Simulation Based Propulsion Evaluation of Deployed J-2X Nozzle

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***Abstract*—Area ratio of convergent-divergent nozzle plays a vital role in its performance and structural integrity. Nozzle thrust highly depends upon the expansion of gases in the divergent section. Expansion of gases depends upon the area ratio and outside atmospheric pressure. Atmospheric pressure decreases with altitude and therefore a nozzle design for sea level cannot perform optimally at higher altitudes. Altitude compensation nozzles are therefore used to overcome this problem because they work competently at the range of altitude. A variety of altitude compensation nozzles exist, and an extendable nozzle is one of them. Design and analysis of these nozzles is a cyclic process and requires a number of design iterations. The J-2 rocket engine was developed by Rocketdyne and used as an upper stage propulsion system. Extension of the nozzle was then developed and mounted to the basic J-2 nozzle exit to extend its area ratio up to 55:1. The extended J-2 nozzle is known as the J-2X nozzle, and it is an altitude compensating nozzle. The present work investigates the flow physics inside of the J-2 and J-2X nozzles. Computational Fluid Dynamics (CFD) is a numerical tool frequently used for flow prediction and investigation. In the present study, CFD computations are carried out for J-2 and J-2X nozzles. The gain in the thrust for altitude compensating nozzle has been computed. Results are encouraging and depicting the benefit of the nozzle extensions. Improvement in the thrust of altitude compensating nozzle is considerable, but at the same time the weight of the engine is increased. A comparative study between the gain in the thrust and an increase in the weight would be carried out in the future.**

***Keywords*—Altitude Adaptive Nozzle, J-2 Rocket Engine, Extendable Rocket Nozzle and Convergent-Divergent Nozzle**

I. INTRODUCTION

PROPULSION system [1] of a rocket is composed of several parts and includes a combustion chamber followed by a nozzle. Chemical propellant burns in the combustion chamber and pressurized hot gas is produced which is propelled through a nozzle [2], [3]. Chemical and thermal energy of propellant gas is converted to useful work by means of the nozzle and resultant thrust is obtained. The efficiency of thrust depends on the design and area ratio of the nozzle [4]. A variety of nozzles have been designed, built, and tested for ideal performance and generation of maximum thrust for the launch vehicle. J-2 engine is a high-performance rocket engine utilizing liquid oxygen and liquid hydrogen propellants that was built by Rocketdyne [5], its vacuum thrust ranges from 200,000 pounds to 225,000 pounds. The cluster of five J-2 nozzles on the second stage and one J-2 nozzle on the third stage were installed in Saturn V rockets that have been used for the Apollo missions, as shown in Fig. 1.

Fig. 1: J-2 Nozzle and Saturn V Rocket, taken from NASA website

The gradual decrease in atmospheric pressure from sea level to high altitude interrupts the optimum thrust of a rocket engine. Nozzle designed and tested for the desired thrust at sea level does not work well at altitude and causes fuel loss, which constrains the concept of single-stage-to-orbit (SSTO) vehicles [6]. Varying ambient pressure controls the flow separation phenomenon [7], [8] in the nozzle therefore three cases of flow separation arise, as shown in Fig. 2.

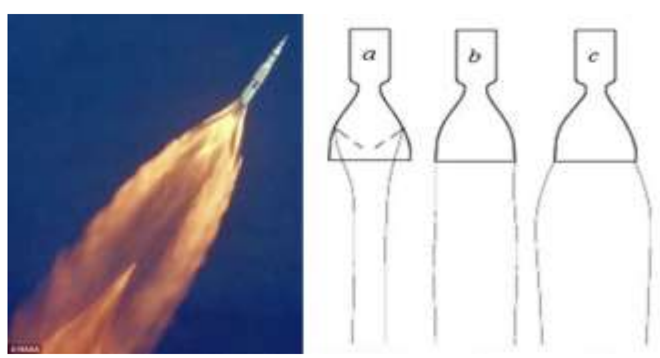

Fig. 2: Types of Flow Separation in Nozzle, taken from NASA website

The extendable nozzle is a type of altitude compensating nozzle in which the throat to exit ratio of the nozzle is increased by deploying external nozzle extension at a predefined altitude. The increased area ratio of the extended nozzle improves the performance of the rocket and compensates for thrust loss due to altitude. The J-2X nozzle is an altitude compensating extendible nozzle that is based on the J-2 nozzle. Goodyear Aerospace Corporation (GAC) designed and developed a nozzle extension [9] made of conically woven stainless steel Airmat, as shown in Fig. 3. The extension was attached to the existing J-2 nozzle at an area ratio of 27.5:1 that resulted in an extended nozzle with an increased area ratio of 55:1. The extended version of the J-2 nozzle was termed the J-2X nozzle.

