Analysis of Various Nozzle Designs to Improve Rocket Engine Performance

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Abstract

This paper suggests a nozzle geometry that has the greatest potential to improve rocket engine parameters, such as thrust and efficiency, beyond their current status. Increasing these would increase the payload mass that can be sent into space and help create a viable Single-Stage-to-Orbit (SSTO) platform. Various performance metrics and physical phenomena regarding rocket science, particularly rocket engines, are explained. Next, the paper discusses various nozzle geometries and discuss their performance benefits and drawbacks. This is followed by an analysis of the risk and the payoff factors of each of the nozzle geometries proposed and a recommendation on which shows the most promise. This paper has found that dual bell and aerospike nozzles have acceptable risk-to-payoff ratios and the former should be developed and integrated into existing platforms until the technology for the latter reaches its maturity. One limitation of the discussion presented is that it is limited to nozzle geometries that have already been discussed, hence no novel geometries can be proposed by this paper.

Keywords: *aerospike nozzle; two step nozzle; expansion deflection nozzle; dual bell nozzle; altitude compensation; overexpansion; underexpansion*

Nomenclature:

Nomenclature

M- mass flow rate

V_e- exhaust velocity

P_e- flow exit pressure

P_a- atmospheric pressure

A_e- nozzle exit area

ΔV-the delta-V of the rocket

V_e- exhaust velocity of the engine

m_w-wet mass (total mass of rocket on the launchpad)

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m_d-dry mass (mass of the rocket without fuel and oxidizer)

I_{sp}- Specific Impulse

F- Average thrust

g_0- acceleration due to gravity on Earth

ε- Expansion ratio

A_e- Area of the exit of the nozzle

A_t- Area of the throat of the nozzle

1. Introduction

Finding ways of improving current technology is a crucial endeavour in any STEM field, including rocket science. With our current technology, we would reach Mars in about seven to ten months [1]. This is not an ideal situation. To decrease travel times, it is essential to increase the thrust that engines are capable of. The formula for thrust from a rocket engine nozzle is defined as this [2]:

$$F = M * V_e + (P_e - P_a) * A_e \quad (1)$$

Understanding the physics behind thrust generation reveals why exhaust velocity is so critical. As you can see, the exhaust velocity is one of the parameters of the force of thrust of the engine and that force will increase with an increased exhaust velocity. This gives rockets a greater acceleration and hence a greater velocity to reach its destination in less time. Increasing the mass flow rate can also increase thrust; however, it will also increase the rate at which the rocket consumes fuel. In fact, the only accepted way to increase the thrust of a rocket engine is to increase its exhaust velocity. And most of the effort in the field of rocket science is concentrated towards finding ways to increase this parameter.

If we consider the ideal rocket engine, we can also see another potential benefit of a greater exhaust velocity [3]:

$$\Delta V = V_e ln(m_w / m_d) \quad (2)$$

ΔV-the delta-V of the rocket

V_e- exhaust velocity of the engine

m_w-wet mass (total mass of rocket on the launchpad)

m_d-dry mass (mass of the rocket without fuel and oxidizer)

The delta-V of a rocket is commonly considered to be a measure of the capability of the rocket. A rocket with a greater delta-V will be able to accelerate a heavier payload to a greater speed [2]. Here, we can see another benefit for increasing the exhaust velocity: the delta-V of the rocket increases. Consequently, the rocket would be able to carry greater payloads further distances in less time. As companies begin to recognize the commercial significance of other planets, and begin to send supplies to build infrastructure, payloads will get heavier and the capabilities of rockets will have to increase along with industry requirements.

2. Theoretical Background

Before discussing nozzle geometries, we must first present some key parameters and some important physical phenomena that occur in rocket nozzles and explain their significance.

2.1 Nozzle Operating Principles

Rocket nozzles operate on Newton's third law: every action has an equal and opposite reaction. First, the fuel is mixed in the combustion chamber and is ignited. Now, the gas is expanding in all directions, but we need the gas to travel through the nozzle, out of the exit. This is why nozzle geometry is critical: it needs to be able to direct these particles towards the exit of the nozzle efficiently and without damage. It is able to do this due to the law of conservation of energy; the thermal energy of the molecules is converted into kinetic energy, allowing the particles to move with greater speed. Now, as the flow exits the nozzle, it provides a force with which the rocket moves, in accordance with Newton's third law [2]. There are certain parameters that can describe these nozzles.

