CONSIDERATIONS REGARDING JET ENGINE COMBUSTOR PARAMETERS

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Abstract: *The thermo-gas dynamics of fuel combustion in the combustor of aircraft engines involves thermochemical activity and combustion dynamics, but also the geometric volume of the combustion process. Research around the topic provides clues regarding the fluctuations of the combustor's performance depending on the fuels used and the kinetics of the gas mixture determined by the internal geometry of the combustor, clues that can help initiate numerical approaches regarding the optimization of the mixture and combustion temperatures. The article proposes an approach to the combustion process in jet engines both from the perspective of the fuels used and from the perspective of combustion thermo-gas dynamics through numerical analyzes designed to highlight the relevant parameters and performances of the jet engine combustor.*

Keywords: *combustion thermodynamics, combustor, GasTurb, numerical analysis.*

Nomenclature:

T_3	*inlet combustor temperature*	T_4	*inlet turbine temperature*
V_c	*combustor volume*	p_3	*inlet pressure combustor*
q_v, q_s	*thermal loading*	r	*radius*
C_3 , C_4,	*combustor speeds*	ζ_c	*burn efficiency*
α	*air exceed*	θ	*gradient heat*
Q_g	*heat of burning gases*	δ	*thermal distribution*
σ_c	*pressure loss*	*JP*	*jet petrol (JP-1, JP-4, JP-10)*
BDE	*burner design efficiency*	*BPR*	*burner pressure ratio*
TSFC	*true specific fuel consumption*	*W*	*flow gases*
P	*total pressure*	*T*	*total temperature*
ρ	*Air density*	p_{lf}	*pressure loss factor*
Q_{grr}	*heat release rate*	V_f	*fuel volume*
m	*air mass*	A_c	*max. surface section of the combustor*
k_1, k_2	*experimental factors*		

1. INTRODUCTION

This paper reveals a concept of analysis of the combustion phenomenon both through thermochemical approaches and through thermo-gas dynamic-related considerations, approaches instrumented through the use of software solutions necessary for the stages of geometric parameterization and numerical analysis. The addressed problem provides clues regarding the modification of the combustor performances depending on the fuels used and the kinetics of the mixture gases determined by the internal geometry of the combustor, clues that can initiate numerical approaches regarding the optimization of the mixture and combustion temperatures. The analytical approaches presented provide logical educational and research benchmarks using software tools based on commercial numerical codes.

The approach focuses on a comparative analysis of the combustion kinetics performances and their influence on the overall performance of the propulsion system, using a series of aviation fuels in fixed volume enclosures similar to jet engines. The analysis cases comprise numerical approaches with the GasTurb tool for the ground operation of a classic turbojet engine.

2. ABOUT COMBUSTION TERMODYNAMICS

2.1. About the combustion process. Combustion thermodynamics

An optimal process of the combustion process of a fuel in the first phase is necessary to connect it with the combustion agent (air or O_2) and in the second phase to produce the ignition. Depending on the state of aggregation of the fuel and the combustion agent, two types of combustion are distinguished: homogeneous combustion, when the two phases have the same state of aggregation, so it is characteristic of gaseous fuels (combustion takes place in volume, in the fuel mixture and oxidant) and heterogeneous combustion, when the two phases are in different states of aggregation, being characteristic of solid and liquid fuels (the combustion process takes place at the contact surface between fuel and oxidant). [1].

The burning process of any fuel is preceded by the stage called ignition. This can be achieved under the following conditions: the existence of a certain local proportion between fuel and oxidizer (stoichiometric ratio) and the existence of an energy source for heating the fuel up to its ignition temperature. The quantitative assessment of the combustion process of a fuel is carried out by calculating the combustion, which determines: the amount of air required for combustion; the amount and composition of combustion products; combustion temperature. Specialists in the field of aviation propulsion systems pay special attention to combustion management (combustion control and monitoring) by minimizing the coefficient of excess air to ensure complete combustion (α=1.15÷1.4). This coefficient is determined indirectly, using the analysis of the composition of combustion gases carried out with gas analyzers.

