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V. GOPALA DEVA KOWSIK
Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai – 600119.,
vgd.kowsik@gmail.com

THRUST FORCE ANALYSIS OF SPIKE BELL NOZZLE

V.GOPALA DEVA KOWSIK[1], CHRIS JOSEPH[2], M.P.ARUN JUSTIN[3], R.SAINATH4, D.THANIKAIVEL MURUGAN[5], S.ILAKKIYA[6]

[1to4]: UG Students, [5&6]: Assistant Professor
Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai – 600119.

Abstract- Aerospike nozzle is often described as an inside-out bell shaped nozzle and named for its prominent spike located at centre. This project mainly focuses on design of various types of nozzles such as aerospike, truncated aerospike and spike bell nozzles. In theoretical approach, the efficiency of rocket nozzles is calculated with design parameters such as throat area, exit area, chamber pressure and so on. From theoretical approach it is inferred that the spike bell nozzle has an increased value of thrust when compared to other nozzle types. So meshing and internal flow analysis is carried out for spike bell nozzle alone by using ANSYS CFX 13.0 software. From this flow analysis it can be inferred that the exit Mach number of spike bell nozzle comes close to the theoretical design exit Mach number .Also the flow simulations for the spike bell nozzle is carried out for various parameters such as pressure, temperature and velocity.

Keywords*- aerospike, altitude, Mach number, bell nozzle, efficiency, thrust*

1.0 INTRODUCTION

The most popular altitude-compensating rocket nozzle to date is the Aerospike nozzle, the origin of which dates back to Rocketdyne in the 1950s. This type of nozzle was designed to allow for better overall performance than conventional nozzle designs. This concept was thoroughly explored by the Germans during the time of the world war wherein they were to be posted as a threat for their rivals. It was after the unveiling of the Lockheed Martin's X-33 concept that the performance of the aerospike nozzle has received its fame in research. The structure of this type of nozzle roots on its advantages of minimising the losses encountered in the previous versions of the conventional types. The literature survey has been thoroughly studied and their researches were beneficial. Some of them are,[1]"D.S.Jain,D.A.Pinto,R.A.Joshi, S.S.Sawant, and Dipak.J.Choudari has examined the performance of Aerospike nozzle against the conventional bell nozzles and proved that the efficiency of aerospike nozzle outweighs bell nozzle at different working altitudes. [2] "Trong.T.Bui, James.E.Murray "has performed a flight research on aerospike nozzle using high power solid rockets and their results are compared with ground test results. They have stated that the rockets reached a Mach number of 1.6 with a very high efficiency of 0.96. [3] "Gerald Hagemann, Gennady. E.Dumnov "has researched on altitude adaptive nozzles such as dual bell nozzles and plug nozzles. Their flow phenomena were experimented and numerical simulations were conducted and they have highlighted the superior performance of them.

2.0 AEROSPIKE NOZZLE

The aerospike nozzle has a central contoured ramp leading into a spike in the center and is open to the atmosphere on both sides. An aerospike 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.

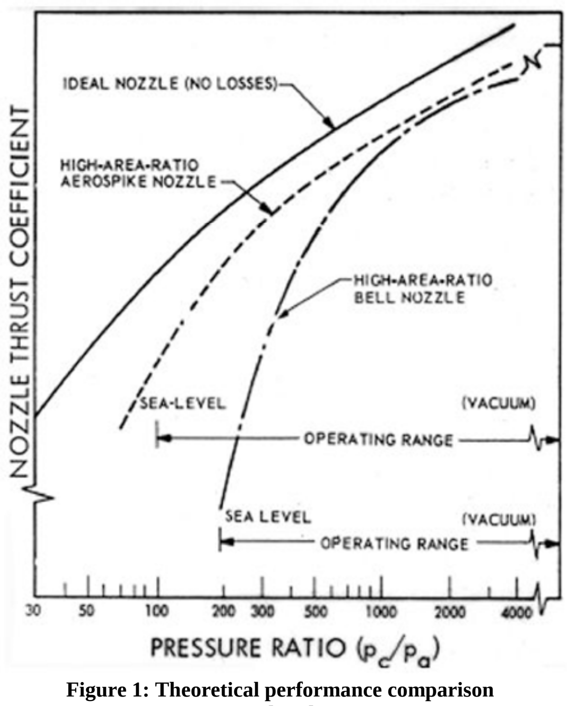

Figure 1: Theoretical performance comparison Courtesy: Huzel and Huang, 1967

From Figure 1 it is shown that the aerospike nozzle is substantially better at low altitudes whereas the bell and cone nozzles are likely to be over expanded.