2.2 Performance Metrices

Nozzle efficiency

When the fuel and oxidizer combust in the combustion chamber, the gas expands in all directions. However, the particles need to travel in the direction of the exit. The ideal nozzle is a nozzle which does this perfectly, and does not have to deal with flow separation, perfect expansion (when exit pressure and ambient pressure are equal) and no shockwaves. However, an engine can only be optimized for one altitude (and the altitude of the rocket is changing) and must deal with flow separation and shockwaves. Engineers define nozzle efficiency as how close the rocket nozzle comes to the ideal nozzle. Since the nozzle is converting the thermal energy of the particles into kinetic energy, the formula for nozzle efficiency is as follows:

$$\eta = (V_{actual})^2/(V_{ideal})^2 \quad (3)$$

Where V_{actual} is the actual exhaust velocity of the flow and V_{ideal} is the ideal exhaust velocity of the flow. Since nozzle efficiency is a ratio of two velocities, the maximum value that can be obtained is 1, where the closer the value is to 1 the better the nozzle is. Nozzle efficiency is a dimensionless quantity, which means it has no value. Nozzle efficiencies of rockets are values lower than one due to boundary layers, flow separation, shocks and roughness of the surface of the nozzle (roughness adds friction, which can cause particles to lose energy) [2].

Specific Impulse

Specific impulse is defined as the thrust force obtained per weight flow of propellant mass. Impulse is defined as the average force into the time for which it acts. However, this is not very useful to compare engines and rockets of different mass. Hence, the quantity of specific impulse is defined. It is commonly accepted as a measure of the overall efficiency of an engine, covering the combustion of the fuel and oxidiser The formula for specific impulse is [2]:

$$I_{sp} = F/(Mg_0) \quad (4)$$

When the flow is operating under perfectly expanded conditions (P_e and P_a are equal), the formula for I_{sp} is this:

$$I_{sp} = V_e/g_0 \quad (5)$$

Where V_e is the exhaust velocity of the flow. As one can see, the exhaust velocity of the gas is directly proportional to I_{sp} [2]. This is another reason why engineers aim to increase exhaust velocity; increasing exhaust velocity would increase specific impulse, making the engine more efficient.

2.3 Loss Mechanisms

Truncation Loss

In the case of the conical and bell nozzle, each section of the wall is expanding the flow and turning it in the axial direction. Each conical and bell nozzle has an ideal length that provides the maximum amount of thrust possible. However, this would mean that the nozzle becomes longer, which makes it heavier and more expensive. Hence, engineers decide to drop the extra length and go for a truncated nozzle. The loss of greater exhaust velocity and the portion of the wall that the flow would be pushing against is known as truncation loss. Truncation loss can be expressed mathematically in this form:

$$\Delta C_F = C_{f,full} - C_{f,truncated} \quad (6)$$

Usually, bell nozzles can be shortened to about 60 to 80 percent of their ideal length and only have a truncation loss of 1 to 2 percent. This is extremely beneficial for rockets, where a premium is placed on lowering the structural mass of a rocket [2]. However, if the nozzle is shortened beyond a certain length, there can be drastic losses in the thrust coefficient of the nozzle, as demonstrated in Figure 1 below [4].

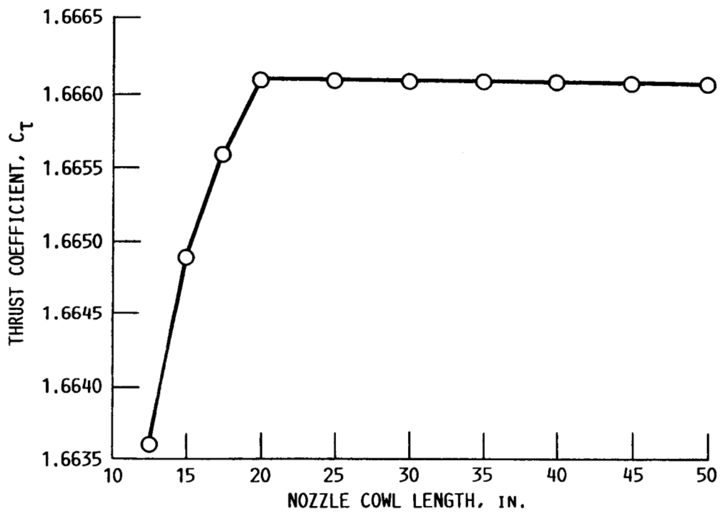

FIG. 17. - PLOT OF NOZZLE COWL LENGTH VERSUS NOZZLE THRUST COEFFICIENT

Fig. 1: A graph of the nozzle cowl length versus the thrust coefficient for a scarfed nozzle (one that is truncated at an angle) [4]

