Aspects regarding internal flow in combustion chamber of turbojet engines

CONSTANTIN ROTARU
DORU GHEORGHE SAFTA
CRISTIAN BARBU
Department of Aviation Integrated Systems
Military Technical Academy
George Cosbuc Avenue no. 81-83, sectorul 5 Bucharest
ROMANIA

Abstract

In this paper are presented the results obtained by modelling and simulation of the combustion in a turbojet engine. The study of the mathematical model represented by the equations which described the combustion process was made by using the software FLUENT 6.1.

The paper is focused on the establishment of the link between the control laws of the turbojet engine (whose main parameter is the fuel flow rate in combustion chamber), optimal characteristics of the burned process and the shape of combustion chamber.

Taking into account the characteristics of the fuel for turbojet engines, the software used allows to study the optimal shape of the combustion chamber, position of injectors, outlet section (which represents the inlet section of turbine) and also, allows to study the optimal control law for a certain type of turbojet engine (monorotor, birotor, turbofan, etc).

The main conclusion is represented by the link between the performance of burned process which takes place in the combustion chamber and implication upon optimal control law and programme for a turbojet engine. Even if the combined control laws have more parameters, the most important of them is the fuel rate.

Keywords: CFD, combustion, turbojet engine

Nomenclature

G	[Kg/s]	flow rate
M	[-]	mach number
R	[j/Kg K]	gas-law constant
S	[m^2]	area
T	[K]	temperature
p	[Pa]	pressure
$\underline{v}$	[m/s]	velocity vector
γ	[-]	ratio of specific heats
η	[-]	effectiveness factor
ρ	[Kg/m^3]	density

Subscripts and Superscripts

1-5	characteristic sections of a turbojet engine
C	compressor
H	altitude
T	turbine
C	fuel
r	relative

1. Introduction

The combustion chamber of the turbojet engines (Fig.1) is one of the most important components which assures the chemical energy transformation of the fuel in caloric energy and it transmits this energy to the working fluid with a high level efficiency.

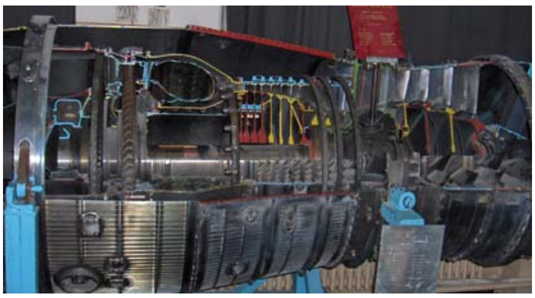

Fig. 1. Turbojet engine

The mathematical model that describes the work of the turbojet engine parts, from thermogasodynamic point of view, is represented by a system of equation at which the number of the unknown parts is bigger than the number of the equations. In order to solve this system of equations it is necessary to impose additional conditions (named control laws and control programmes).

Choosing a certain law or program represents a very important issue, with implications on the height and speed characteristics of the engine. The control laws and programmes of the turbojet engine can be analysed starting from the equation of the set compressor – combustion chamber – turbine [1]

$\dfrac{q(\lambda_1)^2\left(\pi_C^{*\frac{\gamma-1}{\gamma}}-1\right)}{\pi_C^{*2}\left(1-\dfrac{1}{\pi_T^{*\frac{\gamma'-1}{\gamma'}}}\right)\cdot\eta_C^*}=const.$	(1)

where

$q(\lambda_1)=\lambda_1\left(1-\dfrac{\gamma-1}{\gamma+1}\lambda_1^2\right)^{\frac{1}{\gamma-1}}\cdot\left(\dfrac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}$ $\lambda_1=\dfrac{M_1}{\sqrt{\dfrac{2}{\gamma+1}\left(1+\dfrac{\gamma-1}{2}M_1^2\right)}}$ $\pi_C^*=\dfrac{p_2^*}{p_1^*};\ \pi_T^*=\dfrac{p_3^*}{p_4^*};$ $\pi_T^*\sqrt{1-\left(1-\dfrac{1}{\pi_T^{*\frac{\gamma'-1}{\gamma'}}}\right)\cdot\eta_T^*}=$ $=\left[S_{5crt}\cdot q(\lambda_{5crt})/S_{3'}\right]\cdot const.$	(2)

The turbine pressure ratio π_T^* depends on S_{5crt}, $S_{3'}$ and $q(\lambda_{5crt})$. The equation (1) allows to draw the compressor work line in the coordinates $(\pi_C^*, q(\lambda_1))$ for a certain control law of turbojet engine.