2.1 OPERATION OF NOZZLE

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,

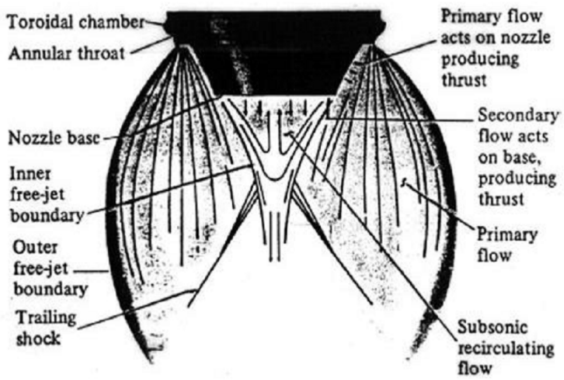

Figure 2: Truncated aerospike operation
Courtesy: Hill and Peterson

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 aerospike 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 "aerospike." 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.

2.2 MERITS

The aerospike nozzle has 90% overall better performance than the conventional bell-shaped nozzle. The efficiency at low altitudes is much higher because the atmospheric pressure restricts the expansion of the exhaust gas. A vehicle using an aerospike nozzle also saves 25-30% more fuel at low altitudes. At high altitudes, the aerospike nozzle is able to expand the engine exhaust to a larger effective nozzle area ratio. An aerospike nozzle with an expansion ratio of 200:1 to 300:1 can increase the thrust and specific impulse by five to six percent. The aerospike design is suitable for Single Stage to Orbit (SSTO) flight. Other advantages are that the aerospike nozzle makes better use of the base area, and has higher thrust efficiency and thus a higher average specific impulse.

2.3 DEMERITS

The after body induces heat, and to cool means that the performance reduces along with the pressure against the nozzle. Another issue is weight, which as previously stated can be resolved through truncation. Finally, the performance is more difficult to evaluate because of the complex flow field and the turbulence involved.

3.0 METHODOLOGY

A detailed study of concepts for the project is carried out. A procedural theoretical approach of nozzles is carried out and the models of nozzles namely the full length aerospike, truncated aerospike, and the spike bell types are created using Pro-E Wildfire 2.0 software. The next step goes to the meshing and analysis of the spike bell model using ANSYS 13.0 CFX software. The behaviour of flow along the spike bell nozzle is thus obtained and comparison on the basis of Mach number is henceforth done using theoretical calculations.

4.0 THEORETICAL APPROACH

The theoretical approach can be identified as the core section of the project whereas the efficiency analysis is carried out with design parameters.

Rocket nozzle efficiency,

$$\eta_C = \frac{\text{Actual thrust coefficient}}{\text{Ideal thrust coefficient}}$$

$$\eta_c = \frac{C_{thrust\ .a}}{C_{thrust\ .i}}$$

Now,

Actual Thrust Coefficient = $\frac{\text{Thrust}}{P_c . A_t}$

Ideal thrust Coefficient is given by,

$$C_{thrust\ .i} = (A^* P_c \sqrt{\left(\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}}\right]\right.} + (P_e - P_a)A_e$$

Prandtl-Meyer Function is given by,

$$= \sqrt{\frac{k+1}{k-1}} \tan^{-1}\sqrt{\frac{k-1}{k+1}(m^2-1)} - \tan^{-1}\sqrt{(m^2-1)}$$

Thrust force is given by,

$$F = (A^* P_c \sqrt{\left(\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}}\right]\right.} + (P_e - P_a)A_e \cos\ )$$

Table 1: Design parameters

Design Parameters	Values
Throat area, A_t	1.853 in^2
Exit area, A_e	9.621 in^2
Exit area ratio, A_e/A_t	5.192
Rocket flow specific heat ratio, γ	1.194
Nozzle exit Mach number M_e	2.802
Rocket chamber pressure P_c	500 psia
Nozzle exit pressure P_e	15.34 psia

The table 1 shows the values of the necessary parameters to design the nozzles. These values are taken from [2] and they are set as standard dimensions for the purpose of various nozzle designs. Hence the performance parameters are calculated and their results are compared theoretically.

