



Design and CFD analysis of flow through C-D nozzle and Aerospike nozzle at different operating conditions

Mr. Samynathan.R

Dept of M.E - Computer aided design,
A.K.T Memorial College of engineering and technology,
Kallakurichi-620 009, Tamilnadu,
Samyn21@gmail.com

Mr. Durairaj.S

Assistant professor,
Dept of mechanical engineering,
A.K.T Memorial College of engineering and technology,
Kallakurichi-620 009, Tamilnadu.

Mr. Manikandan.M

Assistant professor,
Dept of mechanical engineering,
A.K.T Memorial College of engineering and technology,
Kallakurichi-620 009, Tamilnadu.

Mr. Balaji.E

Head of the Department,
Dept of mechanical engineering,
A.K.T Memorial College of engineering and technology,
Kallakurichi-620 009, Tamilnadu.

Abstract— For future fully reusable SSTOs and rocket engines, light weight and high performance propulsion system from low altitude to high altitude are essential. Engines with aero spike nozzles are drawing attention as promising candidates which satisfy these requirements. A renewed interest into aerospoke nozzles has surfaced for the possible replacement of standard contoured nozzles used for the propulsion systems of space vehicles. Although a more complex flow field develops on aerospoke nozzles, the potential thrust and structural gains are attractive as the propulsive flow is free to adapt to the external stream. In this paper a study on various types of C-D nozzle and aero spike nozzle is carried out. In this paper CFD analysis of flow through C-D nozzle and aerospoke nozzle is carried out at different operating condition and the performance of these two nozzles are compared. The solid modeling of C-D nozzle and aerospoke nozzle is done using CATIA V5R19 design toolkit, meshing and analysis is done using Ansys Fluent 12.0 software.

Keywords—rocket nozzles;CFD analysis;

I. DESIGN AND ANALYSIS OF C-D NOZZLE

Every supersonic wind tunnel and some rocket nozzle use converging section followed by diverging section to accelerate flow from reservoir (combustion chamber) to supersonic at exit. This nozzle configuration is called as converging-diverging (C-D) nozzle. Minimum length nozzle design is employed to design the diverging section of the C-D nozzle. Desired exit Mach number is 2, the design of nozzle wall contour for diverging section of C-D nozzle is illustrated below. Let us consider the specific problem of designing a diverging section of C-D nozzle using minimum length nozzle design to expand the flow from $M=1$ at the throat to $M=2.0$ at exit, where the flow is to be uniform and shock free. Since minimum length nozzle is to be designed, sharp cornered nozzle assumption will be made. For characteristics it can be proved that,

1. along left-running characteristic or across right-running characteristic,

$$\vartheta - \theta = \text{constant};$$

2. along right-running characteristic or across left-running characteristic,

$$\vartheta + \theta = \text{constant};$$

Where,

ϑ Is the Prandtl- Meyer function

θ Is the flow turning angle.

In the region-to-region method, flow is divided into various regions by the incident and reflected characteristics from the centerline. With the help of ϑ and θ , Mach numbers in the regions can be calculated using the above mentioned relation between ϑ and θ . The sonic line at the throat is assumed to be straight and the design is done for one-half of the nozzle, because of symmetry the other half is only the mirror image of the first.

WALL CONTOUR FOR DIVERGING SECTION OF C-D NOZZLE

Using minimum length nozzle design, wall contour of diverging section of converging-diverging nozzle is obtained and is tabulated.

TABLE I: X AND Y COORDINATES OF DIVERGING SECTION OF C-D NOZZLE.

X	Y
0	1
1.505654	1.352867
2.220435	1.495767
2.695119	1.566533
3.179689	1.622557
3.693233	1.664874
4.24809	1.692267
4.854601	1.702241

Exit Mach no	2
A_e/A^*	1.688
Throat radius	1

BOUNDARY CONDITION FOR DIVERGING SECTION OF C-D NOZZLE AT SEA LEVEL

$$P_o = 792812 \text{ Pa.}$$

$$P^* = 419477 \text{ Pa.}$$

$$P_e = 101325 \text{ Pa.}$$

$$P_a = 101325 \text{ Pa.}$$

$$\gamma = 1.4$$

MACH NUMBER VARIATION ALONG LENGTH OF DIVERGING SECTION OF C-D NOZZLE

Flow is gradually expanded from $M = 1$ at throat to $M = 2$ at exit in diverging section of converging – diverging nozzle. Gradual increase in Mach number indicates absence of shock waves inside diverging section of converging-diverging nozzle.

