Thermodynamic performances of the turbojet combustion chambers – numerical evaluation

Constantin Rotaru, Mihai Mihaila-Andres, Pericle Gabriel Matei and Raluca Ioana Edu

***Abstract*—**This paper presents the results of a study on the thermodynamic performances of a typical turbojet combustion chamber using a chemical reactor network. Several approaches of the aerodynamic shapes of the combustion chamber were considered to choose the methodology that better predicts the temperature field in front of the turbine. In order to find the optimal characteristics of the burned process, the modelling and simulation of the combustion in the turbojet engine were made with Fluent and Maple software.

***Keywords*—**Aircraft engine, CFD, Combustion chamber, Turbojet.

I. Introduction

THE thrust of the present aircraft engine is developed by compressing air in the inlet and compressor, mixing the air with fuel, burning the mixture in the combustor and expanding the gas stream through the turbine and nozzle. The expansion of gas through the turbine supplies the power to turn the compressor and the net thrust delivered by the engine is the result of converting internal energy to kinetic energy.

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

The modeling of the combustion systems in energy conversion equipment, such as the turbojet combustion chambers, has many challenges especially concerning the limitations of the predictive capacity of the models based on the computational fluid dynamics and their associated computational cost. A complete description of the combustion processes needs a simultaneous solution of the laws that govern the fluid mechanics and reaction kinetics, and its complexity increases as grows the number of species and reactions of the kinetics mechanism.

Constantin Rotaru is with the Aviation Integrated Systems and Mechanics Department, Military Technical Academy, Bucharest, Romania (tel: +40745974488; fax: +4021 335 57 63; e-mail: rotaruconstantin@ yahoo.com).

Mihai Mihaila-Andres is with the Aviation Integrated Systems and Mechanics Department, Military Technical Academy, Bucharest, Romania (e-mail: mihailmi@rdslink.ro)

Pericle Gabriel Matei is with the Aviation Integrated Systems and Mechanics Department, Military Technical Academy, Bucharest, Romania (e-mail: pgmatei@ yahoo.com).

Raluca Ioana Edu is with the Aviation Integrated Systems and Mechanics Department, Military Technical Academy, Bucharest, Romania (e-mail: edu_ioana_raluca@yahoo.com).

A first approach that aims the attenuation of the computational effort in the simulation of practical combustion systems such as the turbojet combustors, consists in the simplification of the chemical kinetics description while retaining the fluid mechanics description. This simplification involves a set of reduced elementary reactions and chemical species. However, the reduced schemes are valid only within a narrow range of pressure, temperature and composition in which the reduced mechanism is capable to simulate, not being able to represent in detail the chemical process.

The chemical reactor network is an alternative to the simulation of air-breathing engine combustors because it simplifies the fluid mechanics descriptions while keeping the details of the chemical kinetic description. This approach consists in the resolution of simplified transport equations to describe the operation of trivial combustion models such as well stirred reactor (WSR) and plug flow reactor (PFR), which are systematically arranged into a structured scheme with the purpose to represent the combustion process occurring within combustion equipment. These models are very useful in the prediction of relevant thermochemical properties such as temperature and pollutants emissions, which are the most significant parameters in the aircraft engines operation. While the PFR model assumes that the confined fluid moves through plugs, as a result of the absence of axial diffusion, the WRS model considers the mixing among reactants and products as being homogenous and instantaneous [1].

The principal advantage in the simulation of gas turbine combustors by mean of the chemical reactor network approach is the relatively low computational cost, when compared with the CFD approach. However, this benefit appears as detriment to a detailed description of the flow within the domain under analysis. To develop a model that simulates the operation of a gas turbine combustor, several hypotheses must be made, which aim to reduce the complexity of the governing equations related to the fluid mechanics. Thus, with the usage of the chemical reactor network approach, it is possible to obtain an accurate description of the combustion process in confined regions of a gas turbine combustor. For this purpose it is required the use of WSR and PFR models, which must be linked in a systematic and structured arrangement. The WSR models are used in the description of the combustion process occurring in the flame or primary zone of the combustion, whereas PFR models simulate the combustion in the intermediate and dilution zones.

