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Thermodynamic Analysis of a Jet Engine Using a Liquid Propellant

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Abstract: Combustion-chamber is a critical component of the propulsion engine, which is widely used in the space industry and aeronautics. The goal of this article is to perform a numerical-analysis on the combustion process using a liquid-type propellant. The steps that must be followed until total combustion is achieved are emphasized. It concerns the fuel feeding phase, its injection and the combustion operation. The amount of combustion products and the energy generated are evaluated. It has been shown that the liquid propellant may present an efficient alternative fuel than the kerosene. In addition, the temperature of combustion does not exceed a certain limit to avoid structural problems in the chamber. The parametric survey allowed determining the range of the most influence factors, including the pressure, mixture richness, velocity and flow rates of injection for the fuel and oxidizer. The number and type of injectors revealed a considerable influence on the velocity and flow rates of injection. To maximize thrust force and system

propulsion, a careful selection of chamber material and ignition methods is required. A thorough inspection on the issues of walls cooling showed the necessary survey of maximum temperatures that may be reached during the combustion. Finally, an investigation of the thermal exchange through the walls will be very interesting.

Keywords: Numerical simulation; complex engineering phenomena, combustion process; propulsion engine; liquid propellant.

1 Introduction

In the last decades, the significant changes were introduced in the ‘space’ area, and competitive commercial solution of engines were launched. Various issues remain a challenge to be addressed: maintaining of highly efficient materials and control of the development costs. This needs the best product quality and high level of knowledge level about the efficacy of materials [1,2].

Until present, various investigations have been made on combustion phenomena under high pressure mixing conditions. A theoretical formulation based on thermodynamic laws was applied to assess the propulsive efficiency of jet engines. It concerns combining the momentum balance and the analysis of fluid flows [1-3]. Arntz et al. [4] and Turan et al. [5] developed a methodology formulation based on exergy to inspect the efficiency of aircraft. Identical formulation was presented by Bastani et al. [6].

In other hand, Patrício et al. [7] used the thermodynamic laws to examine the behavior of jet engines. Fursh et al. [8] looked at the combustion chamber in tiny jet-engines that produce less than 1000 N of thrust. The liquid-type propellant rocket techniques have recently gotten a lot of attention. The pressure inside the chamber has been augmented to meet the requirements of efficiency and compactness [9-11]. Neill et al. [9] showed some liquid propellants used in this field.

They claimed that the liquid methane and liquid oxygen propulsion is far more cost-effective than the present booster and in-space propellant combinations. For a small turbojet engine, Schrötter et al. [12] used a thermographic camera to conduct their analysis. They determined the temperature in different nodes of the engine.

The combustion of liquid propellants in a propulsion engine is numerically inspected. The fuel injection and the combustion operation are well detailed. The chemical affinity technique allows solving such a complicated phenomenon after some iterations. The composition of the combustion products is also determined.

2 Details on the Combustion

Several aspects may characterize the combustion phenomenon, depending on the thermodynamic conditions. A very slow oxidation may cause the beginning of combustion. Then, the oxidation becomes active under certain conditions of temperature, pressure and mixture. At this condition, the combustion is the auto-ignition. To generate auto-ignition, a kinetic source of a spark plug was used in this study.

2.1 Thermodynamic Details

Depending on the temperature of the reaction, the chemicals created by combustion that results from the reaction between fuels and oxygen are water, carbon dioxide, and other elements. This reaction is expressed chemically as:

The dissociation of products that happens during the combustion at significant temperature is given as:

The equilibrium coefficients are utilized to determine the rate of dissociation as:

$$k_1(T) = \frac{[CO][O_2]^{1/2}}{[CO_2]} \quad (7)$$

$$K_2(T) = \frac{[H_2][CO_2]^{1/2}}{[H_2O]} \quad (8)$$

$$K_3(T) = \frac{[H_2]^{1/2}[OH]}{[H_2O]} \quad (9)$$

$$K_4(T) = \frac{[H]^2}{[H_2]} \quad (10)$$

$$K_5(T) = \frac{[O]^2}{[O_2]} \quad (11)$$

The concentrations depend mainly on the number of moles and the pressure. The reactions (2-6) are endothermic, because the temperature of combustion is higher than that of the equilibrium.