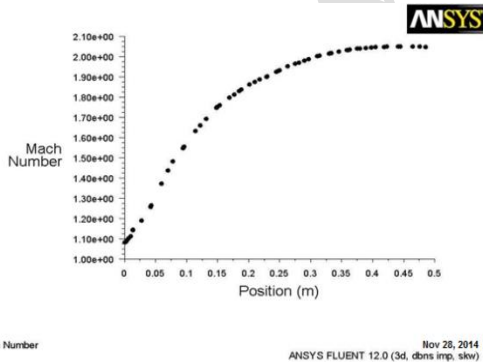


Fig 1: Mach number variation along length of diverging section of c-d nozzle

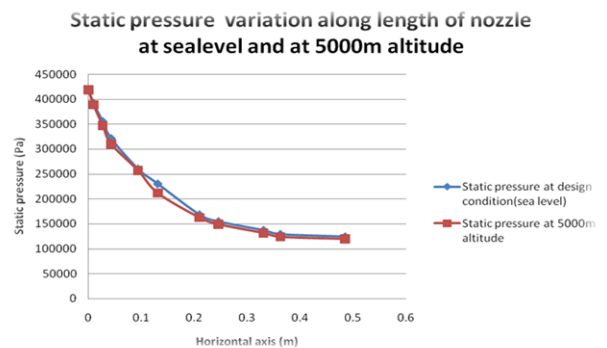


Fig 2: Static pressure variation along length of nozzle at sea level condition and 5000 m altitude

Table 2: Static pressure variation along length of nozzle at sea level condition and 5000 m altitude

Length of nozzle(m)	Static pressure at design condition(sea level) Pa	Static pressure at 5000m altitude (Pa)
0	419423	419423
0.00953	392454	389243
0.02700	355684	346794
0.04307	321476	310045
0.09381	260503	257129
0.13115	230459	211601
0.20988	168685	162383
0.24599	154842	148669
0.33103	137316	131324
0.36289	129215	123466
0.48546	104365	119112

C-D NOZZLE PERFORMANCE AT SEA LEVEL

$P_e = 104365 \text{ Pa}$

$P_a = 101325 \text{ Pa}$

$P_e = P_a$ (almost), so optimum expansion occurs at the exit of nozzle and maximum thrust is achieved.

C-D NOZZLE PERFORMANCE AT 5000m HIGH ALTITUDE

$P_e = 119112 \text{ Pa}$

$P_a = 54019 \text{ Pa}$

$P_e > P_a$, so under expansion occurs at the exit of nozzle and so nozzle efficiency of converting thermal energy into kinetic energy is reduced which results in loss of thrust.

II. DESIGN AND ANALYSIS OF AEROSPIKE NOZZLE

The spike forms one side of a virtual bell, with the other side being formed by the outside air thus the name "aerospike". The idea behind the aerospike design is that at low altitude the ambient pressure compresses the wake against the nozzle.

MESHING DETAILS

Flow domain in aerospike nozzle is split into smaller sub-domain using tetrahedral element in 3D.

Sub-domain element - Tetrahedral

Total element - 52416

Total nodes - 58674

Turbulence model – STANDARD TURBULENT MODEL

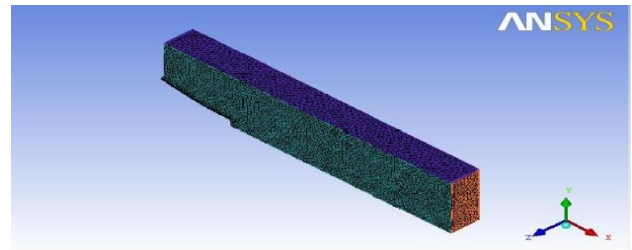


Fig 3 : Mesh model of aero spike nozzle

BOUNDARY CONDITIONS FOR AEROSPIKE NOZZLE AT SEA LEVEL

Aero spike is designed as an invert of diverging section of C-D nozzle, so boundary conditions of C-D nozzle is used for aerospike nozzle.

Design condition is sea level condition

$$P_o = 792812 \text{ Pa.}$$

$$P^* = 419477 \text{ Pa.}$$

$$P_a = \text{atmospheric pressure, Pa}$$

$$\gamma = 1.4$$

Where,

$$P_o = \text{Stagnation pressure, Pa}$$

$$P^* = \text{pressure at thruster (M = 1), Pa}$$

$$P_a = \text{atmospheric pressure, Pa}$$

$$\gamma = \text{Ratio of specific heat.}$$

At design condition and all operating conditions, the flow is directly exposed to ambient atmosphere and it expands to the external environment, so exit pressure is expected to be atmospheric pressure at all operating condition i.e. optimum expansion is expected at all operating conditions. Optimum expansion condition in aerospike nozzle exit at all operating condition can be checked only by flow analysis through aerospike nozzle at all operating condition.