Divergence Losses

This form of thrust loss is common in conical nozzles. Since conical nozzles are shaped like a cone, the flow of exhaust gases will fill up the entire volume of the nozzle. So particles at the edges of the nozzle will have two components of their momentum: momentum in the axial direction and momentum in the non-axial direction. The momentum in the axial direction is the only component that is contributing to the thrust of the rocket engine as the non-axial component of the particles is cancelled out due to axial symmetry of the exhaust gas. This is known as divergence loss and is a major problem for conical nozzles. A correction factor can be applied to the coefficient of thrust known as C_θ, defined as the ratio of the axial momentum of the particles to the ratio of the momentum of the particles if the flow is ideal and in the axial direction. It can be expressed numerically as:

$$C_{\Theta} = F_{G_{axial}}/F_{G_{Ideal}} \quad (7)$$

This parameter can also be expressed in terms of the half angle of the conical nozzle (where the half angle is the angle at which the walls diverge at) in this form:

$$C_{\theta} = (1 + cos\ \theta)/2 \quad (8)$$

Where θ is the half angle of the nozzle. As the half angle of the conical nozzle increases, the loss of thrust due to divergence increases [5]. However, this problem has largely been countered by the introduction of bell nozzles. Due to the change in their contour, which can be quantified by its turn-back angle, the exhaust flow can be redirected into the axial direction [2].

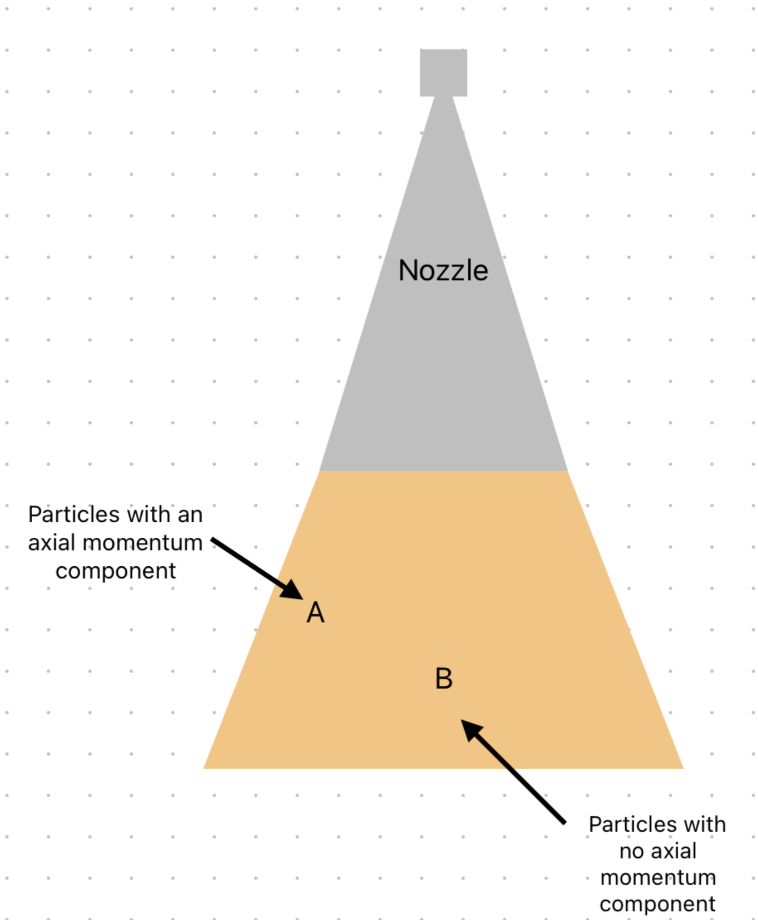

Fig. 2: Divergence loss in a conical nozzle

Underexpansion and Overexpansion

These two forms of losses are the main culprit behind overall thrust losses in rockets. In bell nozzles, increasing the exit area of the nozzle is a method to increase the exhaust velocity of the flow. However, doing this would also decrease the pressure of the exhaust flow. And, in an ideal nozzle the exit pressure is equal to the atmospheric pressure. Engineers call this as perfectly expanded flow.

