# Evaluating and Benchmarking the Performance of DualBell, Plug and Conical Nozzles for Enhanced Thrust Efficiency in Aerospace Propulsion

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**Abstract**
**This paper presents a comparative analysis of dual-bell, plug and conical nozzles taking into consideration various factors such as fuel efficiency, specific impulse, exhaust flow pattern, thermal stresses, acoustic impact, complexity of design and manufacturing underdifferent operating conditionsbystudy and review of multiple papers. The aim of this study is to summarize the various configurations of nozzles and contribute to future research by identifying potential design optimizations for specific mission profiles by combining the best features of each nozzle type.**

**Keywords: De Laval Nozzle, Rocket Nozzle Design, Bell Nozzle, Plug Nozzle, Conical Nozzle, Thrust Efficiency, Specific Impulse,Pressure Energy, Nozzle Efficiency.**

## I. INTRODUCTION

The nozzles serve as an exhaust system, exhausted at very high velocities, propellant gases. Nozzles provide the thrust force in all flight conditions. These are major components of propulsion systems that convert energy stored in the high-pressure gas into thrust to move forward the aircraft or spacecraft. This indeed affects design and optimization, in terms of nozzles, for example, bell, conical, or plug nozzles-theoretically though, even with great influence, bearing on such matters as fuel efficiency, payload capacity, and the successful completion of a mission. For such complex missions, like space exploration missions, nozzles are of great importance for the enhancement of the propulsion systems of spacecraft. When the vacuum conditions prevail, as in the case of deep space, nozzle design will be even more important because pressure exerted by the atmosphere directly influences how the expansion of exhaust gases occurs. The nozzle effectiveness of a rocket will determine ultimately which rocket is a fuel-efficient one and which is the consummation of a successful space mission: launching satellites, cargo transport towards a space station, or propelling an exploratory mission to distant planets and moons. As further exploration of space goes on, the nozzles will be a very important and innovative technology in spacecrafts, reflecting the future thrust of aerospace engineering. Multimillion-dollar research does have justification. Despite whether it is part of a rocket or a jet engine, nozzles are the device which provides the velocity and efficiency that do propel an aircraft to the air. Modern aircraft, jets, and turbines nozzles have three purposes: thrust, carrying exhaust gases back into the free stream, and setting a mass flow rate through the engine. The nozzle is located downstream of the power turbine. The principle followed in the manufacture of thrust has been Newton's Third Law of Motion: For every action, there is an equal and opposite reaction.

High-velocity gases are expelled out through the nozzle. Due to this expulsion, the vehicle is pushed back in the opposite direction. However, here it is to be noted that thrust produced is directly proportional to the momentum of the expelledgases.
**This is schematically indicated in Fig 1, and the working is described below.**

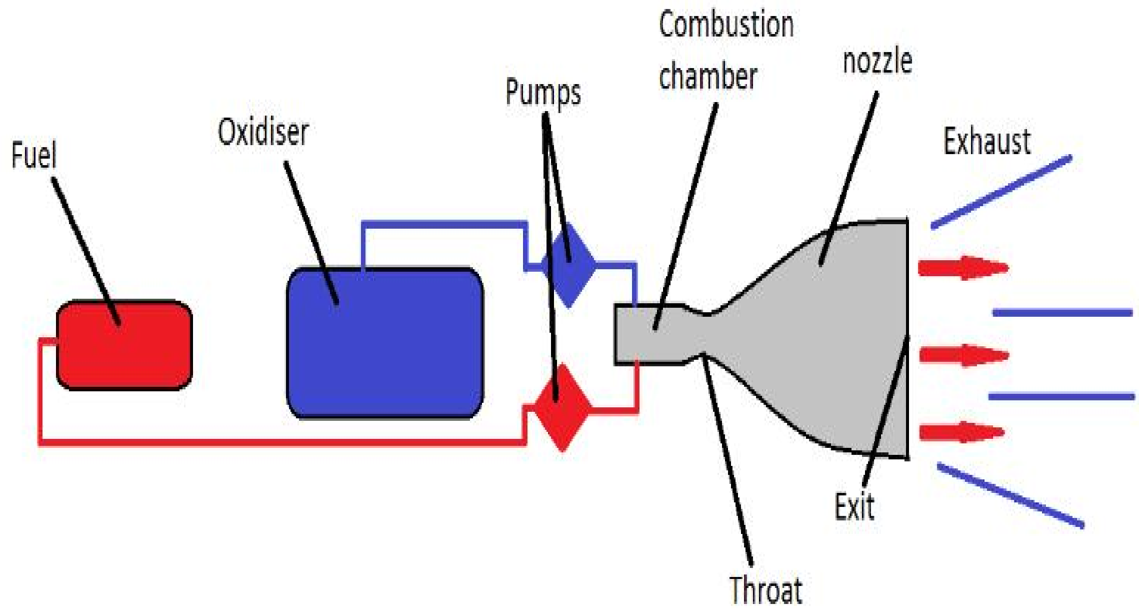



**Figure 1: The basic schematic of working of rocket nozzles.**

In a subsonic flow the gas is compressible and sound will propagate. A choked flow condition is referred to in this paper in which the gases reach the speed of sound [1]. Once the nozzle cross sectional area increases the gas starts expanding and the gas flow increases towards supersonic velocities. Difficulties will arise to operate nozzles when atmosphere is different than one on Earth. There are numerous important planets where the atmosphere is made up of many other gases like hydrogen, helium, methane, and carbon dioxide, in which the nozzle efficiency has to be maintained. Based on the experience and performance of the earlier subscale nozzle manufacturing and test hardware, the development process continues on large-scale hardware. Many modern fabrication technologies come to light, which include Laser Wire Direct Closeout (LWDC), Directed Energy Deposition (DED), specifically Blown Powder DED, and DED Deposition for liners and jacket preforms, such as Arc-based DED and blown powder DED [2].
The noise pollution introduced by the nozzle during its testing is demonstrated by Tinney [3]. Acoustic measurements were obtained by using a traversing microphone array [3]. Peak noise was found to happen at near $135^{\circ}$ for all shapes tested [3].

