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Original Article

Analysis and Design of Plug Shape of an Aerospike Nozzle

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Abstract. The present work investigates the influence of gas at high temperature on the design and analysis of two-dimensional plug nozzle. The thermochemical and combustion studies of liquid launchers propellants make it possible to choose the gases to be studied. For example, four cases of bi-propellants engines have been studied. The combinations studied are: H_2/O_2, $RP1/O_2$, CH_4/O_2 et MMH/N_2O_4. The selected gas are: CO_2, H_2O H_2, N_2 and CO. Once the profile is generated, an analysis of the thermodynamic-parameters evolution (such as: length, Mach number, mass, thrust coefficient) and aerodynamic performances is conducted. Some results were presented and compared with previous research using air. The comparison shows that the presence of H_2O and CO2 gases considerably increases the performance of nozzles. The percentage of gases in the combustion has an influence on these increases. In order to minimize the weight of this nozzle, the truncation of Plug nozzle in order to increase their performances is studied in this research.

Keywords: rocket propulsion, high temperature, Prandtl-Meyer function, aerospike nozzle

1. Introduction

An aerospace vehicle is accelerated by a propulsion system to a velocity dictated by requirements specific to the vehicle's mission. However, it should be noted that one of the most basic requirements in the design loop of an actual rocket nozzle is to minimize weight. For this, it is advisable to control the length and / or the surface of the nozzle [1]. Unlike conventional bell-shaped nozzles, which operate optimally at one particular altitude, plug nozzles (Aerospike) allow the flow expansion to self-adjust, thus improving thrust coefficients. This improvement over conventional bell-shaped nozzles occurs at altitudes lower than the design altitude. At altitudes higher than the design altitude, plug nozzles essentially operate similarly to bell nozzles. The plug nozzle rocket engine was once a candidate for the space shuttle propulsion. A lot of investigation on aerospike nozzle has been carried by researchers. The activities concerned include contour design and its performance [2-7] and numerical simulations [8-9]. The previous contributions cited above were realized in the case of a perfect gas (PG) where to specific heat to constant pressure CP and specific heat ratio γ are constant. In reality, these two parameters vary with the temperature [10]. The researchers have developed a new mathematical model that takes account of this temperature. The study is done at high temperature, lower than the dissociation threshold of the molecules. The variation of the specific heats with the temperature is considered. The new model allows making corrections to the perfect gas model designed for low stagnation temperature and low Mach number.

For a chemical rocket, the working fluid of exhaust gases is produced by active combustion of propellant (oxidizer/fuel) [12-14]. In this context, the study of the combustion of liquid propellants, gives us information necessary for the choice of gases for this study. The combustion of the following propellant combinations was studied: hydrogen/oxygen, methane/oxygen, RP.1/oxygen and monomethyl hydrazine/nitrogen tetroxide. The gases which have the highest percentages are respectively: H_2O, CO_2, H_2, CO and N_2. In the present study, is to develop a numerical program (Fortran language) for studying the effect of these gases (H_2O, CO_2, H_2, CO and N_2) on the performance of the two-dimensional plug nozzle, using the length, the exit Mach number, the mass and the thrust coefficient parameters.

2. Design method of the two-dimensional plug nozzle

In this section, we will present the method of designing at high temperature of the center body of the two-dimensional plug nozzle (Aerospike). In this nozzle, the flow is uniform and parallel to the exit section [16-17]. Two nozzle forms exist for this type of nozzle as shown in Fig. 1. The first type is called a plug nozzle (Fig. 1 (a)), while the second type is called the expansion-deflexion nozzle (Fig. 1 (b)). The design method is the same for both types of nozzles. The difference between this nozzle and bell-shaped is that the flow at the throat is titled of an angle θ* compared to the horizontal as indicates in Fig. 1, which is not the case for the others models where the flow is horizontal at the throat. Consequently, the lip is inclined at an angle Ψ relative to the vertical as shown in Fig. 2. To obtain the geometric shape of the central body, the stream line determined by calculation is replaced by a rigid surface limiting the flow field, and consequently the central body shape is obtained.

