ALTITUDE COMPENSATION NOZZLE

SUMMARY OF ALTITUDE COMPENSATION IN ROCKET NOZZLES AS PART OF THE REQUIREMENT FOR ROCKET PROPULSION COURSE
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1 Introduction

High temperature Gas contains random moment distribution. In order to gain thrust from such gas we need to direct the Flow in Optimised direction. The essential job of nozzle is to direct the flow in optimal direction to gain maximum thrust.

Now when gas is produced From burning the propellent in Rocket the produced gas effectively has no direction. when we direct the high pressure gas to nozzle it flows towards the low pressure direction.If we allow uncontrolled expansion of high temperature gas from combustion chamber to low pressured atmosphere the gas will flow in all directions resulting in little to no thrust generation in the nozzle.In conventional or bell nozzle we allow high pressured gas to expand in rear direction gradually thus the force acting on the wall of the nozzle is maximised and inturn used to drive the rocket.This is achieved by carefully direction flow to rear direcction which maximizes the thrust acting on the nozzle.

Now We have two types of the nozzles that are regularly tested and used. Conical nozzle and bell shaped nozzle. Traditional Nozzle allows for expansion of the gases Using constant Conical shaped expansion angle. Since we have High Pressure at the diverging section of a converging Diverging nozzle, the expansion rates are quite high at that section of the nozzle and as we go the expansion rate is decreased. Bell shaped nozzle or contour nozzle is the most commonly used nozzle design that allows for the higher expansion rate at beginning with high divergence angle and low divergence angle later in the nozzle.

Conventional Bell or Conical nozzles are point pressure designs means that are designed for efficient Operation at single atmospheric temperature.At nozzle Exit If the pressure of gas is greater than ambient pressure then gas furthuer expands into the atmosphere. Such condition is caller Under-Expansion.If pressure is less than ambient then the gass flow Contracts this is called overexpansion. We desire that the Exit Flow is Expanded to pressure of the ambient pressure. We can design a nozzle for a fixed pressure that the Expansion is Optimal. But at any other pressure different from different pressure there will be a Deviance from ideal and the flow is either Under or Over Expanded thus affecting the Efficiency. Now even with the bell shaped nozzle the problem of the altitude variation of the expansion of gas due to atmospheric pressure is not solved.We implement Different designs for the altitude compensation of Flow expansion.Here the Base section and the Ramp section of the nozzle should be Cooled continuously as the Hot Flow is directly fired on the Ramp of the AeroSpike nozzle.

2 Altitude compensation Nozzles

There are Few Altitude compensation nozzle designs that adapt to the changing ambinet conditions. Below are the prominent Nozzle Designs in them.

- Aerospike engine
- Plug nozzle
- Expanding nozzle

2.1 Aerospike engine

The aerospike nozzle/engine is designed to maintain nozzle efficiency over the range of Ambient Pressure. Thus Aerospike engine is a potential candidate for Single stage to orbit Concept Machines. which doesnt contain external boosters to achive the payload delivery into Space orbits.

In Aerospike Nozzle The Flow is allow to Expand against atmosphere as we fire against a Ramp like structure.Aerospike engine also have an additional advantage in thrust vectoring. In conventional Nozzle we use Gimbal systems to Achieve Thrust vector Control while in Aerospike we can Differentially throttle Thrusters relative to other bank.

At Low Altitude The Recirculation below the base of the truncated Aerospike nozzle would Reach to Ambient Pressure thus Not losing any thrust although it wouldn't provide any additional thrust. At higher altitudes the Ambient Pressure is low and thus the wake/Recirculation zone in the base of the Nozzle would provide additional thrust. Now as the We Fire Flow on the Ramp of the Aerospike the Flow Expands to the ambient pressure. Thus The Atmospheric pressure acts as Boundary for the plume. In space/vacccum the Expansion of the Flow is is governed by the Prantl-Meyer expansion wave theory.