## II. Dual-bell type

A Planar dual bell nozzles (PDBN) is the most widely used shape after the bell nozzle. It allows the controlled inflection of the wall that can facilitate an adaptation of the vehicle with respect to altitude. Here, at low altitudes, the dual bell nozzle attains a controlled and symmetric separation of flow at the wall inflection and hence attains a smaller expansion ratio. The walls of the nozzles trace the gas flow from the inlet of the gas up to the exhaust gas exit (along the nozzle's axis of symmetry). Nozzle pressure ratio (NPR) is very important for determining the behavior of inviscid flow in the dual-bell nozzle. The thrust efficiency increases the more the NPR is. Usually, the NPR must be greater than the normal shock strength, so NPR rises with an increase in NPR. Rocket engines that work in a vacuum and most common jet engines would have an NPR between 1.5 and 2.5. However, it is possible for rocket engines to have very high NPRs sometimes even reaching 100 or more.

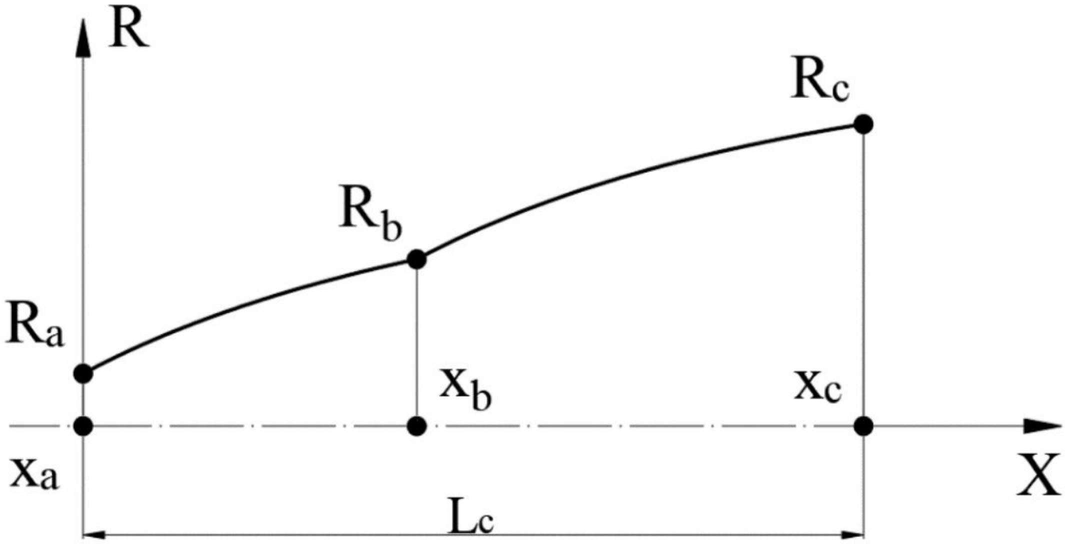



**Figure 2: The geometry parameters of dual-bell nozzle**

**(source:** [5]**)**

Just as the use of higher temperatures would affect the relative merits of nozzle materials, in like manner the use of very low chamber pressures. Thus, at very low pressures, these materials may be preferable to refractory metals, especially where weight and fabricability are important factors [5]. The effect of nozzle size on thermal stresses is complex and cannot be determined readily.

## III. CONICAL TYPE

These nozzles possess the same divergence and thickness all along the length of the nozzle. Performance of a bell nozzle is poorer at lesser altitudes on account of over-expansion of the exit jet and higher altitudes is due to under-expansion of exit jet [6]. Conical nozzles offer linear expansion cross-section which accelerates propellent gases in divergent direction. Conical nozzles have an edge over conventional nozzles especially in high-speed applications due to predictable performance under varied flow conditions, hence a substantial application in many small-scale and large-scale missions.

