Research Article

DESIGN AND THRUST/WEIGHT OPTIMIZATION OF A SUPERSONIC PLUG NOZZLE BY TRUNCATION

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ABSTRACT

The popular problem for space propulsion researchers is fuel consumption, which is associated with the weight of the vehicle, and from there, any weight gain leads to fuel gain. We studied the weight reduction of the supersonic nozzle of a space vehicle without any significant effect on the thrust. We first created the contour of theplug nozzle using the method of characteristics, According to the analysis of the pressure profile on the wall of the Plug nozzle we notice that the pressure first decreases very quickly in the initial expansion area, at the level of the col, and continuously decreases in the divergent part before it stabilizes at the tip of the nozzle, approaching the atmospheric pressure value at the outlet of the nozzle. So the last part of the divergent is substantially constant. Therefore, if truncated in this part, this does not lead to a significant decrease in the maximum thrust. In this study, we truncated an ideal supersonic plug nozzle into four different points and we have four Plug nozzles of different lengths and maximum thrust as well. We then choose the Plug nozzle which has an optimized thrust/weight ratio. Finally, we have a Plug nozzle with significant weight gain and a slight maximum thrust loss compared to the ideal plug nozzle.

Keywords: *Method of characteristics, Supersonic plug nozzle.*

1.INTRODUCTION

In this work, we will focus on the plug nozzle study. The plug nozzle is an advanced rocket nozzle that consists of a primary nozzle with a fairly conventional

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shape and a plug that allows external expansion. The main characteristics of this nozzle are its interaction with the external environment, which avoids the separation phenomenon that affects a conventional profile nozzle. These advantages derive from the generation of an expansion fan at the lip of the primary nozzle and its influence on the evolution of the pressure along the wall of the plug. The plug nozzle concept was first developed by the Germans prior to World War II for aeronautical applications. Plug nozzles have a central body in the vicinity of the neck and the process of gas expansion is directly or indirectly regulated by ambient pressure, the gas flow is regulated by detent waves from the flow deviation due to the plug surface [1]. Based on weight/push ratio considerations, the cap is generally truncated, resulting in a very complex base flow. The use of these nozzles in the past is very rare, for example the Second World War fighter aircraft named Messerschmitt Me 262 was equipped with an annular plug nozzle. For the first time in 1950 Griffith of Rolls-Royce, Ltd is proposed the concept of a plug nozzle for rocket propulsion in an American patent [2]. In 1959, Krase was the first to propose methods to designate ideal plug nozzle contours by simple approximate calculations [3]. In 1961 Berman and Cromp made studies on the modification of the end of plug and they obtained that if one uses half-cone angles at the end of the plug one has a decrease in performance of only 1% [4]. In the same year Rao discussed the use of plug contour optimization as the case in the conventional nozzle and obtained optimal contours [5]. In 1964, Angelino described an approximate method for axisymmetrical and two-dimensional plug nozzle design based on a simple technique [6]. Balasaygun studied the deference of performance between the plug nozzles and the Conventional nozzles, he obtained that the nature of the flow in the plug nozzles is auto-adjustable to allow it when operating at a pressure ratio lower than a design ratio to obtain a thrust advantage over a conventional nozzle [7]. In 1974, Johnson and al presented an optimization analysis for axial plug nozzles with variable input geometry [8]. In 1997, Rommel and al studied the development of the flow field as a function of ambient pressure variations using a computer study of a plug nozzle [9]. To minimize weight McConnaughey conducted a numerical study of a three-dimensional aerospike and concluded that a 50% truncation of the plug nozzle resulted in a 0.5% reduction in performance only [10]. In 1998, Hagemann G and al carried out a numerical study based on the method of characteristics for the flow field simulations of plug nozzles, and they discussed the flow phenomena observed in experiments and numerical simulations of different adaptive plug nozzles in altitude [11]. In 2002, Ito and Al studied flow structures and thrust performance of axisymmetric trancated plug nozzles using a numerical simulation, they obtained a high gain from the plane plug nozzle (aerospike) of about 5 to 6% compared to the axisymmetric plug nozzle and for pressure ratios greater than the design ratio the pressure distribution on the nozzle wall was not affected by the external flow [12]. Besnard and al presented the manufacture, design, and testing of a thrust engine equal to 1000 lbf of plug nozzle type, the results showed that variations in heat capacity ratio led to a difference in thrust characteristics [13]. In 2006, Zebbiche plotted the profiles of the plug nozzle on the use of the Prandtl Meyer function for several forms by changing the ratio of specific gamma heat and comparing the performance of the plug nozzle compared to an MLN nozzle. Performance is better compared to MLN [14]. In 2010, Shahrokhi and Noori used CFD to study the deferential flow properties of the Aerospike nozzle [15]. In 2012, Karthikeyan. N and Al studied the effect of plug truncation of an aerospike nozzle on acoustic behavior [16]. In 2014, Chutkey and Al conducted a numerical and experimental study on the behavior of flow fields at truncated annular plug nozzle of different lengths [17]. In 2015, Shanmuganathan and Al conducted a numerical comparative study on linear and annular plug nozzles and obtainedthat the annular nozzle was better than the linear nozzles [18]. In 2017, Kumar, N. and All compared the full length to the optimized plug nozzle models and discussed the aerospike nozzle design procedure and the parameters governing its design [19].

