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# A Review on Effect of Control Flow Separation in Rocket Nozzle on variations of Pressure Ratio and Convergent-Divergent Nozzle angle

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## ABSTRACT

The convergent – divergent nozzle is the most common type used in rocketry and it works by converting pressure energy from the fuel flow and heat energy from the combustion of fuel into kinetic energy in the form of high exhaust velocity. In the converging section of a rocket nozzle, the exhaust is travelling at relatively low speed (sub-sonic) and it becomes sonic at throat. The compressible exhaust increases until it reaches the exit and it is supersonic in the divergent section. This paper a brief on calculation of and related responses like thrust coefficient etc. Thrust coefficient is one of the most important parameters for its performance. It is the thrust per unit chamber pressure and throat area. It is a dimensionless multiplication factor and signifies the degree to which the thrust is amplified by the nozzle. It is a function of gas property i.e., specific heat ratio of the gas and other thermodynamic parameters. It is also a function of nozzle geometry i.e., expansion ratio and pressure ratio.

Keywords - Convergent – Divergent, Nozzle, Expansion Ratio, Pressure Ratio, Thrust Coefficient.

## Introduction

A nozzle is a device used to control the direction and, at the same time, characteristics of a fluid flow. It is used primarily to increase velocity as it exits or enters a closed chamber or pipe [1]. A nozzle is often a pipe or tube of a varying cross-sectional area, and it can be used to modify the flow of a fluid and is frequently used to control flow, speed, direction, and mass when the mixture of fuel and propellant is burnt in a combustion chamber [2]. Energy is obtained (for producing thrust). This energy is added to the induced air, and when this hot air passes through the nozzle, its kinetic energy increases, but its pressure and internal energy get used up in this process. A nozzle has a converging area or diverging area or both. Thus, fluid passes through it first converges and then diverges or includes only one. It has a minimum diameter in the throat where it reaches the highest velocity, i.e., sonic velocity. This phenomenon is also known as choking of the nozzle. When the area decreases continuously from the entrance to exit, it is known as a converging nozzle.

In contrast, when the area increases from the entrance to the exit, it is the diverging nozzle. When the cross-sectional area first decreases from the entrance to the throat and then expands from the throat to exit, then it is known as the convergent-divergent nozzle. The convergent nozzle comes into play when Backpressure is equal to or more than the critical pressure ratio. The divergent nozzle is used when back pressure is less than the critical pressure ratio.

This work cannot increase Mach number beyond unity by increasing the nozzle pressure ratio. But after exiting from the nozzle outlet, the gas flow is free to expand to supersonic velocities. As know, the Mach number is directly proportional to the square root of temperature. Thus, speed at the throat of the nozzle is way more than that of sound at sea level. By this, we can also say that Mach number 1 denotes a very high speed for hot gas. This helps us in generating a hypersonic flow. Also, it has been selecting propellant mixtures for increasing the sonic speed to a further extent.

Today, humans have visited the moon and launched artificial satellites beyond the Sun's heliosphere. Such specialised missions need for specialised Space Transportation Systems (STS), such as rockets and space shuttles, whose development humanity is still attempting to perfect. For more than 50 years, several nations have attempted to create both disposable and reusable STSs. There*are*several government*organisations doing space*research, but only*a select number are fully equipped to launch rockets.

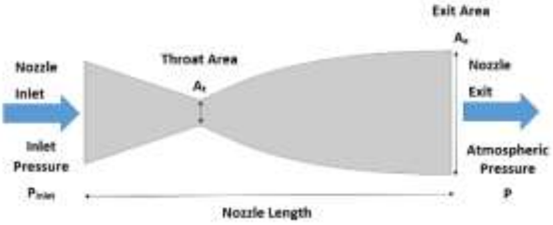

Figure 1. Schematic diagram of Convergent-Divergent nozzle

## Literature Review

The headings and subheadings, starting with "1. Olson [1], Discharge coefficients for compressible flow in nozzles, based on calculated boundary layer displacement thickness, agree closely with those recommended by the ASME. Furthermore, a Mach number effect indicated by the calculations has been confirmed for a nozzle profile in which two-dimensional effects in the core flow are minimized. Taken together, these facts suggest that the boundary layer calculations are adequate for the accurate determination of discharge coefficient provided the actual core flow is well represented in the analytical model.