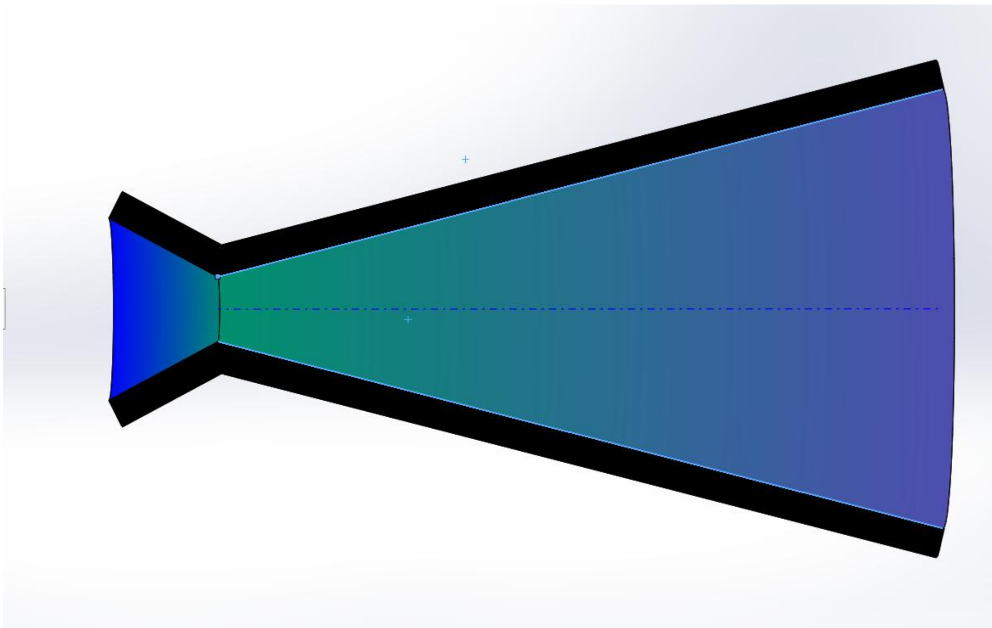


**Figure 3: Cross-section of conical nozzle**

These come in various shapes according to their geometry and orientation such as truncated conical nozzle, conical-plug nozzle, truncated conical-plug nozzle. Divergence angle ranges from 10° to 15° [7]. May cause flow separation at higher angles [7]. One more important dimension is the throat diameter. There is reduction of nozzle performance by up to 8-10% due to the wall separation in flow-oscillations [8]. Such instabilities cause flows passing through these nozzles often to deviate near the transonic region [6].

## IV. Plug type

Plugs nozzles pave the way toward minimal noise, and acoustic impact in the course of their operation. Incorporating particular geometries such as porous plugs reduce noise levels to up to 30% in some regimes of supersonic flow [9]. The plug nozzle design has an exterior contour that varies the exhaust gas expansion according to height and is developed so that the thrust is maximized over a given range of flight conditions [10]. This self-adaptive nature gives an important advantage to plug nozzles over the traditional bell nozzles.

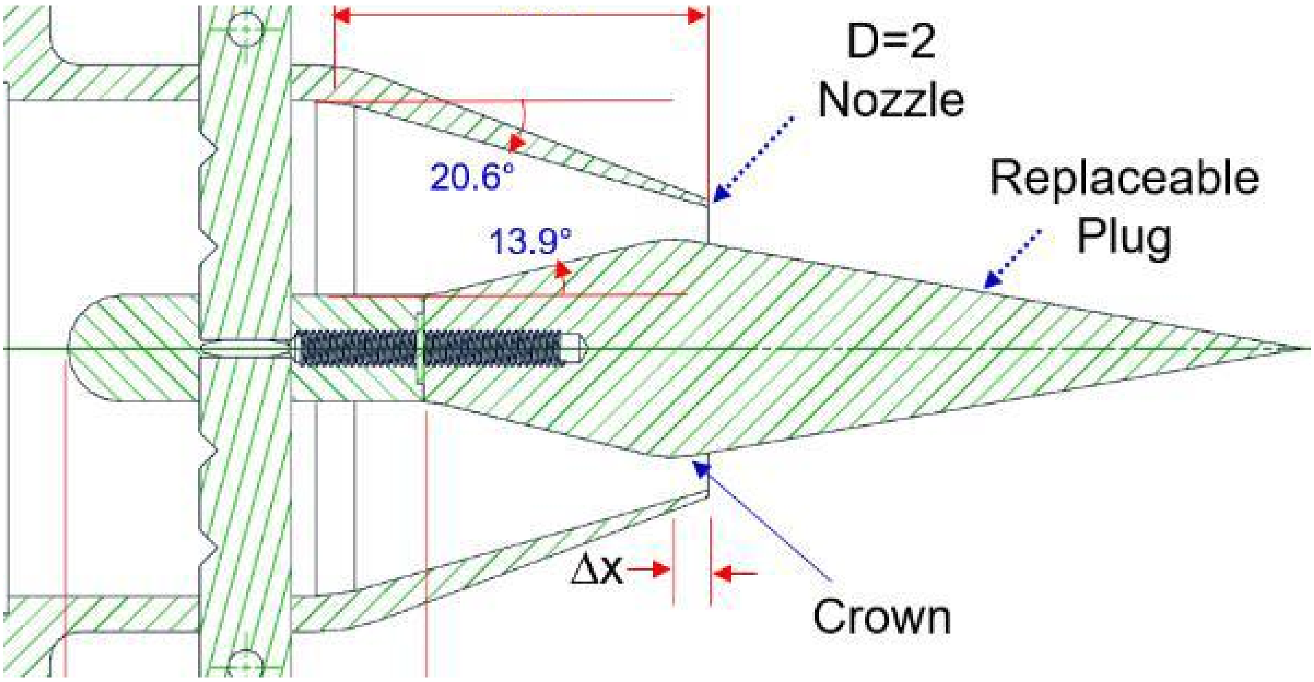



**Figure 4: Schematic of plug nozzle**

**(source -**[9]**)**

Flow separation is not a problem in such nozzles until very high supersonic speeds. So, these are well optimized for overall efficiency. They tend to have a more uniform flow profile, and so can be improved for performance as much as 20% in some configurations. The shock structure observed at different Mach numbers in the flow depicts how these truncated designs can handle the formation of shock waves much more effectively than conventional nozzles [11]. This not only adapts to the external pressures but also minimizes drag, as well as maximizes thrust. Base bleed is believed to be permitting the optimization of the exhaust gases flow for an improvement in the total thrust developed by a rocket [12]. The injected gas helps maintain a higher momentum by the primary flow, thereby increasing the thrust efficiency. It has been reported that this is associated with thrust increases of as much as 5-10% in specific conditions [12]. An injected gas interferes with the formation of the low-pressure region at the base of a nozzle.