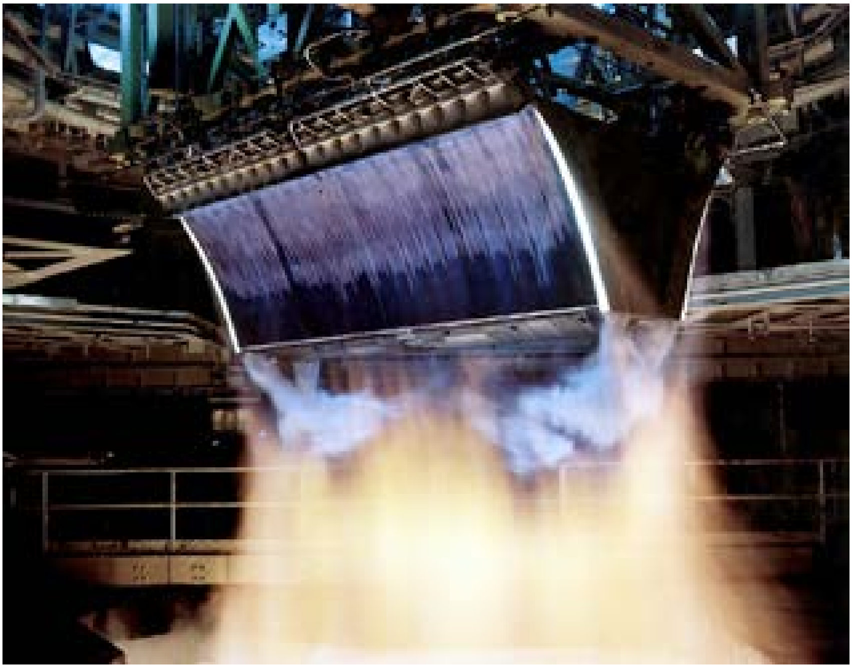

Figure1. Picture of the Plug nozzle from Wikipedia

2.THEORY

A FORTRAN program was created based on the characteristic method that was described in the reference [14]. In mathematics, the method of characteristics is a technique for solving partial differential equations. The characteristic method applied to the two-dimensional isentropic flow of an ideal gas is used for the design of supersonic nozzles which produce a uniform parallel flow at the outlet of the nozzle. The program designed the contour of the bi-dimensional supersonic plug nozzle. The design method is based on the function of Prandtl Meyer.

$$\nu(M) = \left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}} \tan^{-1}\left[\frac{\gamma-1}{\gamma+1}(M_e^{2}-1)\right]^{\frac{1}{2}} - \tan^{-1}(M_e^{2}-1)^{\frac{1}{2}} \quad (1)$$

The number of Mach M = 1.00 at the col and accelerates to the Mach number M_E at the exit section. v Is the angle between the velocity vector of the col and the x-axis. The lines shown in figure 1 represent the Mach waves, they are inclined with an angle u, and the flow properties are constant along each line of Mach exits from point A.

