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A Review on Structural Benefits of Nozzle in Propulsion Systems

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Abstract

As a matter of fact nozzles play a very important role in providing the necessary thrust required for very high velocity, to the vehicle with which it is attached. The jet propulsion exhaust nozzle system is an integral part of a turbine engine and critically depends on overall performance. It faces challenges in terms of the structure, design and manufacturing nozzle to get vehicle speed increased. Researchers have worked on various structures with additional features such as variable throat and exit area, noise suppression, and reverse thrust controlling the direction of a fluid flow at exits or entrance of orifice. The selection of nozzle also depends on type of fluid being considered. In this review paper, an attempt is made to collect different structures of nozzle with their construction details and mechanism of performance. The discussion includes a general comparison of performance of different structures of nozzles for particular fluid.

Keywords: analysis, nozzles, review, structures

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INTRODUCTION

The nozzle is a form of reaction engines. Like rocket engines, reaction engines obtain thrust in accordance with Newton's law of motion. As no external material is needed to form jet, rocket engines are designed for propulsion as well as other terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although noncombustible forms also exist. Rocket engines have maximum exhaust velocities, are the lightest, and are the least energy efficient of all types of jet engines. The rockets are powered by exothermic chemical reactions of the rocket propellant used. Gas velocities from 2 to 4.5 km per second can be achieved in rocket nozzles.[1] The de Laval nozzle has the minimum flow area at the convergent and divergent section.

The nozzle plays a role in converting the low velocity, high pressure and high temperature gas in the combustion chamber into high velocity gas of lower pressure and temperature. A nozzle guides to the direction to the gases coming out of combustion chamber. The nozzle is also like a tube with different cross-sectional area. Nozzles control the rate of flow, direction, mass, shape, speed and the pressure of the exhaust stream. The need of nozzle rises because rocket engines produce thrust by creating a high-speed fluid exhaust, by high pressure (up to 200 bar) by the combustion of solid or liquid propellants, within combustion chamber. Such a high speed cannot be met with piston and other fuel arrangements.

THEORY BEHIND THE GEOMETRY OF VARIOUS NOZZLES

Nozzle Structure Based on Propellant Used

Rockets use either solid or liquid propellants to function. They have different structures for particular propellant. In case of rocket fuel, it is both fuel and oxidizer. Oxidizer is present to burn as there is no air intake and there is no atmosphere in space. Jet engines have inlet went to take oxygen into the engine from the space. Solid rocket propellants being dry contain the combination of fuel and oxidizer. The fuel is hydrocarbons and the oxidizer consisting of oxygen. Liquid propellants are often gases but have been compressed until they change into liquids. These propellants or fuel and oxidizer are kept in different chambers. Fuel and oxidizer are getting mixed just before ignition (Figure 1).

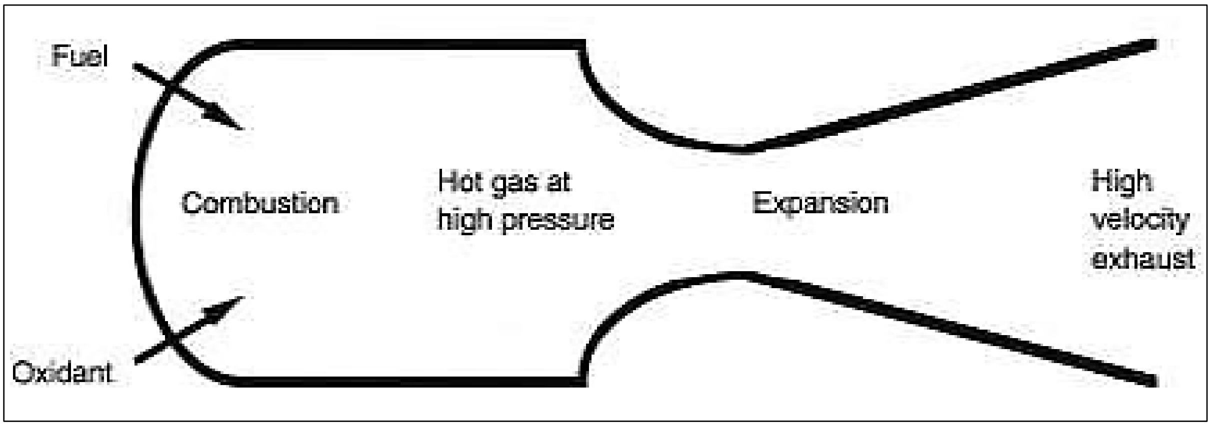

Fig. 1. *A Liquid-Fueled Rocket Engine.*

Rocket having solid propellants contains nozzle, a case, insulation, propellant and an igniter. For higher thrust, the hollow core is used to increase the surface area of the propellants for burning. The solid-propellant engines have opening at the back (nozzle like) of the rocket for the exit of gases. The nozzle, over here, increases the acceleration of the gases and thus increases the thrust. Liquid propellants are kept in separate chambers or storage of fuel and oxidizer. Fuel gets injected through the small nozzles of combustion chamber. Combustion chamber operates under high pressures, thus weight or net mass is one of the most important factors in any rocket. The pumps and hoses of these engines make it heavier and complex then solid propellant rocket engines (Figure 2).