## V. Research Objective:

- Perform in-depth comparative thrust efficiency study of different nozzle designs, mainly Dual-Bell, Plug and Conic shape at various altitudes.
- Determination of the various factors that influence nozzles' performance for inputs into future designs in propulsion systems.

- Reviewing and assessment of nozzles and the determinations of how nozzle shape affects factors such as shock wave formation, the separation of boundary layers, and thermal losses in different operating conditions.

## VI. METHODOLOGY

For each one of the nozzle shapes, we had carried out a research survey and come to develop a keen understanding of their working, operating parameters, experimental results, and limitations. In that, it was found that even minute change in the shape over the contours of the nozzle impacts the thrust produced.

• Compare and Benchmark: Gather the information obtained in experiments and plot a comparison of the benefits of Bell, Conical and Plug nozzles.

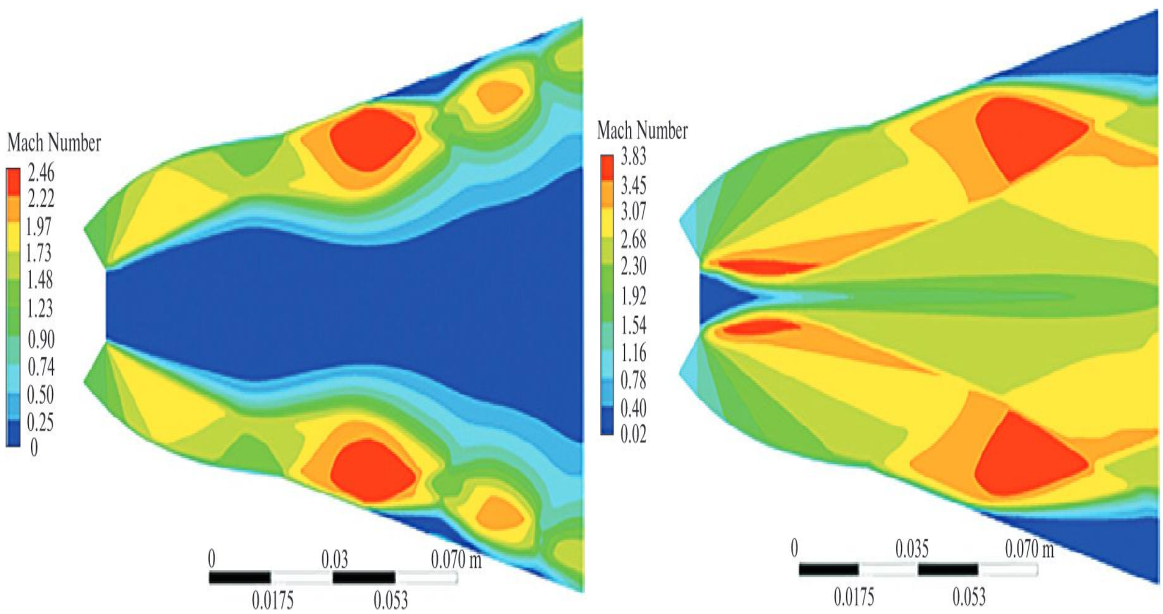
• Trade-offs interpretation: Understanding where each nozzle performs better in various regimes and what are the benefits compared to disadvantages of using another one.

• Gaps Identification: Common trends among the literature and gaps that exist in order to give an achievable insight on propulsion efficiency improvement and further innovation in aerospace engineering.

Considering the thrust, the efficiency of fuel utilization and specific impulse of the exhaust, separation of flow, and shock structures. In addition, the complexity of the design and manufacturing process, management of thermal stress, Nozzle erosion, acoustic influence, and flexibility towards conditions of operation.

### DUAL-BELL TYPE

These nozzles have a design optimization by variable geometry adjustment systems to obtain higher performance and efficiency. The ANSYS-Fluent software is used in a series of simulations with more attention dedicated to the fluid behavior next to the nozzle wall. The k-ῳ SST model was designed as turbulence. [4]



