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Design and Optimization of the Effect of Base Bleed on Thrust of A Truncated Spike Nozzle

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Abstract:
To increase the performance of the current satellite launch capability, new rocket designs must be undertaken. One concept that has been around since the 1950s but yet to be utilized on a launch platform is the spike, or plug nozzle. The spike nozzle concept demonstrates globally better performance compared to a conventional bell nozzle, since the expansion of the jet is not bounded by a wall and therefore can adjust to the environment by changing the outer jet boundary. Aspike nozzle is designed and analyzed using Computational Fluid Dynamics Software (FLUENT). In order to improve the performance of the spike nozzle for various conditions, optimization of the nozzle will be carried out for some important design parameters and their performance will be studied for cold flow conditions. Initially a model is designed of a spike nozzle is created for certain parameters, and then the optimization process is carried out for the nozzle (Truncated model & Base bleed model). Optimized model also designed by the software GAMBIT and the flow behavior is analyzed by the Computational Fluid Dynamics (CFD) software called FLUENT. Comparison also takes place between the full length and the optimized models.

Key words: Gambit, Fluent, Optimized models, Spike or plug nozzle, Truncated model.

I. INTRODUCTION

Spike nozzle geometry is often described as an inside-out bell-shaped nozzle. It has a central contoured ramp leading into a spike in the center and is open to the atmosphere on both sides. Note that the length of the spike can be truncated to what is referred to as a plug nozzle. The advantage of truncation is a lighter and more compact nozzle with matched efficiency.

The function of a rocket nozzle is to direct all gases, generated in the combustion chamber of the engine and accelerated by the throat, out of the nozzle. The key feature of the spike engine is that, as the launch vehicle ascends during its trajectory, the decreasing ambient pressure allows the effective nozzle area ratio of the engine to increase. Aspike nozzle is often referred to as an altitude-compensating nozzle, because of its specific design capability of maintaining aerodynamic efficiency as altitude increases and thus throughout the entire trajectory.

At the outer cowl lip, the gas expands to the atmospheric pressure immediately, and then causes serious expansion waves propagating inward at an angle through the gas stream. At the location where the last expansion wave intercepts the spike, the gas pressure is equal to the atmospheric pressure. For the over expanded case, the spike changes the gas to be directed outward, and thus compression waves form and propagate outward at an angle and reflect off the jet boundary as expansion waves.

This process then begins again. The spike features a series of small combustion chambers along the ramp that shoot hot gases along the ramp's outside surface to produce thrust in a spike-shaped plume, hence the name" spike. "The ramp serves as the inner wall of the bell nozzle, while atmospheric pressure serves as the "invisible" outer wall. The combustion gases race along the inner wall (the ramp) and the outer wall (atmospheric pressure) to produce the thrust force.

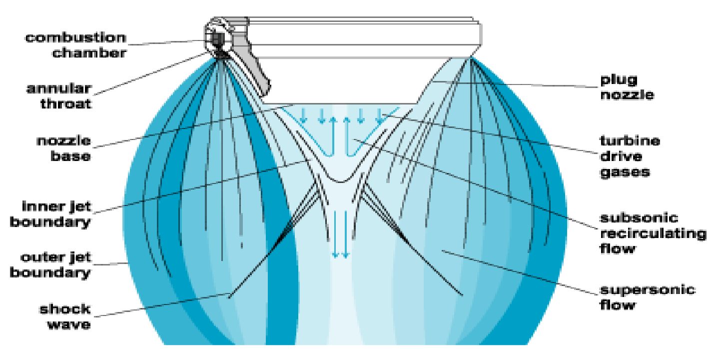

Figure. 1. Flows around Spike Nozzle

The main advantage to the annular spike nozzle design (both full length and truncated spike) is its altitude compensation ability below or at its design altitude. More specifically, the spike will not suffer from the same overexpansion losses a bell nozzle suffers and can operate near optimally, giving the highest possible performance at every altitude up to its design altitude. Above the design altitude, the spike behaves much like a conventional bell nozzle. Figure below shows the exhaust flow along aspike at low altitudes, design altitude, and high altitudes for a full spike and a truncated spike. Multiple expansion and compression, or shock, waves are evident in the flow in Figure these waves lead to losses in thrust