Fig. 3: Manufacturing of Nozzle Extension, taken from [9]

NASA performed the cold flow test for the J-2X nozzle extension while it was not possible to execute the actual hot firing test due to the unavailability of proper altitude test opportunity, as shown in Fig. 4. Present work examines the flow physics inside the J-2 and J-2X nozzles through Computational Fluid Dynamics (CFD) [10] [11]. CFD is a numerical tool that is used to simulate flow dynamics if the experimental method is not possible or costly. In the present study, GRIDGEN software has been used to generate the meshes for the J-2 and J-2X nozzle geometries [12]. Contours of Mach number, velocity, static pressure, and static temperature have been produced using flow simulation software ANSYS Fluent [13]. The thrust computed for the J-2 nozzle resembles its actual vacuum thrust and the computation performed for the J-2X nozzle predicts additional thrust due to an extension which is encouraging and depicting the benefit of the extendable nozzle.

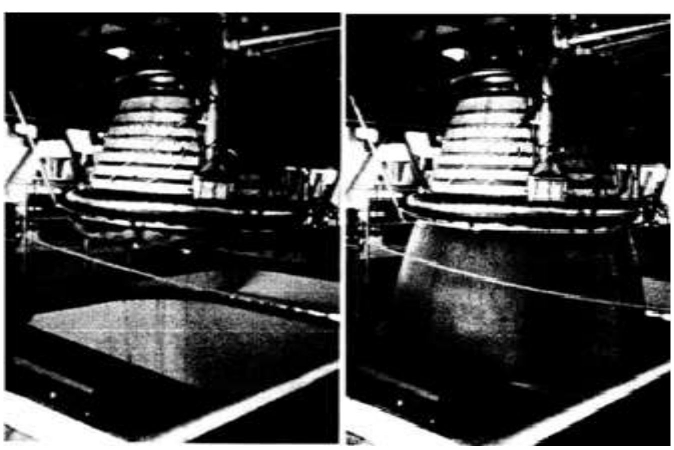

Fig. 4: Cold Flow Test of J-2X Nozzle, taken from [9]

II. MESH GENERATION AND BOUNDARY CONDITIONS

Dimensions of the J-2 and J-2X nozzle [5], [9] are shown in Fig. 5 and Fig. 6. The bell contour of the J-2 nozzle has been drafted according to Rao's parabolic technique [14], [15] and then to gain the area ratio 55:1 for the J-2X nozzle an additional extension has been added. To capture viscous effects accurately near-wall mesh has been resolved, as shown in Fig. 7 and Fig. 8. Also, the mesh quality at the throat has been kept fine. Fig. 9 shows a near throat view of both nozzles.

Boundary conditions (BC) applied on the test case are illustrated in Fig. 10 and specified below:

- Pressure inlet: 5260700 Pascals
- Pressure outlet: zero Pascals (vacuum condition)
- Temperature inlet: 3450K
- Temperature outlet: 300K
- Control volume: stationary wall, no-slip condition
- Algorithm: Reynolds-Averaged Navier-Stokes (RANS)
- Solver: 2D-axisymmetry pressure based
- Model: viscous, k-Ω SST (Shear-Stress Transport), energy equation applied
- Compressibility: ideal gas law
- Thermal conductivity: kinetic theory
- Viscosity: Sutherland
- Scheme: coupled
- Multigrid: Full Multi-Grid (FMG)

Simulations are carried out on 2D-axisymmetry cases with given values of BC acquired from the literature [9]. Initially, the calculation has been run with the appropriate number of iterations by using the first-order upwind coupled solver with k-Ω SST turbulence model to stabilize the solution then second-order upwind coupled solver with k-Ω SST turbulence model has been used.