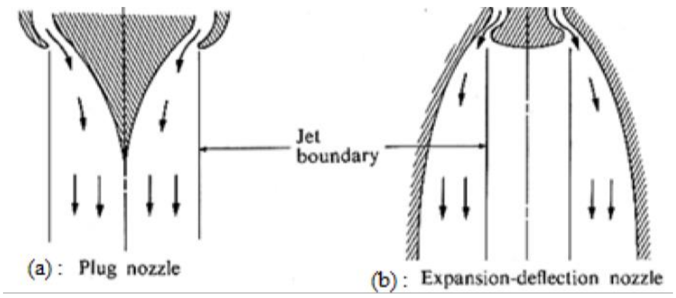

Figure 1. Type of plug nozzle geometry

The plug shape of the two-dimensional plug nozzle accelerates the flow of Mach number M=1.00 at the throat to a Mach number M = ME at the exit section of the nozzle. The flow through the central body straightens from the angle θ=θ* at the throat to the angle θ=0 at the exit section. The ratio of the critical sections remains valid in our high temperature model in order to compare the numerical calculations with those of the theory.

$$\frac{A_E}{A_*} = \mathrm{Exp}\left(\int_{T_S}^{T_*} C_p(T)\left[\frac{1}{a^2(T)} - \frac{1}{2H(T)}\right] dT\right) \tag{1}$$

The search for the central body shape for a perfect gas at high temperature is based on the Prandtl-Meyer expansion presented by the following equation: [11,15,17]

$$\nu(T) = \int_{T}^{T_*} -\frac{Cp(T)}{2\,H(T)}\sqrt{\frac{2\,H(T)}{a^2(T)} - 1}\; dT \tag{2}$$

In Fig. 2, the lines AB and AS respectively present the Mach waves of the throat and the exit section. These lines are inclined to the angles μB and μE given respectively by μB=90° and μE=arcsin [1/ME] < 90°. Between these two Mach lines, there is an infinity of centred divergent Mach waves exists from point A of the lip. Each line gives a Mach number, which we can easily from this number deduct a point of the plug shape. We can easily determine those of the next point until we reach the exit section point.

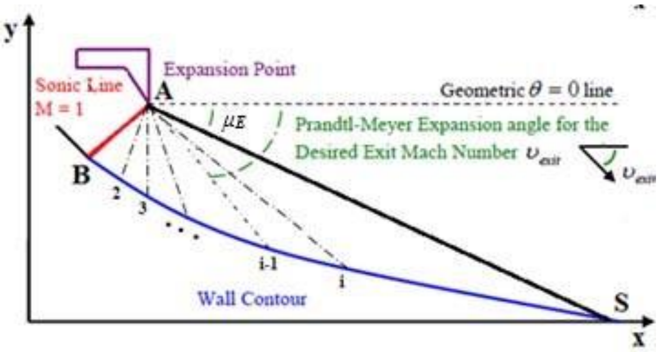

Figure 2. Generic geometry of a 2D plug Nozzle

To have a good presentation of the plug shape; the number N of the Mach waves must be large. If we know the position and the properties of a point on the wall, we can easily determine those of the next point until we reach the exit section point. The relationship between Mach line and flow direction is illustrated in Fig. 3.

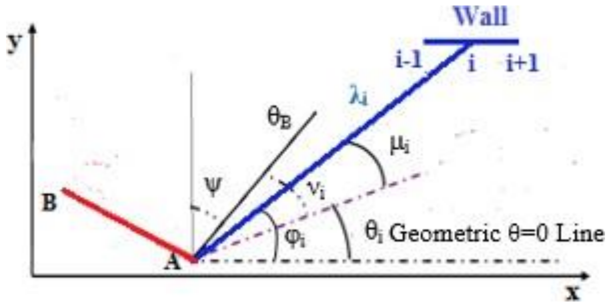

Figure 3. Geometric relationship between Mach lines and flow direction

After finding the plug shape of the nozzle, the performance of the mass of the nozzle and the thrust force exerted thereon can be calculated by the following equations:

$$\frac{Masse}{\rho_M\ t_M\ A_*} = C_{Masse} = \sum_{i=1}^{i=N-1} \sqrt{\left(\frac{x_{i+1}}{\lambda_B} - \frac{x_i}{\lambda_B}\right)^2 + \left(\frac{y_{i+1}}{\lambda_B} - \frac{y_i}{\lambda_B}\right)^2} \tag{3}$$

$$\frac{F_x}{P_0\ A_*} = C_{Force} = \sum_{i=1}^{i=N-1} \left(\frac{P}{P_0}\right)_{(i)} \left[\frac{y_{i+1}}{\lambda_B} - \frac{y_i}{\lambda_B}\right] \tag{4}$$

Where CF is the thrust force coefficient.