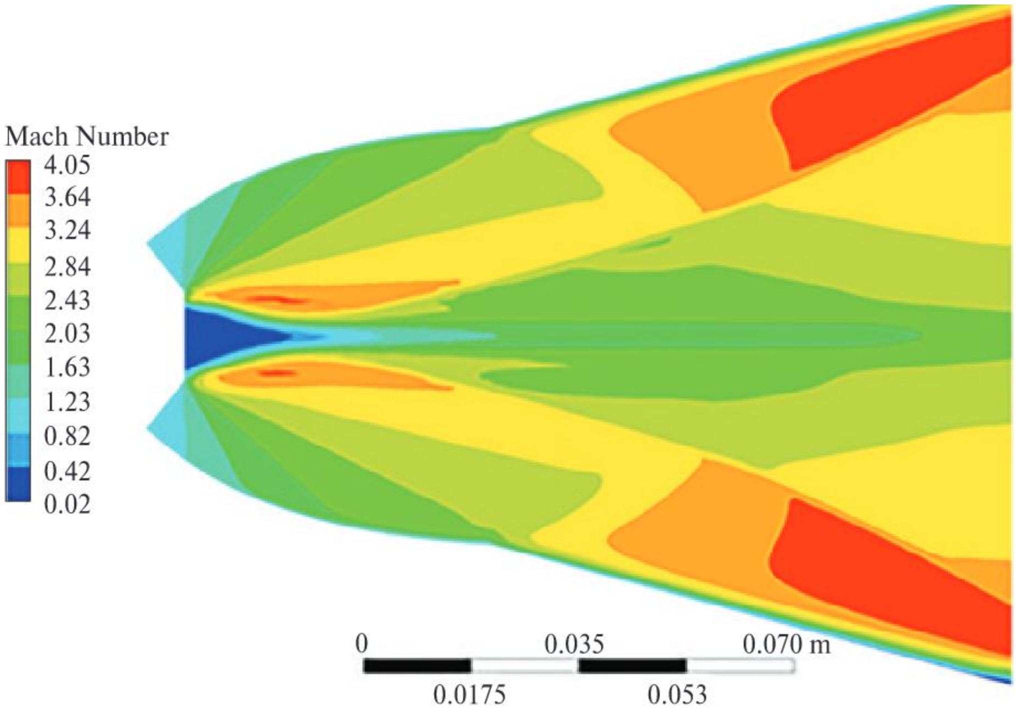



**Figure 5: Operating at sea level mode, transition mode, high altitude mode(source -** [4])

Contour inflection provides a controllable and symmetrical detachment of the flow, reducing the generation of lateral forces by a lot, hence enhancing the performance at sea-level

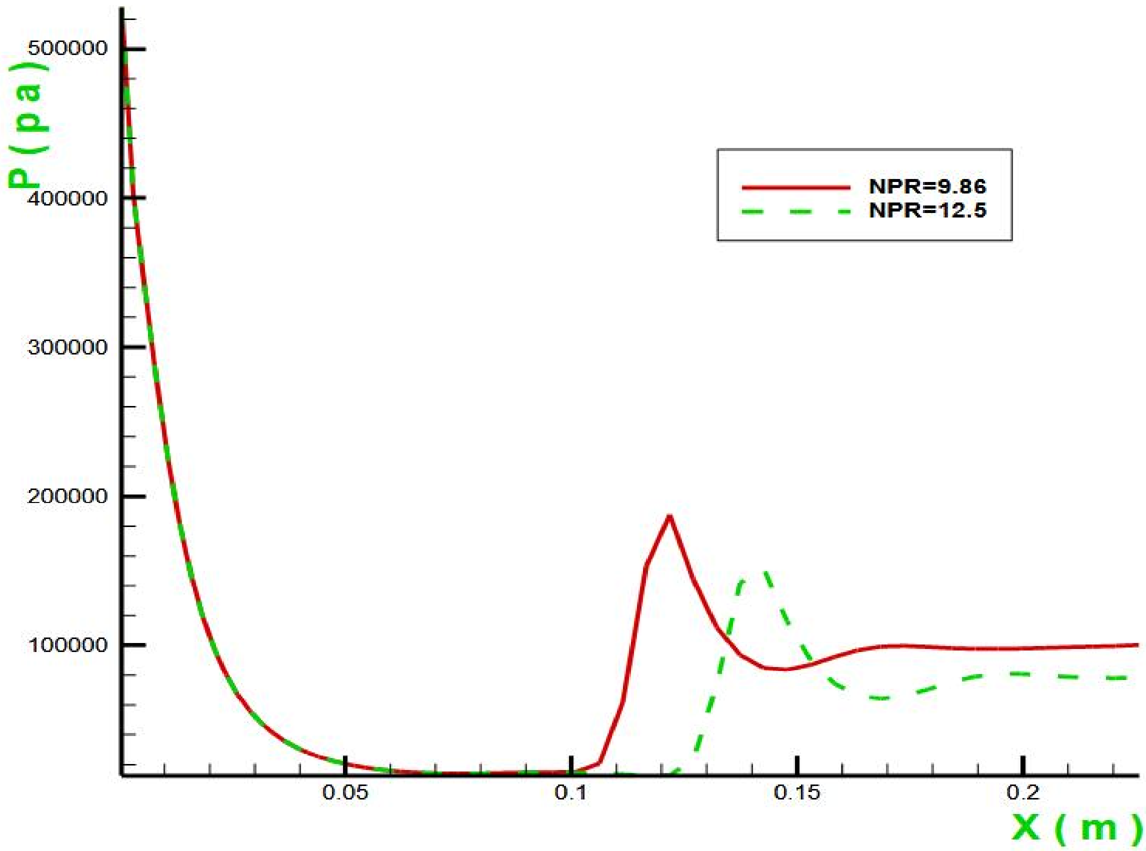



**Figure 6: Appearance of shock wave at different pressure ratios**[13]

For NPR = 9.86, the shock waves appeared inside the nozzle, and the flow downstream of the shock wave separates from the wall as the pressure in the downstream is extremely high [13]. They have tracked movements of the shock wave and proved that they tend to increase sharply with the increase of NPRs. With further boost of NPR level, shock wave travels in a downstream sluggish manner. During the sneaky transition process, it leads to nozzle erosion or unwanted flow turbulence [14].

More attractive and simple than plug nozzle. Since expansion rates are high, a cooling effect is seen while moving downward along the contour of this nozzle. Shock starts at the axis, which is indicated by a sudden increase in dynamic pressure after the throat [15].

