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Development and Numerical validation of an Aerospike nozzle Contour Design

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Abstract. Aerospike nozzle simplified design and analysis, as well as test results, are presented. New techniques in nozzle design have been used to improve the performance of current rocket engines. The use of an aerospike nozzle is one such technique. It outperforms the existing proven bell nozzle in terms of overall performance. This study analyses the development and flow analysis of an aerospike nozzle at sea level, validating their results by taking into account currently used bell nozzles. The flow over the aerospike pump is investigated in higher depth using computational fluid dynamics under an autonomous fire testing condition. This test showed that the approximate design method used to determine an aerospike nozzle shape can lead to extremely effective nozzles. A model of the current 7.45 kN bell nozzle was selected as a specimen to develop an aerospike Nozzle. Gambit and Fluent software were used to model and examine the flow characteristics of building the aerospike nozzle. The developed aerospike nozzle shows a nearly 2% increase in performance over the existing nozzle.

1 Introduction

To achieve an advanced launching vehicle, one of the most important components is a highly efficient propulsion system. Future aerospace propulsion technology will inevitably focus on researching and developing reusable propulsion systems that are lightweight, affordable, and highly effective. Since the bell-shaped nozzle rocket engine has reached the pinnacle of development, it is challenging to significantly increase its performance in comparison to conventional rocket engines. The aerospike nozzle engine is a good contender to power an advanced launching vehicle in the future because of its small size, lightweight, excellent performance at all altitudes, and improved use of the vehicle base [1]. This kind of nozzle has the ability to continuously adjust for altitude. Since its plume is free to adapt and open to the outside atmosphere, it is thought to function better at off-design altitudes than the usual bell-shaped nozzle. This is because it enables the engine to run at its maximum expansion at all altitudes. This paper initially examines the spike nozzle design and contrasts it with the

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bell nozzle that has been in use up to this point [2]. The principle behind the aerospike nozzles will then be discussed. Furthermore, this nozzle type's benefits and drawbacks will be examined in relation to the conventional converging-diverging nozzle [3].

1.1 Nozzle concepts, Thrust and Performance

A nozzle is a mechanical device used to regulate the flow characteristics or direction of fluid out of (or into) a pipe or enclosed chamber. A nozzle is often a pipe or tube with a variable cross-sectional area that is used to control or guide fluid flow [5]. The rate of flow, speed, direction, mass, form, and/or pressure of the stream that emerges from nozzles are commonly controlled. The purpose of the rocket nozzle is to efficiently transform the propellant's thermal energy into kinetic energy so that high exhaust velocity can be achieved in the intended direction [7]. The three primary components of a rocket nozzle are the throat, the divergent section, and the convergent section [6].

The ratio of the cross-sectional exit area to the throat cross-sectional area determines a rocket nozzle's performance. We refer to this as the expansion area ratio. Since the geometry of the nozzle usually does not change, this value normally stays constant. During engine operation, the pressure inside the combustion chamber and the mass flow rates also stay relatively constant. Based on the anticipated operating circumstances, the rocket engineer selects the nozzle designs and characteristics. The most basic performance metric for a rocket motor is the thrust it produces. “Thrust, being the force that a motor exerts, is what propels a rocket. Thrust is generated by the expelling of mass (the exhaust) flowing through the nozzle at high velocity. The expression for thrust is given by the following equation (1).”[4]

$$F = \int P\, dA = V_e + (P_e - P_a)\, A_e \qquad (1)$$

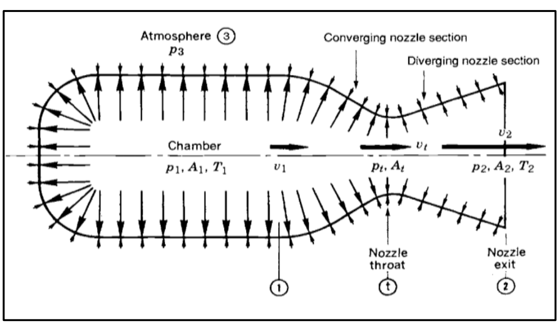
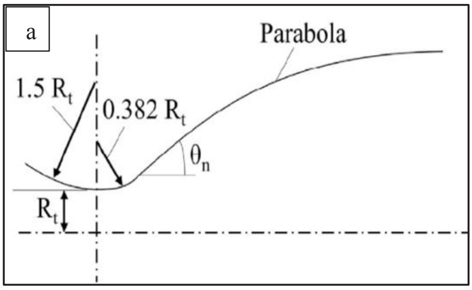