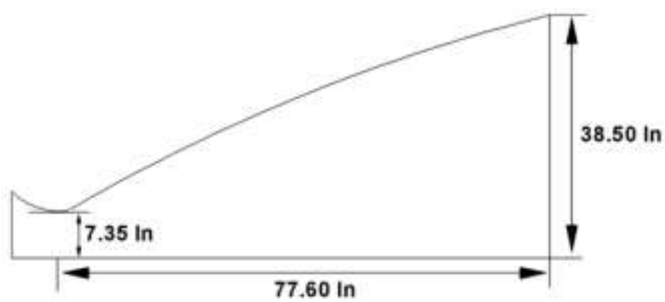

Fig. 5: Dimensions of J-2 Nozzle

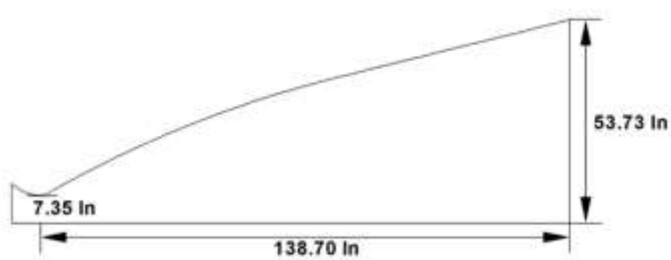

Fig. 6: Dimensions of J-2X Nozzle

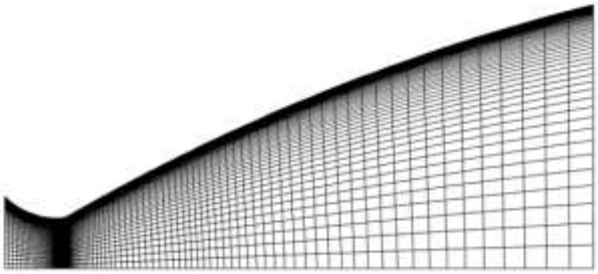

Fig. 7: 2D Mesh of J-2 Nozzle

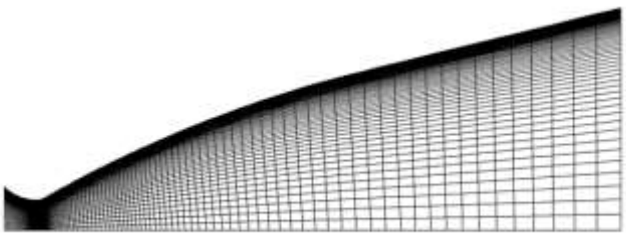

Fig. 8: 2D Mesh of J-2X Nozzle

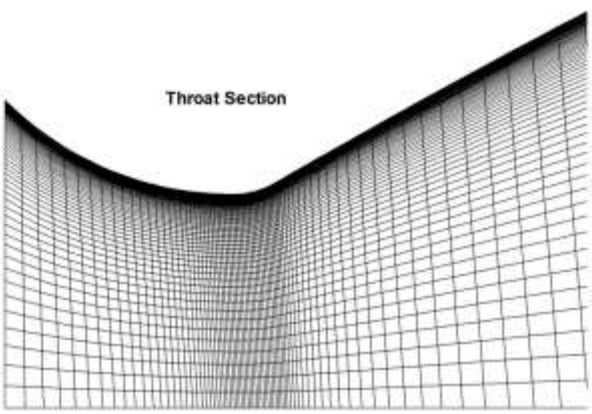

Fig. 9: Near Throat Mesh of J-2 & J-2X Nozzle

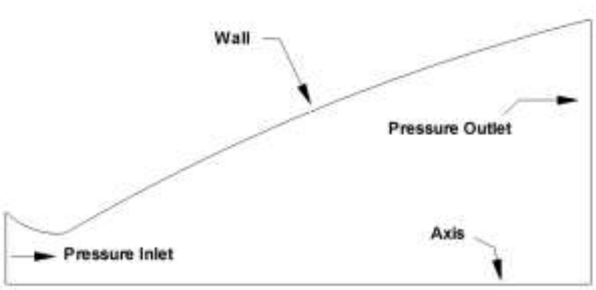

Fig. 10: Boundary Conditions for J-2 & J-2X Nozzle

III. RESULTS AND DISCUSSION

Nozzle converts the potential energy of gases into kinetic energy. Flow inside the nozzle expands, accelerates, and provides useful thrust. Results for the J-2 and J-2X nozzles are discussed in this section. The quality of grids directly dictates the accuracy of the results. Grid size and refinement are very important considerations to perform accurate simulation within a stipulated time frame. In the present study, boundary layer near the solid surface has been resolved and structured mesh has been generated for the J-2 and J-2X nozzles. Mesh far from solid boundaries has been coarsened to maintain mesh size within a manageable limit. 2D axisymmetric flow simulations with second-order accuracy for the flow and turbulence variables have been performed.