Using the principle of energy conservation allows:

$$(\Delta H)_{T_f} = \int_{T_i}^{T_f} C_{p_{produit}} dT \quad (12)$$

The temperature of combustion may be obtained by solving the above-mentioned equations.

2.2 Details on the Kinetics

2.2.1 Reaction Mechanism

The reaction is typically carried out with more than 2 or 3 molecules at the same time and in separate steps, which is the reaction mechanism. For the combustion, stable molecules are formed at the end of this mechanism. The permanent production of free radicals allows obtaining a characteristic chain, transforming thus a significant amount of matters to radicals [13]. Chemically efficient radicals can greatly speed up the reaction, and its velocity can increase (theoretically) until it explodes.

2.2.2 The quickness of Reaction

Changes in concentrations vs. temperature can be used to determine the reaction speed (VR):

$$V_R = -\frac{d[B]}{dt \cdot P} = \frac{1}{n} \frac{d[C]}{dt \cdot P} \quad (13)$$

where n is a coefficient indicating that from a single molecule of fuel, n CO_2 molecules are produced.

The reaction velocity is defined as follows [14,15]:

i) Phase of Extension

The next relation may be utilized to express the speed of reaction in the prolongation phase:

or:

$$V_P = \frac{R}{P} \cdot \alpha \cdot Z \quad (14)$$

with:

$$\alpha = \frac{R_1}{R} \cdot \frac{A}{P} \cdot \exp\left[\frac{-E_p}{RT}\right] \cdot f \quad (15)$$

ii) Phase of Ramification Phase

For this step, the speed of reaction is given as:

$$V_R = Z \cdot \frac{R}{P} \cdot \delta' \quad (16)$$

where

$$\delta' = \frac{R_1}{R} \cdot \frac{A}{P} \cdot \exp\left(\frac{-E_r}{RT}\right) \cdot f \quad (16\text{bis})$$

iii) Phase of Homogeneous Rupture

During rupture step, the speed of burning is defined as:

$$V_t = Z \cdot \beta_g \cdot \frac{R}{P} = Z \cdot F \cdot \frac{R^2}{P^2} \quad (17)$$

with:

$$\beta_g = F \cdot \frac{R}{P} = \frac{R}{P} \cdot \frac{R_1}{R} \cdot \frac{R_2}{R} \cdot \text{EXP}\left(\frac{-E_t}{RT}\right) \cdot f \quad (17\text{bis})$$

The exponential term in the Eqs. (17) and (17bis) is significantly essential, because it presents the impact of temperature on the velocity.

2.3 Radiation and Dissociation Phenomena

The temperature of generated gases during the combustion may exceed 2,000 K. In this situation, it is necessary to consider the impact of molecules dissociation, which induces species such as CO, O, H, H₂, etc. The present investigation aims to compute the details of these species for the case of oxy-gen-kerosene. The radiation will be considered at significant temperatures of combustion, which means that the process is not adiabatic.

3 Details on the Method

Generally, many compounds are formed at elevated temperatures of the operation. Their characterization needs to solve a complicated system with nonlinear equations. Besides, the precision and computational time are the main difficulties encountered during the determination of the gas components composition. Among the different techniques in this area, the equilibrium constants approach is the most utilized.

3.1 The Mixture's Composition

The composition of the mixture is determined by defining m atoms and picking n , which results in an equation with $n - m$ degrees. To obtain satisfactory reliability in computed temperatures of the mixture combustion, it is required to take into account the number of products (about ten) [14,16].

A mixture of m atoms of various species at temperature T and pressure P is considered. The n

products of reaction must be selected to evaluate the mixture composition [13,17]. The lowest free energy yields the thermodynamic equilibrium:

$$dG = V.dP - s.dT + \sum_{i=1}^n \mu_i dx_i = 0 \quad (18)$$

The molar quantity $\bar{X}$ is:

$$\bar{X} = \sum_{i=1}^n x_i \quad (19)$$

In this situation, Eq. (18) is expressed as: $m, \dots, 1-j$

$$dG = \sum_{i=1}^n \mu_i dx_i \quad (20)$$

Furthermore, the mole conservation (d_j) in each atoms ($m, \dots, 1-j$) results in m line-ar eqs:

$$dj = \sum_{i=1}^n a_{ji} dx_i \quad (j = 1, \dots, m) \quad (21)$$

Also, the next condition appears, because the number of species moles may not be negative:

$$X_i \geq 0 \quad (i = 1, \dots, N) \quad (22)$$

Many analysis approaches utilize the degree R_j of the reaction progress (laws of mass effect):

$$dr_j = \frac{dx_i}{n_{ij}} \quad (23)$$

Taking into account (n-m) reactions, Eq. (20) is now:

$$\sum \mu_i dX_i = \sum_{i=1}^n \sum_{j=1}^{n-m} \mu_i n_{ij} dr_j \quad (24)$$

Giving thus:

$$dG = \sum_{j=1}^{n-m} dr_j \left(\sum_{i=1}^n \mu_i n_{ij} \right) = 0 \quad (25)$$

The (n-m) reactions defined in Eq. (26) are sufficient for the condition in Eq. (20):

$$\sum_{i=1}^n \mu_i n_{ij} = 0 \quad (26)$$

‘n’ unknown factors X_i may be obtained when ‘m’ linear equations (21) are added. The chemical potential of perfect gases is:

$$\frac{\mu_i}{RT} = \frac{G_i(T)}{RT} + \ln(P_i) = \frac{G_i(T)}{RT} + \ln(P) + \ln\left(\frac{X_i}{X}\right) \quad (27)$$

Eq. (26) is now:

$$\sum_{i=1}^n \frac{G_i(T)}{RT} + \sum_{i=1}^n n_{ij} \ln(P_i) = 0 \quad (28)$$

When considering: $K_{pj} = \prod_{i=1}^n P_i^{n_{ij}}$ and $\Delta G_j^0(T) = \sum_{i=1}^n n_{ij} G_i^0(T)$, it gives:

$$\ln(K_{pj}) = \frac{-\Delta G_j^0(T)}{RT} \quad (29)$$

The right part of Eq. (29) is available in the thermodynamic tables.

This approach may be also utilized if one or two reactions are needed for balance. The computation of equilibrium becomes complicated and iterative when the term $\ln(X_i)$ appears in the equation of chemical potential. The ‘Equilibrium Constants Method’ is one of the oldest methods used in these situations. However, the advance in computer machines, allowed developing other methods such as BRINKLEY, WHITHE, and ALBASEE. In these numerical methods, the initial composition should be well estimated to overcome the issue of convergence [14,16,18]. In our case, the ‘Chemical Affinity Method’ was utilized, where the chemical affinity is supposed to be neglected at ‘j’ reactions [13,15].

3.2 Computational Technique

The use of a combination in terms of m species and n elements was proposed. The law of the conservation in the mass is represented as a set of m linear equations:

$$D = A^t X \quad (30)$$

The matrices [D, A, and X] have [m, m × n, and m] dimensions, respectively. Therefore, the system must contain (n-m) equations, which may be obtained by chemical affinity:

$$Y_j = \frac{-\partial G_j}{\partial r_j}, \quad j = 1, \dots, n-m \quad (31)$$

$$dG = \sum \mu_i dX_i \quad (32)$$

with:

$$\begin{aligned} \mu_i &= G_i^0(T) + RT \cdot \ln(P) + RT \cdot \ln\left(\frac{X_i}{\bar{X}}\right) \\ \bar{X} &= \sum X_i \end{aligned} \quad (32bis)$$

‘r_j’ is given as:

$$dr_j = \frac{dX_j}{n_{ij}}, \quad i = 1, n \quad j = 1, n-m \quad (33)$$

The following chemical affinity is reached by replacing Eqs. (32) and (33) in Eq. (30):

$$Y_j = -\sum_{i=1}^n \mu_i n_{ij} \quad (34)$$

The balance is performed if:

$$Y_j = 0, \quad j = 1, \dots, n-m \quad (35)$$

So, the proper equations of equilibrium must be selected. The use of atomic species can be used to characterize each component:

$$(R_0) = (A_0)(M) \Leftrightarrow R_{0i} = \sum_{j=1}^m (a_{ij})_0 M_j \quad (36a)$$

$$(R_1) = (A_1)(M) \Leftrightarrow R_{1i} = \sum_{j=1}^m (a_{ij})_1 M_j \quad (36b)$$