5.0 DESIGN OF NOZZLES

The design of the nozzle is carried out according to the dimensions which can be cited in Figure 3.

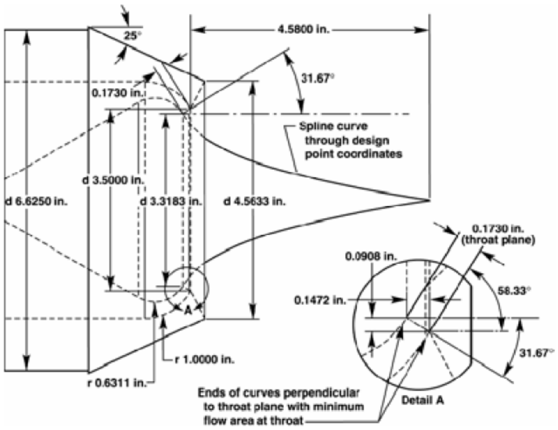

Figure 3: Aerospike Nozzle Design
Courtesy: Dryden Aerospike Rocket test

Using the afore mentioned dimension as a base the forthcoming models are made with Pro-E Wildfire software and the new model is also created by combining the bell nozzle and truncated aerospike nozzle shapes.

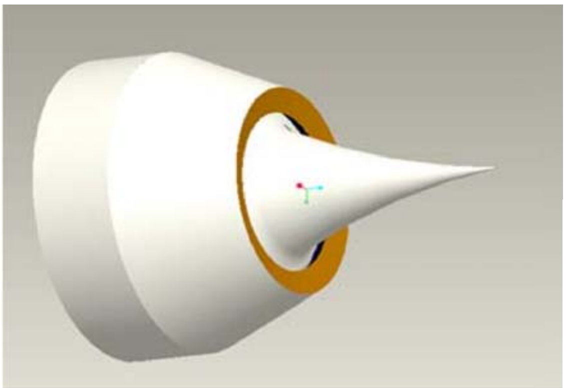

Figure 4: Pro-E Model of Aerospike nozzle

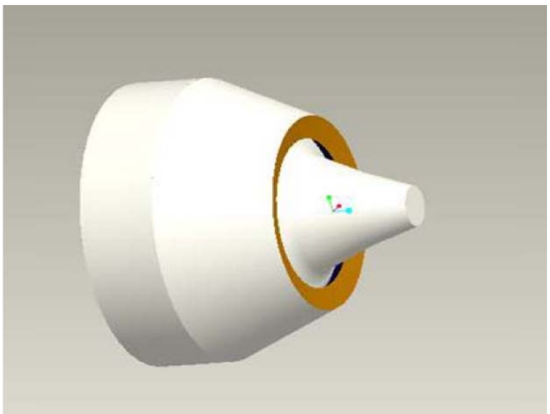

Figure 5: Pro-E Model of Truncated Aerospike nozzle

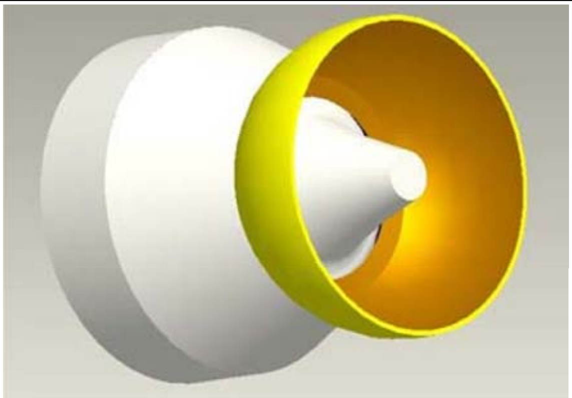

Figure 6: Pro-E Model of Spike Bell nozzle (Side View)