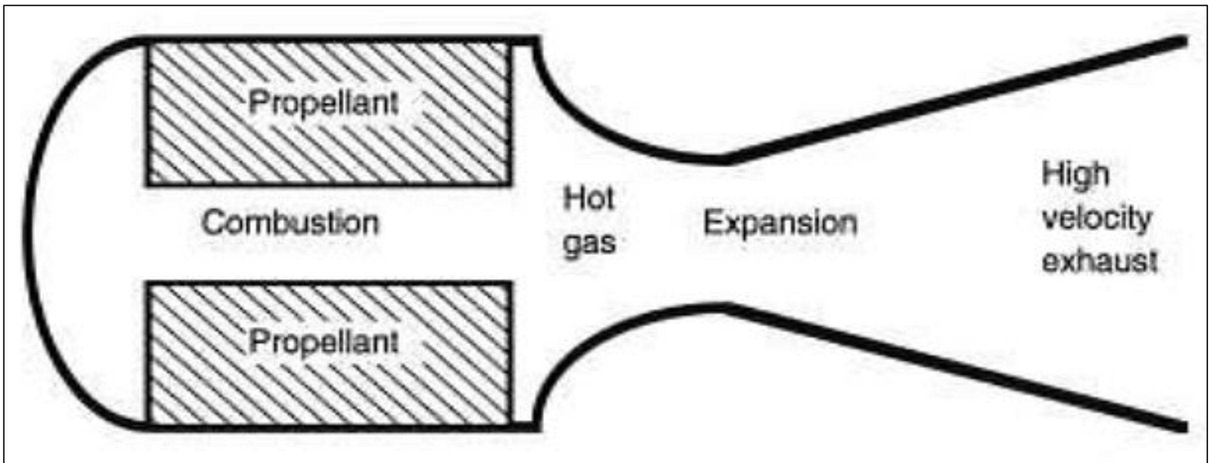

Fig. 2. *A Solid-Fueled Rocket Engine.*

The thermal rockets engine is similar like heat engine. The heat energy being generated by burning of fuel and propellant in chamber is converted into kinetic energy or momentum of the exhaust. The conversion of heat into work is same whether work is done on a piston, or on steam, of exhaust gases.

ROCKET ENGINE NOZZLE

John Berggren[2] has considered two different nozzles. First one is Volcain 2, is built up by two parts, an upper part built up by large number of spirally welded tubes and a lower skirt of sheet metal. Liquid hydrogen flows through the tube to cool down the upper part and is then, together with the exhaust from the turbines, ejected along inside of the nozzle wall to cool the lower metal skirt.

The second one is modified form of the first one i.e. Volcain 2+ which is based on Volvos new Sandwich Technology where channels are placed axially in contrast to the Volcain 2 nozzle. Both axial and radial stability are considered in the analysis above nozzle.

FUEL INJECTOR NOZZLE AND ROLE OF CAVITATION

The fuel injector nozzle has cavitation, induced by an abrupt change in the geometry of the nozzle to make the pressure fall below the saturated pressure.

Therefore fuel injectors are small, and are used to inject the fuel in the combustion chamber in a controlled manner.

The sudden contraction at the inlet of the nozzle causes a boundary layer tends to separate for re-circulation with a fall in pressure (Figures 3, 4).[3]

The separation at the inlet forms a vena contract, to reduce the area available for the flow, leading to an increase in velocity at the inlet, which helps downstream atomization, for the quality of the fuel/air mixture available for combustion.

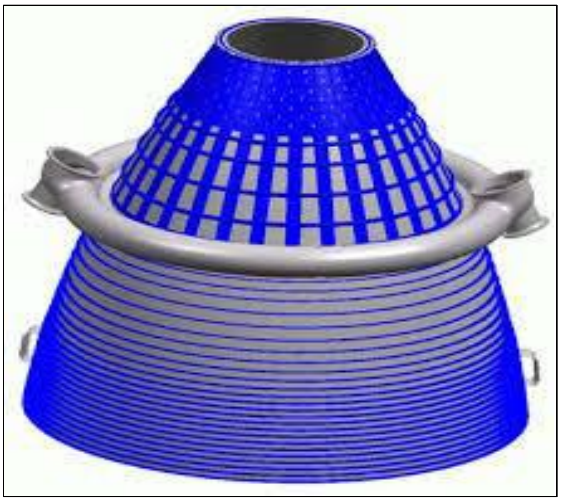

Fig. 3. *Volcain Nozzle.*

This facilitates reduction of hydrocarbon emissions and thus improves the engine efficiency. n experimental study with a scaled-up fuel injector nozzle is performed by Arcoumanis et al.[4,5] A vortex formation is observed in a multi-hole nozzle inlet and a string like film, "string cavitation" has appeared inside the nozzle.