CMass is the mass of the nozzle in non-dimensionnal value with the following nomenclature:

A	=	Section area (m^2)
A	=	Coefficient of the specific heat at constant pressure function
C_F	=	Thrust coefficient
C_{Mass}	=	Coefficient of the mass of the structure
C_P	=	Specific heat at constant pressure ($J.Kg^{-1}.K^{-1}$)
F	=	Force exerted on the internal wall of the nozzle (N)
H	=	Enthalpy (KJ)
HT	=	Abbreviation for high temperature
L	=	Length of the nozzle (m)
M	=	Mach number

Mass	=	Mass through the nozzle normalized by (ρ_M t_M) (m^2)
N	=	Number of the discretization points.
P	=	Pressure (bar)
PG	=	Abbreviation for Perfect Gas
R	=	Thermodynamic constant of gas
T	=	Temperature (K)
X_{plug}	=	Distance between the exit section and the lip
x	=	Abscissa of a section in the nozzle
y	=	Radius of a section in the nozzle
γ	=	Specific heats ratio
ρ	=	Density (Kg/m^3)
ψ	=	Deviation of the Lip compared to the vertical
θ	=	Flow angle deviation (rad)
μ	=	Mach angle
φ	=	Polar angle of a Mach wave
λ	=	Polar ray of a Mach wave
ν	=	Prandtl Meyer angle
ε	=	Tolerance of calculation (desired precision)
0	=	Stagnation condition (combustion chamber)
*	=	Critical condition
S	=	Supersonic section
E	=	Exit section
M	=	Material
i	=	Nodes

3. Study of combustion for bi-propellant

The objectives here are to determine the theoretical combustion temperature and the theoretical composition of the resulting reaction products. The first principle concerns the conservation of energy. The heat created by the combustion is equal to the heat necessary to raise the resulting gases adiabatically to their final combustion temperature. The heat of reaction of the combustion Δr H has to equal the enthalpy change ΔH of the gases.

$$\Delta_r H = \sum_1^n n_j \int_{T_{ref}}^{T_1} C_p dT = \sum_1^n n_j \Delta h_j \Big|_{T_{ref}}^{T_1} \qquad (5)$$

Where ΔHr was the energy difference between the reactants and products under standard conditions (kJ).

The second principle is the conservation of mass. The mass of any of the atomic species present in the reactants before the chemical reaction must be equal to the mass of the same species in the products. The combustion of the following propellant combinations was studied: hydrogen/oxygen, kerosene/oxygen, methane/oxygen and mono-methyl hydrazine/Nitrogen tetroxide. The following four (04) chemical reactions were considered as follow:

- Liquid hydrogen (H_2) and liquid oxygen (O_2)

$$2\alpha H_2+O_2 \rightarrow n_{H_2O}H_2O+n_{H_2}H_2+n_{O_2}O_2+n_OO+n_HH+n_{OH}OH \tag{6}$$

- Kerosene (CnHm) and liquid oxygen (O2)

$$\alpha C_nH_m+O_2 \rightarrow n_{CO_2}CO_2+n_{H_2O}H_2O+n_{O_2}O_2+n_{CO}CO++n_{OH}OH$$
$$+n_{H_2}H_2+n_OO+n_HH \tag{7}$$

- Methane liquid (CH4) and liquid oxygen (O2)

$$\alpha CH_4+2O_2 \rightarrow n_{CO_2}CO_2+n_{H_2O}H_2O+n_{O_2}O_2+n_{CO}CO++n_{OH}OH$$
$$+n_{H_2}H_2+n_OO+n_HH \tag{8}$$

- Mono-methyl hydrazine (MMH) and nitrogen tetroxide (N2O4)

$$2\alpha CH_3\text{-}NH\text{-}NH_2+5N_2O_4 \rightarrow n_{CO_2}CO_2+n_{H_2O}H_2O+n_{O_2}O_2$$
$$+n_{N_2}N_2+n_{NO}NO+n_{CO}CO+n_{OH}OH+n_{H_2}H_2+n_OO+n_HH+n_NN \tag{9}$$

A practical calculation is made on the following engines: Ariane-5 first stage (Vulcain 2), Energia stage engine (RD-170), Falcon 9 upper engine (Raptor) and Ariane-5 upper stage engine (Aestus). Table 1 shows the characteristics of each engine used for this study.

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

	Fuel	Oxidizer	Mixture ratio	Chamber pressure (bar)	Nozzle area ratio
VULCAIN 2	H_2(L)	O_2(L)	6.1	115	58.5
AESTUS	MMH	N_2O_4	2.05	10.0	83.17
RD-170	RP-1	O_2(L)	2.6	245	36.87
RAPTOR	CH_4(L)	O_2(L)	3.8	250	150

The method used for the determination of combustion products and flame temperature basse on the bisection and Lieberstein's numerical methods, the inputs of calculation are the reactants temperature, combustion pressure and mixture ratio by mass (mass oxidizer/mass fuel). Using the bisection method, we suppose a large temperature range [1000,6000], where the flame temperature is inside the selected range. Then, we subdivide the interval until obtaining the flame temperature which verifies the energy equation with a good precision. After determination of the flame temperature and number of moles of the products, the molecular mass (M) and politropic parameter (γ) of the combustion products can be calculated. Fig. 5 gives the combustion products at the exhaust of the four engines.