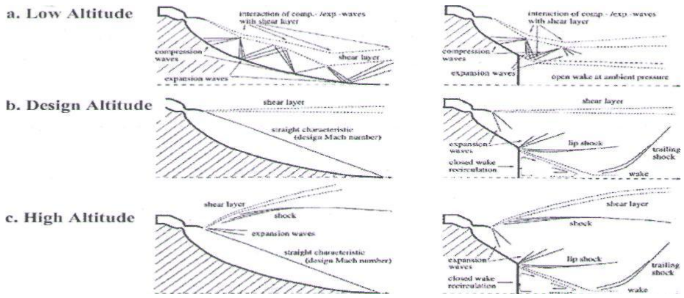

Figure.2. Exhaust Flow from a Full and Truncated Spike

At the design altitude of the nozzle, the exhaust flow at the chamber exit lip will follow a parallel path to the centerline to the exit plane. Therefore, the expansion ratio for a full-length spike at design altitude is equivalent to the chamber exit lip area divided by the throat area. As the ambient pressure decreases, the hot gas/ambient air boundary expands outward changing the pressure distribution along the spike; as a result, the expansion ratio increases. As the ambient pressure increases (low altitudes), the higher ambient pressure compresses the hot gas/ambient air boundary closer to the spike resulting in an expansion ratio decrease. The pressure distribution change along the spike and the location of the hot gas/ambient air boundary is automatic thus permitting altitude compensation up to the design altitude of the nozzle. Above the design altitude of the nozzle, the pressure distribution along the nozzle wall is constant. The expansion of the flow exiting the combustion chamber is governed by the Prandtl-Meyer turning angle at the throat.

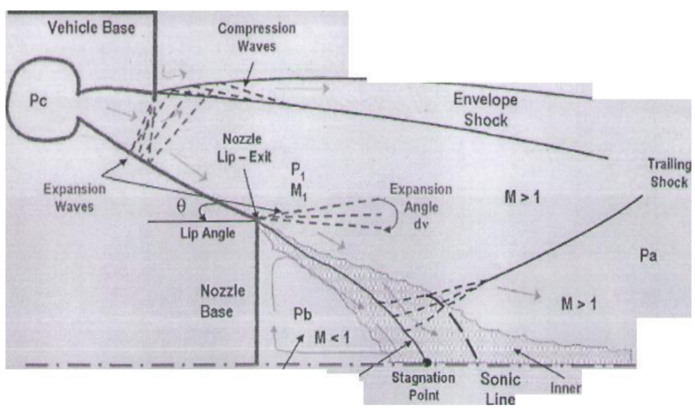

Figure.3. Exhaust Flow along a Truncated Spike Nozzle

According to the spike nozzle numerical analyses the results of the altitude compensation capabilities of anspike up to the design altitude are undeniable. Furthermore, the spike performs worse at high altitudes compared to bell nozzles with equal expansion ratios (exit area divided by throat area); therefore, to get the benefit of the spike, the design pressure ratio and the expansion ratio should be chosen as high as possible. The design pressure ratio is the ratio of the chamber pressure to the ambient pressure; ambient pressure is based on the chosen design altitude. If the spike is truncated, the spike advantage at higher altitudes (orbit transfer missions) includes shortened nozzle length and lower mass as compared to an equivalent performance bell nozzle design for orbit transfer missions.