Fig. 11 to Fig. 18 presents Mach number, velocity, static pressure, and static temperature contours, respectively. Combustion gases are expended till 2431 Pa pressure for the J-2 nozzle, as shown in Fig. 15. The J-2 nozzle exit to throat area ratio is 27.5:1. Extension has mounted to the existing J-2 nozzle and its expansion ratio has increased from 27.5:1 to 55:1, known as the J-2X nozzle. Fig. 15 and Fig. 16 depict that expansion in the J-2X nozzle is larger which is certainly due to the larger exit to throat ratio. Since the contour of both the nozzles is the same therefore flow expansion is also identical in both the nozzles till the end of the J-2 nozzle. However, extended part of the J-2X nozzle further expands gases as compared to the J-2 nozzle, as shown in Fig. 16. This further expansion generates larger velocities and Mach number at exit plane of the J-2X nozzle, as shown from Fig. 11 to Fig. 14. As gas expands, its velocity and Mach number increase at the expense of pressure and temperature. It is portrayed from Fig. 11 to Fig. 18 and from Fig. 19 to Fig. 22. The gas temperature at the J-2X nozzle exit plane is lesser than the J-2 nozzle. Since throat diameter and combustion chamber conditions are the same for both cases therefore mass flow rate for both cases is same. Since velocity at exit plane for the J-2X nozzle is greater than the J-2 nozzle, therefore, its momentum thrust is larger, as summarized in TABLE 1. The pressure thrust of the J-2X nozzle is smaller due to the larger expansion inside the nozzle. However total thrust for the J-2X nozzle is greater and showing the benefit of the nozzle extension.