2. Control laws

2.1. Control law $n = const.$

For a turbojet engine with $S_{3'}$ (the exit section from the stator of the first turbine step) and $S_{5crt.}$ (the critical exit section of the engine) constant, the control factor consists of the fuel flow rate $G_c = \mathrm{var}$. The automatic control system of the engine ensures the modification of the fuel flow so that the modification of the inlet parameters in the engine (accomplished by the modification of the flight conditions V_H and H) ensures continuously the condition $n = const.$ In this way it is obvious that the following conditions should be obeyed [2]:

$T_3^* \le T_{3\max}^*,\quad \Delta K_y \ge \Delta K_{y\min}$	(3)

where

$K_y=\dfrac{\left[\pi_C^*/q(\lambda_1)\right]_{instability.\,line}}{\left[\pi_C^*/q(\lambda_1)\right]_{work\ line.}}$ $\Delta K_y=(K_y-1)\cdot 100\%$	(4)

In order to determine the engine parameters, under this control rule, as an independent variable can be considered: the equivalent rotational speed $\overline{n}_r=\dfrac{n}{n_0}\cdot\sqrt{T_0/T_1^*}$, where $T_0 = 288\,K$, n_0 is the maximal rotational speed of the engine in conditions $M_H = 0$ and $H = 0$.

The independent variable is linked to the flight regime by the temperature T_1^*, which is definite by the equation

$T_1^*=T_H\left(1+\dfrac{\gamma-1}{2}M_H^2\right)$	(5)

The parameter $\overline{n}_r$ depends on flight regime: if T_1^* increases (namely T_H or M_H) the $\overline{n}_r$ decreases (obviously for this control law).

2.2. Control law $T_3^* = const.$

Maintaining a temperature T_3^* constant in front of the turbine with the geometry of the flow sections, invariable, this control law can be achieved by he modification of the fuel flow, so that $T_3^*/T_4^* = const$. In this way the engine rotational speed will be modified because of the T_1^* at the compressor inlet section. The work line for a turbojet with uncontrolled sections are traced with help of equation (1), so, for the two control law ($n = const.$ and $T_3^* = const.$) the position of this line in the compressor characteristic is the same, but for the same value of $\overline{n}_r$ corresponds different values of the engine speed rate. For this control rule, the conditions (6) must be accomplished.

$n \le n_{\max},\quad \Delta K_y \ge \Delta K_{y\min}$	(6)

2.2. Control law $\overline{n}_r = const.$

By this control rule the engine automatic control system modifies the fuel flow, at the modification of the flight conditions (which depend on T_1^*), so that, the speed rate is proportional with the parameter $\sqrt{T_0/T_1^*}$. The imposed limitations will be:

$n \le n_{\max},\quad T_3^* \le T_{3\max}^*$	(7)

The work line (which verifies the equation(1) from the compressor characteristic) goes to a single point, that corresponds to the calculus regime, so that for all flight regimes, the values of the parameters π_C^*, $q(\lambda_1)$ and ΔK_y will be constant and equal with values corresponding to the calculus regime. So, through this point in compressor characteristic only a line will cross, corresponding to $\sqrt{\frac{T_3^* \cdot T_0}{T_1^*}} = const.$

Obviously, the control of the engine can be done after one or more parameters. In order to obtain a better characteristic, the combined control rule are used, namely a certain control law for a certain flight regimes.

3. Problem description for fluent calculation

In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams. The local mass fraction of burnt and unburned fuel stream is definite by the mixture fraction, denoted by f. The species concentrations are derived from the predicted mixture fraction fields and the interaction of turbulence and chemistry is accounted for with a probability density function. The mixture fraction can be written in terms of the atomic mass fraction as [3]:

$$f = \frac{Z_i - Z_{i.ox}}{Z_{i.fuel} - Z_{i.ox}} \tag{8}$$

where Z_i is the elemental mass fraction for element i.