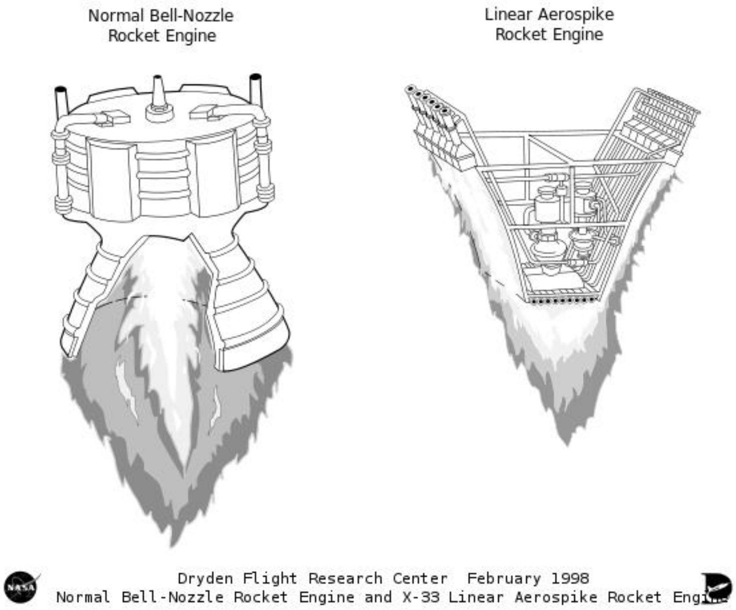


Figure 1: Comparison of Aerospike and Bell nozzle

3 Analytical model of Linear Aerospike nozzle

We Derive Analytical Model For the Aerospike Nozzle to calulate the Properties like thrust Produced and the Temperature, Pressure along the Wall section of the Linear Aerospike.Consider Truncated Aero spike nozzle.

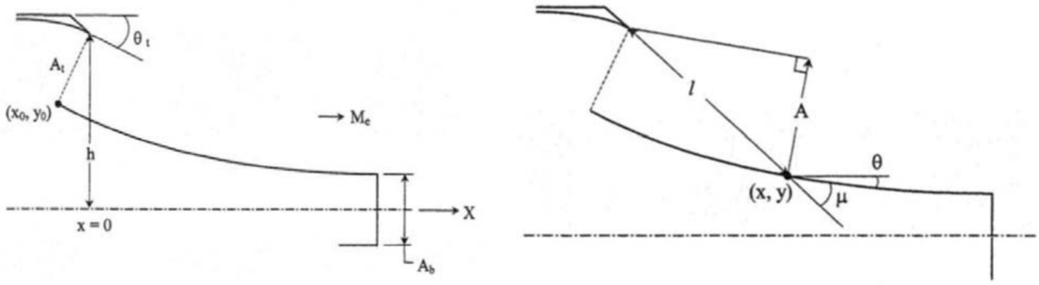


Figure 2: Truncated Aero Spike Nozzle

3.1 Assumptions

- Exaust Flow at the Thruster is Steady invicid and Irrotational and iso-entropic
- Sonic Conditions at Thruster Exit / Throat

Now the Mach no is Governed By Prandtl Meyer Expansion Theory

$$\nu(M_e) = \theta_t = \sqrt{\frac{\gamma+1}{\gamma-1}} \tan^{-1} \sqrt{\frac{\gamma-1}{\gamma+1}}(M^2-1) - \tan^{-1}\sqrt{M^2-1} \tag{1}$$

$$M_t = 1 \tag{2}$$

$$\Delta\theta = \nu(M_e) - \nu(M=1) = \theta_t \tag{3}$$

Now From the geometric Definitions above figure

$$\frac{x}{A_t} = \frac{l}{A_t}\cos\mu + \theta \tag{4}$$

$$\frac{y}{A_t} = \frac{h}{A_t} - \frac{l}{A_t}\sin\mu + \theta \tag{5}$$

As we have assumed that the isoentropic Flow the following relations are also valid on the Flow

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2}M^2 \tag{6}$$

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{1}{\gamma-1}} \tag{7}$$

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{\frac{1}{\gamma-1}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{1}{\gamma-1}} \tag{8}$$

For Thrust Calculations We have that From the Thruster exit area we have

$$F_1 = 2(mu_t + (p_t - p_\infty)A_t)\cos\theta_t \tag{9}$$

where m = mass flow rate of thruster p_∞ = Ambient Pressure at design Altitude
Using the isoentropic Relations here we see

$$F_1 = 2A^*\left(p_0\sqrt{\frac{2\gamma^2}{\gamma+1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} + \left(p_0\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right) - p_\infty\right)\cos\theta_t \tag{10}$$

And Calculating the Thrust against the walls here

$$F_2 = -2\int_{x_0}^{L}(p(x_0) - p_\infty)\frac{dy}{dx}dx \tag{11}$$

As the recirculation Zone Pressure is nearly equal to the Ambient the Thrust obtained from base is zero.Now the Thrust Cofficient is given by

$$C_F = \frac{F}{p_0 A^*} \tag{12}$$

Now From the Result of this Code we can see the Pressure Dropping from along the cross section of the wall we see that Pressure dropped Exponentially thus We dont lose much efficiency truncating the nozzle.