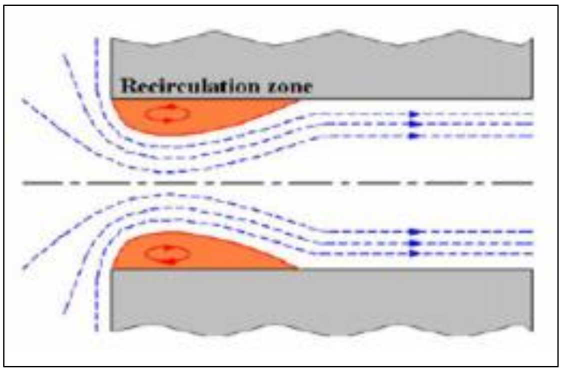

Fig. 4. *Streamlines at the Inlet of a Nozzle as Shown by Payri et al.*[3]

The string like film was observed before the development of the cavitation, more frequently in the flow with a low nozzle lift. Laser Doppler velocimetry was applied to measure the local mean velocity and the turbulent kinetic energy inside the nozzle. Separation of fluid flow was observed in the flow and the cavitation film appeared near the walls. However it was correlated them with the cavitation number and the Reynolds number (Figure 5).

Nurick[6] developed a useful relation between the cavitation characteristic in terms of coefficient of discharge of the nozzle. He performed numerous experiments on circular and rectangular orifices with varying length to diameter ratio for upstream and downstream conditions. [7] He assumed that the flow of liquid separates off the corner and contracts to an area that is a fixed fraction of the nozzle cross-sectional area. The liquid experiences no head losses between the upstream stagnation state and the contraction. The pressure at the contraction is equal to the vapor pressure of the fluid.

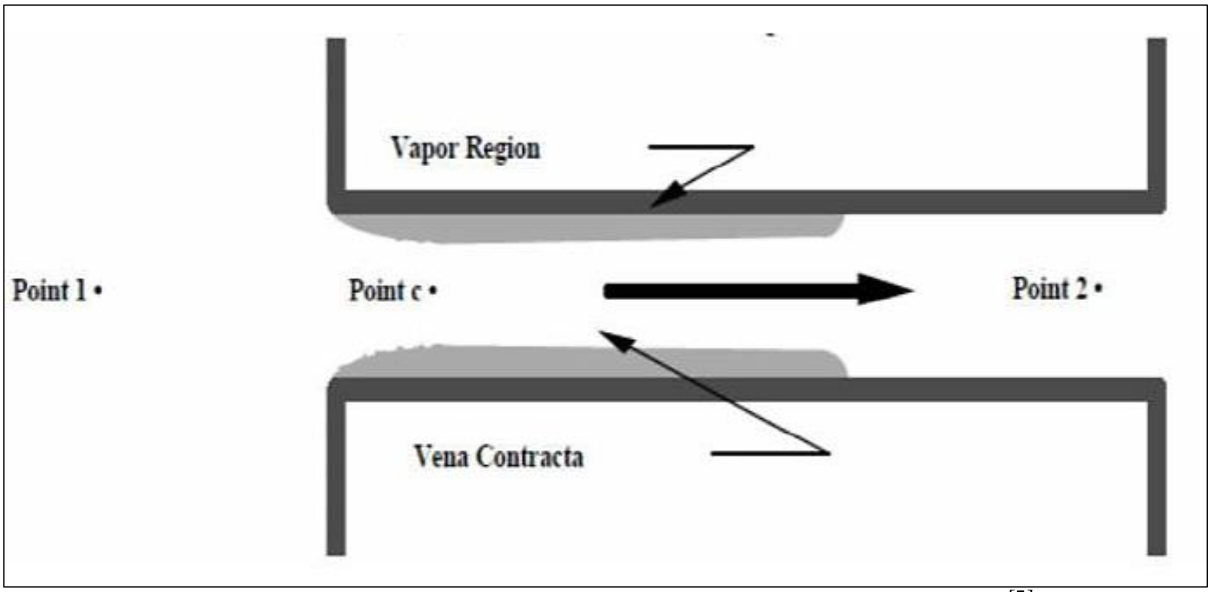

Fig. 5. *Schematic of a Nozzle That Cavitates From Schmidt et al.[5]*

DUAL BELL NOZZLE

It is the altitude-compensating rocket nozzle. The Dual bell nozzle was originated from Rocket dyne in the 1950s. This type of nozzle was designed to overcome conventional nozzle designs by the Germans during the time of the world war wherein they were to be posted as a threat for their rivals.