The mass conservation is then:

$$D = (A_0^t)(X_0) + (A_1^t)(X_1) \Leftrightarrow d_j = \sum_{i=1}^m a_{ij} X_i \quad (37)$$

The matrix (R_0) may be selected to have invertible (A_0) :

$$(R_1) = (A_1)(M) = (A_1)(A_0^{-1})(R_0) \quad (38)$$

The $(n-m)$ equations indicating the ‘no-basic bodies’ are:

$$-(R_1) + (A_1)(A_0^{-1})(R_0) = 0 \Leftrightarrow -R_{ij} + \sum_{i=1}^n n_{ij} R_{oi} \quad (39)$$

Therefore:

$$(n_{ij}) = (n) = (A_1)(A_0^{-1}) \quad (40)$$

In comparison with Eq. (39), the chemical affinity becomes:

$$(y) = (G_1) - (N)(G_0) = (G_1) - (A_1)(A_0^{-1})(G_0) \quad (41)$$

Solving the system by using this procedure allows the determination of a no-null chemical affinity:

$$D = A_0^t \cdot X_0 + A_1^t \cdot X_i \quad (42)$$

$$Y = G_1 - A_1 A_0^{-1} G_0 = 0 \quad (43)$$

X_1 is unspecified chosen. Eq. (42) allows defining X_0 , G_0 , G_1 , and Y if A_0^T is invertible and a suitable selection of basic bodies was made.

3.2.1 Solving Procedure

The determination of mixture composition was conducted according to the next steps:

1- The $[D, A_0, A_1]$ matrixes, then $[X_0$ and $X_1]$ are written with their initial values.

2- Matrix evaluation:

$$(A_0)^{-1}, (A_0^{-1})^T, (A_0) \times (A_0^{-1}), A_1^T \quad (44)$$

$$G_i^0(T)/RT \quad (45)$$

$$G_i = G_i^0(T)/RT + Ln(P/P^*) \quad (46)$$

3- Using an iterative strategy to Solve the problem.

3.2.2 Iterative Method

1. $[G_0$ and $G_i]$ are calculated after determine the n mole total-number.

2. Deducing:

$$(Y) = G_1 - (A_1)(A_0^{-1})(G_0) \quad (47)$$

3. Using the number of iteration (p) to determine the X_i mole new-number:

$$(X_1)_i^{p+1} = (X_1)_i^p \text{Exp}(-Y_i/\alpha') \quad (48)$$

4. Deducing:

$$(X_0) = (A_0^{-1})((D) - (A_1^T)(X_1)) \quad (49)$$

2 new matrices $[(X_0)$ and $(X_1)]$ are created and combined in a (X) matrix. It is essential to verify that all (X_0) matrix element are positive before passing to the next iteration. If one element is negative, the program will stop, which indicates the bad selection of bases bodies.

3.2.3 Assumptions (X_0) and (X_1)

The combustion was considered adiabatic and isobar. The generated gases were supposed perfect. A constant temperature of oxygen and fuel was set at the inlet. The pressure was considered in the whole volume of the chamber.

3.3 Flame Temperature

The temperature of combustion TB may be evaluated after determining the composition of products.

At constant pressure, an adiabatic transformation's change in enthalpy is negligible:

$$dH = d(U + PV) = dQ + PdV + d(PV) = dQ - VdP \quad (50)$$

Then, before combustion, the enthalpy of products equals that of the mixture:

$$H_b^{Tb} = H_f^{Tf} \quad (51)$$

Generally, C, H and O are supposed to be the main components of the mixture. So, the enthalpy is:

$$H_f(T) = [1014 + 6.5[(T_f/298) - 1]](T - 298) + H_f(298) \quad (52)$$

3.4 Enthalpy of Products

The values $T_R = 298.16$ K, $P_R = 1$ atm are usually utilized to evaluate the enthalpy, which is given as:

$$H_{produit}^T = \sum X_i H_i^T \quad (53)$$

Where

$$H_i^T = H_{fi}^{Tr} + \int_{Tr}^{Ti} C_{pli} dT + L_{1-2}^{Ti} + \int_{Ti}^T C_{p2i} dT + \int_{Pr}^{P0} \left(\frac{\partial H_i}{\partial P} \right) dP \quad (54)$$

The term $\left(\frac{\partial H_i}{\partial P} \right)$ is negligible, so:

$$H_i^T = H_{fi}^{Tr} + \int_{Tr}^{Ti} C_{pli} dT + L_{1-2i}^{Ti} + \int_{Ti}^T C_{p2i} dT \quad (55)$$

4 Findings and Analysis

Cylindrical chambers of combustion are generally employed in the rocket's technology. The slightly convergent chambers from the injector to the nozzle are also utilized. In our investigation, a section with

contracting rate was used.