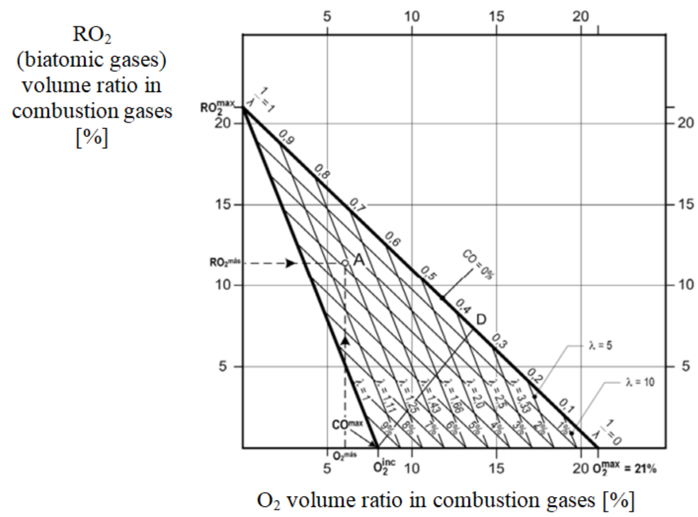

FIG. 1 Oswald diagram (combustion triangle), [2].

Combustion control is done using the Oswald diagram (combustion triangle) specific to each fuel, in Fig.1 we have the combustion triangle for solid fuel (CO_{2max}). The rapid ignition of a fuel depends on the contact surface between the fuel and the oxygen in the air; partial pressure of oxygen in air; the (auto)-ignition temperature of the fuel relative to the local one. [1].

2.2. The fundamental requirements and performances of the combustor

a. Combustor requirements

The combustor is the defined volume for managing the stoichiometric combustion process at maximum performance at a maximum mixture velocity for a combustor of minimum dimensions and mass (Fig. 2). Due to the short time in which the gases remain in the combustor, a precise control of the flame front regarding its shape and frequency is required [3, 4, 5, 6].

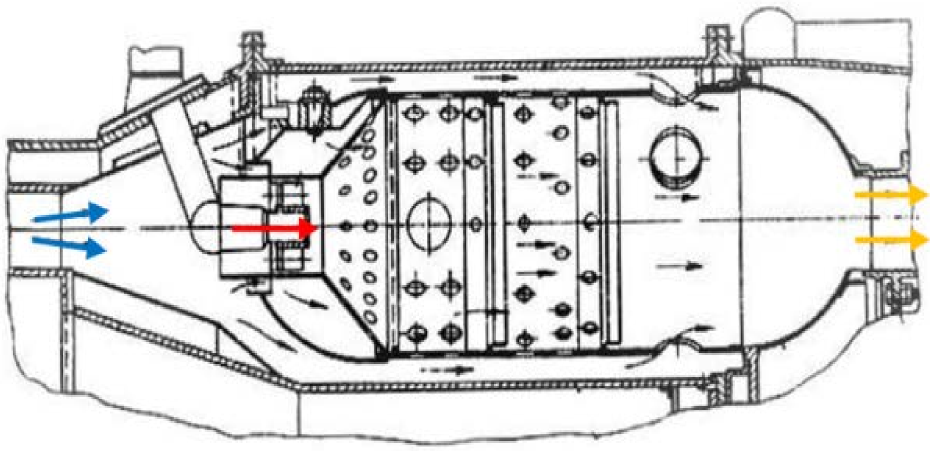

FIG. 2 The combustor. Mix gases circuit, [7].

The general requirements of the combustor are focused on simple manufacturing technology; an exploitation process at minimal costs; optimized mechanical strength and high reliability. The specific requirements of the combustor are: ensuring a stable combustion process at a maximum efficiency (0.94÷0.97), ensuring minimum pressure losses (total pressure losses max. 0.95-0.98); achieving a uniform maximum temperature distribution and uniform kinematic parameters at the turbine inlet section, defined by the degree of unevenness of the distribution $\delta<0.2$ (equation 1); a high thermal load and a high operating resource, (equations 2 and 3).