Underexpansion occurs when the exhaust flow is greater than the ambient pressure. This means that the flow of the exhaust gases could be expanded to a greater area, giving it a greater exhaust velocity. This can easily be observed from the ground, as the plume of exhaust gases would expand further than the diameter of the exit of the nozzle as the flow pushes out against the atmosphere due to its greater pressure. The reason why underexpansion poses a problem for engineers is that there is a loss of potential exhaust velocity, which reduces the efficiency and the thrust provided by the engine [6]. However, this is a relatively smaller problem than the one posed by overexpansion.

Overexpansion is a nozzle flow phenomenon which occurs when the exhaust flow is at a pressure that is lower than atmospheric pressure. Here, the flow has been expanded too much by the nozzle and leads to two problems. The equation of the thrust that a rocket provides is this [2]:

$$F = M * V_e + (P_e - P_a) * A_e \quad (1)$$

If the atmospheric pressure is greater than the pressure of the exhaust flow, this means that the coefficient of the nozzle exit area is negative, which leads to a loss of thrust, and overall efficiency. This is the first problem. The second is that the flow of exhaust gas separates from the wall of the nozzle, causing shocks to form. This flow can work its way up the walls of the nozzle, leading to side loads which can break the nozzle, and cause it to fail [6]. The Summerfield criterion states that this kind of flow separation occurs when the exit pressure is 40 percent of atmospheric pressure [7]. These are the biggest losses faced by nozzles today. Having established the fundamental principles, we can now examine specific nozzle geometries.

Table 1 Performance losses in conventional rocket nozzles[a]

Losses	Vulcain 1, %	SSME, %
Chemical nonequilibrium	0.2	0.1
Friction	1.1	0.6
Divergence, nonuniformity of exit flow	1.2	1.0
Imperfections in mixing and combustion	1.0	0.5
Nonadapted nozzle flow	0–15	0–15

Fig. 3: Performance losses as percentages in the Vulcain 1 and Space Shuttle Main Engines [8]

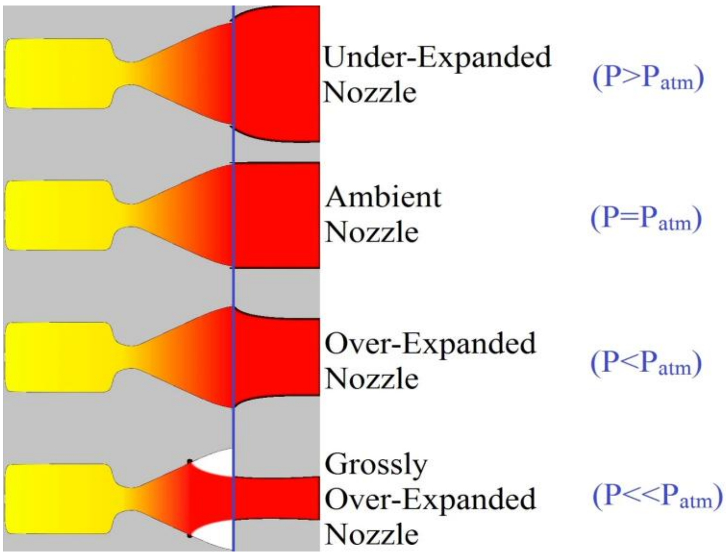

Fig. 4: Diagrammatic representation of underexpansion and overexpansion in rocket nozzles [9]

3. Nozzle Geometrics

Now, an understanding of each of the basics of the nozzle geometries that will be discussed in this paper is crucial to understanding the advantages and disadvantages of each nozzle. Each nozzle will be discussed in detail before progressing to evaluating them for future development.

3.1 Conventional Designs

Conical Nozzles

Conical nozzles are simple. It consists of a divergent section which is shaped like a cone. There is no change in contour and the angle made by the walls of the nozzle stay constant. It is the most basic rocket nozzle. The main advantage of this nozzle is its ease in manufacturing. Since it is a simple cone, the cost of manufacturing is small. However, it is susceptible to divergence losses, which come due to its half angle. Reducing the half angle would reduce divergence losses and exhaust velocity but would make the nozzle longer which would drive up the manufacturing cost [10].