After calculating the molar fractions for each product from the four combinations (oxidizer / fuel), choosing those most responsive. Then find the shape of the two-dimensional plug nozzle for each selected gas. In order to have the contours, all the thermodynamic properties of these gases must be known. We are mainly interested in the variation of the specific heat at constant pressure CP(T) and the thermodynamic constant of gases γ(T). Our calculation program requires us to have analytical forms for the CP(T) function of each gas [18]. The CP interpolation function chosen in this study is given in the following equation:

$$CP(T)=a1+T(a2T(a3+T(a4+T(a5+T(a6+T(a7+T(a8+T(a9+T(a10))))))))) \tag{9}$$

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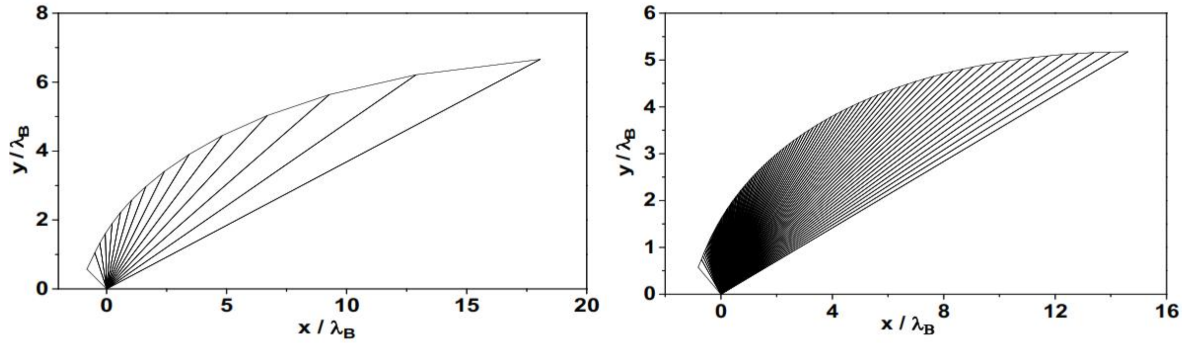
4. Results and comments

Fig. 4 illustrates an example of mesh with the two-dimensional plug nozzle at high- temperature for an exit Mach number ME = 3.00 and T0 = 2000 K. The application is for air. One large mesh and the fine other mesh are shown in Fig. 4(a-b). The convergence of the design results depends on the mesh considered for the calculation. A fine mesh gives good results.

The convergence of the results is ensured when AE/A* computed numerically by the relation (1) according to the chosen mesh converges to the theoretical value. The other parameters θ*, M*, L/λB, CMass, CF and the shape of the nozzle also converge towards the exact solution, as on Fig. 5.



(a) : Large mesh (N=15) (b) : Fine mesh (N=99)

Figure 4. Contour nozzle and mesh of the nozzle for ME=3.00 and T0=2000 K

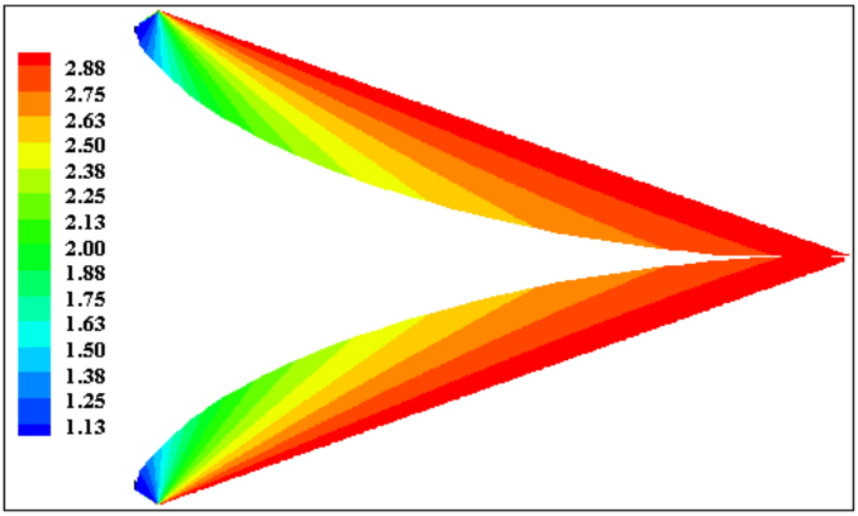


Figure 5. Profile and mesh of the nozzle for ME=3.00 and T0=2000 K

Fig. 6 gives the results the combustion products at the exhaust of the four engines. According to Fig. 6, H_2O, CO_2, H_2, CO and N_2 gases are chosen which are the most dominant in the combinations (oxidizer/fuel). Then determine and compare the shapes and performances of the two-dimensional nozzle plug nozzles for each gas. The results were compared with numerical databases of previous research using air [15].