- the degree of non-uniformity of the thermal distribution:

$$\delta_c = \frac{T^*_{3max} - T^*_{3min}}{T^*_{3max}} \qquad (1)$$

- the thermal load is defined as a function of the volume of the combustion chamber (qv) or in relation to the cross section (q_s):

$$q_v = \frac{Q_g}{V_c \cdot p^*_3} \qquad (2)$$

$$q_s = \frac{Q_g}{S_c \cdot p^*_3} \qquad (3)$$

where Q_g *– heat of the combustion gases;*
V_c *– combustor volume;*
S_c *– surface of the transversal section;*
p^*_3 *– inlet gases pressure of the combustor*
for q_v=5000÷10000 kJ/m^{3}bar.

b. The basic performance of the combustion chamber

The fundamental performances of the combustor are: total pressure loss (caused by the processes of friction, heating and mixing of combustion gases), combustion efficiency, combustion stability limits, degree of fluid heating or combustion intensity, [15]:

- The loss in total pressure takes place according to the following pattern (Fig.3):

$$\sigma_c^* = f\left(C_3, C_4, \frac{T_4^*}{T_3^*}\right) \tag{4}$$

or pressure loss due to friction [15], turbulence and combustion temperature increase, is defined by PLF (pressure loss factor), has the form:

$$p_{lf} = \frac{\Delta p_o}{\frac{m^2}{2\rho_1 A_c^2}} = k_1 + k_2\left(\frac{T_4}{T_3} - 1\right) \tag{5}$$

where m-air mass
A_c *–max. section of combustor,*
C_3, C_4 *-inlet and outlet speed of the combustor,*
T_3, T_4 *–inlet and outlet temperature of the combustor,*
k_1, k_2 *– experimental factors (could and hot test process)*

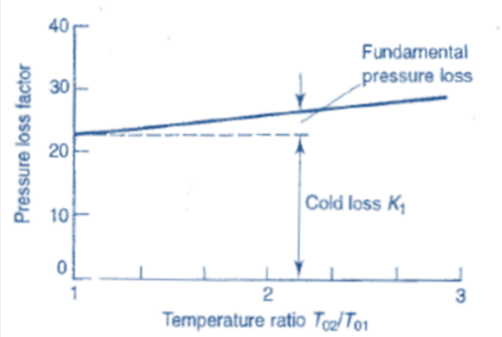

FIG. 3 Pressure loss variation, [15].

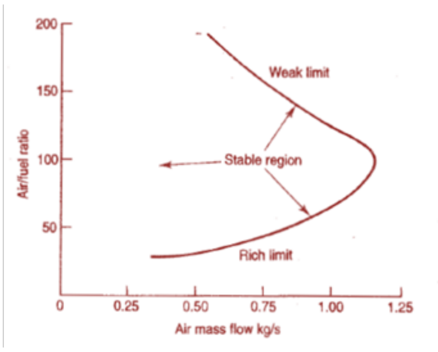

FIG. 4 Stability limtis of combustion, [15].

-combustion efficiency is a function:

$$\zeta_c = f(p_3, T_3, \alpha, C_3) \tag{6}$$

where p_3 *–pressure inlet gases of the combustor,*
α *–air exceed.*

-stability limits of combustion, see Fig. 4,

-fluid heat gradient, is a function:

$$\theta_c = f(C_3, C_4) \tag{7}$$

or combustion intensity:

$$I_c = \frac{Q_{grr}}{V_f \cdot P} \tag{8}$$

where Q_{grr}*- heat loss rate,*
Vf- fuel volume,
P-total pressure

3. METHODOLOGY AND INSTRUMENTS USED IN THE ANALYSIS

The scope of these numerical analyzes is focused on highlighting the influence of the combustion parameters on the global performance of the propulsion system and the main objective is to quantify the performance of the propellant according to the combustion parameters and the type of fuel used with the help of the GasTurb software tool, [8, 9]. The analysis methodology comprises numerical linear analyzes for a single duty cycle.

GasTurb software offers three levels of numerical analysis with varying degrees of detail: basic thermodynamic analyses, performance analyzes for the study of gas turbine cycles, and numerical analyzes for preliminary engine design.

GasTurb software offers a number of numerical analysis approaches, the most relevant are:

-*the design of the operating cycle*, which is based on a series of predefined jet engines for global performance studies or for certain constructive elements (device, intake, compressor, combustor, turbine, exhaust device), using both the parameters atmospheric (temperature T_1, pressure p_1, humidity), local operating parameters (flow rates, pressures, temperatures) as well as constructive parameters (efficiency, revolutions, angles, coefficients);

-*parametric design*, provides a complete picture of the analyzed engine design concept, by choosing two parameters (atmospheric, operational, constructive) that can generate numerical results and relevant 2D graphic diagrams;

-*parametric optimization analysis*, can be used to calculate the best duty cycle relative to certain variables and analysis limits.