The structure of this type of nozzle is used for minimizing the losses encountered in the conventional types. The propulsion system requires exhaust nozzles to work at ambient operating conditions. Bell nozzles are good for all aerospace applications.

At low altitudes, controlled and symmetrical flow separation occurs due to wall inflection as shown in Figure 6. For higher altitudes, the nozzle flow is attached to the wall and the exit plane, and full geometrical area is used. Because of the higher area ratio, an improved vacuum performance is achieved. Flow transition behavior largely depends on the contour of the nozzle extension.

A sudden transition from sea-level to vacuum operation may be achieved by two different extensions, with a zero wall pressure gradient, or a positive wall pressure gradient.

The critical analysis of the transition behavior by authors [8] while considering decreasing ambient pressures during the launcher ascent depicted that a considerable time with uncontrolled flow separation exists even for these types of extensions. The duration of this period can be reduced drastically by throttling the chamber pressure.

DE LAVAL NOZZLE

The Swedish inventor Gustaf de Laval in 1888 invented for use on a steam turbine. This principle was first used in a rocket engine by Robert Goddard. Modern rocket engines engaging hot gas combustion use de Laval nozzles these days. It is a pinched tube in the middle, carefully balanced, asymmetric hourglass-shaped, accelerates pressurized gas to a supersonic speed. It is based on three laws of conservation viz., mass, momentum and energy. Momentum being constant, mass of rocket decreases due to the loss of fuel increasing the velocity (Figure 7).

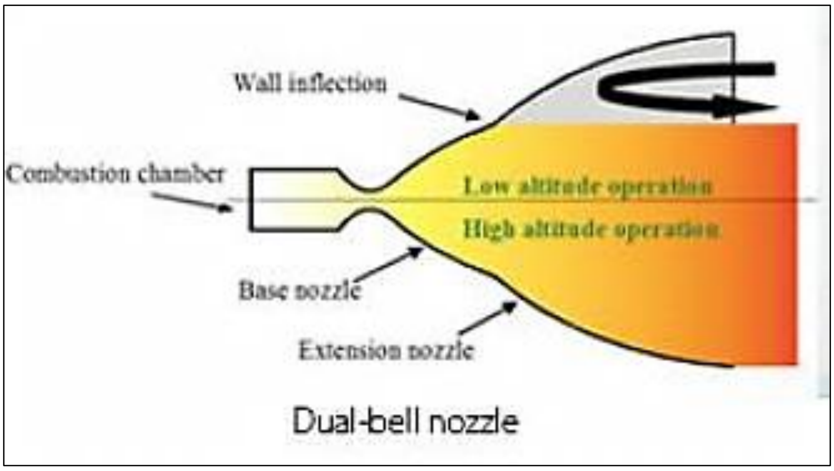

Fig. 6. Dual-Bell Nozzle.

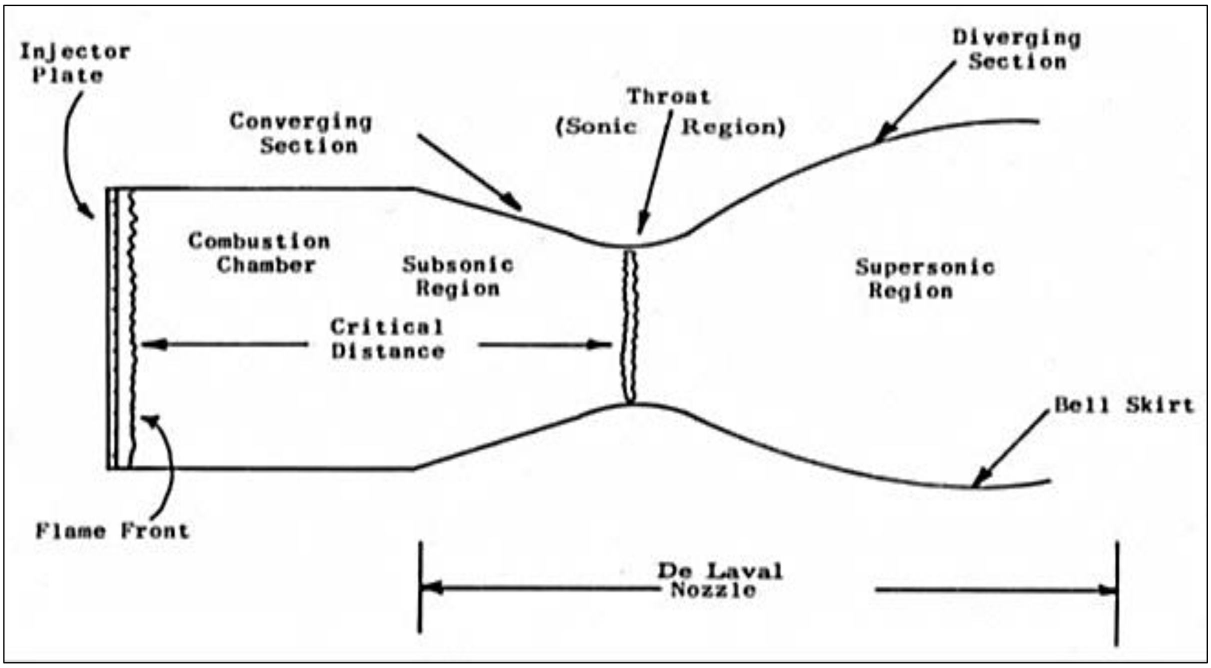

Fig. 7. De Laval Nozzle.