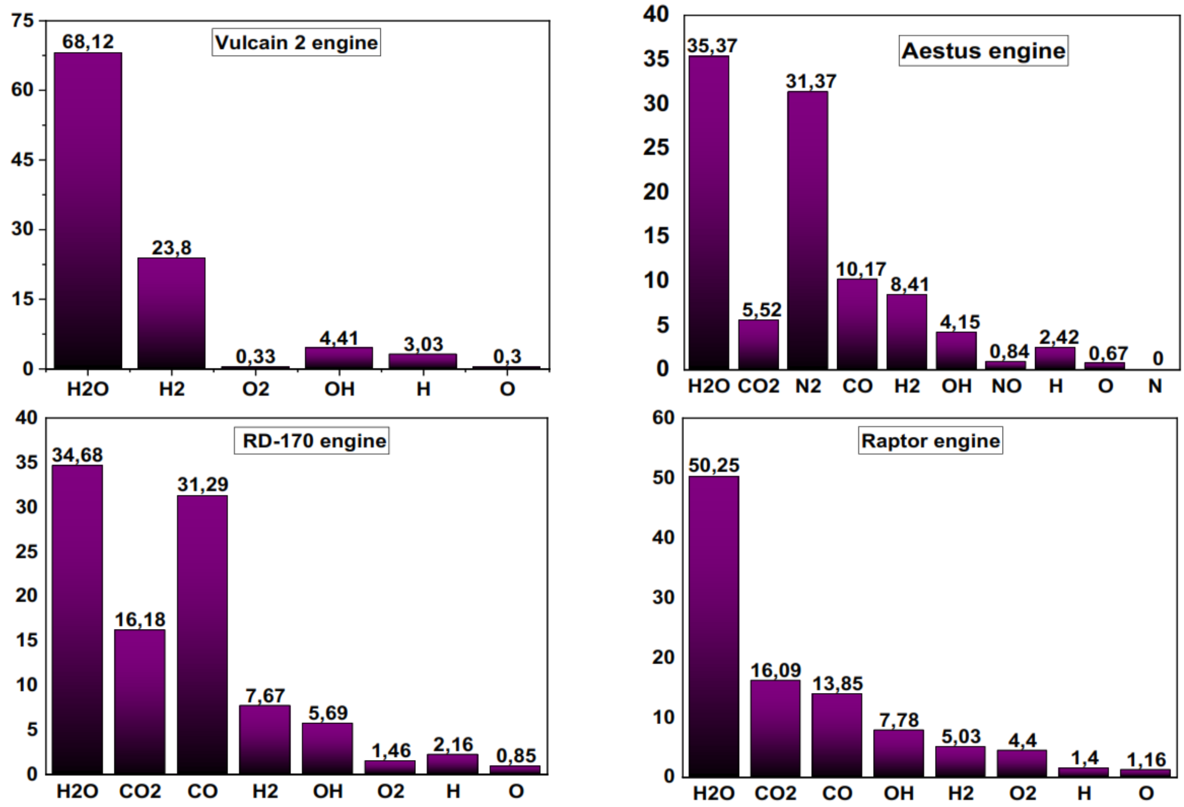


Figure 6. Examples of combustion products (%) of the various engines

In order to shown the influence of the stagnation temperature T0 on the parameters design of the plug shape for the selected gases, an error analysis is established with respect to those of the air as shown in Table 2. From the numerical results obtained, the difference between contours is negligible for the gases H_2, CO and N_2, with deviations not exceeding 8%. On the other hand, the difference of the plug shape corresponding to H_2O and CO_2 gas is very large, compared to that of air. The error is of the order of 20% to more than 53% depending on the temperature T0. These errors are due to variations in the function γ(T) for each gas. It is shown, therefore, that the profiles of the diatomic gas nozzles are almost identical with those of the air, which is also a 99% diatomic gas. However, the contour of the triatomic gases is very different from that of the air. Another important result is the non-influence of the molar mass on the nozzles design, since all of the chosen gases have different molar masses.