-*the analysis of the influence of small effects*, is used to highlight the mutual influence of the operating parameters within the operating cycles of the analyzed aerojet engine.

-*Monte Carlo analysis*, this type of numerical simulation uses the selection of input parameters of randomly distributed cycles (with specified standard deviation), having results with Gaussian distribution.

4. ANALYSIS OF COMBUSTOR PERFORMANCES

a. Input data

The analysis is for a single operation cycle of a theoretical scenario, which uses the initial parameters from Table 1 for 7 types of fuels having the calorific values from Table 2.

Table 1.Analysis parameters

Parameter	Value	Parameter	Value
Altitude	0 m	Mach number	0
T_1 (total temperature)	280 ^oK	Ambient pressure	100 kPa
Inlet flow	32 kg/s	Pressure ratio	12
T_3 (burner exit)	1450 ^oK	Burner design efficiency	0,99
Burner pressure ratio	0,97	Burner part-load constant	1,6

Table 2. Fuels and corresponding calorific values

Fuel	Calorific value	Fuel	Calorific value
JP-4	43,323 MJ/kg	H	118,429 MJ/kg
JP-10	42,075 MJ/Kg	Diesel	42,743 MJ/kg
Bioethanol	36,000 MJ/Kg	Propane	50,000 MJ/kg
Natural gas	49,736 MJ/Kg		

b. Output data.

In the initial simulation conditions imposed on a jet engine (Tables 1 and 2) the use of the 7 types of fuels generates a series of results highlighted in figures 5÷7.

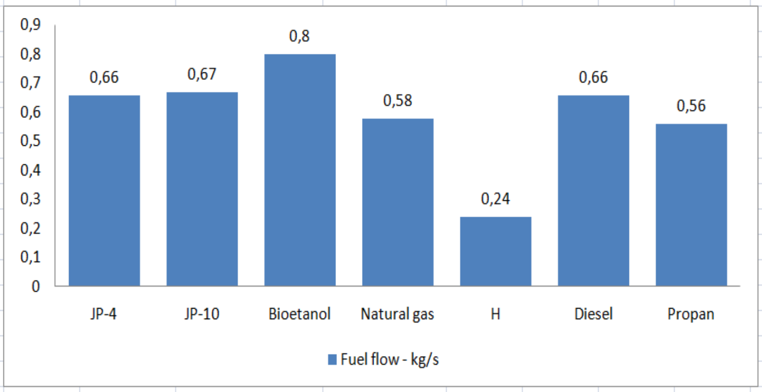

FIG. 5 Fuels flow proprieties

By using the types of fuels with the values of the flow properties in Fig. 5, the values of the nominal traction forces are according to Fig.6 and the specific consumption resulted (Fig. 7).

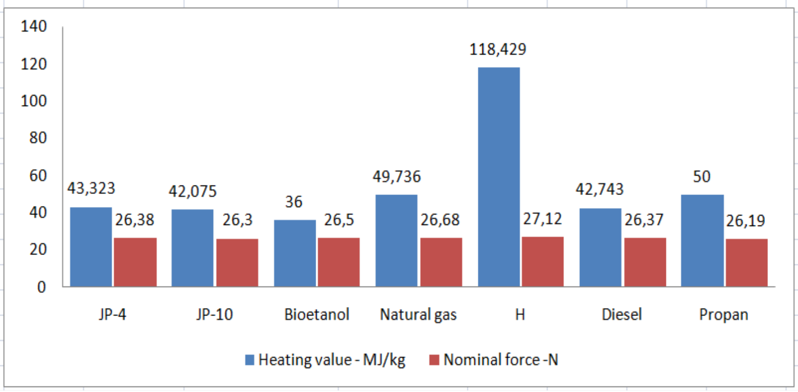

FIG. 6 Traction performance depending fuels

We observe a small value of the flow properties for hydrogen (Fig. 3) at a high value of the specific heat and the nominal traction force (Fig. 4) with a low specific consumption (Fig. 7).