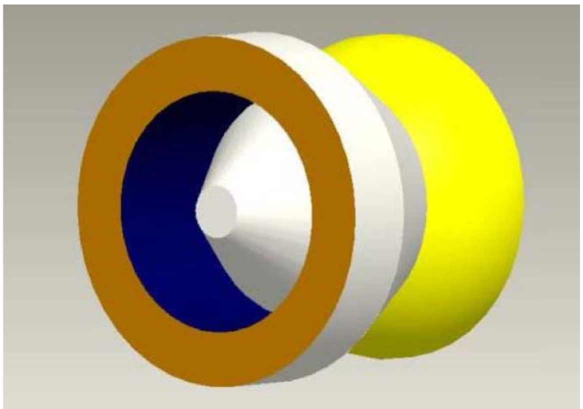

Figure 7: .Pro-E Model of Spike Bell nozzle (Side View)

6.0 MESHED GEOMETRY

As said above in nozzle design the spike bell nozzle is modelled and is further meshed using ANSYS 13.0 CFX Software. The mesh is of unstructured type.2D mesh contains triangular elements and the 3D mesh contains tetragonal mesh elements.

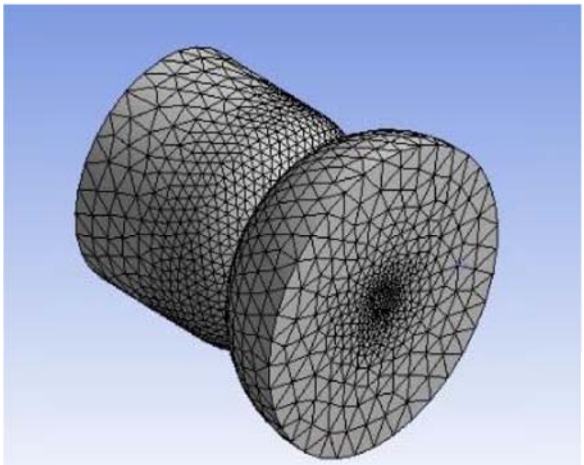

Figure 8: Meshed Model of Spike Bell nozzle

7.0 FLOW ANALYSIS

The flow analysis for the spike bell nozzle is carried out using ANSYS 13.0 CFX software. In this process first the models are imported, meshed and flow analysis is carried out in major three steps;

1. The first step is CFX-PRE, where the meshed model is imported and boundaries are created and corresponding boundary conditions are assigned to the boundaries.
2. The second step is CFX-SOLVER, where the solutions are obtained by solving the equations and process is highlighted in terms of codes and graphs and once the run is over it reaches next step.
3. The third step is CFX-POST, where the corresponding contours are created for following major parameters such as Pressure, Temperature and Mach number.

Boundary conditions are detailed as follows,

Table 2: Boundary Conditions

S.No	Boundary Type	Boundary Conditions
1	Inlet	Entry at Subsonic speed, Relative pressure value as 500 psia Turbulence at Medium Intensity Static temperature at 1500 k
2	Wall	No slip Wall Wall roughness option as smooth wall Heat transfer option as Adiabatic
3	Outlet	Entry out at Supersonic speed

The Figure 9 represents the Mach number volume rendering of the spike bell nozzle wherein at the exit section the flow reaches a mach number of nearly equal to 2.8 which equals the design mach number value which is used previously in theoretical section.

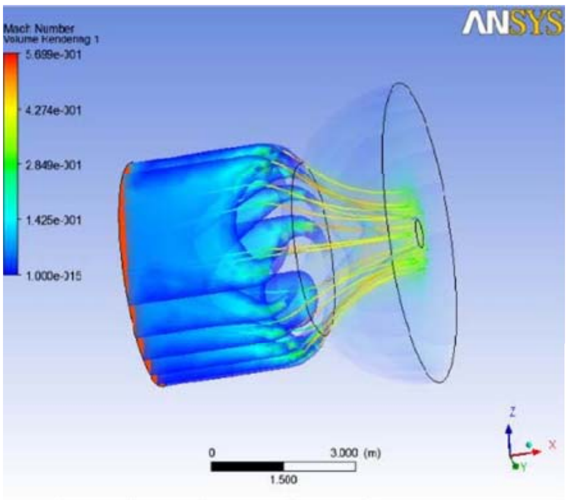

Figure 9: Mach number plot of Spike Bell nozzle

The following figures shown below depict the flow behaviour of the spike bell nozzle.