Table 2. Dimensional values of the 2D plug nozzles for ME=3.00

	T_0=1000 K		T_0=2000 K		T_0=3000 K	
	L/λ_B	y_E/λ_B	L/λ_B	y_E/λ_B	L/λ_B	y_E/λ_B
Air	13.62	4.54	15.18	5.08	15.81	5.30
H_2O	16.21	5.44	19.49	6.58	21.27	7.21
ε (%)	19.02	19.82	28.39	29.53	34.54	36.04
CO_2	20.64	6.99	22.86	7.77	23.49	7.99
ε (%)	51.54	53.97	50.59	52.95	48.58	50.76
H_2	13.03	4.34	13.89	4.64	15.08	5.05
ε (%)	-4.33	-4.41	-8.50	-8.66	-4.62	-4.72
CO/N_2	13.50	4.50	15.05	5.04	15.75	5.28
ε (%)	-0.88	-0.88	-0.86	-0.79	-0.34	-0.38

Figs. 7-10 show the shape of the two-dimensional plug nozzles rocket engine for the following gases: air, H_2O, CO_2, H_2, CO and N_2, calculated at ME=2.00, 3.00, 4.00 and 5.00 for T0=2000 K. These figures show that the volume and the mass of the nozzle increase with the exit Mach number ME. For example, for ME=2.00, the plug shapes for the gases (H_2, CO, N_2) are almost the same as those of air, while for the other two gases (H_2O, CO_2), the difference is a little greater. In the range of ME from 3.00 to 5.00, the nozzle shape design considered with H2 gas is very small, but with (CO, N_2) are almost identical to that of air. On the other hand, the difference becomes pronounced for H_2O - CO_2 and increases considerably with the increase of ME.

It appears that for an exit Mach number ME of less than 2.00, the difference of the results among the different gases is generally small and the variation for all parameters does not exceed 5%, which gives the possibility of choosing only one of the following gases: air, H_2O, CO_2, H_2, CO and N_2 for the design of two-dimensional plug nozzle rocket engine.

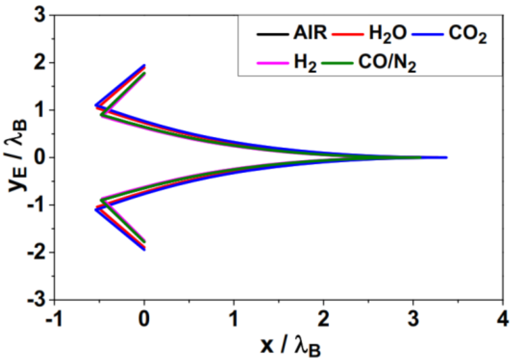


Figure 7. Gas effect on the plug shape giving ME=2.00 and T0=2000 K

Table 3. Numerical Values of the 2D plug nozzle for ME=2.00 and T0=2000 K

	y_E/λ_B	x_B/λ_B	y_B/λ_B	L/λ_B	C_{Mass}	C_F
Air	1.78	-0.479	0.878	3.557	7.437	0.330
H_2O	1.89	-0.523	0.852	3.802	8.012	0.390
CO_2	1.94	-0.540	0.841	3.907	8.261	0.417
H_2	1.75	-0.468	0.884	3.495	7.292	0.314
CO/N_2	1.78	-0.479	0.878	3.556	7.434	0.330

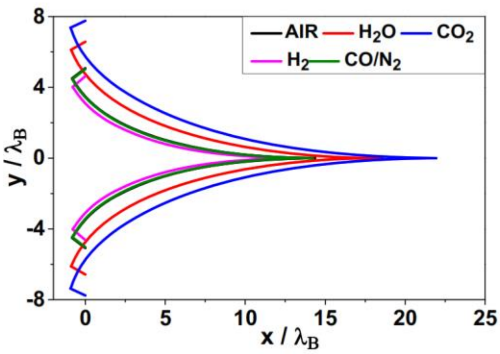


Figure 8. Gas effect on the plug shape giving ME=3.00 and T0=2000 K

Table 4. Numerical Values of the 2D plug nozzle for ME=3.00 and T0=2000 K

	y_E/λ_B	x_B/λ_B	y_B/λ_B	L/λ_B	C_{Mass}	C_F
Air	5.08	-0.819	0.574	15.184	32.793	0.882
H_2O	6.58	-0.888	0.459	19.489	42.562	1.100
CO_2	7.77	-0.922	0.388	22.856	50.202	1.239
H_2	4.64	-0.792	0.610	13.893	29.881	0.811
CO/N_2	5.04	-0.817	0.577	15.050	32.491	0.876

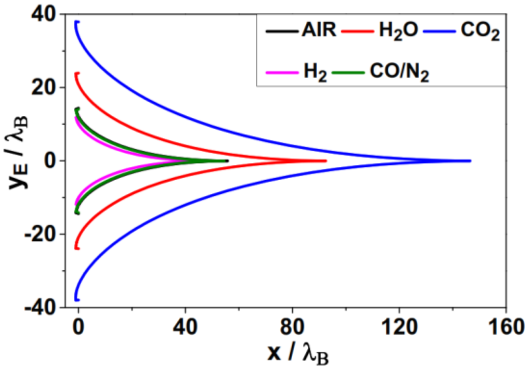


Figure 9. Gas effect on the plug shape giving ME=5.00 and T0=2000 K

Table 5. Numerical Values of the 2D plug nozzle for ME=4.00 and T0=2000 K

	y_E/λ_B	x_B/λ_B	y_B/λ_B	L/λ_B	C_{Mass}	C_F
Air	14.42	-0.954	0.299	56.720	120.98	1.327
H_2O	23.94	-0.995	0.096	93.474	200.27	1.690
CO_2	37.91	-0.998	-0.067	147.43	316.30	1.966
H_2	12.19	-0.932	0.362	48.080	102.34	1.211
CO/N_2	14.09	-0.952	0.306	55.430	118.20	1.313