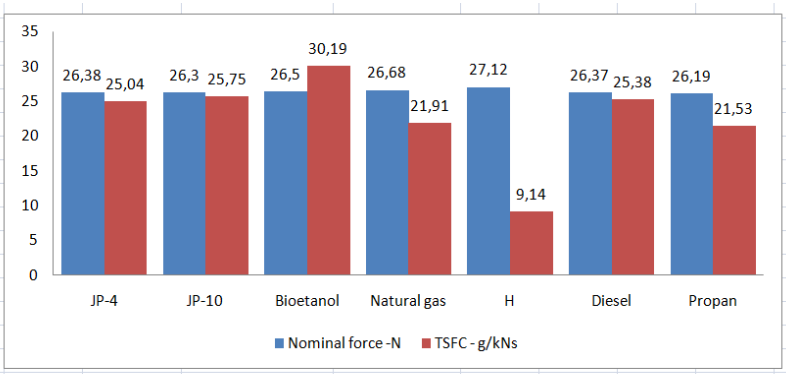

FIG. 7 Traction performance depending specific consuption

The fuel types selected for analysis generate the temperature-entropy thermodynamic diagram having similar shapes (see Fig. 8), however a comparative analysis reveals a range of refined thermo-kinetic results, with the initial analysis data recorded in Table 1. A temperature jump is observed in front of the combustion chamber inlet section (3-3.1) from 613 oK to 1450 oK (red arrow) and a slight cooling (4-4.1) in the vicinity of the outlet section (blue arrow).

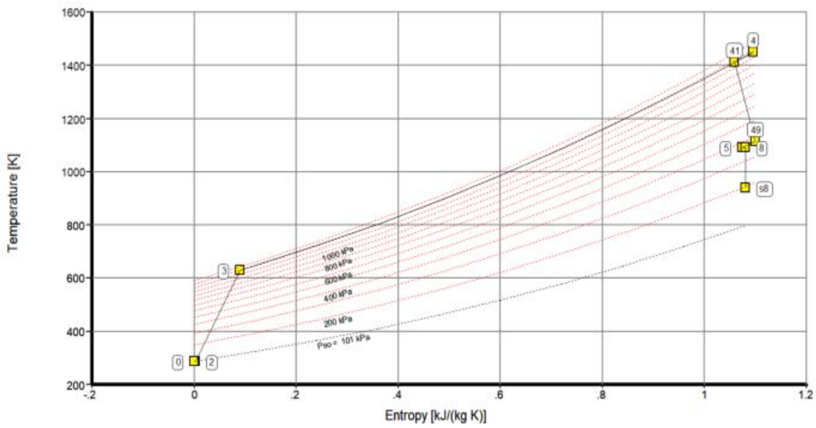

FIG. 8 Thermodynamic diagram (for JP-4 fuel)

The comparative thermo-kinetic results in the jet engine sections have the numerical values from figures 9÷11, they provide indications regarding the operation of the combustion chamber depending on the fuel used.

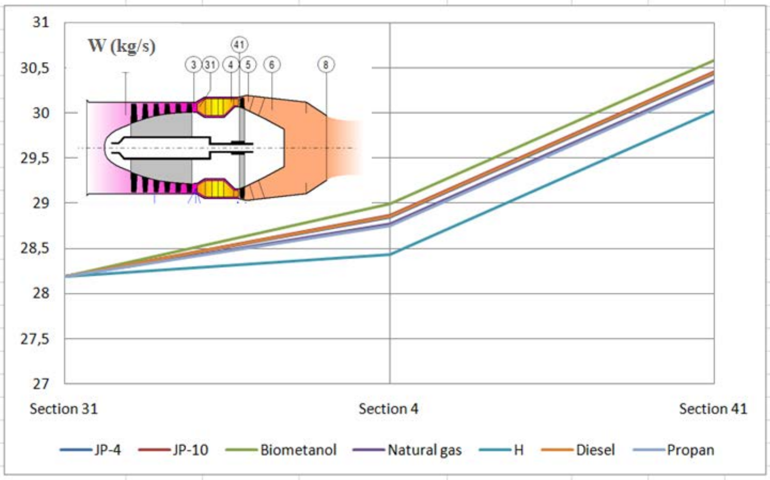

FIG. 9 Comparative diagram for flow gases W (kg/s) in combustor sections

Having identical numerical values for the gas flow at the inlet to the combustion chamber (see Fig. 9), the density and calorific values of the fuels determine different kinetic behaviors, with an increase in the flow of the fuel mixture in the various sections of the combustor, with extreme values for biofuel and hydrogen.