**Table 1: Bell type Nozzle advantages.**

| Notable advantages | Over conventional bell nozzle |
|---|---|
| Altitude adaptability | Performs better at sea-level and efficiency gain of up to **5%** at high altitudes.[14] |
| Improved ISP | **3-6%** over conventional bell nozzles[13] |
| Durable | Reduced thermal loads by **10-15%** [15] |
| Controlled expansion | Ensures relatively smooth transition between modes, so less noise |
| Flexibility | Offers **3-5%** better performance in the vacuum, useful for space missions[13] |

**CONICAL TYPE**

Studies reveal that conical nozzles exhibit unique flow features and shock dynamics compared to planar nozzles, with shorter shock excursion lengths and reduced shock movement amplitudes due to strong adverse pressure gradients [16].

Conical convergent-divergent nozzles produce unique flow structures, including a "double diamond" shock pattern, and produces high levels of shock-associated noise, even at perfect expansion [17].Nozzles having 15° divergence angle tend to produce 12% higher acoustic levels than those with sharper angles[17].

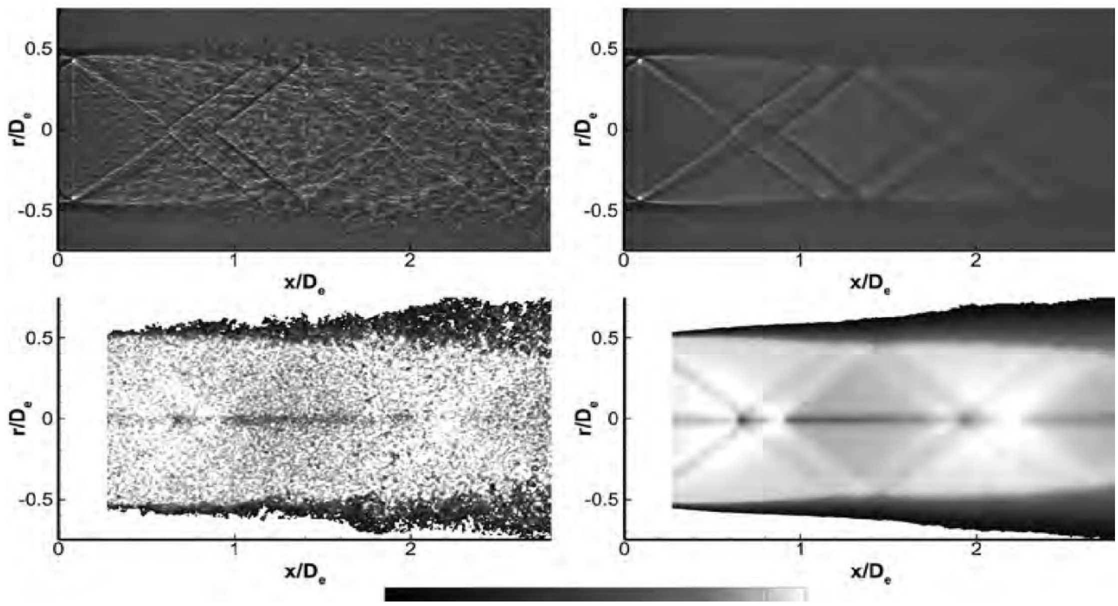



**Figure 7: Shock pattern observed from shadowgraph**[17]

Maximum performance was realized with a divergence angle of 12° for a 15% enhancement in the flow uniformity compared with other angles [7]. The application of the base-bleed technology with truncated conical nozzles proved fruitful in terms of thrust and aerodynamic performance [12]. In another effort, the experiment result was compared with the simulation of CFD. These results showed considerable difference, especially in the supersonic flow conditions. These are caused by shock pattern and boundary layer separation that affects pressure gradients and with a huge impact on accuracy [6]. Results show that dissipation of heat and thermal management is improved with the use of conical nozzles over the conventional one [18]. Results show that the flow efficiency in the whole process for parabolic nozzles was 15% better than the conical nozzle at higher Mach numbers. Various angle studies selected 3° divergence angle as optimum for minimum separation in the boundary layer and maximum uniformity of flow [8].

**Table 2: Conical type Nozzle advantages.**

| Notable advantages | Over parabolic nozzles |
| --- | --- |
| Simple design | Easier to manufacture, **15-20%** savings in production [17] |
| High Structural Integrity | Uniform wall thickness ensures no additional stresses.[19] |
| Better Acoustics | Reduced noise by **10-15 dB**[17] |
| Uniform shock patterns | Predictable shock-wave structures and consistent performance[7] |
| Easier cooling techniques | **10-15%** better heat dissipation, film or regenerative cooling[18] |
| Less Erosion | distributes heat loads evenly, leading to slower erosion [19] |

## PLUG TYPE

They may present acoustic advantages over conventional convergent and convergent-divergent nozzles, particularly in the critical landing and take-off (LTO) scenarios, which are under close regulatory scrutiny.