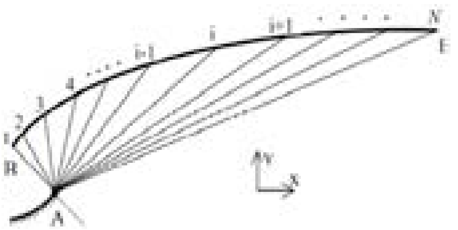

Figure 2. Discretization of the expansion zone

The main idea of this method is considered the velocity vector as the contour of the required plug wall, the latter is tangent to the current line. To have a Mach number required at the exit, the flow to the col must be tilted at an angle 0_B .

$$0_B = (M_E) \quad (2)$$

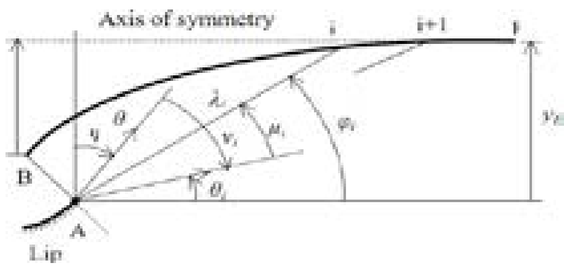

Figure 3. Parameters of an intermediate Mach

The determination of wall points is made explicitly. The lines are iso-Mach curves, so the number of Mach in the center of expansion A equals also the number of Mach on the wall. The number of Mach in point i is given by:

$$M_i = 1 + (i - 1)\left[\frac{M_E - 1}{N - 1}\right] \quad (i = 1,2,3,\dots,N) \qquad (3)$$

With N is the selected point number.
Once the number of Mach M_i in point i is known. In this case we can write:

$$u_i = \sin^{-1}\left(\frac{1}{M_i}\right) \qquad (4)$$

$$v_i = v(M_i) \qquad (5)$$

$$\theta_i = \varphi_i - u_i \qquad (6)$$

$$\frac{x_{i+1}}{\lambda_B} = \left(\frac{\lambda_{i+1}}{\lambda_B}\right)\cos\varphi_{i+1} \qquad (7)$$

$$\frac{y_{i+1}}{\lambda_B} = \left(\frac{\lambda_{i+1}}{\lambda_B}\right)\sin\varphi_{i+1} \qquad (8)$$

$$\frac{\lambda_{i+1}}{\lambda_B} = \left(\frac{\lambda_i}{\lambda_B}\right)\frac{\sin\alpha}{\sin\beta} \qquad (9)$$

$$\alpha = \pi - \varphi_i + v_E - v_i \qquad (10)$$

$$\beta = \varphi_{i+1} - v_E + v_i \qquad (11)$$

3.RESULTS AND DISCUSSION

To start the calculation of the program. Give some values among them M_E (number of Mach at the exit) and y (Adiabatic Gas Index) and N (selected point number). The outputs of this program are a set of x and y coordinates that represent the contour of the nozzle. In this study, we based on the following data :

$M_E = 2,4$

$y = 1,4$

$N = 1200000$

Figure 4 above, Illustrates the profile obtained for the plug nozzle with $M_E = 2,4$ and $y = 1,4$.All the geometric characteristics of the designed nozzle are shown in Table 1.

Table 1. Geometrical data of the plug nozzle profile

Quantities	**Values**
Throat radius yt , *m*	0,010
Nozzle length L, *m*	0,052
Nozzle area *S*, m^2	0,062
Area ratio Æt / Æe	0,420

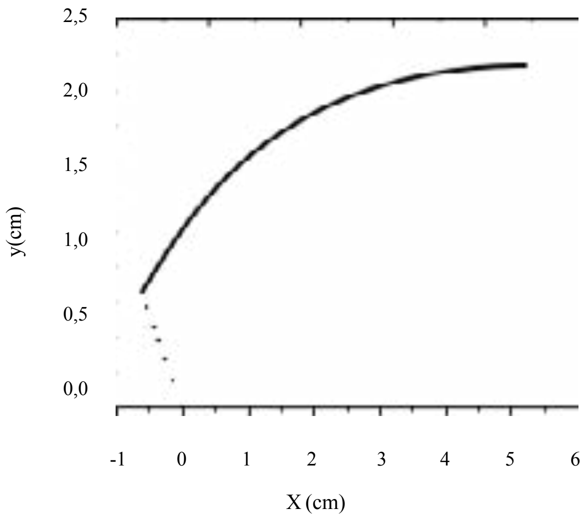

Figure 4. Shapes of the plug nozzle when $M_E = 2,4$ and $y = 1,4$

For the validation of the program, we have a numerical simulation of flows in the obtained plug nozzles achieved using the computer code ANSYS. The table 2 groups the thermodynamic data used during our calculations to draw the profile of the plug nozzle.