Fig. 1. Thrust and Thrust Coefficient

2 Bell Nozzle Design Methodology

2.1 Parabolic Approximation of Bell Nozzles

Designing a nearly-optimal thrust bell nozzle shape can be accomplished by applying G.VR. Rao's recommended parabolic approximation techniques. Figure 2 (a) depicts the design arrangement of a parabolic approximation bell nozzle [8]. A 1.49 Rt circular arc makes up the nozzle shape directly upstream of the throat T. The diverging section nozzle contour consists of a parabola from point N to exit E and a circular entry section with a radius of 0.379 Rt from the throat T [13].



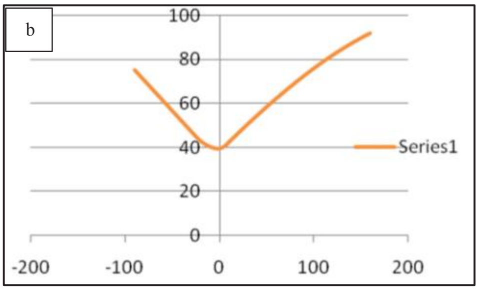


Fig. 2. (a) G.V.R.Rao contour (NASA SP 125) (b) Bell Nozzle Contour

Table 1. Specifications of Bell Nozzle

Parameters	Values
Thrust	F= 7KN
Propellant	Air, Nitrogen
Throat Dia	dt=79mm
Chamber pressure	Po=8.33 bar
Area ratio	A/A*=5.24
Chamber Temperature	To=300k
Gas constant	R=287 KJ/Kg/K
Material	Steel (SS 304)

2.2 Theoretical calculations of Bell Nozzle at sea level

For area ratio A/A*=5.24
πre2/ πrt2 =5.24
re2 = 0.09041
de = 0.1808 m
For Convergent Divergent Nozzle
Lc = 132 mm (given)
Sin 15° = 0.0509 / Z = 0.1966 m Cos 15°= L/Z
LD = Cos 15°× 0.1966
LD =189.9 mm
For Bell Nozzle,
LD = 80% of LD
LD = 150.8 mm
For Sea level Test.
For γ =1.4, Ae/A*=5.2, From Isentropic table, Mach number at exit Me = 3.225

Thrust Calculation:

Thrust F =mp×Ce + (Pe-Pa) Ae

= 9.518×637.826 + (16243.5 – 1.013×105) ×0.02567

F = 3887.42 N

Specific Impulse (I_{sp}):

$I_{sp}= C_j/g$

= 408.42/9.81

I_{sp} = 41.63 sec Specific fuel Consumption:

= 1/ I_{sp}

=0.024018 1/s

Efficiency Calculation:

The definition for efficiency of bell shaped nozzle isgiven by,

$$\eta = \frac{\mathrm{To4 - Te}}{\mathrm{T04 - Tes}}$$

$$\eta = \frac{300 - 97.5}{300 \times (1 - 0.32468)}$$

= 0.9432

η = 94.32 %

2.3 Bell Nozzle Flow Characteristics

Calculation of flow over the bell nozzle, which had been designed earlier in this section, under cold flow conditions is covered in this section. The next stage would be to carry out comparable calculations with different flow conditions by adjusting the Mach number and altitude (or ambient pressure). Fluent software was used for pre-processing after Gambit was used to produce the axis symmetry mesh. For the computations, the Spalart-Allmaras turbulence model was employed. By applying total pressure and temperature inside the chamber and estimating the mass flow rate to meet the sonic flow condition at the throat, the input flow condition was produced [9-10]. Figure.3 (a) shows the velocity contour, as the concept of nozzles function; velocity gets increased at its exit as 411 m/s. Also in the nozzle, there will be temperature shock due to altitude variation. Figure. 4(b) shows the pressure contour. For the area ratio of 5.24 and for the constant γ =1.4, the inlet chamber pressure $8.33\mathrm{x}10^5$ N/m^2 is given as the boundary condition and the outlet pressure is $1.83\mathrm{x}10^4$ N/m^2. Which is closer to the calculated value. The inlet temperature is 302 K and the exit temperature is reduced to 96.5 K as shown in the Figure 2.2 (b). In the bell nozzle Mach number varies throughout the contour with reference to the velocity of the fluid and velocity of sound. Mach at exit for bell nozzle is 1 as shown in the Mach contour in Figure 4 (a).

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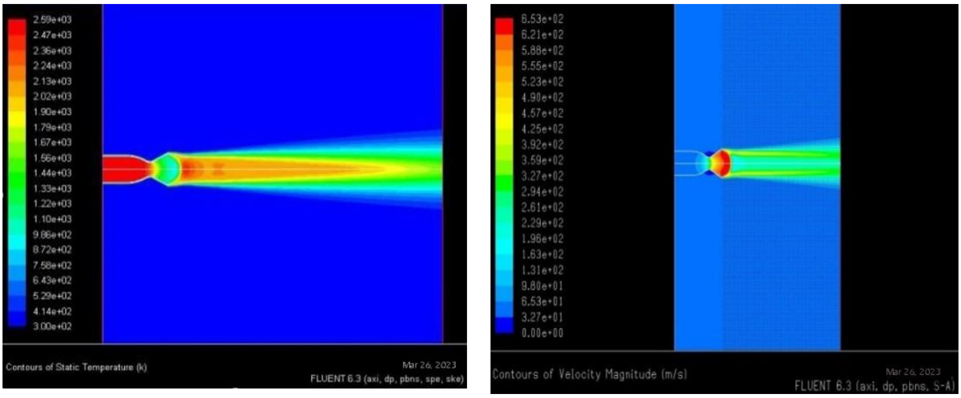

Fig. 3. (a) Velocity contour of Bell Nozzle (b) Temperature contour of Bell Nozzle

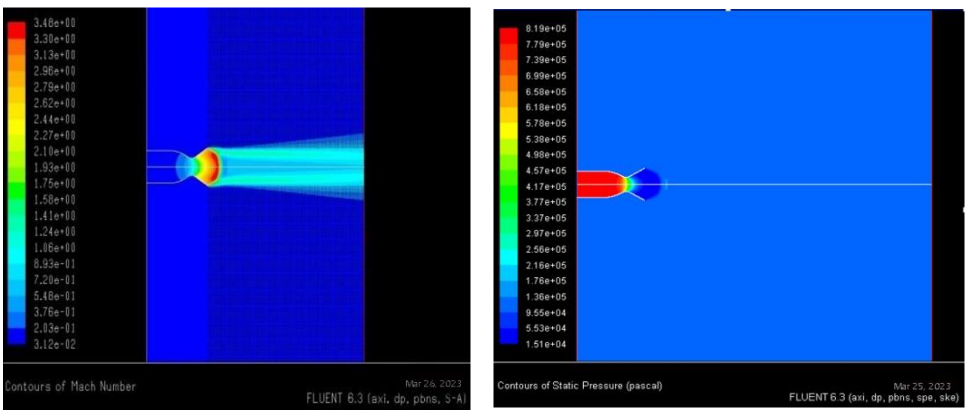

Fig. 4. (a) Mach Contour (b) Pressure contour of Bell Nozzle

3 Aerospike Nozzle Design Methodology

A rocket nozzle design that permits combustion to happen around a spike's (or center plug's) perimeter. The ambient (atmospheric) pressure then shapes and modifies the thrust-producing, hot-exhaust flow. It goes by the names plug nozzle and spike nozzle as well [14]. Using an easy approximation of Rao's method based on calculus variations, it is possible to design the contour of Aerospike Nozzle. The method to be approximated is based on the assumption that a series of hemispherical expansion waves will appear in the cowl lip of the aerospike nozzle. Using this method, the plug nozzle contour for a given expansion ratio, ε, and ratio of specific heats, γ, can be determined. Below is a brief description of the method [15].