The mean time averaged mixture fraction equation is:

$$\frac{\partial}{\partial t}\left(\rho \bar{f}\right) + \nabla \cdot \left(\rho \bar{v} \bar{f}\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \bar{f}\right) + S_m \tag{9}$$

The source term S_m is due to solely to transfer of mass into the gas phase from liquid fuel.

The equation for the mixture fractions variance, $\overline{f'^2}$ is:

$$\frac{\partial}{\partial t}\left(\rho \overline{f'^2}\right) + \nabla \cdot \left(\rho \bar{v}\, \overline{f'^2}\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \overline{f'^2}\right) + + C_q \cdot \mu_t \left(\nabla^2 \overline{f'^2}\right) - C_d \rho \frac{\varepsilon}{k} \overline{f'^2} \tag{10}$$

where $f' = f - \bar{f}$ and μ_t is the subgrid-scale viscosity.

The probability density function, written as $p(f)$ can be thought of as the fraction of time that the fluid spends at the state f, so

$$p(f)\Delta f = \lim_{T \to \infty} \frac{i}{T} \sum_i \tau_i \tag{11}$$

where T is the time scale and τ_i is the amount of time that f spends in the Δf band. The shape of the function $p(f)$ depends on the nature of the turbulent fluctuations in f. In practice, $p(f)$ is expressed as a mathematical function that approximates the PDF shapes. The probability density function $p(f)$ describing the temporal fluctuations of f in the turbulent flow, can be used to compute the time averaged values of variables that depend of f. Time-averaged values of species mole fractions and temperature can be computed as:

$$\overline{\varphi_i} = \int_o^1 p(f) \varphi_i(f) df \tag{12}$$

where

$$\varphi = \frac{(fuel/air)_{actual}}{(fuel/air)_{stoichiometric}} \tag{13}$$

The shape of the assumed PDF is

$$p(f) = \frac{f^{(\alpha-1)}(1-f)^{(\beta-1)}}{\int f^{(\alpha-1)}(1-f)^{(\beta-1)} df} \tag{14}$$

where

$$\alpha = \bar{f}\left[\frac{\bar{f}(1-\bar{f})}{\overline{f'^2}} - 1\right]$$
$$\beta = (1-\bar{f})\left[\frac{\bar{f}(1-\bar{f})}{\overline{f'^2}} - 1\right] \tag{15}$$

Thus, given prediction of $\bar{f}$ and $\overline{f'^2}$ at each point in the flow field, the known PDF shape can be computed and used as the weighting function to determine the time-averaged mean values of species mass fraction, density and temperature.

For non-adiabatic systems $\varphi_i = \varphi_i\left(f, H^*\right)$ where H^* is the instantaneous enthalpy

$H^* = \sum_j m_j H_j =$ $= \sum_j m_j \left[\int_{T_{ref.j}}^{T} c_{P.j} dT + h_j\left(T_{ref.j}\right) \right]$	(16)

3.1. Model of geometry (Gambit)

The combustion chamber which was modeled with the peprocesor Gambit is presented in Fig. 2, and it is a part of a turbofan engine with a presure ratio 22 and an air flow rate 77 Kg/s (at the maximal work regime).

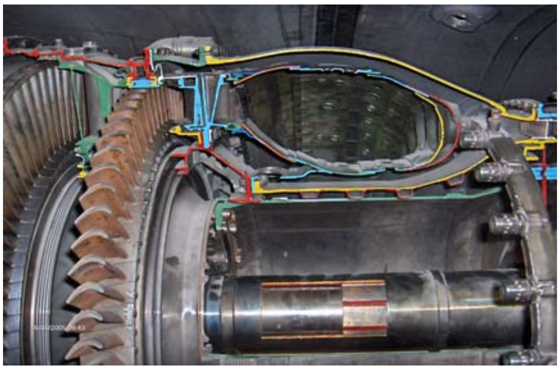

Fig. 2. Combustion chamber

The model of the combustion chamber is presented in Fig.3 and the model of its flame tube is presented in Fig.4. The real flame tube has 24 injectors and a specific fuel consumption of 0.72 [Kg/daN h] at the nonafterburning regime. The number of stator blades for the last compressor stage is 131 and for the first turbine stage is 24.