Convergent end being narrow accelerates subsonic flows. Divergent end tends to accelerate variable density; sonic/supersonic flows. Design criterion are the expansion ratio i.e., the ratio of exit area to that of the throat area. For high pressure ratios chocking occurs.

JET NOZZLE

It is made for the ejection of gas or fluid with the flow stream into the environment. These are fluid jet or hydro jets, mostly seen useful in household equipment such as gas stoves, fountains, ovens or barbecues. It is also used where flow regulation is needed such as in carburetors smooth orifices. Another type of jet is the laminar jet, a water jet with a streamlined flow. Nozzles which are used for feeding hot blast into a blast furnace are called tuyeres. Nozzles are also shaped to produce a stream that is of a particular shape.

For example, in extrusion such nozzle is typically referred to as a die.

SPRAY NOZZLES

These nozzles produce a very fine spray of liquids and hence known as atomizer nozzles are used for spray painting, perfumes, carburetors for internal combustion engines, etc. Air-aspirating nozzle-uses an opening in the cone shaped nozzle to inject air into a stream of water based foam (CAFS/AFFF/FFFP) to make the concentrate “foam up.” Most commonly found on foam extinguishers and foam hand lines. Swirl nozzles inject the liquid in tangential manner and it spirals into the center and then exits through the central hole.

MAGNETIC NOZZLES

Magnetic nozzles are taking space for some types of propulsion in which the flow of plasma is directed by the use of magnetic fields (Figure 8).

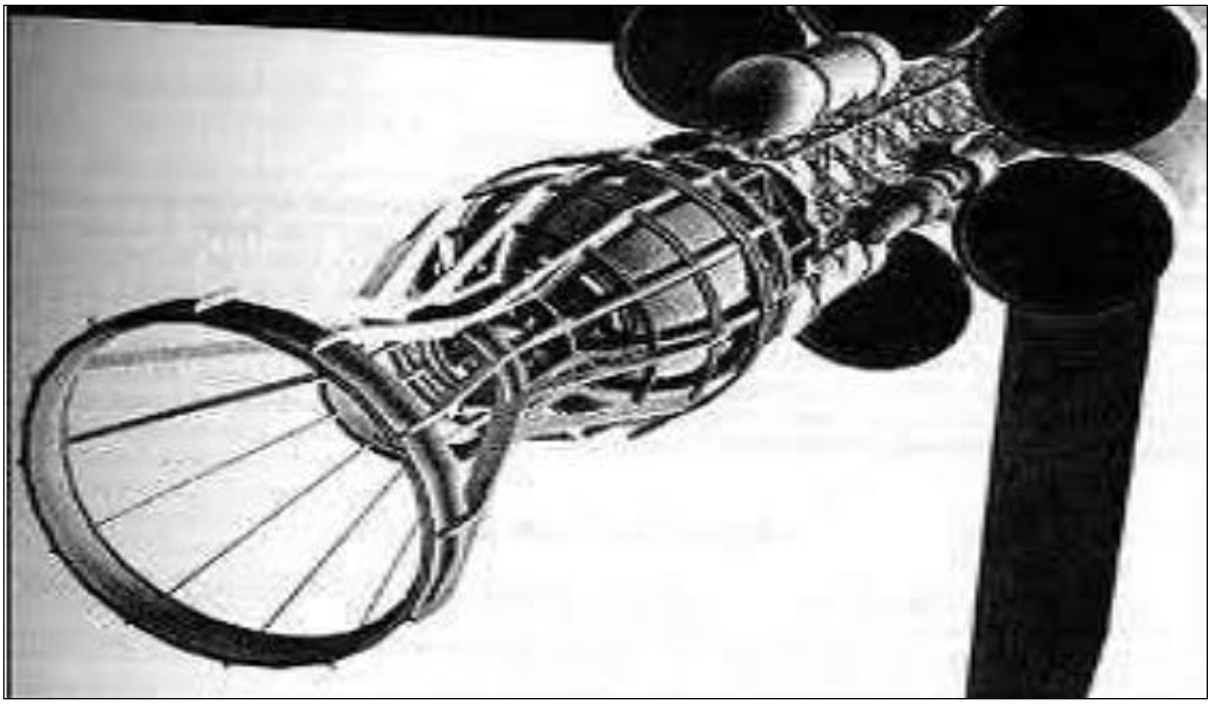

Fig. 8. *Magnetic Nozzle (Adapted).*

CONVERGENT DIVERGENT NOZZLES OF VARIOUS CROSSECTIONAL AREAS

Nozzles are generally bases on cross-sectional areas [9, 10] like square straight nozzle, rectangular straight nozzle, circular straight nozzle, rectangular bent nozzle. Computational Fluid Dynamics (CFD) is used to predict performance of new designs or processes before they are being manufactured or implemented. Pressure and temperature contours depict their behavior (Figure 9).