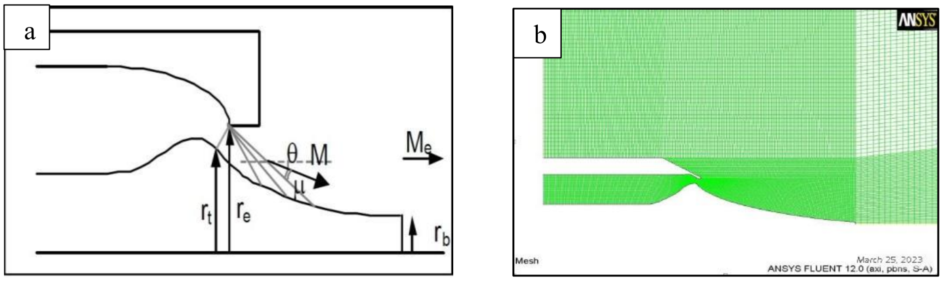

Fig. 5. (a) Plug Contour (b) Meshed Aerospike nozzle contour

For the contour design the Prandtl-Meyer function is used. The thruster angle is provided by θt = v (Me), where Me is the Mach number at the exit and n is the Prandtl-Meyer function, as the flow is assumed to be parallel to the nozzle axis at the exit.

$\nu=\sqrt{((\gamma+1)/(\gamma-1))}\tan^{-1}\sqrt{((\gamma+1)/(\gamma-1))(M^2-1)}-\tan^{-1}\sqrt{(M^2-1)}$

The throat area is $A_t=\pi(r_e^2-r^2)/\cos\theta_t=F/P_cC_F$

Exit area of the aerospike is

$A_e=\pi(r_e^2-r_b^2)$

The expansion ratio

$\varepsilon=A_e/A_t$ is given, re and rt are ascertainable for a fixed at the aerospike nozzle's radial coordinate is provided by

$X=r_e-r/\tan(\mu+\theta)$

Where $\theta=\theta_t-\nu$ and the Mach angle $\mu=\sin^{-1}(1/M)$.

3.1 Aerospike Nozzle Flow Characteristics

This section deals with the computation of the flow over the truncated aerospike nozzles designed in the previous section of the static test as a first step toward validation of the power on CFD. The next step would be to perform similar calculations at a range of flow conditions by altitude, or ambient pressure, Mach number, and angle of attack. The rocket could then be launched with a number of instruments to collect test data and compare the calculations.

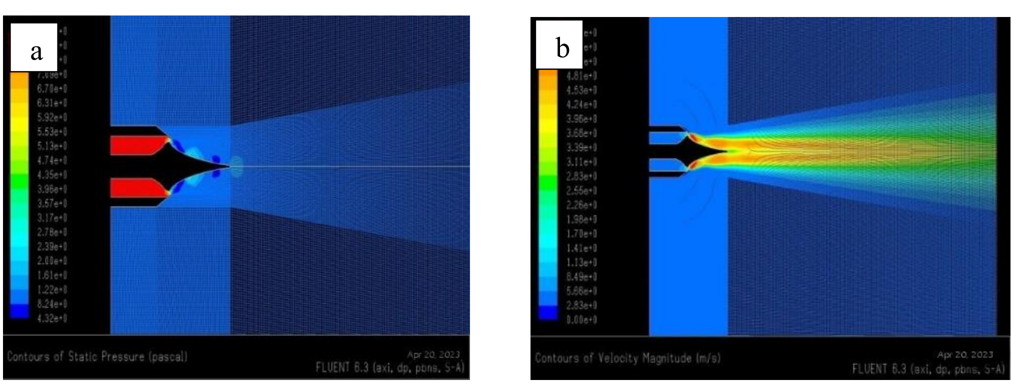

Fig. 6. (a) Pressure Contour of Aerospike Nozzle (b) Velocity contour of Aerospike Nozzle