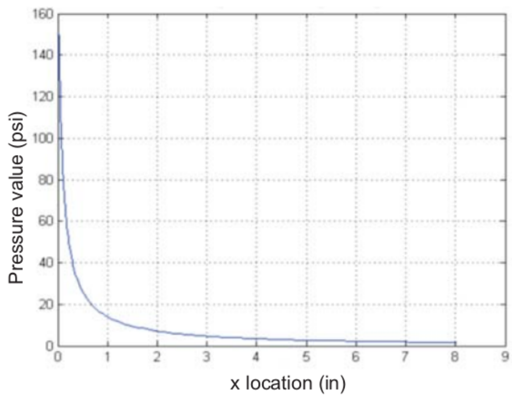
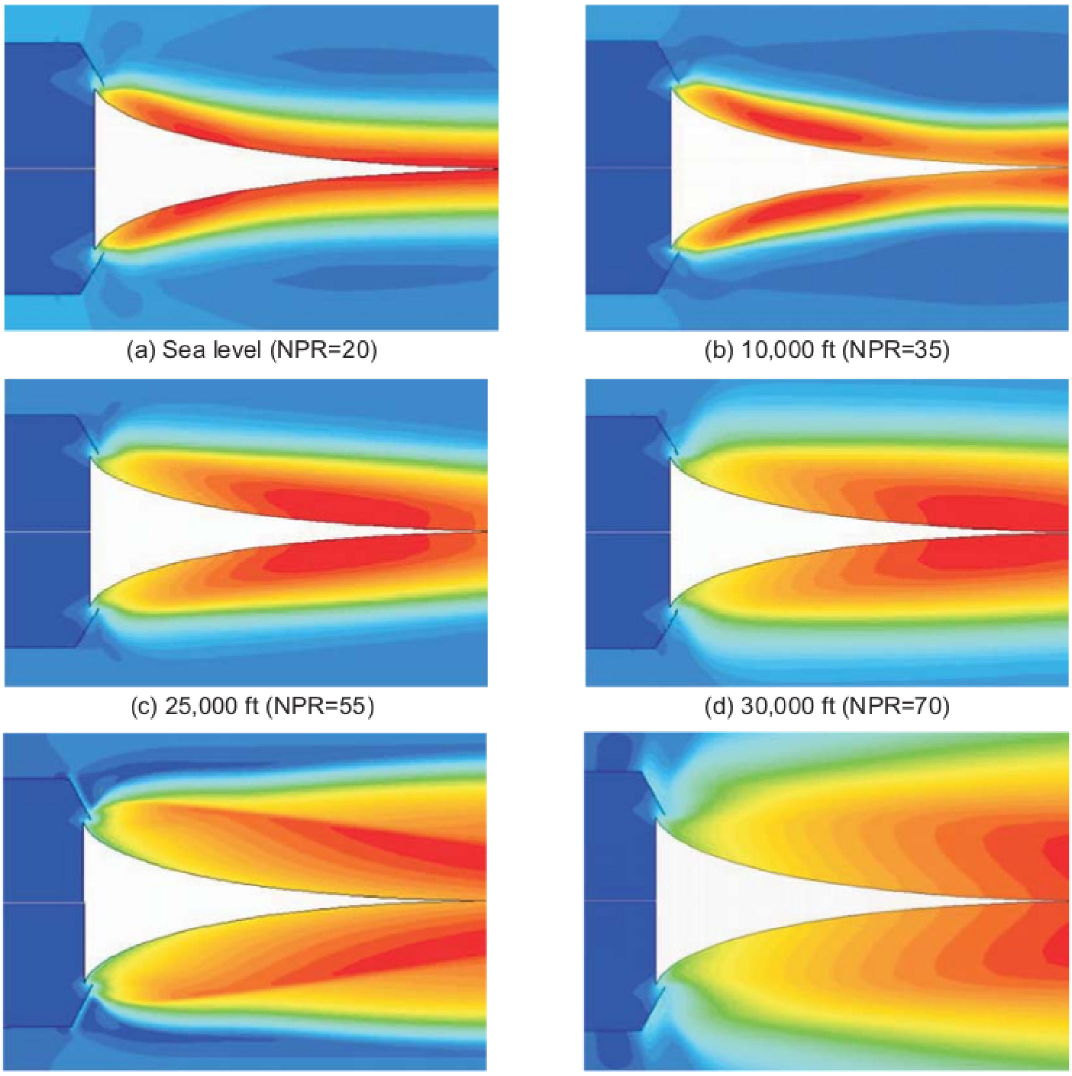