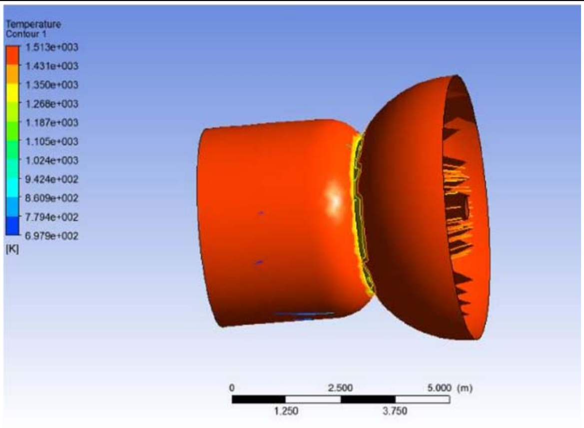

Figure 10: Temperature contour of Spike Bell nozzle

The Figure 10 shows the variation of the temperature about the spike bell nozzle which the range nears to 1500 K.

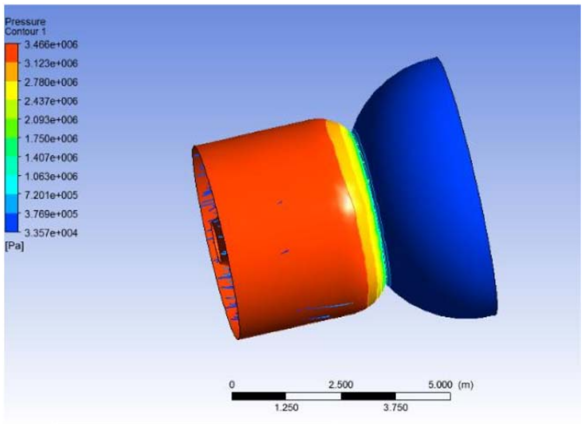

Figure 11:.Pressure contour of Spike Bell nozzle

The Figure 11 represents the variation of pressure about the spike bell nozzle where the pressure increases along the inlet region and then decreases after the throat.

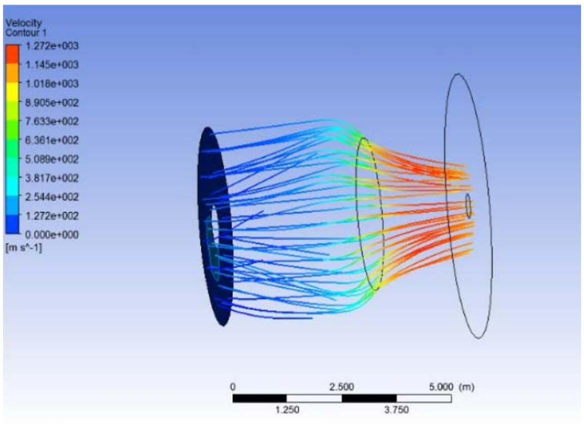

Figure 12: Velocity contour of Spike Bell nozzle

The Figure 12 represents the velocity contour for the spike bell nozzle where the streamline travels throughout the nozzle. It initially has a low value up to the throat and after it the velocity increases drastically up to the exit.

8.1 RESULTS AND CONCLUSION

Table 3: Results

S.No	Nozzle models	Thrust force (N)
1	Aerospike	5930.078
2	Truncated aerospike	5929.932
3	**Spike bell**	**5937.119**

The Figure 13 represents the thrust force results at exit section, which is obtained from theoretical calculations.

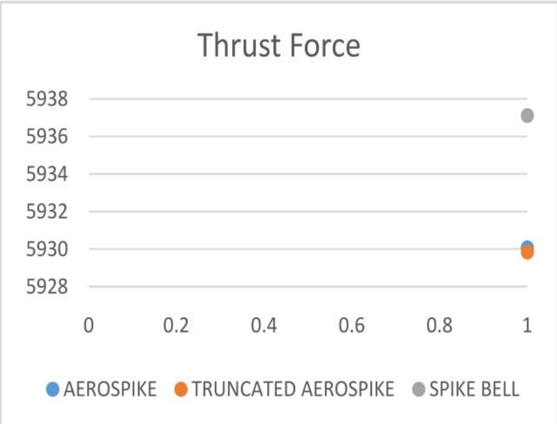

Figure 13: Plot of Nozzle length v/s Thrust force

Figure 14 shows the velocity variation of spike bell nozzle along its length which is obtained from flow analysis results.