The stable combustion requires a minimal volume of the chamber, where many factors play a major role, such as the propellant nature, injector type, and combustion pressure [19,20]. The trust efficiency may be reduced by any pressure drop in the chamber. However, this drop may be negligible at low velocities of gases speed, while it has a significant impact if the converging rate is between 3 and 7 [21-23].

4.1 Selection of the Combustion Chamber

The following criteria are verified when selecting the chamber volume:

- i) A sufficient volume must be provided to ensure a homogeneous mixture, a good vaporization, and complete combustion;
- ii) Also, an adequate injector must be selected to provide a high pressure. A highly efficient propellant is also needed; and
- iii) The extension of combustion time of combustion may be ensured through the cooling of walls by fuel or oxidizer.

4.2 Dimensions of the Chamber

This investigation aims to define the optimal volume of the chamber:

$$V = L^* . A_c \tag{56}$$

with

$$A_c = \frac{F}{\zeta_f C_F P_0} \tag{57}$$

$$\zeta_f = \frac{F_a}{F_i} \tag{58}$$

The real and theoretical thrust forces are:

$$F_a = C_F \cdot A_c \cdot P_1 \quad (59)$$

$$F_i = C \cdot \dot{m} \quad (60)$$

The velocity C is:

$$C = I_s \cdot g \quad (61)$$

and

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{P_2}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \right] + \frac{P_2 - P_1}{P_0} \cdot \frac{A_1}{A_c}} \quad (62)$$

$P_2 = P_3$ in the case of a modified nozzle:

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{P_2}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \right]} \quad (63)$$

4.3 The Chamber's Dimensions

The chamber's internal surface is:

$$A_0 = \frac{F \cdot R \cdot T_0}{V_e \cdot M \cdot P_0 \cdot V_0} \quad (64)$$

In fact, the internal velocity changes usually within the range [60-150]m/s. In our case, $V_0 = 129$ m/s was taken [21,22]. The outlet velocity, V_e is:

$$V_e = C \cdot \xi_v \quad (65)$$

The diameter of the chamber is determined as:

$$D_c = \sqrt{\frac{4.A_0}{\Pi}} \quad (66)$$

Two cases were considered: a fixed pressure and then a fixed thrust force.

4.4 Computation and Selection

4.4.1 Fluid Selection

The liquid oxygen (oxidizer) was selected due to its good properties compared with other oxidizers such as the Fluor (Table 1). We remind that the low viscosity and molar mass, and significant heat capacity are the main properties of a good propellant [21,22]. In addition, oxy-gen is highly available, easily storable and it may be utilized for the chamber cooling. Among the various available fuels (kerosene, hydrogen, liquid hydrazine, etc.), the kerosene is the best due to its availability, low cost, and satisfactory properties [14].

Table 1: Liquid oxidizer and Fluor properties (Barrere, 1972).

	Oxygen	Fluor
Boiling point [K]	90	85
Specific mass [kg/dm ³]	1.114	1.505
Viscosity	0.190	0.240
Specific heat [kg/mole]	0.406	0.367
Molar mass [g/mole]	32	38

4.4.2 Chamber Dimensioning

Two cases were treated:

i) For a fixed thrust force ($F = 500$ daN), the pressure was changed within [40-80] bar. As highlighted in Fig. 1, the diameter decreases with the rise of pressure for a given length of the chamber (L_c), for example 1 m.

ii) In the chamber, the thrust force was varied within [500-100] daN for a $P = 40$ bars fixed pressure.

For the chamber length ($L_c = 1$ m), Fig. 2 reveals clearly the proportional augmentation of the chamber diameter vs. the propulsion force, i.e., the significant push needs a wide chamber diameter.