II. OBJECTIVE

The basic design conditions and parameters are given from the research institution (ISRO). Two types of spike nozzles (full length and truncated) are discussed here. Considering that This thesis designs, analyzes and optimizes the spike nozzle contours where the rockets are designed for high-altitude applications (since most of its flight time is at high altitude) and the effects of density changes in the air will be negligible, the annular nozzle will probably be more appropriate for this application since the automatic altitude adjustment characteristics of the spike nozzle will not be necessary. However, in the interest of knowledge and the application of the data to future proposals, the spike design will be valuable and advantageous. Note that there is not much data publicly available for spike nozzles.

- Literature Review, the methods and results of others research will be discussed. This section will also allow for a clear differentiation between this thesis work and the work previously available to the public.

- Nozzle Design, details the important nozzle design parameters given from the Research Organization (ISRO) and discretion of the characteristic equations used in spike nozzle design and development of the boundary conditions

- CFD Setup & Solutions, will outline the procedure and techniques used in running the previously mentioned nozzle designs using GAMBIT through the well-known CFD program FLUENT. The results given by FLUENT are compared with the required flow exit parameters given by the research institution (ISRO). Based on the required result the design will be optimized and the flow analysis will be conducted in FLUENT (Considering that the Exit Parameters given are the highest possible values

- Conclusions will reiterate the major findings of this paper and highlight its applicability.

- Future Work outlines future work that will be investigated in the project phase II.

III. LITERATURE REVIEW

Chang-HuiWang et al. (2009) [1].Presented a simplified design and optimization method of spike nozzle contour using Lee and Thompson method. They designed three type of spike nozzles (1-cell linear spike nozzle, 3-cell spike nozzle and a 6-cell spike nozzle with the cell inclination angle of a = 30°) based on the types of the tests. A bell nozzle which is having the same optimum Nozzle Pressure Ratio (NPR) also designed and the comparison between this nozzle and spike nozzle conducted. The performance validation revealed that, from sea level to design altitude, efficiencies of the spike nozzle and bell-shaped nozzle varied within the range of 93.0-100.0% and 66.0-100.0%, respectively. The remarkable performance gain of the spike nozzle was 27.0% compared with the conventional nozzle at sea level. Cold flow tests were conducted on the 3-cell spike nozzle and the performance was obtained under two nozzle pressure ratios (NPR) lower than design altitude. At NPR 50 and 350, efficiency reached 92.0-93.5% and 95.0-96.0%, respectively. The performance of the nozzles was calculated experimentally and schlieren technique is adopted for visualization in the tests. Highly pressurized air was used as the propellant in cold flow tests. Numerical calculations were used to compare the results taken from experimental test. The governing equations were Compressible 3D Reynolds-averaged Navier-Stokes equations with k-£ turbulence model. Specified deviation from the linear portion of the record. The KIc value was calculated from this load by equations that have been established. TayoLadeinde and Hsun Chen (2010) [2].Compared the performance of a full-length spike nozzle with that of a nozzle truncated at 20% of the full nozzle length. Validation of the computations was performed using an annular-type conical nozzle with a 25-degree half angle and three values of the pressure ratio. A plug nozzle design was designed using a method of characteristics. Different lengths were designed, starting with the full nozzle and truncating at 20, 30, 40, and 50% of that length and all those nozzles are having same inner ratio 1.7 and outer ratio 6.5. Then the tests were conducted on the nozzles. The end results showed that the thrust produced was extremely close, with only a 0.18% error in thrust produced by the nozzle. These findings are important when it comes to designing air and spacecraft since a nozzle with a lighter weight and equal performance is more attractive than a heavier nozzle. The grid was generated on the nozzle design with the PLOT3D program and the flow analyzing is done by using the multi-disciplinary high-order CFD code AEROFLO. The boundary condition at the ramp is a no-slip wall condition. WANG Chang hui et al. (2006) [3]. Again carried out experimental and numerical studies on a 6-cell tile shaped round to rectangular (RTR) spike nozzle to obtain its altitude compensation capacities and aerodynamic behavior at its base. Results revealed that the 6-cell nozzle has 5% less efficiency compared with the single cell linear spike nozzle due to its imperfect contour and manufacturing defects. The performance of the nozzles was calculated experimentally and schlieren technique is adopted for visualization in the tests. Highly pressurized air was used as the propellant in cold flow tests. Numerical calculations were used to compare the results taken from experimental test. The governing equations were Compressible 3D Reynolds-averaged Navier-Stokes equations with k-£ turbulence model. of elastic stress analysis on specimens of the type described in the standard ASTM D 5045. Liu Yu et al. (2002) [6].give numerical and experimental studies and conclusions for various approximate designs of spike nozzle. The numerical simulations contain both the Method of Characteristic and the solving of the Navier-Stokes equations. They prescribe various spike nozzle designs for future researchers. The experimental system and several kinds of the test spike nozzle are showed here. From test results conducted on the various nozzle designs, the best inclination angle of the primary nozzle is probably about 30° and the angle will be affected strongly by other parameters like Pc, Pa, total expansion ratio and the base mass flow rate.