Table 2. Thermodynamic data of the plug nozzle profile

Quantities	**Values**
Chamber temperature T_C, *K*	300
Chamber pressure P_t, *Bars*	2,00
Design Mach number M_e	2,40
Ambient pressure $P_Æ$, *Bars*	0,14
Specific heat ratio *Y*	1,40

Figure 5 shows the Iso-Pressure contours for a plug nozzle that works in the design Mach number obtained by our simulation, the figure appears the Prandtl–Meyer expansion fan around the lip.

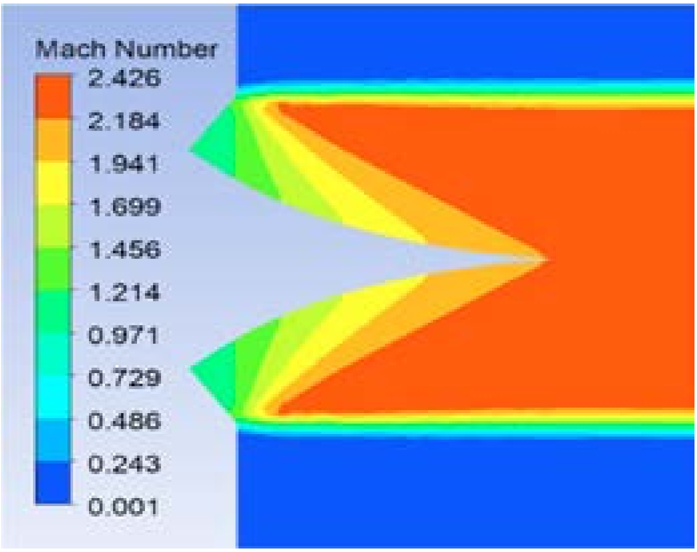

Figure 5. Iso-pressure contours

Figure 6 represents the evolution of the Mach number along the wall of the plug nozzle. We note that in the divergent part, the number of Mach increases until reaching the value of the nozzle designing Mach number at the outlet.

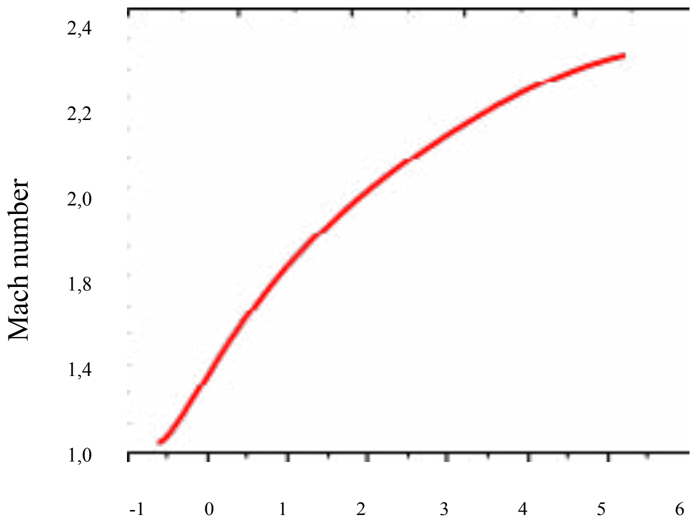

Figure 6. Wall Mach evolution

Figure 7 shows the wall static pressure obtained by the simulation for M_E = 2.4. According to the analysis of the pressure profile on the wall of the nozzle we notice that the pressure first decreases very quickly in the initial expansion area, at the level of the col, and continuously decreases in the divergent part before it stabilizes at the tip of the nozzle, approaching the atmospheric pressure value at the outlet of the nozzle. So the last part of the divergent is substantially constant. Therefore, if truncated in this part, this does not lead to a significant decrease in the maximum thrust. In this study, we truncated an ideal supersonic nozzle into four different points, as figure 8 shows.