The diameter of the chamber is within [0.6382-1.27] m for thrust forces varying between [500-1980] daN at a $P = 50$ bar pressure. However, increasing the pressure value from 2×10 to 10^2 bar requires selecting a design with a diameter ranging from 1.009 m to 0.4513 m for the same chamber.

Figure 1: Changes in the combustion pressure vs. the chamber diameter, at $L_c = 1$ m.

Figure 2: Changes in the thrust force vs. the chamber diameter and combustion pressure, at $L_c = 1$ m.

4.4.3 Process of Combustion

The kerosene reaction with liquid oxygen is:

Eq. (67) allows determining the products composition and the temperature of combustion and released energy. Table 2 summarizes the findings for 0.70 of an equivalence ratio and 60 bar of pressure.

Table 2: Composition of the combustion products at $N = 21.228010$; richness 0.7;

$$T_c = 3409.225\text{K}; P_0 = 60\text{ bar}; H_c = 6424.301\text{kcal}.$$

Element	Number of moles [moles]
CO ₂	6.387577
H ₂ O	7.288832
O ₂	3.761860
CO	2.103981
OH	1.319744
H ₂	3.317401E-01
O	3.978241E-01
H	1.637976E-01

In addition, Table 3 reveals the pressure impact on the temperature and reaction enthalpy. For a 60 bar pressure and a 0.80 richness, the following values are obtained during kerosene-oxygen combustion:

$$T_c = 3409.22\text{K}, H_c = 6424.30\text{kcal}, \gamma = 1.1872, \text{ and molar mass } M = 29.276\text{g/mole}.$$

The rise in temperature with increased chamber pressure and mixture richness is depicted in Fig. 3. The graphs show that an excessive increase in temperature can cause problems with the material chamber's resistance. Details on Gordon-Mc Bride coefficients are required for the calculation of $[S, C_p \text{ and } H]$ [24]. As indicated by Eq. (62), eight elements are induced:

CO₂, CO, H₂O, H₂, H, OH, O₂ and O.

Table 3: Pressure-impact.

P_0 [bar]	T_c [K]	H_c [Kcal]	Gamma	M
20.0	3219.024	4784.427	1.1884	29.277
25.0	3261.919	5595.483	1.1883	29.251
30.0	3299.703	6432.945	1.1884	29.222
35.0	3320.366	6161.394	1.1880	29.247
40.0	3340.997	6141.111	1.1878	29.258
45.0	3362.352	6362.143	1.1877	29.256
50.0	3377.317	6221.119	1.1874	29.271
55.0	3394.110	6340.543	1.1873	29.273
60.0	3409.225	6424.301	1.1872	29.276
65.0	3419.111	6192.229	1.1870	29.294
70.0	3431.560	6222.975	1.1869	29.299
75.0	3442.966	6233.731	1.1867	29.304
80.0	3453.458	6227.595	1.1866	29.310
85.0	3463.153	6207.490	1.1865	29.316
90.0	3475.777	6435.865	1.1865	29.310
95.0	3484.072	6387.122	1.1864	29.317
100.0	3491.809	6330.355	1.1863	29.324

Figure 3: Pressure impact on the temperature of combustion

4.4.4 Computation of the Injection

An injector with ‘3 jets in intersection’ was selected in this survey due to its effectiveness [19-21]. Three injectors of fuel ($m_1 = 3$) and six others of oxidizer ($m_2 = 6$) were utilized. A symmetric distribution

to the chamber axis must be ensure to provide satisfactory homogenization in the mixture. The injector Diameter was $D_{inj} = 1.57$ mm, the discharge coefficient $CD = 0.90$, the over-pressure bar, and the velocity of oxidizer and fuel injection was varied between 20 and 50 m/s.

The computed results of the selected injector under the abovementioned conditions are summarized in Table 4. The flow rate of fuel injection (or oxidizer) is depending on the selected ΔP and number of injectors.