IV. NOZZLE DESIGN

As mentioned earlier, the important nozzle parameters are taken from the Research institute. Simple mathematical calculations are used to define some additional design parameters. From the calculations and the given prescribed values the nozzle is designed manually. Then the resulting spike contour line is then imported into GAMBIT by way of an x-y plot curve. These points are used to define a 2-D spline curve, which is then circular extruded to give the shape contour of the spike body and corresponding throat contour. The rest of the nozzle body is constructed to interface with the test stand and to support the plug that is centrally located.

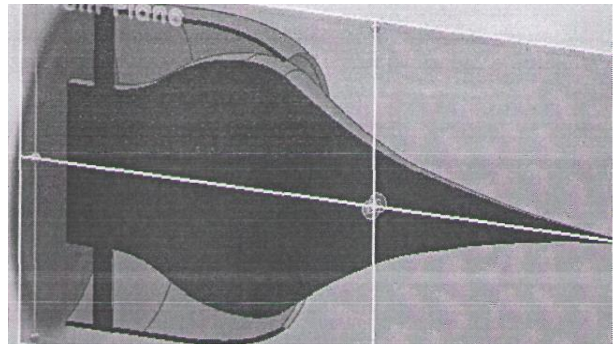

Figure.5. Artistic view of the Nozzle in Design

Here GAMBIT 2.1 is used to design the nozzle structure and FLUENT 6.3.2 is used to analyze the flow in and around the annular spike nozzle. Initially, the annular spike nozzle is designed for the given specifications, the given design parameters are,

- Exit Area ratio (A_e/A_t) = 1.7
- Spike expansion ratio= 10.719
- Chamber Pressure= 60 bar
- Exit Pressure = 1 bar
- Desired exit Mach no = 3
- Exit Diameter = 2 in2
- Throat area = 0.01096m2
- Angle of throat =14.53deg,

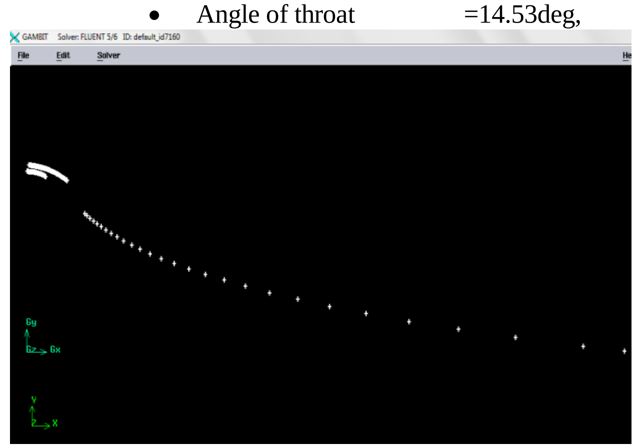

Figure.6. Gambit design of spike nozzle

Then the far field boundary is generated. The length of the far field boundary is designed as 10 times of the outer nozzle diameter (10D) from the tip of the plug in x-axis and 5 times of the outer nozzle diameter in y-axis (5D). Since the nozzle geometry is symmetric and the flow is ax symmetric, upper half of the nozzle only designed for flow analysis in order to reduce the calculation difficulty and iterating time