MACH NUMBER CONTOUR OF AEROSPIKE NOZZLE AT SEA LEVEL

Mach number contour provides Mach number distribution through length of aerospike nozzle. Mach number contour of aerospike nozzle is displayed below.

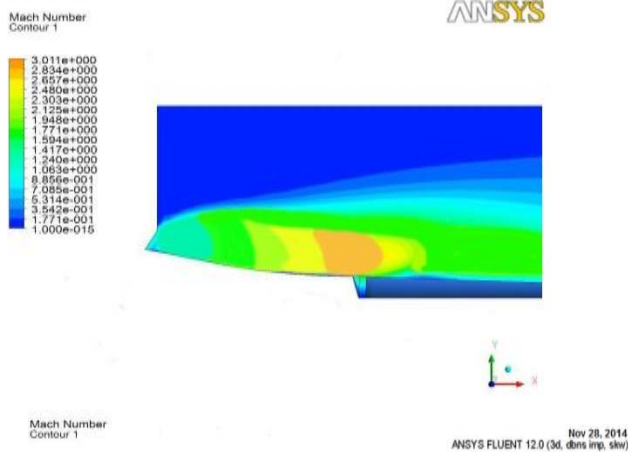


Fig 4: Mach number contour of aero spike nozzle at sea level

MACH NUMBER VARIATION ALONG LENGTH OF AEROSPIKE NOZZLE

Aerospike nozzle is designed as an invert of diverging section of C-D and same boundary conditions are used. By using inverted profile and same boundary of C-D nozzle, Mach number of about 2.7 is achieved at the exit of aerospike nozzle.

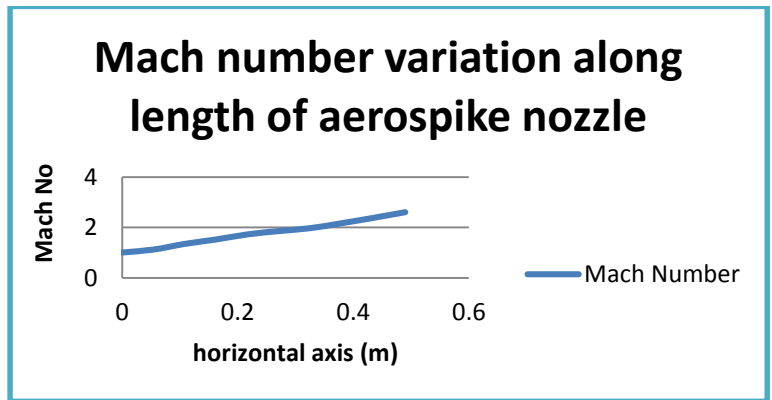


Fig 5: Mach number variation along length of aero spike nozzle at sea level.

VELOCITY VECTOR THROUGH AEROSPIKE NOZZLE AT SEA LEVEL

Velocity vector provides the direction and magnitude of velocity through aerospike nozzle. Mach no contour of aerospike nozzle provides only the distribution of mach no along length of nozzle. Uniformity of flow and flow reverse in aerospike nozzle cannot be checked through Mach no contour. Velocity vector provides magnitude and direction of flow through which flow uniformity and flow reverse can be checked.

STATIC PRESSURE VARIATION ALONG LENGTH OF AEROSPIKE NOZZLE AT DIFFERENT OPERATING CONDITIONS

Aerospike nozzle is designed for sea level condition; the static pressure at nozzle exit is almost atmospheric at sea level condition, so optimum expansion occurs at the exit of aerospike nozzle. When aerospike nozzle is analyzed at 2000m, 4000 and 5000m altitude, static pressure at the exit of aerospike nozzle is almost atmospheric pressure respectively. Static pressure variations along length of aerospike nozzle at design condition and 5000m altitude is shown below