Table 4: Data on the injector of fuel [$\rho_0 = 1.140 \text{ kg} \cdot \text{dm}^{-3}$; $d = 0.01570 \text{ m}$; $C_d = 0.90$]

v (m/s)	ΔP (bar)	$nq \times 10^{-4} (\text{m}^3/\text{s})$		
		n = 6	n = 7	n = 8
20.647	3.000	2.530	2.952	3.373
23.842	4.000	2.921	3.408	3.895
26.656	5.000	3.266	3.810	4.355
29.200	6.000	3.578	4.174	4.770
31.539	7.000	3.865	4.509	5.153
33.717	8.000	4.131	4.820	5.508
35.762	9.000	4.382	5.112	5.843
37.697	10.000	4.619	5.389	6.159
39.537	11.000	4.844	5.652	6.459
41.295	12.000	5.060	5.903	6.746
42.981	13.000	5.266	6.144	7.022
44.604	14.000	5.465	6.376	7.287
46.169	15.000	5.657	6.600	7.543

For instance, at $\Delta P = 10$ bar, $m_1 = 3$, $m_2 = 6$, $\rho_{\text{combustive}} = 1.14 \text{ kg/dm}^3$, and $\rho_{\text{fuel}} = 0.707 \text{ kg/dm}^3$: the speed and flow rate of oxidizer and fuel injection are ($V_{\text{iox}} = 37.697 \text{ m/s}$, $q = 4.619 \times 10^{-4} \text{ m}^3/\text{s}$), and ($V_{\text{fuel}} = 47.86 \text{ m/s}$, $q = 5.865 \times 10^{-4} \text{ m}^3/\text{s}$), respectively. In contrast, as ΔP , or the discharge coefficient, rises, the flow rate and velocity of oxidizer injection increase (Figs. 4 and 5).

Fig. 6 highlights the impact of the number of injector and ΔP on the flow rate of fuel injection. At the end, adequate conditions should be selected to ensure injection velocities of oxidizer and fuel ranging within [20-50] m/s. This range has been recommended by many authors, as given in Refs. [21-23].

Figure 4: Changes in the over pressure vs. the oxidizer injection flow rate.

Figure 5: Changes in the over pressure vs. the flow rate of the oxidizer injection.

Figure 6: Changes in the over pressure vs. the fuel injection rates at $C_d = 0.90$.

5 Conclusion

The combustion of liquid propellants in a propulsion engine was numerically inspected. The chemical affinity technique allowed solving such a complicated phenomenon after some iterations. The composition of the combustion products was also determined. It has been demonstrated that the liquid propellant could be a more effective fuel than the kerosene. Furthermore, the combustion temperature is held below a certain threshold to prevent structural issues in the chamber.

The parametric survey allowed determining the range of the most influential factors, such as pressure, mixture richness, velocity, and fuel and oxidizer injection flow rates, to be determined. The number and configuration of injectors had a significant impact on injection velocity and flow rates.

To optimize thrust force and system propulsion, a careful selection of chamber material and ignition methods is needed. A detailed examination of the cooling of the walls revealed the need for a survey of the highest temperatures that could be reached during the combustion. Finally, it will be fascinating to look at the thermal exchange through the walls.

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References

- [1] D. W. Riggins, J. Camberos and D. Moorhouse, “*Characterization of aerospace vehicle performance and mission analysis using exergy*,” Chapter 8, vol. 238, AIAA Progress in Astronautics and Aeronautics Series, *Exergy Analysis and Design Optimization for Aerospace Vehicles and Systems*, AIAA, 2011, Reston, Virginia, pp. 275-307.
- [2] C. H. Builder, “On the thermodynamic spectrum of air-breathing propulsion,” In 1st Annual Meeting, pp. 242, 1964.
- [3] D. W. Riggins, “The thermodynamic continuum of jet engine performance; The principle of lost work due to irreversibility in aerospace systems,” *International Journal of Thermodynamics*, vol. 6, no. 3, pp. 107-120, 2003.