Figure 3: Pressure on Wall of Nozzle

Now We can see the Results from CFD Analysis



(a) Sea level (NPR=20)
(b) 10,000 ft (NPR=35)
(c) 25,000 ft (NPR=55)
(d) 30,000 ft (NPR=70)
(e) 45,000 ft (NPR=110)
(f) 60,000 ft (NPR=225)

Figure 4: CFD Results Simulated at Different Altitudes

In the Above Simulation Results We can see that the Change of the Flow pattern Simulated At different altitudes and the Varying Districutions due to the change in ambient Pressure.

Below are some of the very important advantages of Aerospike nozzles:

ADVANTAGES:

- For Given Performance The Aerospike has shortend Length thus having reduced weight.
- Improved performance low altitudes due to the Altitude Compensation capabilities.
- The relatively stagnant region in the center of the nozzle can possibly be used for installation of gas generators, turbo pumps, tanks, auxiliary equipment, and turbine gas discharges.
- The Combustion Chamber can be Divided into smaller segments thus improving Stability and also improved Thust vectoring abilities of Nozzle

DISADVANTAGES:

- The Surface Area Need to be Cooled due to high heat influx from Flow.
- Difficult to manufacture.

- Has been never Flown on actual mission thus only Sea-level Performance tests and Simulation Data is Available.

4 Plug nozzle

Plug Nozzle is a converging divergin class of Nozzle With plug positioned after diverging Section of the Nozzle. The Control Of the Plug Position is inside Assembly of the Nozzle Engine.In the Plug Nozzle Type of Nozzle the Flow Encounters the Plug After entering the Diverging section. Here We are Controlling the Flow Direcion and The Stream Using the Position of the Plug inside the Nozzle diverging section.

