a subject of continuous dedicated efforts within the community of rocket propulsion.

The phenomenon of producing optimum amounts of thrust by a rocket nozzle in off-design conditions is called as altitude compensation. Nozzles with the altitude compensation characteristics are basic feature in realizing the development of Single Stage to Orbit (SSTO) vehicles. Reusable SSTO vehicles offer the promise of reduced launch expenses by eliminating recurring costs associated with hardware replacement inherent in expendable launch systems.The most popular altitude compensating rocket nozzle to date is the aerospike nozzle, the origin of which dates back to Rocketdyne in 1950s.

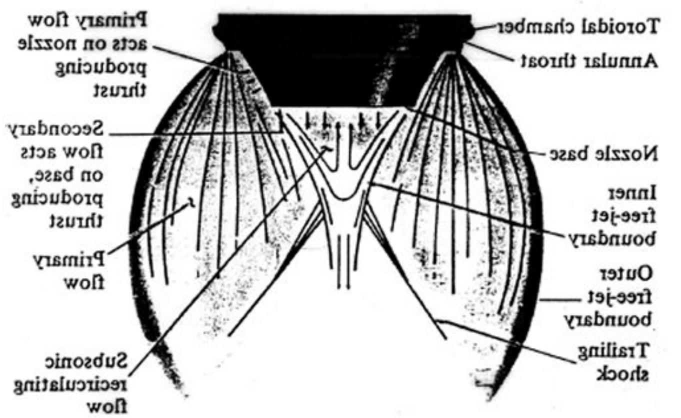
Aerospike Nozzles:

Previously, we discussed methods of reducing the length of a spike nozzle centerbody by replacing the ideal spike with a conical spike. While this method does indeed result in a much shorter nozzle length, we can go even further by removing the pointed spike altogether and replacing it with a flat base. This configuration is known as a truncated spike, an example of which is shown below.



Example of a truncated, conical spike [from Berman and Crimp, 1961]

As any fluid dynamicist recognizes, the significant disadvantage of the "flat" plug is that a turbulent wake forms aft of the base at high altitudes resulting in high base drag and reduced efficiency. However, this problem can be greatly alleviated in an improved version of the truncated spike that introduces a "base bleed," or secondary subsonic flow, into the region aft of the base.

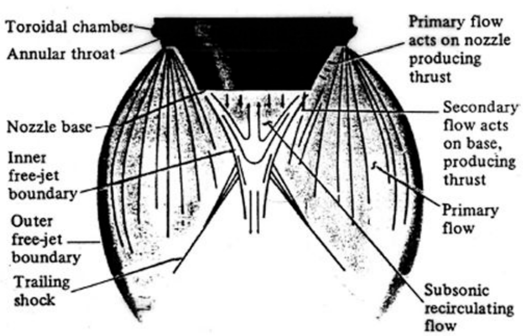


Example of an aerospike nozzle with a subsonic, recirculating flow [from Hill and Peterson, 1992]

The circulation of this secondary flow and its interaction with the engine exhaust creates an "aerodynamic spike" that behaves much like the ideal, isentropic spike. In addition, the secondary flow re-circulates upward pushing on the base to produce additional thrust. It is this artificial aerodynamic spike for which the aerospike nozzle is named.

Aerospike Aerodynamics
Thrust Characteristics:

The basic thrust characteristics of the aerospike nozzle can be better understood by referring to the following figure.



Example of an aerospike nozzle with a subsonic, recirculating flow [from Hill and Peterson, 1992]

The nozzle generates thrust in three ways. First, the thrusters in the toroidal chamber, located at the base of the nozzle, generate thrust as the fuel is combusted and exhausted. We shall label this thrust component $F_{thruster}$, and we can compute this thrust using the equation

$$F_{thruster} = (\dot{m}\, v_{exit} + (p_{exit} - p_{\infty})\, A_{exit}) \cos\theta$$

where

$F_{thruster}$	=	thrust force acting on the thruster
$\dot{m}$	=	mass flow rate
v_{exit}	=	exhaust gas velocity at the nozzle exit
p_{exit}	=	pressure of the exhaust gases at the nozzle exit
p_{∞}	=	ambient pressure of the atmosphere
A_{exit}	=	cross-sectional area of the nozzle exit
θ	=	angle between the thrust axis and the vertical

We previously discussed how nozzles generate thrust when the exhaust gases expand against the nozzle walls. Although we used the bell nozzle to illustrate that discussion, the exhaust gases in a spike nozzle expand against the spike centerbody rather than outer walls. Thus, the expansion of the exhaust gases exerts a thrust force that we will call $F_{centerbody}$.