AERO SPIKE NOZZLE

The aero spike engine maintains its aerodynamic efficiency across a wide range of altitudes, and hence kept in the class of altitude compensating nozzle engines. The making of this nozzle is shown below in Figure 10. Hot gases leave combustion chamber through nozzle support struts. The gas compresses between spike and wall tube as they move towards the throat. Gases expand to ambient pressure and high velocity as they leave the rocket. A vehicle with an aero spike engine uses 25–30% less fuel at low altitudes, where most missions have the greatest need for thrust.

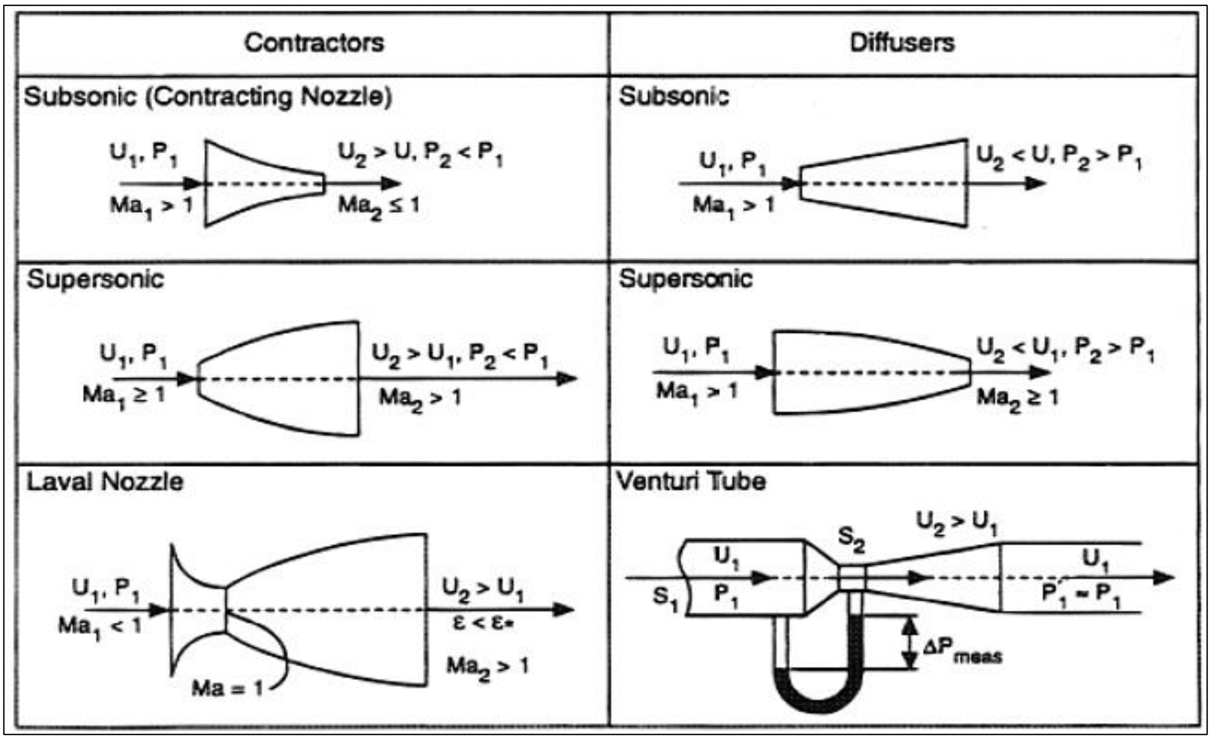

Fig. 9. *Brief Structures and Their Thrust/Outputs. The Notations Have Their Usual Meaning.*