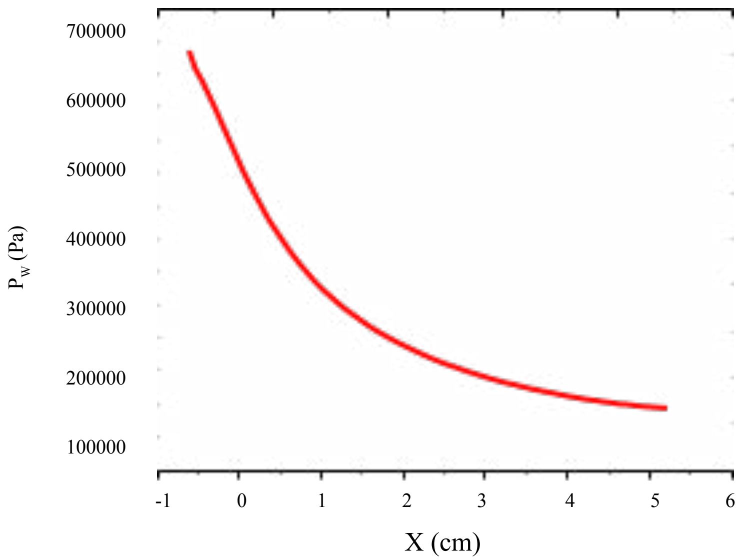

Figure 7. Wall pressure evolution

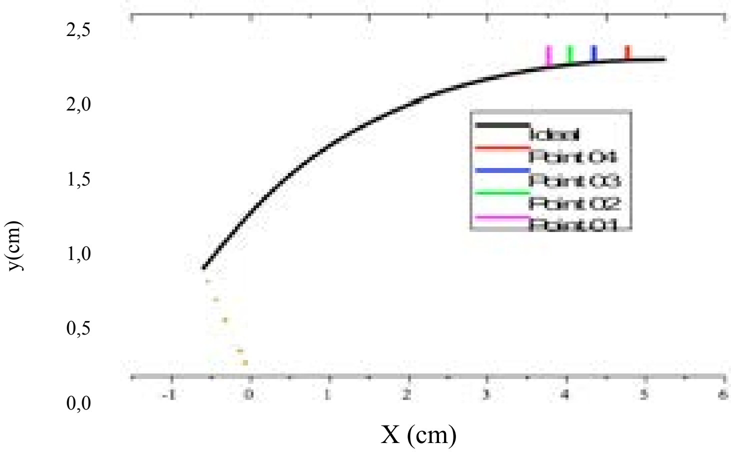

Figure 8. Truncated profil

Table 3. Truncated point

	Point 01	Point 02	Point 03	Point 04	ideal
Thrust (N)	9246,07	9328,47	9397,47	9496,21	9706,15
Mach in the exit	2,20	2,25	2,29	2,34	2,40
Length (cm)	3,77	4,05	4,35	4,78	5,24
Surface (m2)	0,0475	0,0499	0,0529	0,0572	0,0618
Loss of thrust%	4,74	3,89	3,18	2,16	/
Weightloss %	23,14	19,26	14,40	7,44	/
Thrust/ Weight	0,186	0,202	0.22	0.29	/

Table 3 summarizes the truncated nozzle performances in terms of thrust, Mach in the exit, Length, Surface, Loss of thrust, and Loss of weight for four truncation points whose abscissas are: 3,77 cm 4,05 cm 4,35 cm, and 4,78 cm respectively. It is noticed that for truncation in point 2, the thrust losses are equal to 3,89%. On the other hand, the gain concerning the Surface is about 19,26% which will affect the weight of the nozzle.