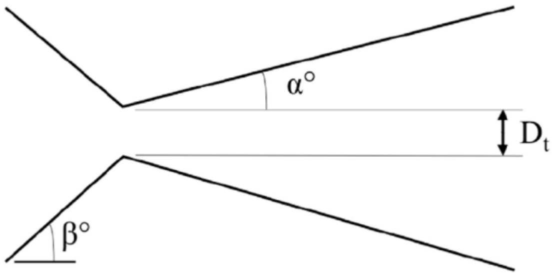

Fig. 5: Diagram of a conical nozzle where α represents the half angle and D_t represents the diameter of the throat [11]

Bell Nozzles

Bell nozzles, or De Laval nozzles, are the most common nozzles in rockets today. The bell nozzle is characterized by a converging section, a diverging section, and a throat section. When the fuel and oxidiser are combusted in the converging section, the velocity of the particles are below the speed of sound, or less than Mach 1. Here, due to the contour of the wall, the flow is compressed, and velocity of the particles increases. Eventually, the area of the nozzle reaches a minimum. This is known as the throat of the nozzle. Here, the flow is considered to be choked, and the cross-sectional area of the throat is called the throat area, A_t. Once the exhaust flow reaches the speed of sound, it is no longer considered to be incompressible and obeys different laws. An increase in cross-sectional area, not a decrease, would increase the speed of exhaust flow. The purpose of the divergent section is to increase the diameter and the velocity of the exhaust flow. This section continues until it reaches the exit of the nozzle [2].

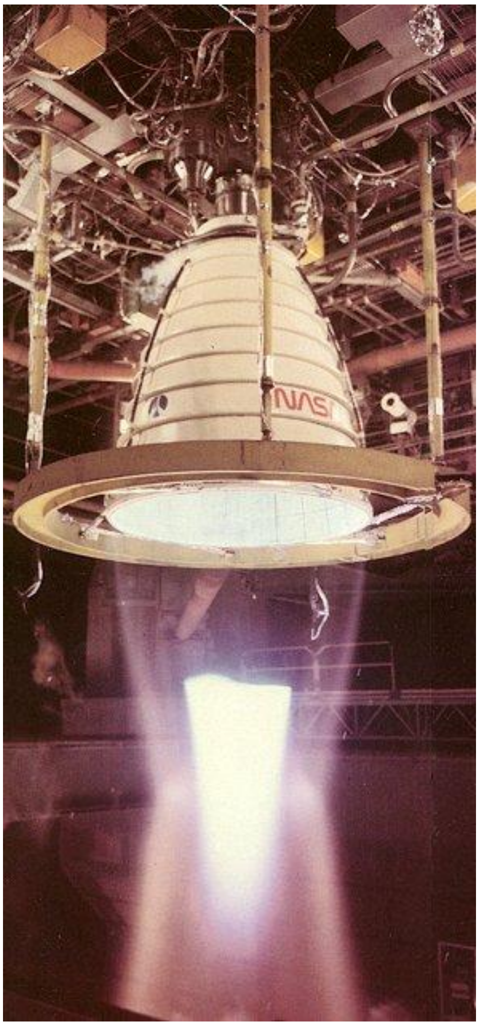

Fig. 6: Diagram of a bell nozzle [12].

It is necessary to define a parameter known as the expansion ratio of the nozzle [2]:

$$\varepsilon = A_e/A_t$$

The larger the expansion ratio is, the greater the exhaust velocity of the nozzle and the lower the exit pressure is. However, this creates a problem, which is that the exit pressure can only be one value while the ambient pressure decreases as the rocket moves through the atmosphere. This means that the nozzle is only optimised for a single altitude and operates in underexpanded or overexpanded conditions most of the time, losing efficiency [10]. This is the biggest problem faced by rocket engineers and a primary reason why other nozzles are being explored.

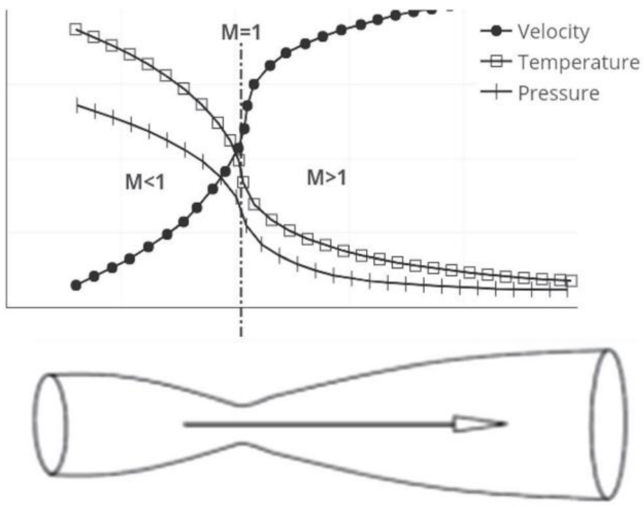

Fig. 7: Variation of temperature, pressure and velocity of exhaust flow[10]