$$F_{centerbody} = \int A_{centerbody}\, (p_{centerbody} - p_{\infty})\, dA$$

where

$F_{centerbody}$	=	thrust force acting on the centerbody
$A_{centerbody}$	=	cross-sectional area of the centerbody moving along the nozzle axis
$p_{centerbody}$	=	pressure of the exhaust gases on the centerbody moving along the nozzle axis
p_{∞}	=	ambient pressure of the atmosphere

Finally, we mentioned that the aerospike nozzle is so named because an "aerodynamic spike" is created through the addition of a secondary, circulating flow aft of the flat nozzle base. As the supersonic primary flow, consisting of the high-pressure gases exhausted from the thrusters, expands downstream of the base, the primary flow interacts with the subsonic, secondary flow causing it to circulate. This low-pressure flow then re-circulates upward to exert an additional thrust force on the base.

$$F_{base} = (p_{base} - p_{\infty})\, A_{base}$$

where

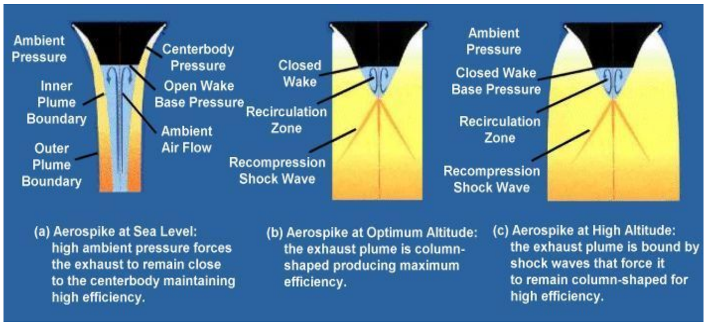
F_{base}	=	thrust force acting on the base
p_{base}	=	pressure of the re-circulating flow on the base
p_{∞}	=	ambient pressure of the atmosphere
A_{base}	=	cross-sectional area of the base

Summing up these three thrust components yields the following relationship for the total thrust force (T) generated by an aerospike nozzle:

$$T = F_{thruster} + F_{centerbody} + F_{base}$$

Altitude Compensation
Altitude Compensation:

However, many claim that the ultimate strength of the aerospike nozzle is its inherent altitude compensation capability, as shown below.



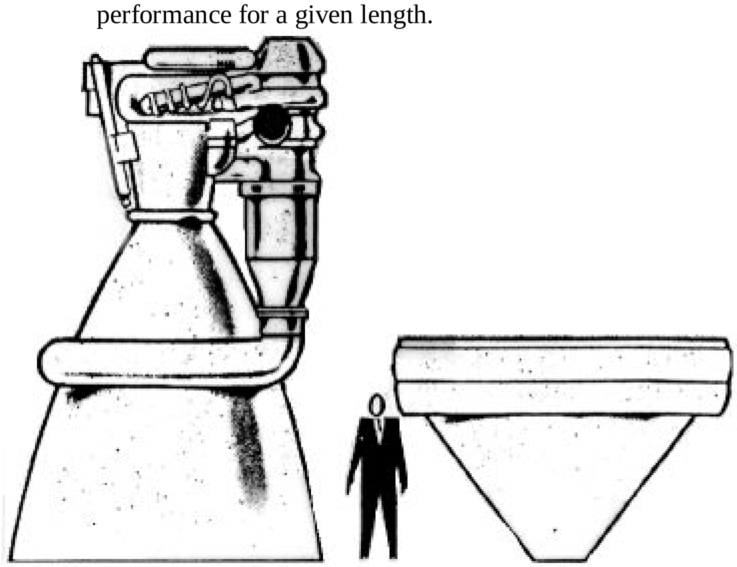
Aerospike nozzle behavior during flight [from Rocketdyne, 1999]

This ideal behavior results from the fact that the outer plume boundary of the primary flow is acted upon only by the ambient pressure of the atmosphere. Recall from our discussion of aerospike thrust characteristics, high ambient pressure at low altitudes forces the exhaust inward increasing the pressure on the "centerbody" and the centerbody component of thrust. In addition, the base region is open to high ambient pressure resulting in a greater "base" thrust component. At design pressure, the flow becomes column shaped, much like a bell nozzle, for maximum efficiency. When operating at low ambient pressure (at high altitude or in a vacuum), the flow is constrained by expansion/compression waves that direct the exhaust axially to maintain the thrust force on the centerbody. At low pressures, however, the nozzle operates in a "closed wake" state. Since the base is not subject to a high ambient pressure, there is no altitude compensation benefit, and the aerospike behaves like a high area ratio bell nozzle. Thus, in theory at least, the aerospike nozzle meets or exceeds the performance of the bell nozzle at all operating pressures.