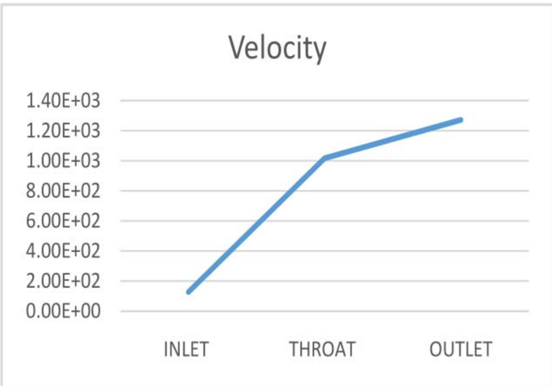

Figure 14: Plot of Nozzle length v/s Velocity

It can be concluded that the thrust output of the spike bell nozzle is higher in comparison to bell nozzle and the truncated aerospike nozzle. In the flow simulation analysis the nozzle reaches a Mach number value which nearly equals to the theoretical design exit Mach number. Thus we expect our project to be useful to the aerospace industry in the near future.

8.0 FUTURE PROGRESS

The spike bell nozzle design is modified with a clustered arrangement at the throat section. It is believed that the nozzle would achieve an even higher performance by making an optimal use of the flow.

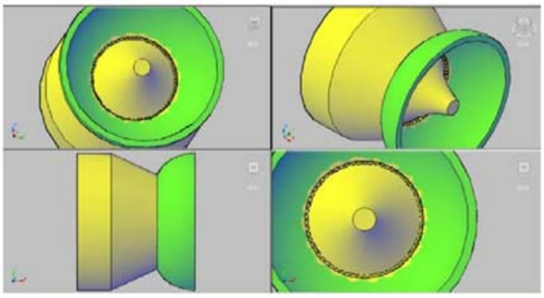

Figure 15: Model of Clustered Spike Bell nozzle

By achieving above task mentioned, this model is further implemented into below rocket model and further research is carried out.

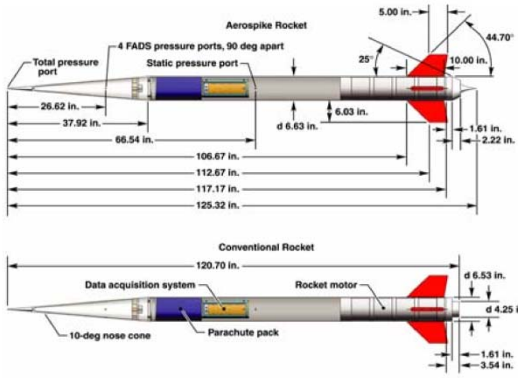

Figure 16: Engineering drawing of Rocket design
Courtesy: Dryden Aerospike Rocket test

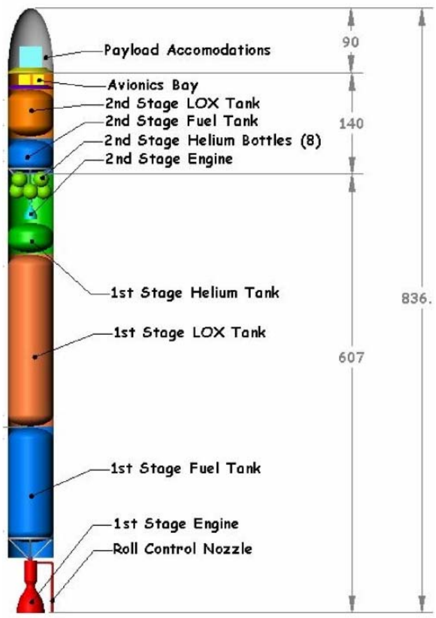

Figure 17: Model of NLV – Stage Characteristics
Courtesy: CALVEIN Team

After a successful implementation of spike bell nozzle in above mentioned model with various analysis carried out and next the stage and pressure fed fuel system is built with reference to Figure 17. And also fuel selection and gas selection is made with an most important part which falls on material selection (mostly composite materials) is carried out to obtain suitable mass fraction at each stage. And also various parameters for each stage such as dry mass, Chamber pressure, Sea level Thrust, Vacuum thrust and Separation/Burnout (for time and altitude) are identified.

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