Combustion stability, intensity and efficiency depend on the

ISBN: 978-1-61804-220-0

fluid flow and turbulence distribution within the combustor. To create the high turbulence necessary for intense combustion, there must be considerable pressure drop across the small holes in the chamber liner through which most of the air enters the combustion zone. Other causes of pressure drop in combustors include the bulk acceleration of the hot gas as its density decreases because of combustion and friction on the channels walls. For best engine performance the sum of these pressure losses should not be greater than a few percentage points of the combustor inlet pressure. A typical turbojet combustion chamber is presented in Fig. 1.

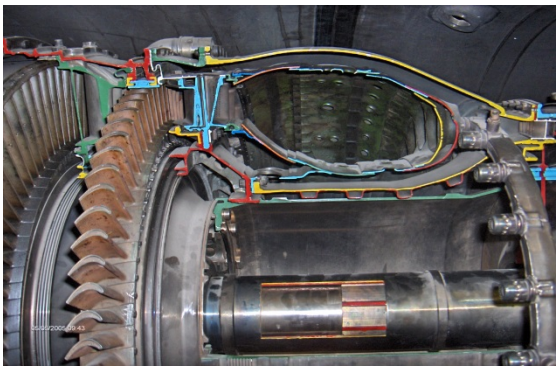

Fig. 1 Combustion chamber

The performances of a turbojet engine are strongly dependent on the mass flow rate per unit cross-sectional area of the engine. A large area for a given flow rate implies not only large engine mass per unit thrust but also large nacelle drag for an externally mounted engine (civilian aircrafts) or large volume for an engine placed inside the fuselage (military aircrafts). For this reason it is desirable for the velocity of the working fluid to be as high as possible, without incurring excessive losses due to wall friction and viscous mixing. A limitation is imposed by the combustors since it is necessary to maintain a stationary flame within a moving air stream [2].

The thermal energy of the air/fuel mixture flowing through an air-breathing engine is increased by the combustion process. The fuel must be vaporized and mixed with the air before this chemical reaction can occur. Once this is done, the combustion process can occur and thus increase the thermal energy of the mixture.

The design of the main burner of an air-breathing engine differs in many ways from that of conventional combustion devices because the following properties of the combustion chamber are desired: complete combustion; low total pressure lost; stability of combustion process; short length and small cross section; operation over a wide range of mass flow rates, pressures and temperatures.

The theoretical heat of reaction of the fuels assumes a complete combustion with no unburned hydrocarbon fuel and no dissociation of the products of combustion. The actual heat release is affected by the quality of fuel atomization, vaporization, mixing, ignition, chemical kinetics, flame stabilization, intermediate air flow, liner cooling and the aerodynamics of the combustor. Here a variety of timescales as in residence time, chemical reaction rate timescales, spontaneous ignition delay time that includes vaporization timescale among other time constants enter the real combustion problem.

II. Combustion Chamber Model

A self-stabilized, steady flow combustion system requires two distinct regions: a primary zone (well stirred reactor) in which the flow stream is recirculated in order to promote gross mixing of products, reactants and reaction intermediates (being governed by a coupled set of nonlinear equations) and a secondary zone (Fig. 2) which has the main function to allow sufficient convective residence time for the primary zone effluent to burn out before exiting the combustor (plug flow reactor).