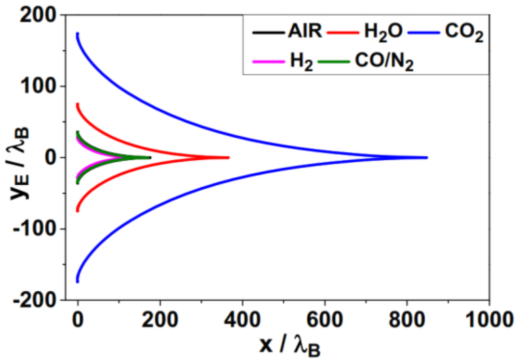


Figure 10. Gas effect on the plug shape giving ME=5.00 and T0=2000 K

Table 6. Numerical Values of the 2D plug nozzle for ME=5.00 and T0=2000 K

	y_E/λ_B	x_B/λ_B	y_B/λ_B	L/λ_B	C_{Mass}	C_F
Air	35.93	-0.995	0.100	176.62	370.15	1.635
H_2O	74.88	-0.988	-0.156	366.41	768.50	2.091
CO_2	173.76	-0.920	-0.393	848.19	1777.0	2.543
H_2	29.34	-0.985	0.175	144.43	302.47	1.502
CO/N_2	34.84	-0.994	0.110	171.26	358.90	1.618

In plug nozzles, the wall section is substantially constant and therefore it contributes only a few percent to the total thrust. For reasons of optimization, these nozzles must be truncated in order to increase their performance. One of the main advantages of plug nozzles is that their performance is not dramatically changed if the plug is truncated at even a small fraction of its length. Indeed, the ending part of the plug (like in the case of conventional nozzles) is fairly flat and its contribution to thrust is a small fraction of the overall nozzle thrust, as the force acting on the plug wall is nearly perpendicular to nozzle axis.

Fig. 11 shows the coefficient of the mass gain and the loss of thrust coefficient calculated by the computation code from a two-dimensional plug nozzle, truncated to any section from the exit section

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to the throat. Table 7 summarizes the performance of the truncated nozzles at the cross sections between 0% and 50% with respect to the length of the nozzle (L/λB).

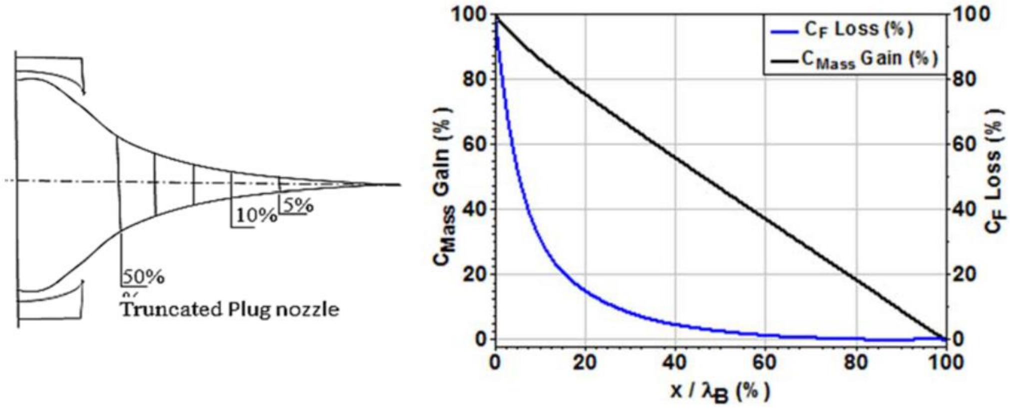

Figure 11. Representation of the gain in mass and the CF loss of a truncated 2D Plug nozzle for ME =3.00 and T0=2000 K

Table 2. Design Values of the truncated 2D Plug nozzle for ME=3.00 and T0=2000 K

Truncated Nozzle at (%)	L/λ_B	C_{Mass}	C_F	Gain % (Mass)	Loss % (C_F)
0	15.18	32.793	0.88211	0.00	0.000
5	14.42	31.579	0.88203	3.70	0.009
10	13.66	29.860	0.88162	8.95	0.056
20	12.14	26.753	0.87977	18.42	0.265
30	10.63	24.031	0.87658	26.72	0.627
40	9.11	20.904	0.87025	36.26	1.345
50	7.59	17.653	0.85908	46.17	2.611