- [4] A. Aurélien, O. Atinault and A. Merlen, "Exergy-based formulation for aircraft aeropropulsive performance assessment: Theoretical development," *AIAA Journal*, vol. 53, no. 6, pp. 1627-639, 2015.
- [5] T. Onder, "Energy and entropy analyses of an experimental turbojet engine for target drone application," *Anadolu Universitesi Bilim ve Teknoloji Dergisi A-Uygulamali Bilimler ve Muhendislik*, vol. 17, no. 5, pp. 936-952, 2016.
- [6] B. Milad, R. Jafari and H. Ghasemi, "Exergy analysis of an aircraft turbojet engine," *International Journal of Engineering Sciences & Research Technology*, vol. 4.4, pp. 380-86, 2015.
- [7] P. Patricio and J.M. Tavares, "Simple thermodynamics of jet engines," *American Journal of Physics*, vol. 78, no. 8, pp. 809-814, 2010.
- [8] F. Fuchs, V. Meidinger, N. Neuburger, T. Reiter and M. Zündel, "Challenges in designing very small jet engines - fuel distribution and atomization," In *Proc. 16th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery*, Honolulu, United States, 2016.
- [9] T. Neill, D. Judd, E. Veith and D. Rousar, "Practical uses of liquid methane in rocket engine applications," *Acta Astronautica*, vol. 65, pp. 696-705, 2009.
- [10] E. Song and J. Song, "Modeling of kerosene combustion under fuel-rich conditions," *Advances in Mechanical Engineering*, vol. 9, no. 7, pp. 1-11, 2017.
- [11] Z. Ji, J. Qin, K. Cheng, F. Guo, S. Zhang, P. Dong, "Thermodynamics analysis of a turbojet engine integrated with a fuel cell and steam injection for high-speed flight," *Energy*, vol. 185, pp. 190-201, 2019.
- [12] M. Schrötter, R. Bréda, R. Andoga, L. Fozo and M. Schreiner, "Basic thermal field analysis of a small turbo-jet engine," In *Proc. 2018 XIII. International Scientific Conference - New Trends in Aviation Development (NTAD)*, pp. 124-127, 2018. Doi:10.1109/NTAD.2018.8551643
- [13] A. V. Pandit, A. Kumar, G. S. Rao, C. Kedarnath, R. Srihari, V. V. Ranade, "Modeling of liquid propellant combustion chamber," *Chemical Engineering Journal*, vol. 207, pp. 151-166, 2012.
- [14] G. L. Borman and K. W. Ragland, *Combustion Engineering*, Edition Mc Graw Hill, New York, USA, 1998.
- [15] H. Burkhardt, M. Sippel, A. Herbertz and J. Klevanski, "Kerosene vs methane: A propellant tradeoff for reusable liquid booster stages," *Journal of Spacecraft and Rockets*, vol. 41, no. 5, pp. 762-769, 2004.
- [16] R. Borghi and M. Champion, *Modélisation et Théorie des Flammes*, Edition Technip, Paris, France, 2001.

- [17] J. J. Smith, G. Schneider, D. Suslov, M. Oswald, O. Haidn, "Steady-state high pressure LO_x/H_2 rocket engine combustion," *Aerospace Science and Technology*, vol. 11, pp. 39-47, 2007.
- [18] J.-P. Bohn, M. Blume, A. Baumgartner, A. Goanta, H. Spliethoff, "Oxyfuel combustion of lignite in a non-stoichiometric operating two burner arrangement," *Fuel*, vol. 104, pp. 398-408.
- [19] A. Goanta, V. Becher, J.-P. Bohn, S. Gleis, H. Spliethoff, "Controlled staging with non-stoichiometric burners for oxy-fuel processes - Numerical validation," in *Proc. 33rd International Technical Conference on Coal Utilization & Fuel Systems*, Clearwater, Florida, 2007.
- [20] X. Li, A. Goanta, J.-P. Bohn, M. Blume, "Study of the effects of low and high stoichiometry on the flame stabilization during oxycoal combustion with non-stoichiometric burners," in *Proc. Power Engineering and Automation Conference (PEAM)*, Wuhan, pp. 205-208, 2011.
- [21] G.C. Cheng and R. Farmer, "Real fluid modeling of multiphase flows in liquid rocket engine combustors," *Journal of Propulsion and Power*, vol. 22, no. 6, pp. 1373-1381, 2006.
- [22] W. Buschulte, "Investigation of an injector concept for throttle able high-energy rocket engines," In *Space Engineering* (pp. 286-297). Springer, Dordrecht, 1970.
- [23] J. Dardare, "Development status of the liquid oxygen-liquid hydrogen H8 propulsion system," in *Proceedings* (Vol. 12, p. 445). Japan Publications Trading Company, 1977.
- [24] B. J. McBride, "Coefficients for Calculating Thermodynamic and transport Properties of Individual Species," NASA Langley Research Center, 1993.