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A Review on CFD Analysis of Effects of Convergence and Divergence Angles on the Performance of a Nozzle

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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. 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. Therefore in this paper a review will be done based on research work conducted by scholars.**

***Keywords*- CFD, Convergence, Divergence Angles, Nozzle.**

I. INTRODUCTION

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. As important as the propeller is to shaft-engine propulsions, so it is the nozzle to jet propulsion, since it is in the nozzle that thermal energy (or any other kind of high-pressure energy source) transforms into kinetic energy of the exhaust, and its associated linear momentum producing thrust.

The flow in a nozzle is very rapid (and thus adiabatic to a first approximation), and with very little frictional loses (because the flow is nearly one-dimensional, with a favorable pressure gradient except if shock waves form, and nozzles are relatively short), so that the isentropic model all along the nozzle is good enough for preliminary design. The nozzle is said to begin where the chamber diameter begins to decrease (by the way, we assume the nozzle is axisymmetric, i.e. with circular cross-sections, in spite that rectangular cross-sections, said two-dimensional nozzles, are sometimes used, particularly for their ease of direction ability). The meridian nozzle shape is irrelevant with the 1D isentropic model; the flow is only dependent on cross-section area ratios.Nozzles have three different sections -converging section, throat and diverging section, as shown inFig. 1. The point where the diameter of the nozzle is the smallest is called the throat. The throat can either be a single point or it can be elongated. The section upstream of the throat is the converging section, and the section downstream of throat is the diverging section. The area of the converging section decreases as the nozzle profile goes from pipe to the beginning of the throat.

The area of diverging section increases as the nozzle profile goes from the end of the throat to the pipe. The fluid flow behavior through nozzles also depends on the type of fluid flowing through the nozzle. The dimensionless Mach number, M, which is the ratio of fluid velocity to velocity of sound in the surrounding medium, can be calculated to deter-mine if the flow is compressible (M>0.2) or incompressible (M<0.2). In this work, compressible flow is considered by using air as working fluid. Flow velocity increases as fluid enters the nozzle, until the nozzle throat is reached. At this point flow is subsonic (i.e. M<1).

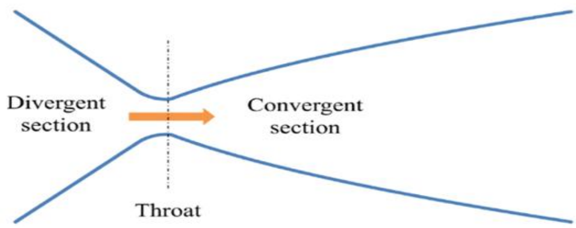

Fig.1. Schematic of a converging-diverging nozzle indicating the different sections of a typical nozzle (Clarke and Carswell, 2007).

Once fluid flows through the throat, given sufficient upstream pressure and flow rate conditions, the fluid velocity could become equal to the velocity of sound, reaching sonic conditions (i.e. M¼1). As fluid flows out of the throat, entering the diverging section, the fluid velocity increases beyond the speed of sound reaching supersonic flow (i.e. M>1). This occurs because whenair is flowing through the diverging section of the nozzle, there is an increase in kinetic energy at the expense of an enthalpy drop due to gas expansion.

The performance of a nozzle is quantified based on critical pressure ratio and pressure drop across the nozzle. Critical pressure ratio is the lowest ratio of downstream pressure to upstream pressure (Pd/Pu) when the flow is choked. Below this pressure ratio, the flow is sub-critical. An optimum nozzle geometry is one where choked flow is achieved at a larger critical pressure ratio value when compared to other nozzle geometries. This is associated with a higher pressure recovery as the fluid exits the throat of the nozzle and travels through the divergent section, minimizing pressure drop across the nozzle.

II. LITERATURE REVIEW

This work studies the effects of geometrical parameters such as nozzle diverging and converging angle on the performance of nozzles. Previous studies conducted focus on evaluating nozzle performance by varying some of the above-mentioned parameters. Almeida (2015)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. [1]Park et al. (2001), 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.[2]Nozzle performance was considered in many experimental and numerical studies, especially from the point offlow and heat transfer characteristics with various inlet boundary conditions and flow geometries. Mason et al. [3]conducted an experiment to determine the effect of throat contouring on the nozzle internal performance. They tested five non-ax symmetric 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.Park et al. [4] 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. [5], who determined higher discharge coefficients with increase of mass flow rate. Spotts et al. [6] 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.Lihong Geng et al. [7] 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 R134aconverging-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. [8] 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, under-expanded 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. [9] focuses on the flow of refrigerants in convergent nozzle which decreases the temperature and pressure of there frigerant vapor. In many refrigerants mostly used is R410a refrigerant which is a mixture of difluoro methane (CH2F2) and penta fluoromethane (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. Kumar et al. [10] investigated results showing better temperature and velocity flows. The 2D nozzle line diagram is done in Ansys 14.5 geometry modular and calculated iteration process can be done in fluid flow. The nozzle is done and meshes using automatic method and sizing of different value of the meshing process. In the order to analyzed the Ansys fluent software and solved the flow process of the convergent-divergent iteration nozzle. Standard nozzle equation manually calculated and compared with analyzing the results.

III. CONCLUSION

The flow through nozzle had been studied through various review. It is found that for smaller exit diameters show more thrust could be achieved. For smaller diameters there are low chances of flow separation hence thrust exerted on the body is larger in case of C-Dnozzle with smaller diameter than the larger diameter. Hence introducing a set of nozzle and allowing flow to pass through it can possibly give more thrust than the single nozzle.

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