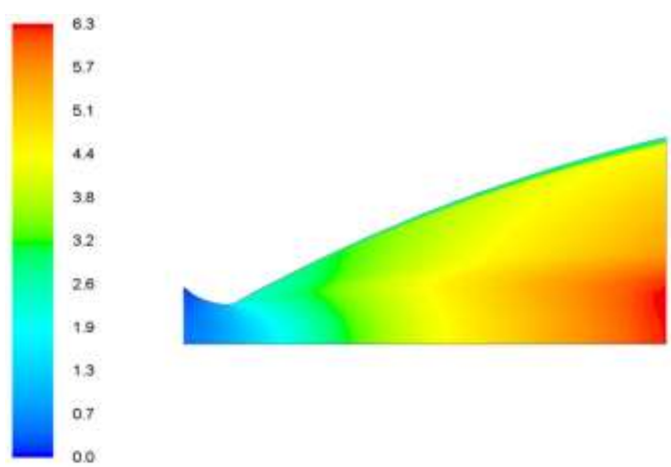

Fig. 11: Mach Number Contour for J-2 Nozzle

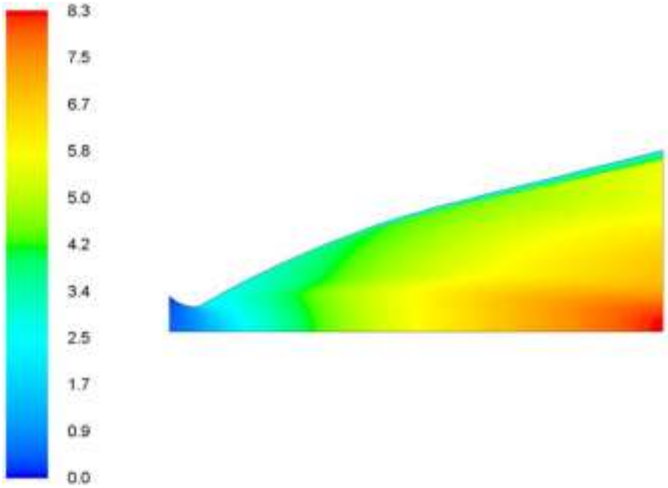

Fig. 12: Mach Number Contour for J-2X Nozzle

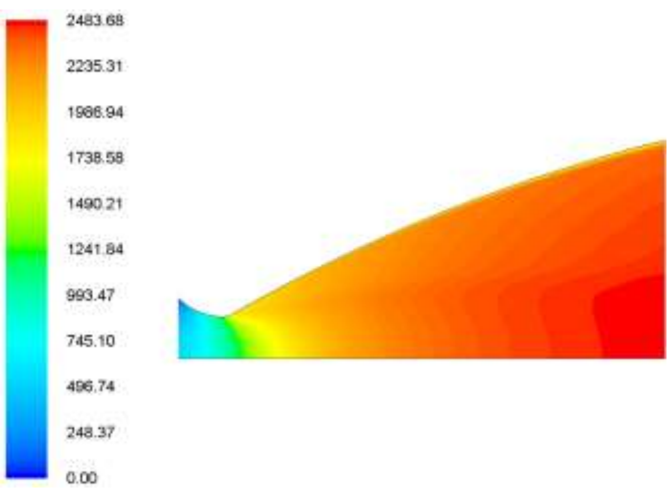

Fig. 13: Velocity Contour for J-2 Nozzle

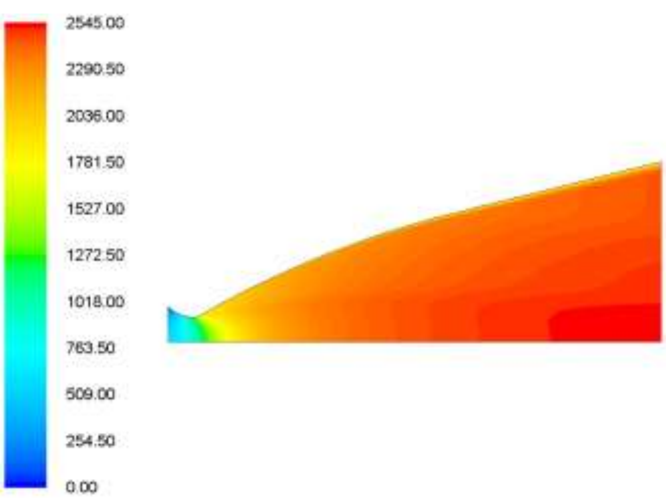

Fig. 14: Velocity Contour for J-2X Nozzle

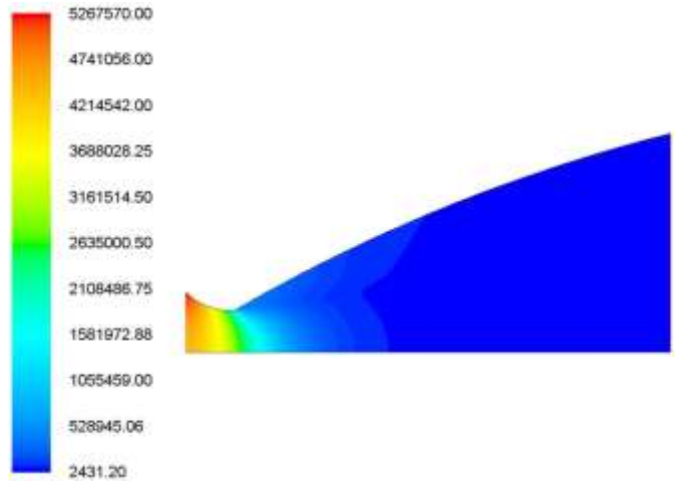

Fig. 15: Static Pressure Contour for J-2 Nozzle

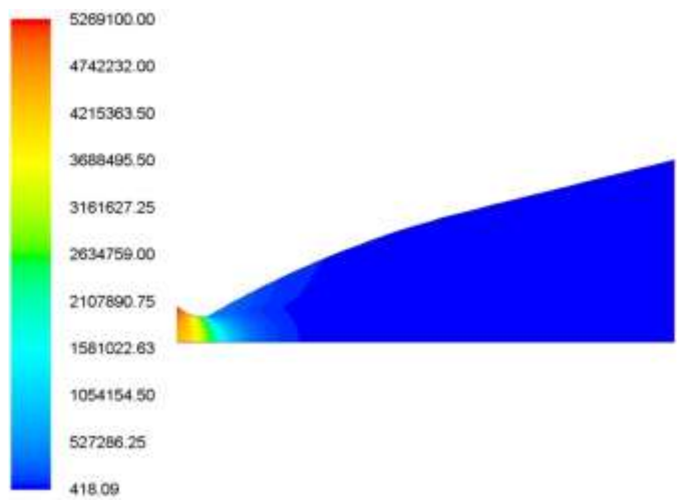

Fig. 16: Static Pressure Contour for J-2X Nozzle

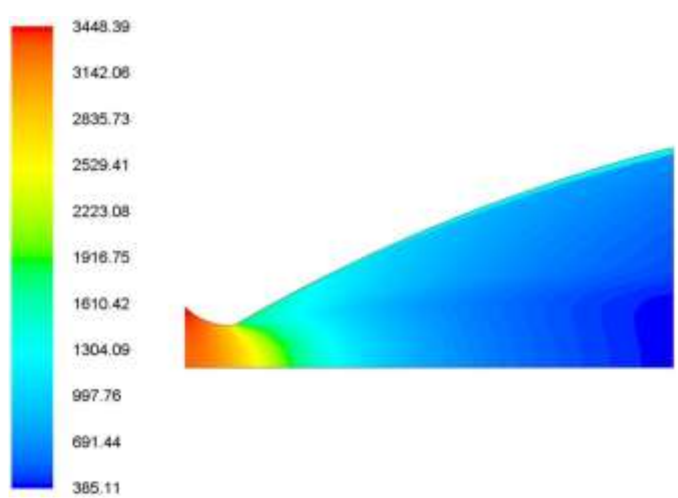

Fig. 17: Static Temperature Contour for J-2 Nozzle

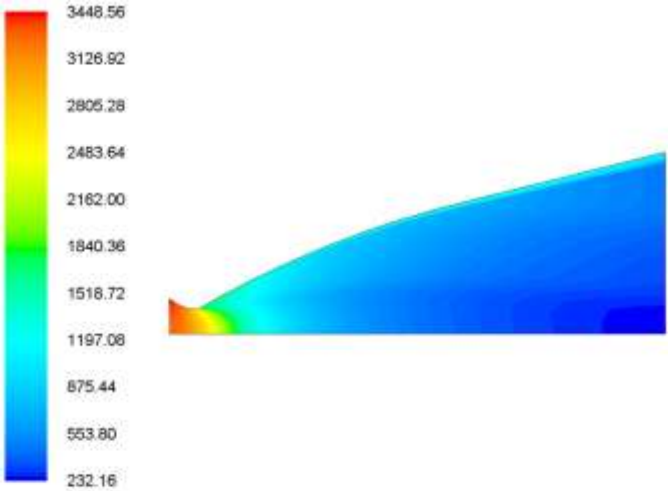

Fig. 18: Static Temperature Contour for J-2X Nozzle

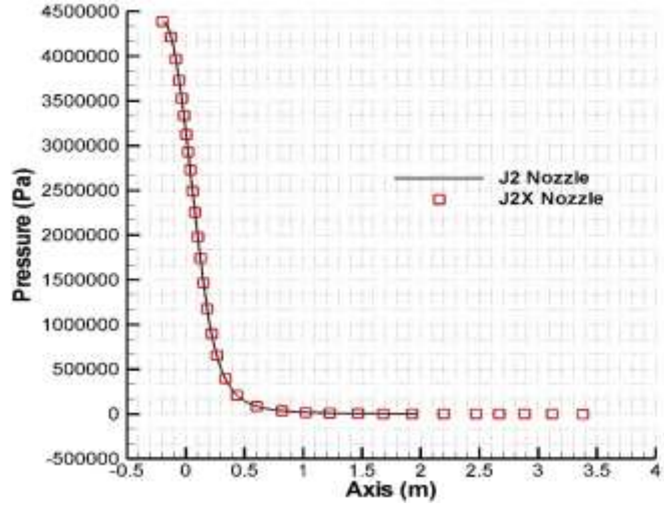

Fig. 21: Comparative Pressure at Axis of both Nozzles

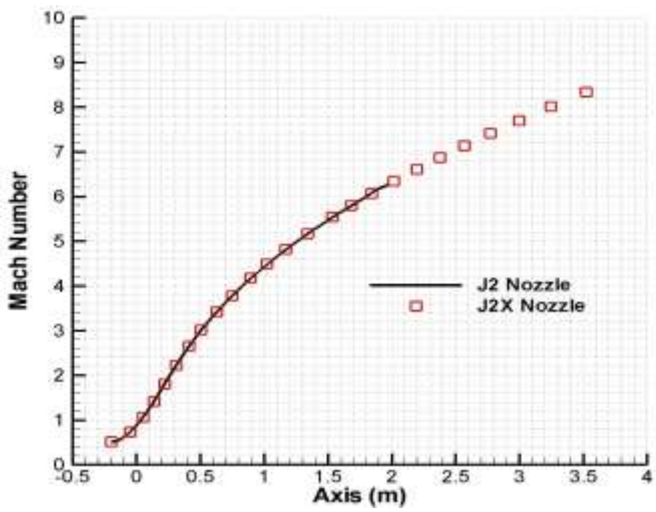

Fig. 19: Comparative Mach Number at Axis of both Nozzles

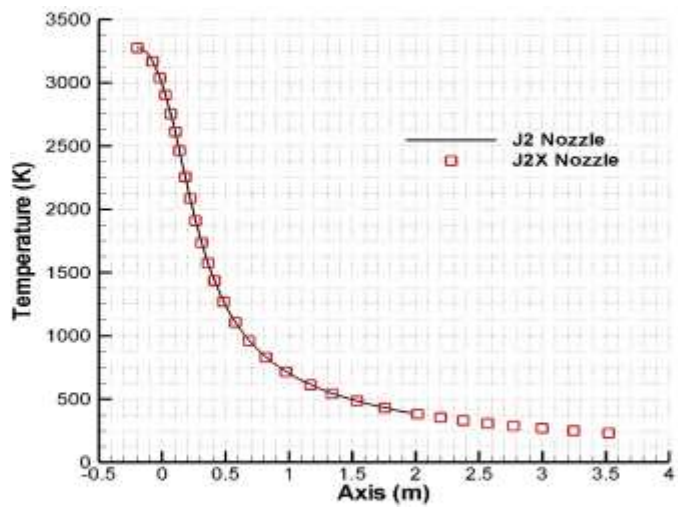