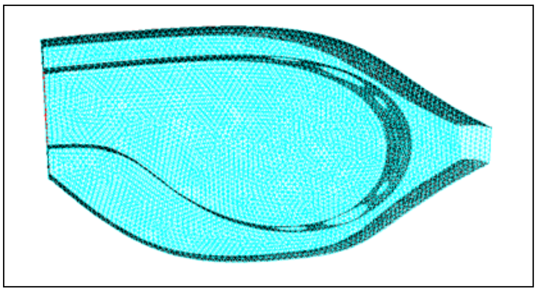

Fig. 3. Model of combustion chamber

The faces were meshed with elements Tri, type Pave and the volume was meshed with elements Tet/Hybrid, type TGrid with an interval size 0.8.

The boundary conditions were;

- pressure inlet;
- pressure outlet;
- wall;
- periodic;

The lenght of combustion chamber is 37 cm.

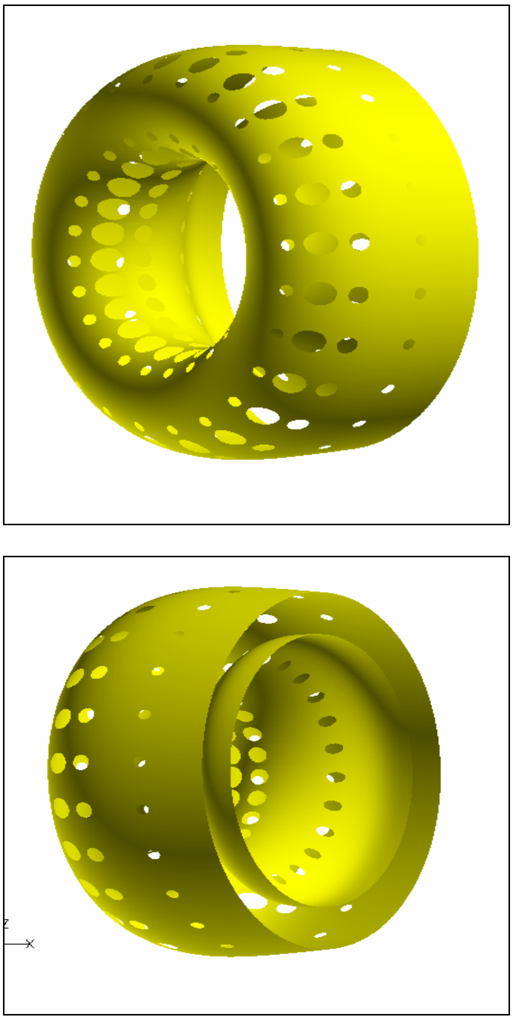

Fig. 4. Model of Flame Tube

3.2. Preparation for prePDF

The combustion was modeled using the mixture-fraction/PDF approach with the equilibrium mixture consisting of 10 chemical species: C_5H_{12} (fuel), CH_4, CO, CO_2, H_2, H_2O, $H_2O(l)$, O_2, OH, $C(s)$, N_2.

In the first step was calculated the adiabatic system chemistry for settings *Adiabatic*, *Equilibrium Chemistry* and *Beta PDF* with 0,7 *Fuel Rich Flamability Limit*.

In the second step was calculated the Nonadiabatic System Chemistry with 0,3 Fuel Rich Flamability Limit. The diagrams of the chemical equilibrium instantaneous temperature and chemical instantaneous species are presented in Fig.5.