Figure.6. (a) shows the pressure of the aerospike nozzle the exit pressure is $1.22\text{x}10^4$ N/m^2. The conventional one is not capable of receiving shocks, in particular weak ones, it will be able to do so. The velocity at exit is increased as expected, it is 566 m/s. The aerospike engine has, as expected, no divergence losses at design pressure altitudes. In addition, the viscous losses for annular aerospike engines are less than those of an equivalent bell shape nozzle due to its smaller diameter. Mach number at the throat of the plug is 1 and it's shown in the mach contour Fig 7 (a).Temperature Contour is shown in the Fig 7 (b) and the outlet temperature is 148.8 k.

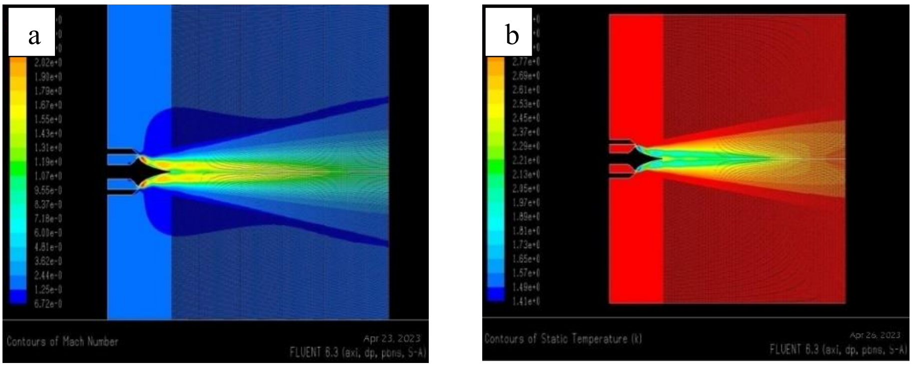

Fig. 7. (a) Mach Number Contour (b) Temperature contour of Aerospike Nozzle

Table 2. Performance Comparison of Bell and Aerospike Nozzle

	Bell Nozzle		**Aerospike Nozzle**
Properties at exit	**Theoretical Result**	**CFD Result**	**CFD Result**
Pressure(P_e)	1.62435 x10^4N/m^2	1.83x10^4 N/m^2	1.22 x10^4N/m^2
Temperature (T_e)	97.35 K	96.5 K	148.8 K
Velocity(C_e)	408.42 m/s	411 m/s	566 m/s
Mach Number(M_e)	3.225	3.2	2.26
Mass flow rate	9.518 kg/s	9.55 kg/s	11.77 kg/s
Efficiency	94.32%		96.26%

4 Conclusion

The design and cold flow analysis of a 7.45 kN thrust engine's bell and aerospike nozzles are presented in this paper. A complete aerospike nozzle contour is suggested, based on the calculus of variation created using the G.V.R.RAO approach. To evaluate the computational capability of current CFD tools to calculate flow over Aerospike nozzles in operating conditions, this flow shall be computed by using FLUENT software. Also, both bell and aerospike nozzle performances have been verified. In comparison to the reference bell nozzle, the aerospike nozzle performs approximately 1.9 percent better in terms of performance when analyzed using CFD for cold flow conditions, taking into account parameters like pressure, velocity, and temperature. Furthermore, the bell nozzle has an efficiency of 94.36% whereas the aerospike nozzle has an overall efficiency of 96.26%. In terms of performance, the bell nozzle is inferior to the aerospike nozzle. Aerospike nozzles may be produced and evaluated based on the comparison of theoretical and CFD values. The current study focuses on two indicators a drop in pressure and an increase in velocity that can be helpful as a basis for designing an aerospike nozzle. However, further work needs to be done to reduce the nozzle's design temperature.

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