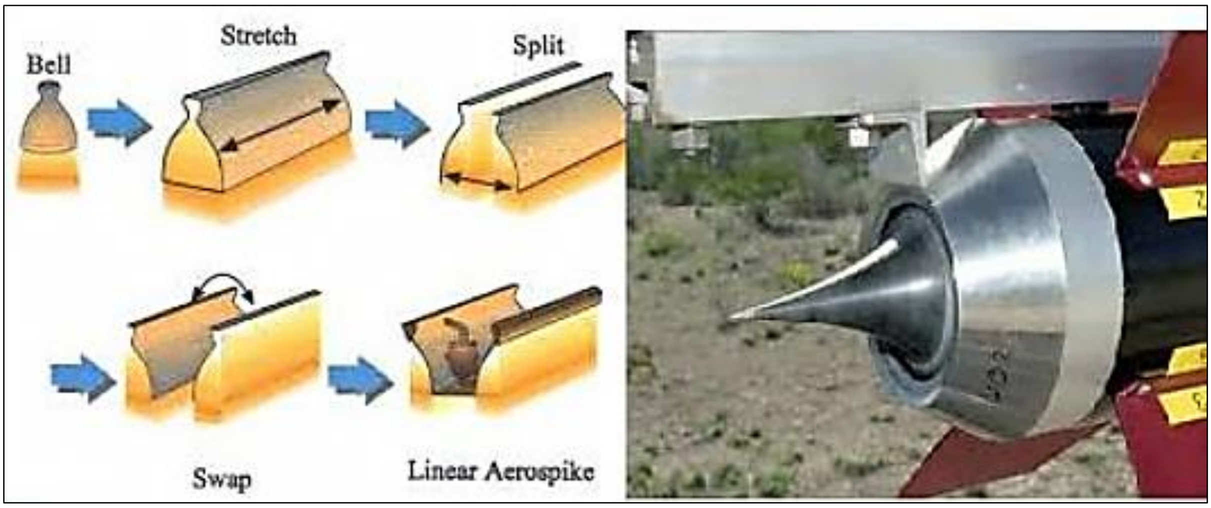

Fig. 10. *Aero Spike Nozzle Making.*

Also called plug nozzles, it includes a center body or plug around which the working fluid flows.

DISCUSSION AND CONCLUSION

In the nozzles review analysis, it is clear that the ambient pressure plays an important role in flow transition.

The base pressure instead of the atmospheric pressure at the specific flight altitude vitally effects. The decrease in the efficiency of the dual-bell nozzle operation along the trajectory is depicted. Dual-bell nozzle accommodates net impulse gain over the entire trajectory as compared to the conventional bell nozzles. The radial contour is a wall inflection point.

The study of Figure 11(a) shows that for lower altitude operation separates at the inflection point whereas Figure 11(b) shows that higher altitude flow remains attached until. Thus, dual-bell nozzle is simple because of the absence of any movable parts and has high reliability. The external flow over the vehicle in flight reduces the pressure at the vehicle base.

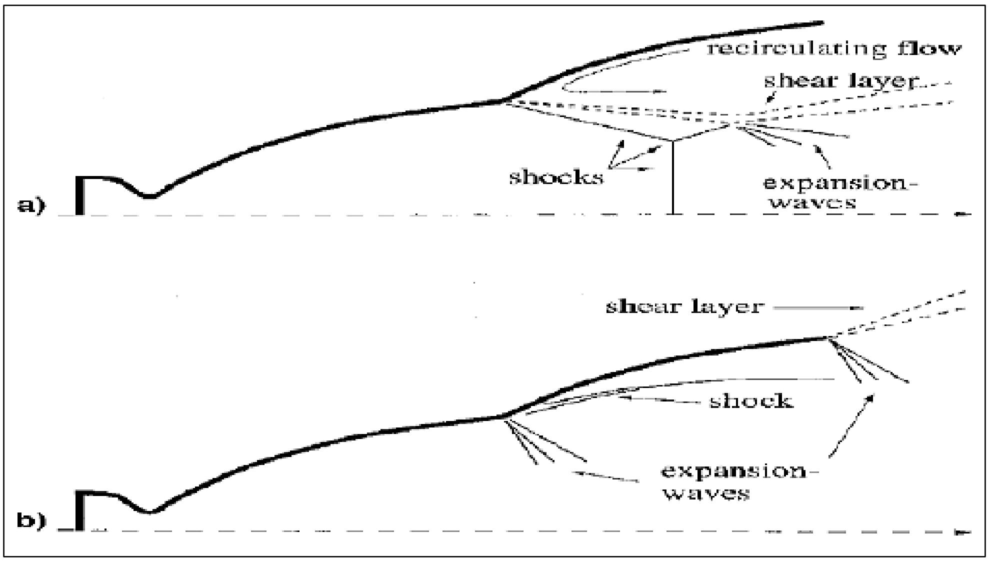

Fig. 11. *Flow Field Phenomena in Dual-Bell Nozzles (a) Sea-Level Mode with Flow Separation at the Wall Inflection Point and (b) Altitude Mode with a Full-Flowing Nozzle.*