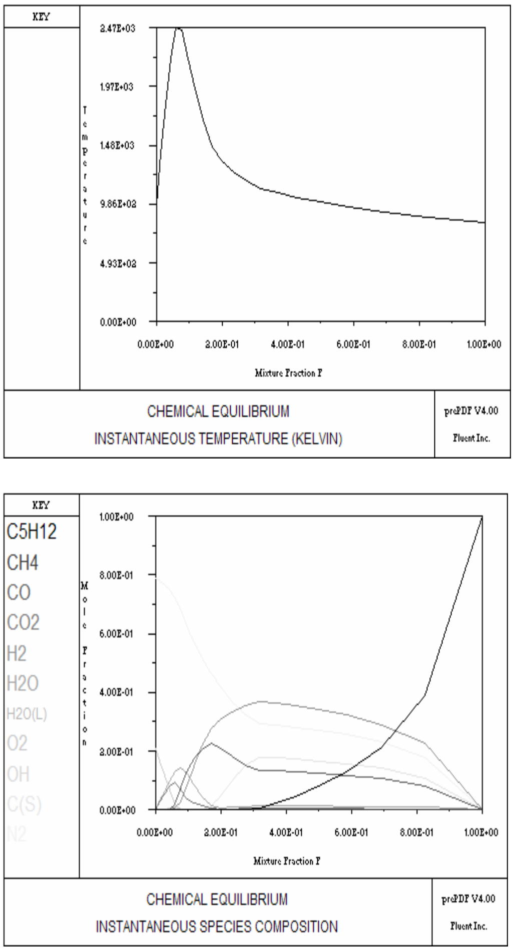

Fig. 5. Chemical equilibrium

4. Fluent calculation

- Segregated implicit sover;
- K-epsilon viscous model;
- Non-Premixed Combustion;
- Injection Type: group;
- Number of Particle Steam: 10;
- Particle Type: Dropelt;
- Diameter Distribution: linear;

Stochastic tracking Model: 10 Number of Tries;

A few results are presented in the following figures:

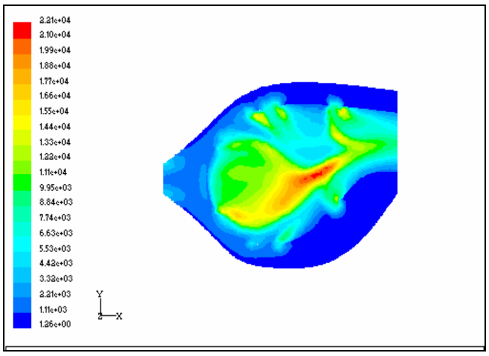

Fig. 6. Turbulent kinetic energy

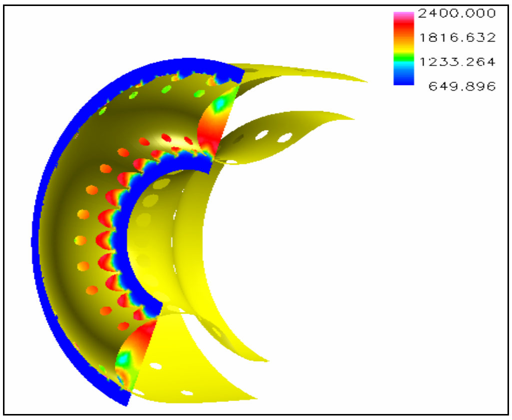

Fig. 7. Static Temperature

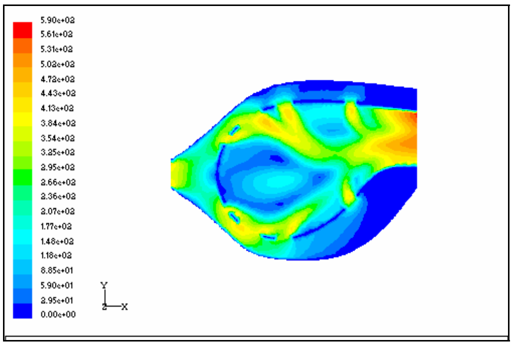

Fig. 8. Velocity magnitude

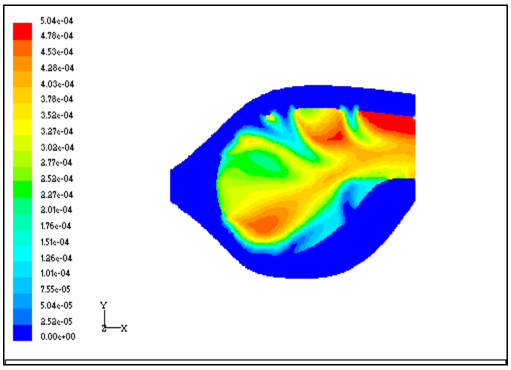

Fig. 9. Molar concentration of CO_2

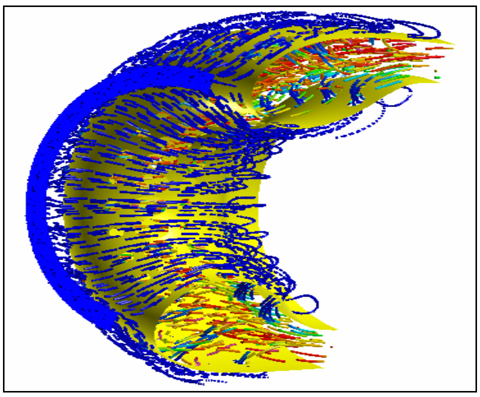

Fig. 10. Stream lines

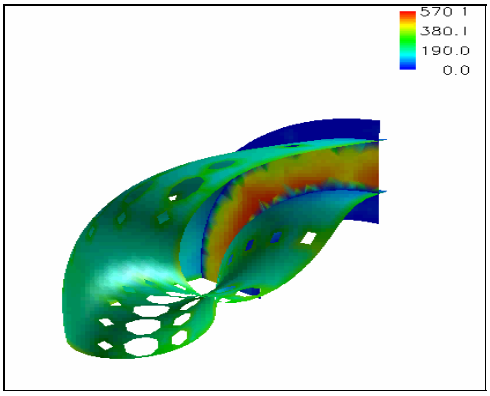

Fig. 11. Velocity magnitude

For the same geometric model were made others simulations, for instance:

Non-premixed combustion

◆ Define Case

- Heat Transfer Option: Adiabatic
- Equilibrium Chemistry
- PDF models: Beta PDF

Setup Species: C7H16, CH4, CO,CO2, H2, H2O, O2, OH, N2, NO.

Setup – Species – Composition

Fuel Stream: C7H16 (Mole fraction=1)

Oxidizer Stream: O2 (Mole fraction=0.21)

N2 (Mole fraction=0.79)

◆ Setup – Operating Conditions

Absolute pressure: 6 atm, 10 atm, 20 atm

Inlet Temperature for Oxidizer: 600 K, 800 K

◆ Setup Solutions Parameters

Fuel Rich Flamability Limit: 0.7

Distribution Center Point: 0.5

For Nonadiabatic System Chemistry

◆ Setup – Case

Heat Transfer Options: Non-adiabatic

PDF Models: Beta PDF

Chemistry Model: Equilibrium Chemistry

◆ Operating Conditions

Min Temperature: 280 K

Max Temperature: 2800 K

◆ Setup Solutions Parameters

Distribution Center Point: 0.2

Fuel Rich Flamability Limit: 0.3

The results correspond to the theoretical expectations

5. Conclusion

Due to the pressure oscillations, the combustion chamber has a vibrating component and this is determined by the following aspects:

- the cutting of the flame border in some regions;
- the pulsatory character of the fuel pressure in the input system;
- the combustion chamber diffuser vortices ignition.

The pressure oscillations could be at low frequency or high frequency. At the vibratory combustion, the pressure oscillations are determined by the acoustical properties of the combustion chamber and the energy source of the pressure oscillations is formed by the temperature and the oscillations of the flame border.

Fluent software is a powerful tools to study the combustion process. For the turbojet engine it allows to establish the optimal shape of the combustion chamber, the optimal type of fuel from the class C_nH_{2n+2} and also the percent of the addition parts of alkanes (C_2H_{2n}) and aromatic hydrocarbons (C_2H_{2n-6}).

Regarding the control laws, characteristic for the turbojet engines, the main conclusion is that the combined control low can assure the optimal field flow in the combustion chamber.

References

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[2] Stoicescu M, Rotaru C, 1999, “Turbojet engines. Characteristics and Control Methods”, *Publishing House of Military Technical Academy, Bucharest.*

[3] FLUENT Documentation.