II. Advantages & Disadvantages

Advantages:

- **Smaller nozzle:** The truncated spike can be far smaller than a typical bell nozzle for the same performance, as shown below. In addition, a spike can give greater performance for a given length.



Size comparison of a bell and a plug nozzle [from Berman and Crimp, 1961]

- **Superior performance:** Altitude compensation may result in greater installed performance.

- **Less risk of failure:** The aerospike engine uses a simple gas generator cycle with a lower chamber pressure than typical rocket engines reducing the risk of a catastrophic explosion. Although low chamber pressures result in reduced performance, the aerospike's high expansion ratio makes up for this deficiency.

- **Lower vehicle drag:** The aerospike nozzle fills the base portion of the vehicle thereby reducing a type of drag called base drag.

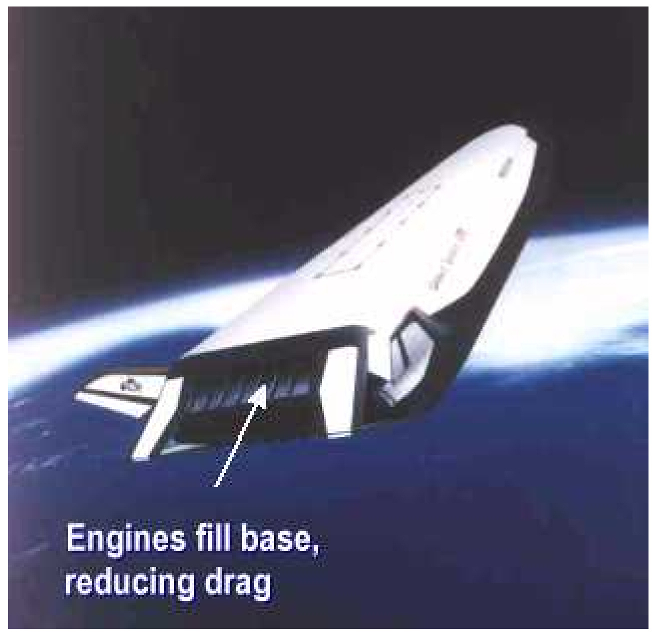
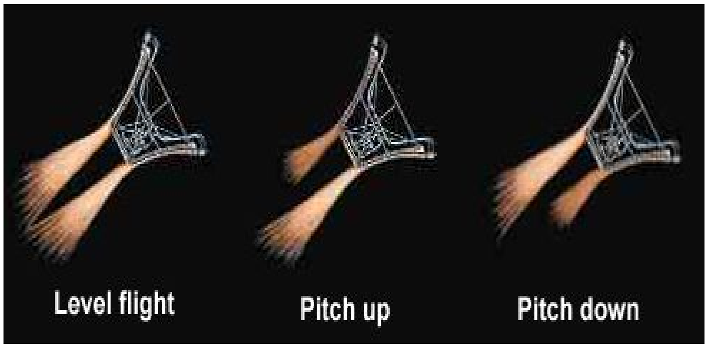


Illustration of aerospike nozzles installed on the X-33 [from Rocketdyne, 1999]

- **Modular combustion chambers:** The linear aerospike engine is made up of these small, easier to develop, less expensive thrusters that give the engine greater versatility.

- **Thrust vectoring:** Because the combustion chambers can be controlled individually, the vehicle can be maneuvered using differential thrust vectoring. This eliminates the need for the heavy gimbals and actuators used to vary the direction of traditional nozzles.



Aerospike thrust vectoring control [from Rocketdyne, 1999]

- **Lower vehicle weight:** Even though the aerospike tends to be heavier than the bell nozzle, it shares many major structural elements with the vehicle reducing overall weight.

Disadvantages:

- **Cooling:** The central spike experiences far greater heat fluxes than does a bell nozzle. This problem can be addressed by truncating the spike to reduce the exposed area and by passing cold cryogenically-cooled fuel through the spike. The secondary flow also helps to cool the centerbody.

- **Manufacturing:** The aerospike is more complex and difficult to manufacture than the bell nozzle. As a result, it is more costly.

- **Flight experience:** No aerospike engine has ever flown in a rocket application. As a result, little flight design experience has been gained.

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