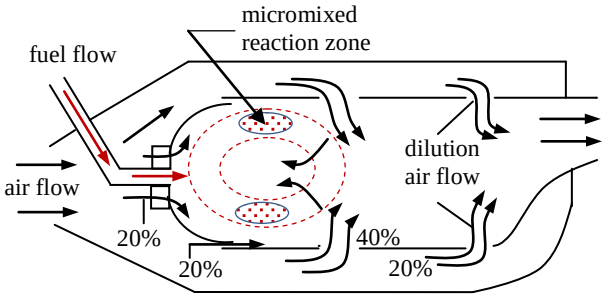

Fig. 2 Combustion chamber flow pattern

A typical distribution of airflow into a can-contained combustion zone is presented in Fig. 2 where about 20% of the intake air passes through swirling vanes that surround the central fuel spray nozzle. The primary zone in which the fuel-air ratio is nearly stoichiometric, is fed by other airflow (about 80%) [3]. These flows are designed to interact in such a way that a large and steady swirl is established in the primary combustion zone.

The rates of reaction in a turbojet combustion chamber are affected by both chemical kinetics and mixture turbulence which controls the rate of mixing of fuel and air, and also the instantaneous geometry of the flame surface. The flame travels into a mixture of reactants at a rate that is dependent on the state of the reactants and is limited either by mixture turbulence or by chemical kinetics. A flame remains stationary in a traveling mixture of reactants if the speed of the flame relative to the reactants is just equal to the reactants mixture velocity. Turbulence can rise the burning velocity, so, the flame tube must have the zones of low velocity in which the flames can propagate into an unburned mixture.

The maximum combustion temperature occurs when hydrocarbon fuel molecules are mixed with just enough air, so that, all of the oxygen atoms are consumed, all of the hydrogen atoms form water vapor and all of the carbon atoms form carbon dioxide CO_2. This ideal mixture of fuel and air is represented by a general atom balance equation, called the stoichiometric equation, given by

ISBN: 978-1-61804-220-0

$$C_xH_y + \left(x + \frac{y}{4}\right)\left[O_2 + \frac{79}{21}N_2\right] \rightarrow$$
$$\rightarrow xCO_2 + \frac{y}{2}H_2O + \frac{79}{21}\left(x + \frac{y}{4}\right)N_2 \quad (1)$$

The stoichiometric mass-basis fuel/air ratio is

$$f_{st} = \frac{36x + y}{103(4x + y)} \quad (2)$$

Although the stoichiometric ratio for most fuels is typically 0.06 to 0.07 and the fuel-to-air ratio for the engine is 0.015 to 0.03, in the primary burning zone of the combustion chamber, the mixture is fuel rich and this ratio is typically 0.08. Because the overall performance of an engine and the life of the turbine, are strongly dependent on burner exit temperature, predicting this temperature is extremely important. All jet fuels are hydrocarbons and most of them have characteristics similar to those of kerosene.

The fuel/air equivalence ratio is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio $\varphi = f / f_{st}$ and it permits representation of either fuel-rich or fuel-lean mixtures by multiplying the fuel term in the atom-balance equation by φ

$$\varphi C_xH_y + \left(x + \frac{y}{4}\right)\left[O_2 + \frac{79}{21}N_2\right] \rightarrow products \quad (3)$$

Ignition of a fuel/air mixture in a turbojet combustion system requires inlet air and fuel conditions within flammability limits, sufficient residence time of a combustible mixture and location of an effective ignition source in the vicinity of the combustible mixture. When the temperature in the combustion system is below the spontaneous ignition temperature, an ignition source is required to bring the local temperature above the spontaneous ignition temperature [4, 5].

The problem of lean mixture in a burner can be overcome by mixing and burning a rich fuel/air mixture in a small region where the local equivalence ratio is near unity. By using only a portion of the total air in a region, a locally rich mixture can be efficiently burned and then the products of combustion diluted and cooled to an acceptable turbine inlet temperature by the remaining air. At usual pressure and temperature, hydrocarbon/air mixture will react for φ from approximately 0.5 to 3 and not at all below 0.2 *atm* at standard temperature. A limitation is imposed by the combustion because it is necessary to maintain a stationary flame within a high velocity airstream. Provided stable combustion is attained, complete combustion in the case of lean mixture is virtually ensured since, with excess oxygen, local fuel-rich areas are unlikely.