5. Conclusions

The present work concerns the design and analysis at high temperature of the profiles of the two-dimensional plug rocket engine nozzle for different gases, as well as with the study of flow parameters (i.e.: pressure, mass, length, mass, and coefficient of thrust). The combustion of the following bi-propellant combinations was studied: hydrogen / oxygen, RP-1 / oxygen, mono-methyl hydrazine / nitrogen tetroxide and methane / oxygen. We conclude that the gases chosen in our study are: H_2O, CO_2, H_2, CO et N_2. Once the profile of each gas is generated, an analysis of the evolution of the thermodynamic parameters (namely length, Mach number, mass, thrust coefficient) is conducted. In this study, the effect of the stagnation temperature T0 on the values of the nozzle design parameters is presented. The numerical results obtained show that the difference between each contour is negligible for diatomic gases with deviations not exceeding 8%. On the other hand, this difference for triatomic gases becomes of the order of 20% to more than 50% depending on the temperature T0. These errors are due to variations in the function γ (T) for each gas. For reasons of optimization of the thrust/weight, the nozzles, initially too long, must be truncated. As an example, we can say that a 40% decrease in the length of the nozzle with ME=3.00 and T0=2000 K results in a gain of 36% of the mass and a loss of 1.35% of CF.

References

1. G.P. Sutton, O. Biblarz, Rocket Propulsion Elements, Seventh edition, John Wiley & Sons, New York, 2001.
2. G.V.R. Rao, Spike Nozzle Contour for Optimum Thrust, Ballistic Missile and Space Technology, Vol. 2, C.W. Morrow (Ed.), Pergamon Press, 1961.
3. G. Angelino, Approximate Method for Plug Nozzle Design, AIAA J., 2(10), 1964.

e-ISSN: 2715-6958 p-ISSN: 2721-5342

4. K. Berman, F.W. Crimp Jr., Performance of Plug-Type Rocket Exhaust Nozzles, ARS J, Jan. 1961.
5. H. Greer, Rapid Method for Plug Nozzle Design, ARS Journal, 31(4), 1961, pp. 560-561.
6. M. Onofri et al, Plug nozzles, Summary of Flow Features and Engine Performance, Paper No.02-0584, 2002.
7. Hui W. Chang, Yu Liu, Li Zi Qin, Aerospike nozzle contour design and its performance validation, Acta Astronautica 64 (2009), pp. 1264-1275.
8. Lee, C. C., S. J. Inman., Numerical analysis of plug nozzles by the Method of conventional nozzle, 11th Australian International Aerospace Congress, Melbourne, Australia, 13-17 March (2005).
9. E. Koutsavdis., G. Stuckert., A, Numerical Investigation of the Flow characteristics of Plug Nozzles using Fluent, 40th AIAA Aerospace Sciences Meeting, 2002.
10. J. D. Jr. Anderson, Fundamentals of Aerodynamics, Second edition, McGraw-Hill Book Company, New York, USA, 1988.
11. T. Zebbiche, Z. Youbi, Effect of stagnation temperature on the supersonic flow parameters with application for air in nozzles, The Aeronautical Journal, 111(115), 2007, pp. 31–40.
12. T. Edwards, Liquid Fuels and Propellants for Aerospace Propulsion, 1903 - 2003, Journal of Propulsion and Power, 19(6), 2003, pp. 1089-1105.
13. R. Amri, T. Rezoug, Numerical Study of liquid propellants combustion for space applications, Acta Astronautica, 69 (2011), 485-498.
14. D.K. Huzel, D.H. Huang, Modern Engineering for Design of Liquid-Propellant Rocket Engines, Progress in Astronautics and Aeronautics, Vol. 147, AIAA, 1992.
15. T. Zebbiche, Z. Youbi, Effect of Stagnation Temperature on the Supersonic Two- Dimensional Plug Nozzle Conception. Application for Air. Chinese Journal of Aeronautics, Volume 20(1), 2007, pp. 15-28.
16. J. D. Jr. Anderson, Modern Compressible Flow With Historical Perspective, Second edition, McGraw-Hill Book Company, New York, USA, 1982.
17. M. Boun-Jad, T. Zebbiche, A. Allali, High temperature gas effect on the prandtl-Meyer function with application for supersonic nozzle design, Mechanics & Industry, 18(2), 2017.
18. D.D. Esch, A. Siripong, R.W. Pike, NASA Technical Report on the thermodynamic properties in polymonial form for carbon hydrogen nitrogen and oxygen systems, Louisiana, USA, November 1970