3.2 Altitude- Compensating Designs

Aerospike Nozzle

The aerospike nozzle is one of the many designs that exist that are said to be altitude compensating, solving the problem of over and underexpansion. The aerospike nozzle has two different types: the linear and the toroidal aerospike nozzle. Each one consists of a large spike that is either circular or linear and no outside wall. Exhaust gases would run along the sides of the aerospike [8].

Fig. 8: Examples of linear and toroidal aerospike nozzles [13]

The concept behind the aerospike nozzle is that it allows for perfect expansion across all altitudes. Since there is no external wall, the exhaust flow can expand against the atmosphere directly, allowing for optimal expansion at all altitudes. At sea level, the exhaust gases will be compressed to the sides of the aerospike as the ambient pressure is much larger than the exhaust pressure. As the rocket moves upwards in the atmosphere, the ambient pressure decreases, which allows for the exhaust plume to push against the atmosphere and expand so that the exhaust pressure is equal to the ambient pressure. This condition is known as perfect expansion and allows the maximum amount of thrust to be delivered. This process is the same for all altitudes, allowing perfect expansion under all conditions, unlike the bell nozzle which is optimized for a single altitude. This is why the aerospike nozzle is said to be altitude compensating [2],[8],[10]. Aerospike nozzles have an ideal length designed to produce a maximum of thrust, but this can be truncated to form the plug nozzle which would result in weight savings with a minimal loss of thrust as there is some recirculating gas present. Even this minimal loss of thrust can be offset by injecting some gas into this area, creating back pressure [2].

Fig. 9: Expansion of exhaust flow at various altitudes [14]

The advantages of this nozzle are huge. The potential for unlimited expansion allows for a greater exhaust velocity which would increase the specific impulse of the rocket. This would allow for a greater efficiency and less propellant mass would be needed to achieve the same delta-V. This type of nozzle would be ideally suited to Single-stage-to-orbit (SSTO) rockets as it can be efficient at all pressure conditions. It also has the potential to minimize divergence losses as, through the process of perfect expansion, the flow of the exhaust gas is turned in the axial direction.

However, there are some disadvantages for this nozzle. One is that a large spike would dramatically increase the weight of the nozzle and make the nozzle less compact. In some cases, this added weight would not be offset by the gains in the specific impulse. Another disadvantage is that the spike would experience extreme amounts of heating and it would be critical to ensure that the spike does not overheat. Cooling channels would have to withstand wall temperatures of 2000 Kelvin without losing structural integrity. The extra cooling requirements would also increase the mass of the rocket. And the special nature of the spike would call for different manufacturing and fabrication techniques which would increase the unit cost of the nozzle [14].

Expansion-Deflection (ED) Nozzle

The Expansion-Deflection Nozzle is another example of an altitude compensating nozzle. The nozzle is shaped in a similar fashion to a conventional bell nozzle, except there is no convergent section. Instead, there is a divergent section, but there is a centerbody in the middle of the throat which deflects the flow towards the walls of the nozzle.

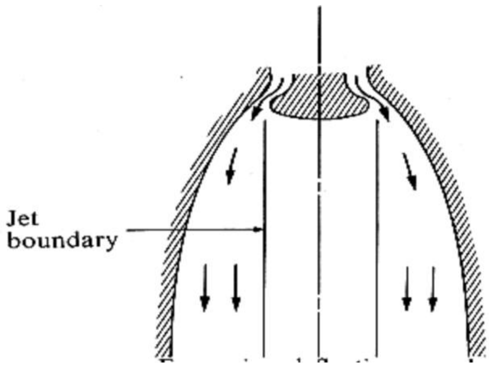

Fig. 10: Expansion-Deflection nozzle [15]

Here, the exhaust gas that is expelled can also expand against the atmosphere. But, it does so inside the rocket nozzle. At sea level, the exhaust gas is directed along the length of the exterior nozzle. The flow is free to expand against the atmosphere, until the flow pressure and the ambient pressure are equal. As the ambient pressure is at its highest at sea level, the exhaust flow will stick to the walls of the nozzle. As the rocket ascends into the atmosphere, the ambient pressure will decrease and the flow of the gas will increase in volume as there is less pressure for the exhaust flow to push against. This process continues as the ambient pressure decreases, which allows for perfect expansion under these conditions [2],[8],[10].