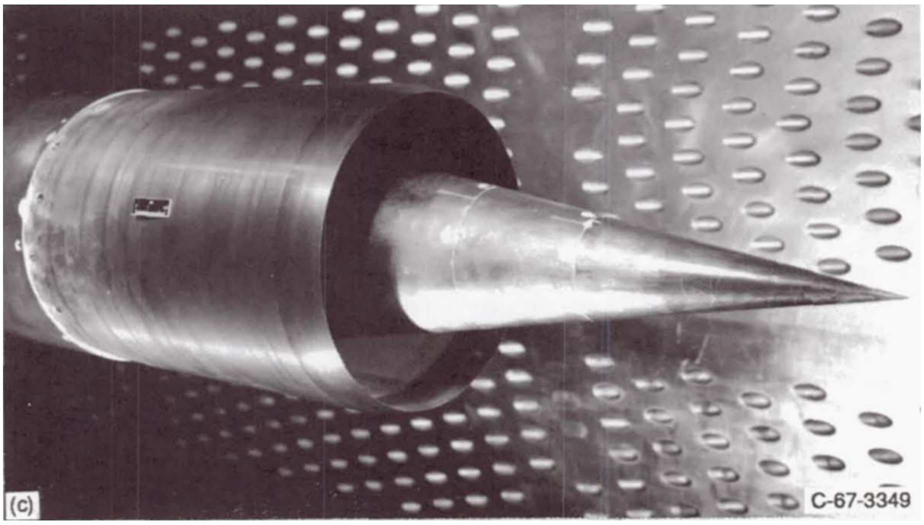


Figure 5: Plug Nozzle

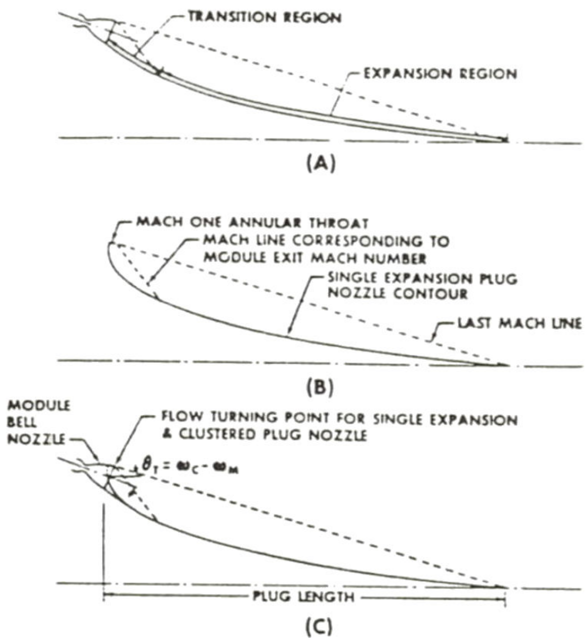


Figure 6: Internal-External Expansion Process of for Plug type Nozzle

The Supersonic Stream Continous to Expand after entering the Diverging Section untill the Static Pressure of the Supersonic Stream Is equal to the Ambient Pressure of the Downstream Environment. As we See in the Above Picture The Expansion Process is Controlled By Prandtl-Meyer Expansion Process. By Proper alignment of Flow to the Plug We can produce Maximum Velocity and Thrust in Axial Direction.

Plug Nozzle is Unique in the method of Controlling Expansion Process. With Careful design We can Achieve a Flow stream that is Completely axial Maximizing the Thrust. To achieve this axial flow, The Flow Is tilted inwards.The Plug Contour is Designed by the Conventional Method of Charecterstics For Prandtl-Meyer Expansion to Produce Shock free turning of Supersonic Flow After internal Expansion.

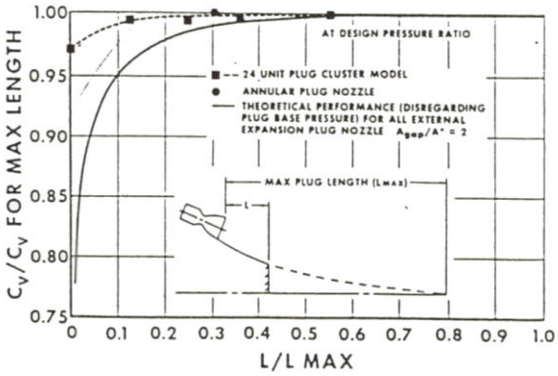


Figure 7: Effect of Plug length on Thrust Coefficient

Now We can Truncate the Nozzle similar to the Aerospike nozzle to Have a recircualtion zone at the Base of the nozzle that also Pressurrises the Base Zone to Provide Additional Thrust. The Aerospike and the Plug Nozzle Have Similar Expansion Process Mechanism but differ in The Place Where the Expansion Take Place. In Plug Nozzle Fully Formed Flow Leaves the Plug Nozzle Where as the Aerosike nozzle the Expansion And Turning Process happen Outside.

5 Expanding nozzle

Now In common nozzle we have problem of point Design. Expanding Nozzle is concept in which there are twi skirts for nozzle as shown in below figure. The basic Idea is When in lower altitude we use small inner nozzle and as we climb higher an the flow furthur expands we push off the inner skirt and the flow uses the Outer nozzle thus solving the problem of Altitude Compensation.This can increase the efficiency and get major performance increases.

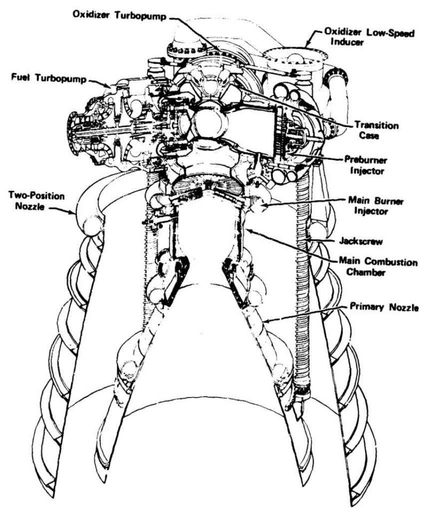


Figure 8: Expanding Nozzle

Although looking Simple, the expanding nozzle is complex to build.The Major issue ie sucessfully building the Expanding nozzle comes from the cooling of nozzle. Usually cooling is schieved with Fuel and oxidiser pumped to take of the heat from the Bell but with expanding nozzle we need to divert the Cooling to new nozzle posing challege of moving parts. This highly increases the Complexity of the Building Process.