Krushna et al. [2], CFD analysis of pressure and temperature for a dual bell rocket nozzle is analyzed with the help of fluent software. when the fuel and air enter in the combustion chamber according to the x and y plot, it is burning due to high velocity and temperature and then temperature increases rapidly in combustion chamber and convergent part of the nozzle and after that temperature decreases in the exit part of the nozzle.

Pandey [6] has conducted a CFD Analysis on four inlet rocket nozzles with a Mach Number of 2.1. The paper showed light on the CFD analysis of the pressure and temperature of the nozzle with four inlets. The Mach Number was kept constant and flow analysis was performed.

Pandey and Yadav [7] performed a CFD Analysis of a Rocket Nozzle with Two Inlets at Mach 2.1. The outcomes, pressure and temperature, for a rocket nozzle with two inlets, were analyzed with the help of ANSYS FLUENT.

Biju Kuttan et.al [8] performed a numerical analysis to find the required divergent angle for the nozzle which will give the maximum outlet velocity and satisfy the thrust requirements. The boundary conditions were saved constant and the divergent angles were varied. It was then realized, how the variation in divergent angle affects the flow through the nozzle. Surya

Kuttan and Sajesh [9] analyzed a convergent-divergent rocket nozzle which was performed by varying the number of divisions in the mesh. The various contours of the nozzle like Cell equi-angle skew, Cell Reynolds number, Pressure, Velocity, Mach Number, and above are calculated at each type of mesh using CFD analysis software ANSYS Fluent.

Madhu et al. [10] performed a study using super-sonic flow is conducted on a Rocket nozzle. It was performed using the numerical method. The parameters, Mach number, static pressure and shocks, were observed for conical and contour nozzles using the axisymmetric model in ANSYS FLUENT software. The results of the convergent-divergent nozzle and contour nozzle were compared by keeping the outlet, inlet, lengths and throat diameter of convergent and divergent nozzles as constant.

Almeida [11] investigated the effect of nozzle parameters (diverging angle, throat length and shape of diverging section) on nozzle performance. The basic design of the nozzle studied included a convex converging section and a linear diverging section. This work concluded that a higher diverging angle, larger throat length and the shape of the diffuser section have significant and detrimental impact on nozzle performance.

Park et al. [12], performed a study that also showed that higher diverging angles resulted in lowered nozzle performance. The considered nozzle shape had a convex converging section and a linear diverging section. Conclusions drawn from this study are in line with the conclusions reached in this paper. Nozzle performance was considered in many experimental and numerical studies, especially from the point off low and heat transfer characteristics with various inlet boundary conditions and flow geometries.

Mason et al. [13] conducted an experiment to determine the effect of throat contouring on the nozzle internal performance. They tested five non-axisymmetric converging–diverging nozzles in the static test facility of the Langley 16- foot transonic tunnel and recorded internal performance data at different nozzle pressure ratios up to 9.0.

Paik et al. [14] investigated sonic nozzles that are applied to gas flow rate measurements and determined that the critical pressure ratio is highly dependent on the Reynolds number rather than area ratio, especially in the cases with low flow velocity. Variation of discharge coefficients for sonic nozzles with flow geometry and Reynolds number was reported by Paik et al. [4], who determined higher discharge coefficients with increase of mass flow rate.

Spotts et al. [15] performed a CFD study of the compressible flow through convergent–conical nozzles to investigate the effect of the nozzle pressure ratio and nozzle angle on the nozzle performance. They confirmed that for smaller nozzle angles, the discharge coefficient increases and the choked nozzle pressure ratio will be reduced.