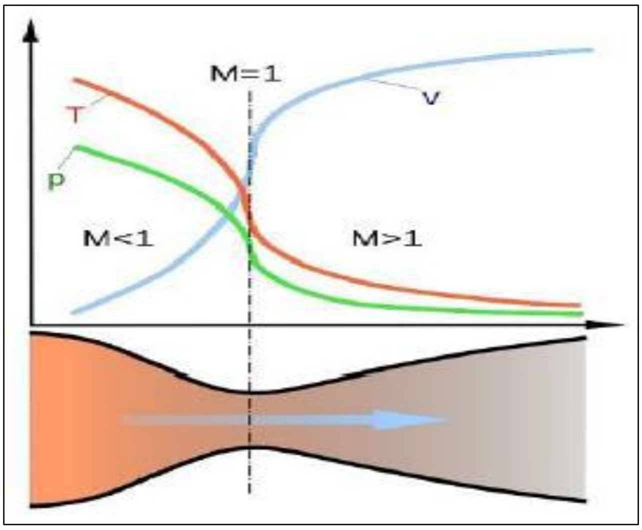

Fig. 12. *Diagram of a de Laval Nozzle, Showing Approximate Flow Velocity (v), Together With the Effect on Temperature (t) and Pressure (p).*

The de Laval nozzle tube is a carefully asymmetric hourglass-shape and balanced which accelerates a hot, pressurized gas in to a supersonic speed, and shapes the exhaust flow into direct kinetic energy. Here for, the nozzle is thus widely used in steam turbines, forming an essential part of the modern rocket engines and supersonic jet engines (Figures 12, 13).

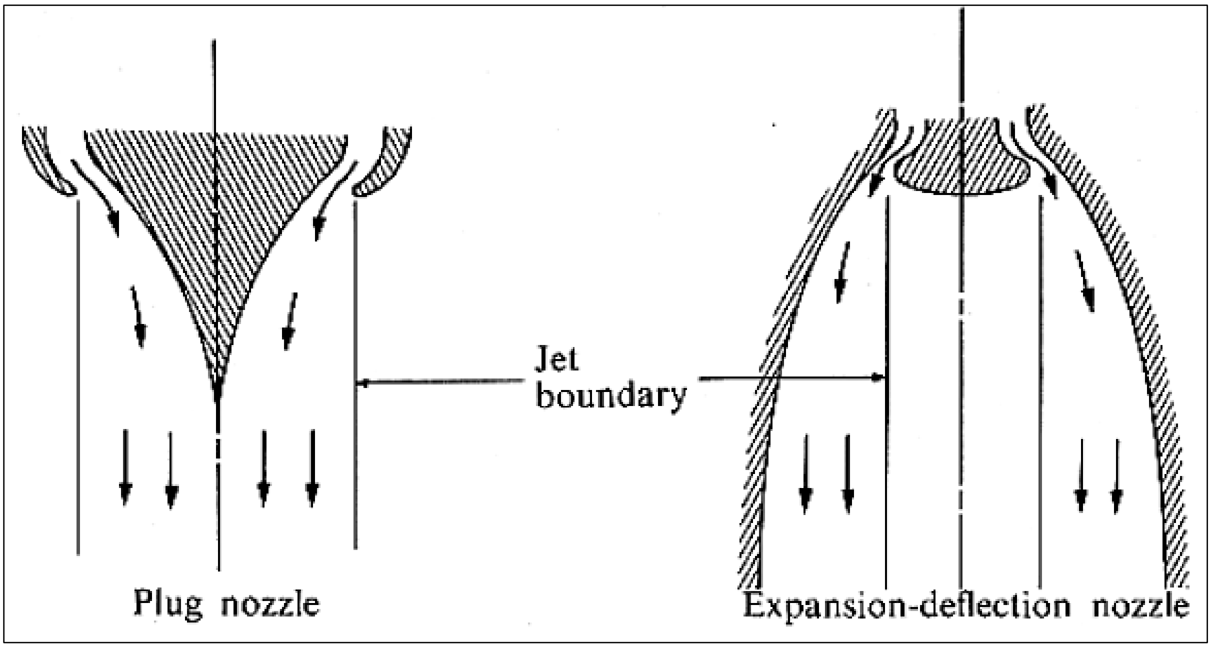

Fig. 13. *Structural Difference in Plug and Expansion-Deflection Nozzle.*

The reviewed papers depict that the analysis of nozzle (rectangular) gives an increased velocity of about 24% compared to square nozzle and about 24.5% compared to circular nozzle. Also rectangular nozzle gives an increased pressure drop of about 23% compared to square nozzle and about 24% compared to circular nozzle.

Thus authors have mentioned that, rectangular nozzle gives an increased temperature drop of about 42% compared to square nozzle and about 43% compared to circular nozzle. Aerospike engines on the other hand have been studied by corresponding authors for a number of years and thus form the baseline engines for many single-stage-to-orbit (SSTO) designs. It also serves a strong contender for the Space Shuttle Main Engine. However, some large-scale aerospikes are in testing phases.

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