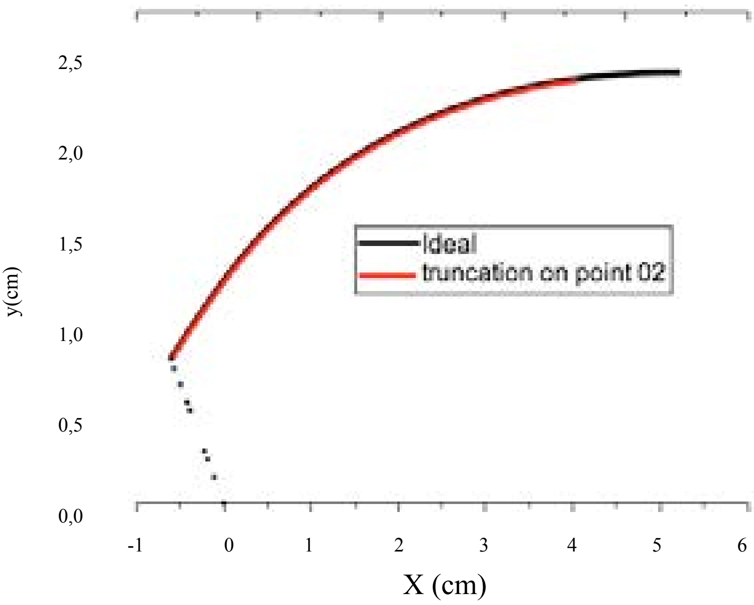

Figure 9. The difference of ideal and truncated profile

4.CONCLUSION

We do truncations on the last part of the divergent in 4 different points. After the truncation of the ideal nozzle, we calculate the thrust, the number of Mach at the Exit, the length, and the area. We use the area variable to express weight. And for the sake of comparison, we calculate the Thrust Loss, Weight Loss, and the Thrust / Weight ratio. We then choose the plug nozzle which has an optimized thrust / weight ratio. Finally, we have a plug nozzle with a weight gain equal to 19,26% and a thrust loss of only 3,89%.

REFERENCES

[1] Hagemann, G., et al., Advanced rocket nozzles. Journal of Propulsion and Power, 1998. 14(5): p. 620-634.

[2] Arnold, G.A., Jet-propulsion nozzle for use at supersonic jet velocities, 1954, Google Patents.

[3] Krase, W., Performance analysis of plug nozzles for turbojet and rocket exhausts. Vol. 79962. 1959:American Society of Mechanical Engineers.

[4] Herman, K. and F. Crimp Jr, Performance of plug-type rocket exhaust nozzles. ARS Journal, 1961. 31(1): p. 18-23.

[5] Rao, G., Spike nozzle contour for optimum thrust. Planetary and Space Science, 1961. 4: p. 92-101.

[6] ANGELINO, G., Approximate method for plug nozzle design. AIAA Journal, 1964. 2(10): p. 1834-1835.

[7] Balasaygun, E., Experimental analysis of plug nozzles. 1964.

[8] Johnson, G.R., H.D. Thompson, and J.D. Hoffman, Design of maximum thrust plug nozzles with variable inlet geometry. Computers & Fluids, 1974. 2(2): p. 173-190.

[9] Rommel, T., et al., Plug nozzle flowfield analysis. Journal of Propulsion and Power, 1997. 13(5): p. 629-634.

[10] Ruf, J. and P. McConaughey. A numerical analysis of a three dimensional aerospike. in 33rd JointPropulsion Conference and Exhibit. 1997.

[11] Hagemann, G., H. Immich, and M. Terhardt. Flow phenomena in advanced rocket nozzles-the plug nozzle.in 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 1998

[12] Ito, T., K. Fujii, and A.K. Hayashi, Computations of axisymmetric plug-nozzle flowfields: Flow structures and thrust performance. Journal of Propulsion and Power, 2002. 18(2): p. 254-260.

[13] Besnard, E., et al. Design, manufacturing and test of a plug nozzle rocket engine. in 38thAIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2002.

[14] Zebbiche, T. Supersonic plug nozzle design. in 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2005.

[15] Shahrokhi, A. and S. Noori. Survey of the central plug shape of the aerospike nozzle. in 17th AustralasianFluid Mechanics Conference, Auckland, New Zealand. 2010.

[16] Karthikeyan, N., et al., Effect of spike truncation on the acoustic behavior of annular aerospike nozzles. AIAA Journal, 2013. 51(9): p. 2168-2182.

[17] Chutkey, K., B. Vasudevan, and N. Balakrishnan, Analysis of annular plug nozzle flowfield. Journal ofspacecraft and rockets, 2014. 51(2): p. 478-490.

[18] Shanmuganathan, V., et al., Comparative study on performance of linear and annular aero-spike nozzles. Aust J Basic Appl Sci, 2015. 9(11): p. 883-892.

[19] Kumar, K.N., et al. Design and Optimization of Aerospike nozzle using CFD. in IOP Conference Series: Materials Science and Engineering. 2017. IOP Publishing.