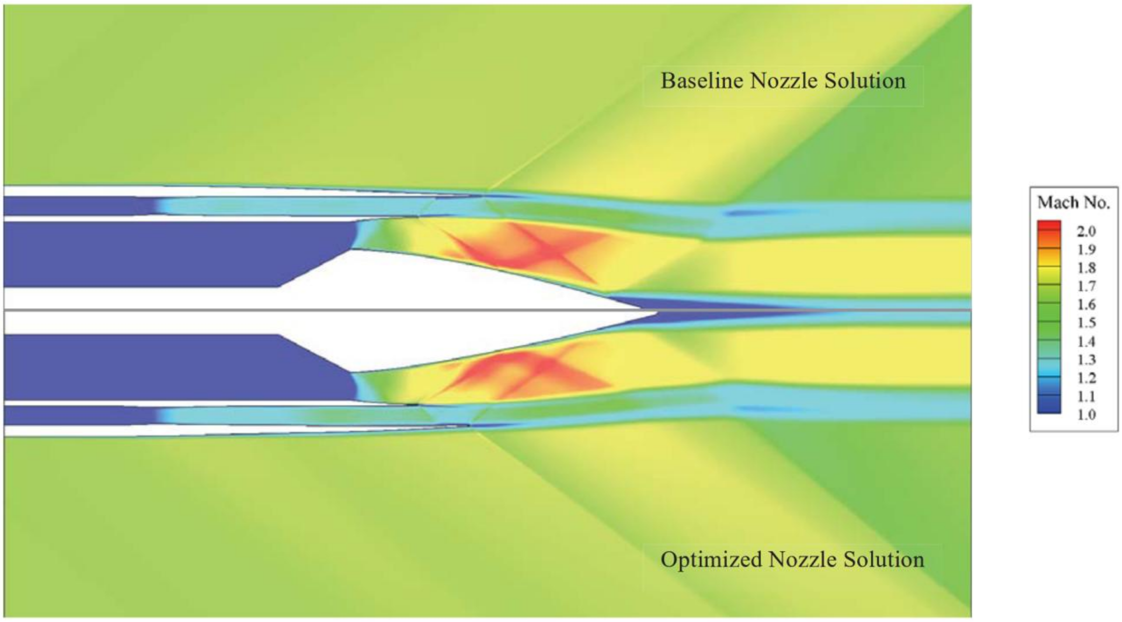



**Figure 8: Mach number flow solution for optimized nozzle (source -** [20])

The shape of the contour of the plug and nozzle lip is modified using only 3 geometric variables. This enhances the aerodynamic performance. Optimization of the design of the plug nozzle resulted in 3-6% thrust efficiency compared with the conventional design [20]. CFD analysis of plug nozzles can reveal that these can attain a maximum of 8% ISP improvements above the conventional bell nozzles at vacuum conditions [11]. Inflow separation reduces, and the pressure recovery of the nozzles increase [12]. Performance of such nozzles can also be tailored to atmospheres leading to efficiency increase in both sea-level and vacuum environments [10]. Cluster configuration of plug nozzle has been tested and promising results obtained on up to 10% increase in overall engine efficiency [10].

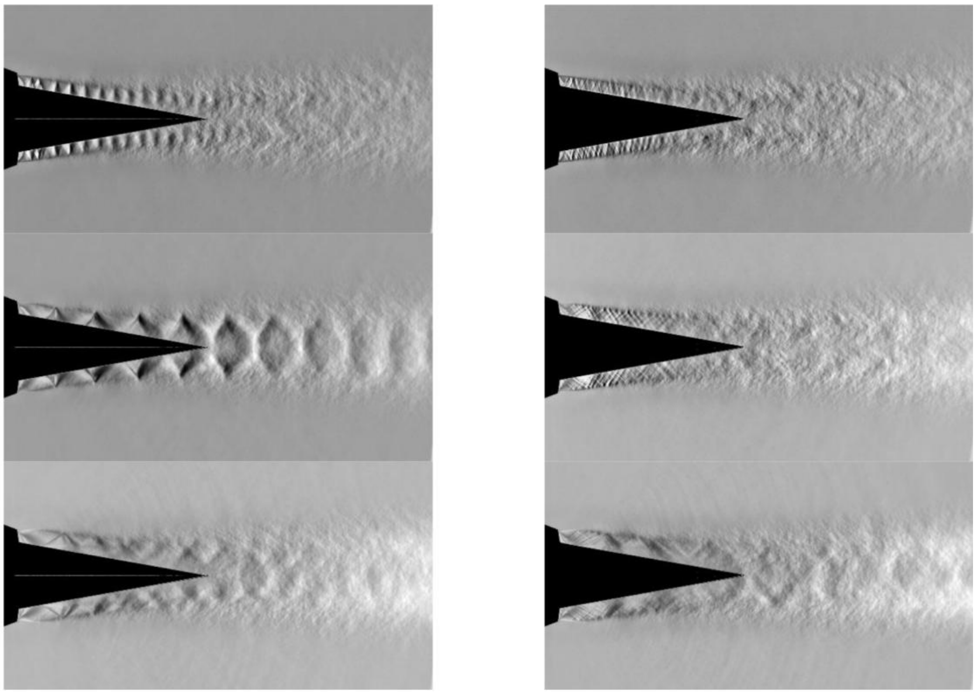


**Figure 9: Shadowgraph flow visualization pictures (source – [10])**

The above Fig 9 illustrates shock diamonds with strong coupling between the expansion and compression waves. They are typically encountered under the conditions of imperfect expansion or over expanded flowin which pressure at nozzle exit is higher than ambient pressure.

Thermally, pose cooling is an extremely demanding since the surface area is high. Of course, thermal management is one of the biggest concerns in the design of a plug nozzle. However, the arrival of aerospike geometry, which is basically a truncated plug nozzle, has relieved this concern somewhat. Simulation of an aerospike engine is complex and difficult because of the interaction between the plume and the external flow, but its data is required to precisely predict thrust [21].