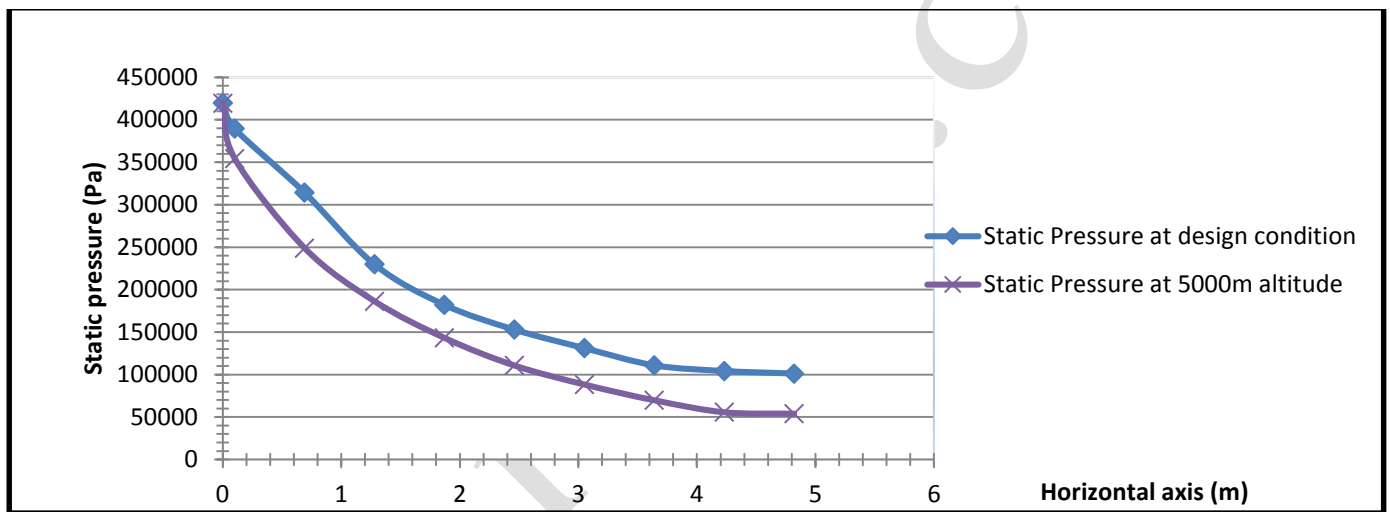


Fig 6: Static pressure variation along length of aero spike nozzle under different operating conditions

Table 3: Static pressure variation along length of aero spike nozzle under different operating conditions

X [m]	Static Pressure at design condition (Pa)	Static pressure at 5000 altitude (Pa)
4.82	101169.214	54048
4.23	104194.742	55701
3.64	110861.101	69819
3.05	131112.415	88365
2.46	152884.6	110711



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International Journal of Innovative Research in Technology, Science & Engineering (IJRTSE)
ISSN: 2395-5619, Volume – 2, Issue – 6. June 2016

1.87	182026.377	143212
1.28	229683.3	186340
0.69	314328.7	248869
0.1	389655	354379
0	419850	419416



AEROSPIKE NOZZLE PERFORMANCE AT SEA LEVEL

$$P_e = 101169 \text{ pa}$$

$$P_a = 101325 \text{ pa}$$

$P_e = P_a$ (very close), so optimum expansion occurs at the exit of nozzle and maximum thrust is achieved.

AEROSPIKE NOZZLE PERFORMANCE AT 5000m HIGH ALTITUDE

$$P_e = 54048 \text{ pa}$$

$$P_a = 54019 \text{ pa}$$

$P_e = P_a$ (very close), so optimum expansion occurs at the exit of the nozzle and maximum thrust is achieved.

III. CONCLUSION

C-D nozzle is designed for Mach number, $M=2$ at sea level condition using minimum length nozzle design. Contour of diverging section of C-D nozzle is inverted to obtain the contour of aerospike nozzle. Converging-diverging nozzle is designed for sea level condition. The Static pressure ($P_e=104365 \text{ pa}$) at nozzle exit is almost equal to the atmospheric pressure ($P_a=101325\text{pa}$) at sea level condition, so optimum expansion occurs at the exit of C-D nozzle and maximum thrust is achieved under sea level condition. At 5000m high altitude, the static pressure ($P_e = 119112 \text{ Pa}$) at nozzle exit is greater than the atmospheric pressure ($P_a=54048 \text{ Pa}$) which leads to under expansion and thrust will be greatly reduced.

Aero spike nozzle is designed from contour of diverging section of C-D nozzle, so boundary condition corresponding to C-D nozzle design at sea level condition is used for aerospike nozzle. At sea level condition, static pressure ($P_e = 101169 \text{ pa}$) at nozzle exit is very close to the atmospheric pressure ($P_a = 101325 \text{ pa}$) at sea level condition as a result optimum expansion occurs at the exit of aerospike nozzle and maximum thrust is achieved. At 5000m high altitude, the static pressure ($P_e=54048 \text{ Pa}$) at nozzle exit is very close to the atmospheric pressure ($P_a=54019 \text{ Pa}$) as a result optimum expansion will occur at the exit of the nozzle and maximum thrust is achieved. So, using aerospike nozzle in rockets and jet engines will improve the overall efficiency of the vehicle and also reduce the fuel consumption greatly.

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