Fig. 22: Comparative Temperature at Axis of both Nozzles

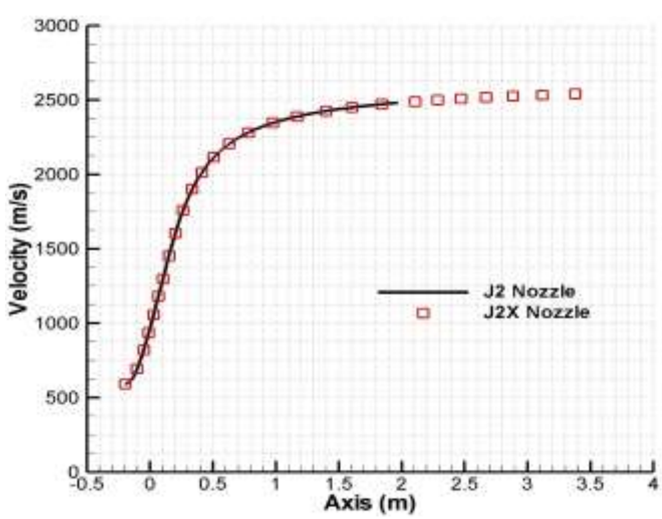

Fig. 20: Comparative Velocity at Axis of both Nozzles

TABLE 1
THRUST DEVELOPED IN BOTH NOZZLES

Nozzle	Momentum Thrust Lb.	Pressure Thrust Lb.	Total Thrust Lb.
J-2	210820	2261	217603
J-2X	215975	862	221017

The gain in the thrust has been achieved at an expense of a complex mechanism and extra weight of the nozzle extension. A comparative study of the merit and shortcoming of the extendable nozzle would be carried out. This technology can be very useful in some cases, however, might not be beneficial in some circumstances.

IV. CONCLUSION

Total thrust or specific impulse is a very important parameter to identify rocket engine performance and it can be improved for an engine through an adapted nozzle. Nozzle extension has been deployed at an appropriate altitude to get the best performance out of the nozzle at a cost of configuration complexities and greater weight of the engine. The present study discusses the improvement of the J-2 nozzle thrust by deploying the nozzle extension.

Simulations for the J-2 and J-2X nozzles have been carried out and variation in Mach number, velocity, static pressure, and static temperature has been examined. Thrust for both nozzles has also been calculated. The results clearly depict that increasing the area ratio of the nozzle gives more thrust. Efficiency loss can also be reduced at a higher altitude that causes under expansion due to reduced ambient pressure. Present results conclude that the design of altitude compensating rocket nozzle allows an overall better performance than conventional nozzles. It has also been concluded that nozzles such as the J-2X reduces fuel loss and the development of such types of nozzles may lead to the production of single-stage-to-orbit (SSTO) vehicles.

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