Geng et al. [16] investigated a CFD-based numerical analysis of the choking flashing flow characteristics in R134a converging-diverging nozzles is presented in this paper. The CFD results are validated with available experimental data of R134a converging diverging nozzles. After that, the critical mass flux and effects of geometric dimensions on the performance of converging-diverging nozzles. Furthermore, the calculated critical mass fluxes are compared to that of the classical models. Results show that the met stable state in R134a converging diverging nozzle is weaker than that of water at the same operating parameters and a higher choking correction factor of R134a compared to that of water is obtained. The optimum ratio of nozzle exit diameter to the throat diameter of 2.4 is recommended among the studied nozzle geometry dimensions. Effect of the divergent length on the nozzle flow characteristics is relatively smaller than that of the nozzle exit diameter.

Estakhrsar et al. [17] The effects of convergence and divergence half-angles on the performance of a nozzle at the different pressure ratios are investigated numerically. SST k - x turbulence model is applied to simulate the compressible gas flow inside the nozzle and its exhaust plume. Exhaust nozzle performance parameters have been calculated and compared with available experimental data to show the validity of the simulations. For this purpose, different nozzle pressure ratios for various operating conditions including over-expanded, underexpanded and design condition are considered. The effects of the nozzle geometry (convergence and divergence half-angle) on the velocity coefficient (Cv), discharge coefficient (Cd), gross thrust coefficient (Cfg) and nozzle adiabatic efficiency (gn) are investigated. Predicted results show that for a given nozzle pressure ratio, by increasing the divergence angle from 5 to 20, there is about 3% loss in the gross thrust coefficient and also by increasing this angle from 20 to 40, the value of the Cv and gn will decrease 5 and 10%, respectively. Increasing the convergence angle reduces the discharge coefficient about 6% and causes a 3% penalty in nozzle gross thrust coefficient.

Mukthiyar et al. [18] focuses on the flow of refrigerants in convergent nozzle which decreases the temperature and pressure of their refrigerant vapor. In many refrigerants mostly used is R410a refrigerant which is a mixture of difluoromethane (CH2F2) and pentafluoro methane (CHF2CF3). Nozzle is designed based on Mach number. Nozzle is a mechanical device which decreases the pressure, Temperature and increases the velocity. This paper aims to calculate the velocity, pressure, and temperature carried out analysis using the Computational Fluid Dynamics (CFD) software ANSYS Fluent and compared by theoretical and CFD analysis values.

Quintao [19], studied to identify the optimal designs of converging-diverging supersonic and hypersonic nozzles that perform at maximum uniformity of thermodynamic and flow-field properties with respect to their average values at the nozzle exit. Since this is a multi-objective design optimization problem, the design variables used are parameters defining the shape of the nozzle. This work presented how variation of such parameters can influence the nozzle exit flow non-uniformities.

Sreerag et al. [20], studied the flow separation in the main nozzle is eliminated with secondary injection at the lip of the main nozzle. This prevents the entry of atmospheric air into the separation zone and full-flowing conditions are achieved in the main nozzle at a relatively lower chamber pressure of main nozzle. The impact of inlet pressure of the main nozzle, the secondary injection, its pressure, and the angle of introduction on the main nozzle flow are studied using computational methods. It was observed that the injection of the secondary nozzle flow parallel to the main nozzle gives better results. The increase in secondary injection pressure seems to be favorable in eliminating flow separation in the main nozzle.

## Conclusion

Size and shape of a rocket nozzle is also very important. The converging section starts at the combustion chamber is usually shaped in a way to make sure that flow is not disrupted in any way i.e., the convergence is not too steep and has no harsh edges. The size of the throat is determined by certain characteristics of engine such as chamber pressure of combustion chamber and chemistry of the exhaust gas. The shape of the divergent section depends on the expansion ratio and amount of required thrust. The ratio of area of exit to the area of throat section is called expansion ratio. Area of exit varies by varying the divergence angle. A nozzle (from nose, meaning 'small spout') is a tube of varying cross-sectional area (usually axisymmetric) aiming at increasing the speed of an outflow, and controlling its direction and shape. Nozzle flow always generates forces associated to the change in flow momentum, as we can feel by handholding a hose and opening the tap. In the simplest case of a rocket nozzle, relative motion is created by ejecting mass from a chamber backwards through the nozzle, with the reaction forces acting mainly on the opposite chamber wall, with a small contribution from nozzle walls.

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