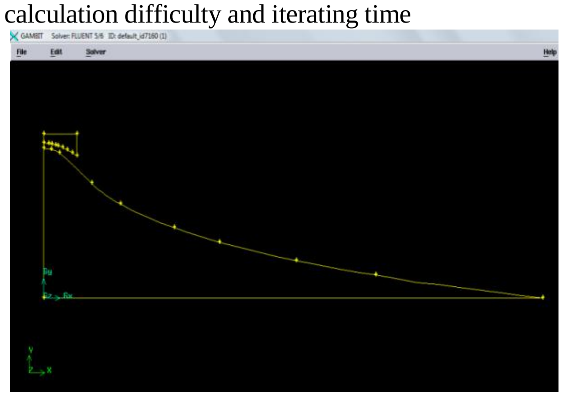

Figure.7. Gambit design of spike nozzle

V. RESULT AND DISCUSSION

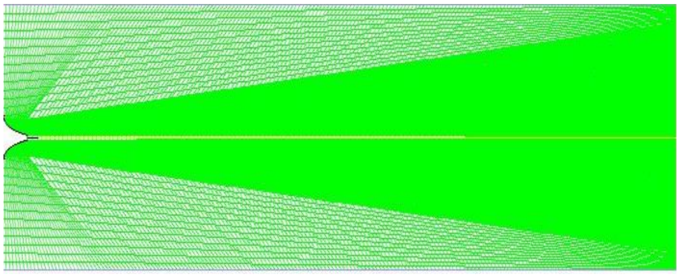

Figure.8. Contours of Mach number

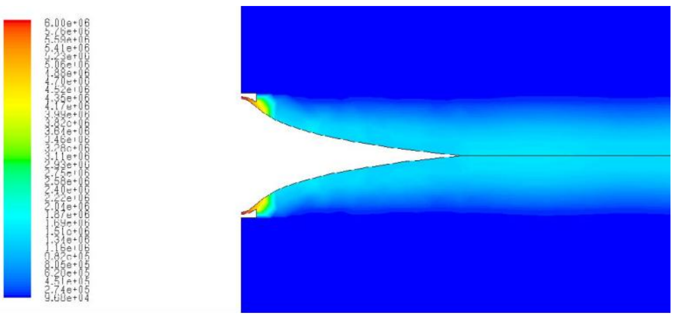

Figure.9. Contour of Total Pressure

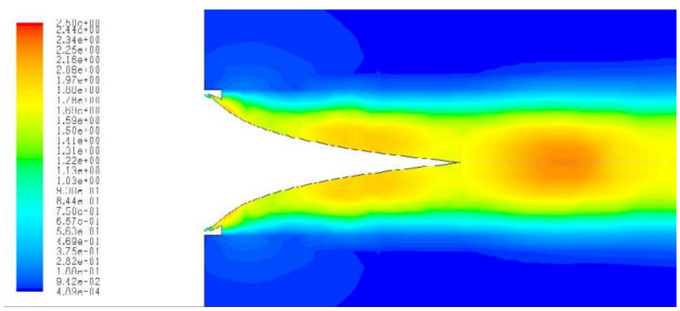

Figure.10. Contour of Mach number

VI. CONCLUSION

This project proves that CD nozzle works best only for the particular designed altitude whereas spike nozzle maintains its efficiency for the changes in the altitude. The results obtained from CFD analysis will be compared with theoretical and experimental values thus accomplishing the validation of the code. The accuracy of each set of approximation is compared through numerical error analysis, graphical analysis, and their capability to generate accurate solutions for four different optimization problems.

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