On the other hand, combustion of a near-stoichiometric mixture requires an essentially uniform distribution of constituents to avoid wasting some fuel in local fuel rich regions.

A fuel air mixture of equivalence ratio leaner than 0.6 and richer 3.0 will not react in room temperature and pressure. With the increase in temperature, the flammability limit boundary widens to $0.3 < \varphi < 4.0$ in the spontaneous ignition temperature range $(T > 225\,C)$ for a kerosene-air mixture (Fig. 3).

At high altitude, where the pressure is reduced, chemical reaction rates may be much slower than turbulent mixing rates. The probability of chemical combination of atoms and molecules depends on the frequency of molecular collisions and on the energy of the colliding molecules. Combustion proceeds as a chain reaction in which energy released from one combination is sufficient to raise neighboring atoms above the threshold energy, so, raising the temperature decreases the energy that, on average, must be added to a particle before the reaction threshold is reached. For a given temperature, high pressure corresponds to high density and this means greater frequency of collision of fuel and oxidant atoms.

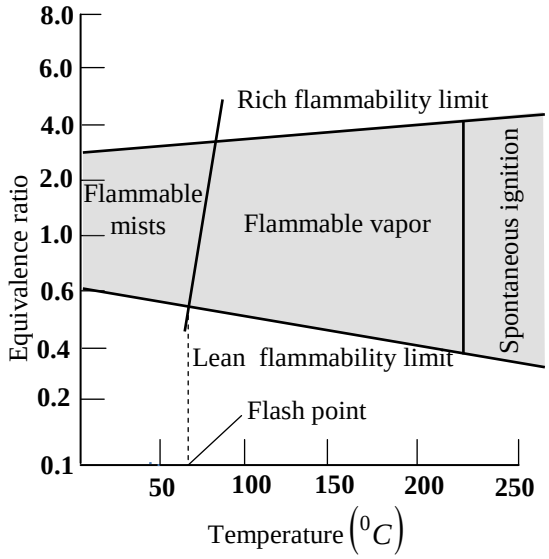

Fig. 3 Flammability limits

Off-stoichiometric fuel/air ratios, as characterized by the equivalence ratio $\varphi \neq 1$, affect the type and distribution of combustion products, as well as the temperature. For off-stoichiometric mixtures, and also for possibly incomplete combustion, the atom-balance equation can be generalized as

$$\varphi C_xH_y + \left(x + \frac{y}{4}\right)\left[O_2 + \frac{79}{21}N_2\right] \rightarrow$$
$$\rightarrow n_{CO_2}CO_2 + n_{CO}CO + n_{H_2O}H_2O + ... +$$
$$+ n_{O_2}O_2 + n_OO + n_{NO_2}NO_2 + n_{N_2O}N_2O + ...etc. \quad (4)$$

where *etc.* indicates that the list of possible product gases may be as many combinations of O, H, C and N atoms as exist in nature [1,3].

Assuming that combustion occurs at constant pressure, without either heat or work transfer with surroundings, then the total enthalpy of the products will be the same as the reactants. The static enthalpy of a mixture of gases is given by

$$H = \sum_{k=1}^{NS} n_k h_k \quad (5)$$

where *NS* is the number of product species, n_k is the mole

numbers and h_k is the static enthalpy of the k^{th} product species. If the reactants are ignited and allowed to burn to the final equilibrium state without heat being added or removed during the process, the final equilibrium temperature is called the adiabatic flame temperature and it is found by solving the algebraically equation $H_P = H_R$, where the indices *P* and *R* represent the products and reactants. Both the adiabatic flame temperature and heat of reaction are end-state quantities calculated on the basis of static change from the given reactant mol numbers $\{n_i\}_R$ to the set of product mole number $\{n_i\}_P$. The product mole numbers can be calculated either from assumed complete combustion or chemical equilibrium. However, neither result considers the instantaneous rates of change mole numbers nor the integrated values of mole numbers that may exist at specific moments. Because fluid particle residence times in any subcomponent of a turbojet engine are less than a millisecond $\left(10^{-3}s\right)$, it is very often the case that insufficient time is available for the exothermic combustion reactions to reach chemical equilibrium. For purpose of mathematical modeling finite-rate chemical kinetics for homogeneous gas-phase chemical reaction, it is assumed that very many individual, reversible, elementary physical-chemical collision reactions of the form $CO + OH \rightarrow CO_2 + H$ can occur.