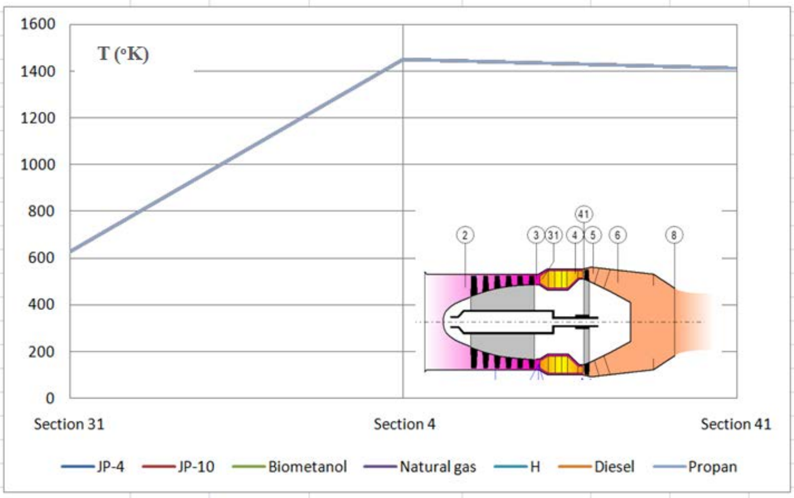

FIG. 10 Comparative diagram for the total temperature T (^{o}K) of gases in combustor sections

According to Fig. 10, the variation of the total temperature values is similar for all the fuels used, with a slight cooling of the gas mixture towards the combustor exit (section 4.1).

The fuels used in the numerical analysis generated similar downward variations of the total pressure in the combustor, with quasi-constant values on the exit section of the combustor (4-4.1), see Fig. 11.

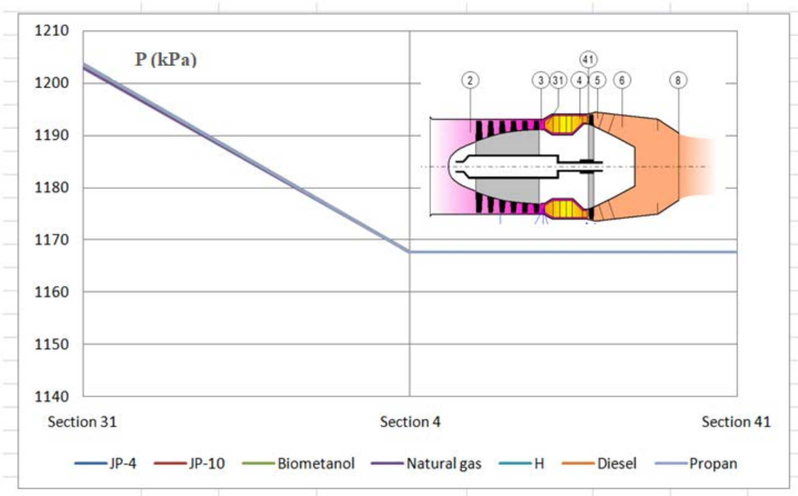

FIG. 11 Comparative diagram for the total pressure P (kPa) of gases in combustor sections

CONCLUSIONS

The combustors of jet engines are the constructive elements with the highest degree of thermal load, which implies a refined thermodynamic design and optimization that can lead to numerical results that are the basis of future experimental research on test benches and verification of parameters and constructive performances.

The article proposed a comparative approach using numerical simulations for a range of fuels used in the aerospace industry in general and jet engines in particular. Although the software tool generated a series of relevant results (thermo-kinetic and traction) regarding the thermodynamic behavior of fuels, the numerical instrumentation was limited to a theoretical model of an aerojet engine that only used the design method of a thermodynamic cycle of operation. Although we have different values of nominal thrusts, the generated results revealed quasi-similar thermodynamic behaviors of the fuels used, which implies future numerical analyzes based on multiple initial data or the use of similar software tools (e.g. GTPsim, Gas Turbine Simulation Program, Mathworks-Turbojet Engine Simulation), [10, 11, 12].

The continuation of research efforts on the performance of combustion chambers of jet engines are focused on parametric numerical analyzes and optimization with the help of GasTurb considering the consideration of valid input data for aerojet engines in use (e.g. Pratt Withney F100 on the F16 Fighting Falcon aircraft). , [13, 14].

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