One advantage of this is that this nozzle is around the same size as a bell nozzle, which means there is no significant weight penalty [2],[8]. However, there are some disadvantages. The wake of the nozzle is defined as the boundary between the layer of the exhaust gas. As the ambient pressure decreases, the flow will fill the volume of the nozzle. When the boundaries of the flow do not touch each other, the nozzle is operating in the open-wake condition. When they do, the nozzle operates in the closed wake conditions. Once this happens, the nozzle can no longer expand against the atmosphere and the nozzle loses its altitude-compensation properties. This causes it to behave like a regular bell nozzle, making it susceptible to underexpansion [16]. Also, the small area through which the exhaust gas flows would cause massive heating of the centerbody, which adds additional cooling requirements to the nozzle [2],[8].

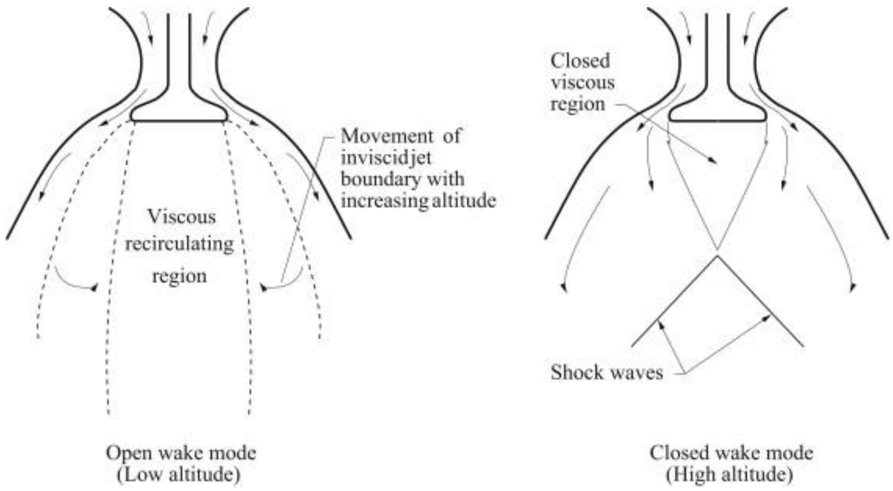

Fig. 11: Open wake and closed-wake conditions [17]

3.3 Two Step Nozzles

These nozzles are a version of altitude compensating nozzles which use two different nozzles with different expansion ratios. As each expansion ratio is optimized for a different altitude, leveraging both designs will give a good performance at the two altitudes. There are various designs for nozzles which fall in the category of two step nozzles [2],[8].

The extendable nozzle consists of an interior nozzle, with a small expansion ratio, and an extension which can be moved into place once the rocket reaches a higher altitude. Once overexpansion is not a risk as the rocket ascends into the atmosphere, the extension that is moved into place will increase exhaust velocity, giving greater thrust. Studies have shown that this contouring method gives a good overall performance, but there are some disadvantages that have to be overcome [8]. One is that at low altitudes, the performance is not ideal as the interior nozzle is truncated. Also, moving the extension would require actuators which could withstand the extreme temperatures and the vibrations of spaceflight. This would add complexity and weight to the engine [2].

Another two step nozzle is one with temporary inserts within the nozzle. Here, the inserts are shaped in the form of a nozzle with a small expansion ratio. This smaller nozzle is placed inside the main nozzle which has a larger expansion ratio. Once the smaller nozzle has been entirely filled by the exhaust flow, the inserts are released and the larger nozzle functions like a basic bell nozzle. The advantages are similar to that of the extendable nozzle. However, a reliable release mechanism needs to be devised for the inserts and there is a possibility that the inserts may damage the wall of the larger nozzle [2],[8].

A third two step nozzle is the dual bell nozzle, which is made of a bell nozzle with a specific contour, but there is a change in contour making it bigger than what the first nozzle would have been.