**Table 3: Plug type Nozzle advantages.**

| Notable advantages | Over conventional nozzles |
|---|---|
| Altitude Compensation | Regulating pressure according to the atmosphere |
| Specific impulse | Improved ISP by up to **8%**[22] |
| Compact | High performance in a smaller package |
| Better Acoustics | Smooth expansion, hence low noise levels |

## VII. CONCLUSION:

Results of this study would finally bring home the point that selection of nozzles should be based on specific application needs rather than a one-size-fits-all approach. A few properties and characteristics tagging onto each type of nozzle are a repeating of the importance of careful considerations in the design and optimization phase of engineering. With this subtle insight into nozzle properties, potential applications would be more efficient and effective across the entire gamut of industries and uses.

- **Dumb-Bell Nozzles**: These provide high performance efficiency, especially in large rockets with a high throat Reynolds number. The nozzles are optimized for a specific condition but perform poorly at off-design conditions. Their performance is as high as 4-12 % thrust coefficients at higher throat Reynolds numbers than that of the conical nozzle in large rockets.
- **Conical Nozzles**: Easier and cheaper in design but not so efficient because of turbulence and interference in the flow. Easier to manufacture and used mostly wherever simplicity and cost are critical aspects. However, much turbulence in the critical section does adversely affect working gases in terms of flow and reduces overall efficiency. A high divergence angle would be capable of producing great thrust, yet still, it would offer much lower performance compared to the situation when having a bell nozzle.
- **Plug Nozzles**: Its versatility is the characteristic feature. To allow alteration of geometries at different altitudes gives it performance over a large altitude range. The thermal management challenges exist but has stable performance at high altitude as well as high speed. Plug nozzles are well suited for atmospheric flight and also at times of high area ratios at short nozzle lengths and it is compact in size. In some conditions, it may even outperform the double bell nozzle.

The dual-bell nozzle is the highest in thrust and efficiency but suffers from flow separation and shock structures. Conical nozzle is simple and easy to manufacture, with some of the performance aspects lagging behind. The plug nozzle is versatile; it can produce thrust very efficiently for altitudes varying from sea level to high altitudes, making it useful for varied applications.

In a nutshell, it sums up the complexity of nozzle design with respect to varied mission profiles and dire need of innovation and optimization, in terms of responding to increasing demands in space exploration and atmospheric flight. With such intense understanding of varied configurations of nozzles and merits and demerits addressed, future propulsion systems could achieve greater leaps in space travel, reduced environmental impact, and enhanced performance.

**Table 4: Comparison of Dual-Bell, Conical and Plug type nozzles**

| Parameters | Dual-bell | Conical | Plug |
|---|---|---|---|
| Thrust | Relatively produces high thrust by controlled expansion to supersonic velocities | 8-10% lower thrust since shock-flow separation not smooth | High thrust at any altitude due to variable geometry control |
| Fuel Efficiency | Efficiency high as it can as smoother flow across both the contours. | Less efficient due to affected pressure gradient | Very high fuel - efficiency because of better adaptability to different conditions |
| Specific Impulse (ISP) | Higher ISP than traditional bell nozzles across both low and high altitudes | Lower ISP due to imperfect expansion, gradual thrust generated | ISP is significantly more than conical nozzles as these are compact and thrust-weight ratio is less |
| Exhaust Flow | Critical pressure is found out and then | Predictable and uniform shock-waves occurring, | Minimized flow separation, ensuring |

| | | | |
|---|---|---|---|
| Separation | nozzle is designed to ensure minimal flow separation at various altitudes | especially at high altitudes | efficient expansion over a wide range of altitudes and operating conditions |
| Shock Structures | Controlled shock structure observed since the gradual transition between the two bell contours, resulting in fewer efficiency losses | Pronounced shockwaves due to divergent wall angle being fixed | Allows free expansion according to the outside conditions, hence smooth structure |
| Design and Manufacturing Complexity | Requires precise calculations over many iterations and getting that dual-profiles is a heavy task | Simple design, easier to manufacture | Manufacturing is highly complex due to its nose inside cowl and its adjustability |
| Thermal Stress Management | Moderate since expansion rate is high leading to cooling down the contour but requires advanced materials for management | Less thermal stress due to simpler geometry | Normal thermal management, but advanced materials required for precision |
| Nozzle Erosion | Moderate erosion due to the change of geometry from first bell to the second | Tiny detonations may occur hence prone to erosion | Erosion is low, since controllability is a major factor |
| Acoustic Impact | Minimal acoustic impact, but less noise produced compared to traditional bell nozzles | Produces louder exhaust noise due to more prominent shock waves | Significant noise reduction due to smooth expansion so, low impact |
| Adaptability to External Operating Conditions | Highly adaptable, with dual-contours ensuring gradual expansion without any discrepancies, thus improving overall efficiency | Not highly adaptable but can be useful for small missions | Highly adaptable due to natural ability to alter its geometry |

## VIII. WAY FORWARD:

Experiments have only been conducted on three nozzle configurations and might not have considered every possible nozzle design. This means more efficient universal solutions are being overlooked. Therefore, nozzle design geometry has much scope for development and also has prospects for optimization and improvement. Future research should be made more streamlined in terms of directing efforts on nozzle design customization or tailoring of nozzles for specific missions based on the objective with the integration of the characteristics of different types of nozzles which are best suited for a particular mission. Conventional fixed geometry nozzles have certain limitation in unpredictable environments, thereby highly encouraged the research and development into adaptive nozzle geometries which can enhance performance when operating in unfavorable conditions. It is not only an area for research and development of advanced materials and manufacturing techniques but also there lies in scope to handle problems arising due to thermal stresses and nozzle erosion. Further study into computational fluid dynamics (CFD) will help predict and identify flow instabilities and shock-induced oscillations.

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