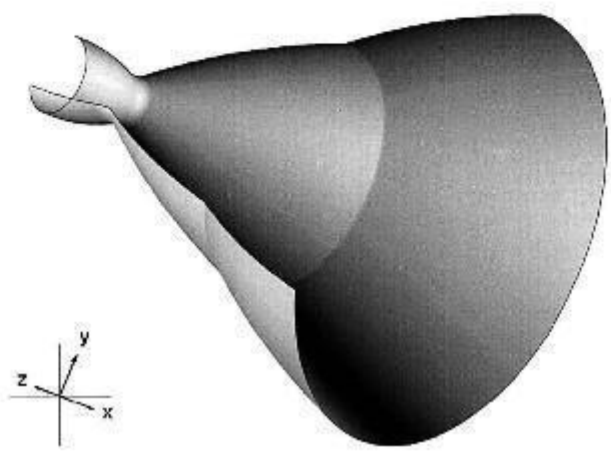

Fig. 12: Dual Bell nozzle[8]

Here, at a lower altitude, the smaller nozzle will be filled with the exhaust flow and the flow will separate from the wall where the change in contour is. As the rocket gains altitude, the nozzle will fill the bigger nozzle, preventing loss of thrust due to overexpansion. Hence, it is able to provide a good efficiency across a range of altitudes. One advantage of this is that it provides altitude compensation without being mechanically complex as the other two step nozzles. And, since it is similar in shape as the conventional bell nozzle, integration into existing rockets will be easier. However, there may be thermal management challenges at the change in contour in a dual bell nozzle. Plus, the nozzle is not fully optimised for an altitude so it will perform worse than a bell nozzle designed for that altitude[2],[8],[18],[19],[20].

4. Comparative Analysis

This paper has presented various potential candidates for future research in nozzle design. The method of gathering information for this literature review was analysing a series of papers and academic texts regarding different shapes of rocket nozzles. To determine their risk and payoff potential, the advantages and disadvantages of each nozzle had to be considered, the summary of which can be seen above.

Nozzle	**Advantages**	**Disadvantages**	**Risk**	**Payoff**
Aerospike nozzle	• Altitude compensation across all altitudes Larger delta-V	• Thermal management issues of central spike • Increased weight	Medium	High

	• Can minimize divergence losses • Can truncate partially without significant loss of thrust	• New manufacturing techniques required		
Expansion-Deflection (ED) nozzle	• Altitude compensation in open wake conditions • Approximately similar weight to bell nozzle	• No altitude compensation in closed wake conditions • Thermal management issues	Medium	Medium
Two step nozzle with extension	• Gives good performance across a range of altitudes	• Non-ideal performance of interior nozzle • Actuators required which would add weight	Medium	Medium
Two step nozzle with inserts	• Gives good performance across a range of altitudes	• Reliable release mechanism needs to be designed • Released inserts may cause damage to exterior nozzle	Medium	Medium
Dual bell nozzle	• Gives good performance across a range of altitudes • Simple integration into existing rockets	• Thermal management issues at change in contour	Low	Medium

5. Result, Discussion and Recommedation

Suitable nozzles need to have a high enough payoff but an acceptable level of risk. There are two nozzles that stand out in this regard: aerospike nozzles and dual bell nozzles. Although aerospike nozzles can produce a greater efficiency and gross thrust, the technology required does not exist yet or has not reached maturity during the writing of this paper. Dual bell nozzles are relatively easier to implement in the near future. Therefore, this paper recommends that researchers and aerospace companies should focus on dual bell nozzles at present and on the technology for aerospike nozzles. Once the technology has been fully developed, aerospike nozzles and rockets optimised for them can then be developed.

6. Conclusion

This paper has examined various parameters and phenomena that are useful in understanding each nozzle geometry. Then, the paper has discussed different nozzle geometries and their advantages and disadvantages. Next, the paper has recommended that dual bell nozzles should be developed in the short term, and aerospike nozzles should be developed in the long term. These dual bell nozzles would serve the purpose of greater efficiency in the short term until the technology required for aerospike nozzles can be developed. These nozzles give greater efficiency and a greater thrust, which would increase the capabilities of rockets and their profitability. Dual bell and aerospike nozzles, which offer greater efficiency across a range of altitudes, are ideal candidates for Single-Stage-to-Orbit (SSTO) rockets which would allow a single engine to propel a rocket into orbit.

7. Conflict Of Interest

The author declares that there are no conflict of interests related to this work.

8. Acknowledgement

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