For incomplete combustion, the atom-balanced equation may be generalized as

$$\varphi C_x H_y + \left(x + \frac{y}{4}\right)\left[O_2 + \frac{79}{21}N_2\right] \rightarrow \varphi(1-\varepsilon)C_x H_y + \\ + x\varphi\varepsilon CO_2 + \frac{y}{2}\varphi\varepsilon H_2O + \left(x + \frac{y}{4}\right)\left[(1-\varphi\varepsilon)O_2 + \frac{79}{21}N_2\right] \tag{6}$$

where ε is the combustion reaction progress variable. When $\varepsilon = 1$, the maximum value of T_{aft} (the adiabatic flame temperature) is realized and may be very well approximated by the linear equation

$$T_{aft} \approx T_i + \frac{\varphi f_{st} h_{PR}}{c_P} \tag{7}$$

where T_i is the air inlet temperature in the combustion chamber, h_{PR} is the heat of reaction and c_P is the specific heat at constant pressure.

The volumetric mass rate of consumption of the fuel can be expressed by a modified Arrhenius equation for the overall combustion reaction

$$\dot{\omega}_f = M_f\left(x + \frac{y}{4}\right)\varphi A e^{-T_{act}/T} \times \\ \times\left(\frac{p}{RT\sum N_P}\right)^2 (1-\varepsilon)(1-\varepsilon\varphi) \tag{8}$$

where $M_f = 12x + y$ is the molecular weight of the fuel, *A* is the pre-exponential factor, T_{act} is the activation temperature, *p* is the pressure in the combustion chamber, *R* is the universal gas constant and $\sum N_P$ has the expression

$$\sum N_P = \frac{100}{21}\left(x + \frac{y}{4}\right) + \varphi\left[1 + \left(\frac{y}{4} - 1\right)\varepsilon\right] \tag{9}$$

The static temperature *T* is represented by the linear equation

$$T = T_i + \varepsilon\left(\frac{\varphi f_{st} h_{PR}}{c_P}\right) \tag{10}$$

The equation (8) could give the optimal value of ε for which $\dot{\omega}_f$ is a maximum. A design goal for combustor primary zone is to achieve as nearly as possible this maximum value of $\dot{\omega}_f$ at some location in the combustion device.

Stable and efficient combustion can be upset by the fuel/air mixture becoming too lean or too rich such that the temperature and reaction rates drop below the level necessary to effectively heat and vaporize the incoming fuel and air. The effects of mass flow rate, combustion volume and pressure on the stability of the combustion process are combined into the combustor loading parameter.

The residence time, t_{res}, in the burner is given by

$$t_{res} = \frac{L}{V_{av}} \approx \frac{L}{V_{ref}} = \frac{\rho_{t3} A_{ref} L}{\dot{m}_3} \tag{11}$$

where V_{ref} is based on the air mass flow rate entering the combustor, A_{ref} is the cross-sectional area normal to the airflow of combustion chamber, *L* is the length of the burner and ρ_{t3} is the density of the air entering the combustion chamber [6].

The minimum external energy needed to initiate a reaction is a function of the equivalence ratio as well as the type of fuel for vaporized fuel-air mixture. Figure 4 shows the level of ignition energy of various vaporized fuel-air mixtures as a function of equivalence ratio [7, 8]. The minimum ignition energy corresponds to a particular equivalence ratio.

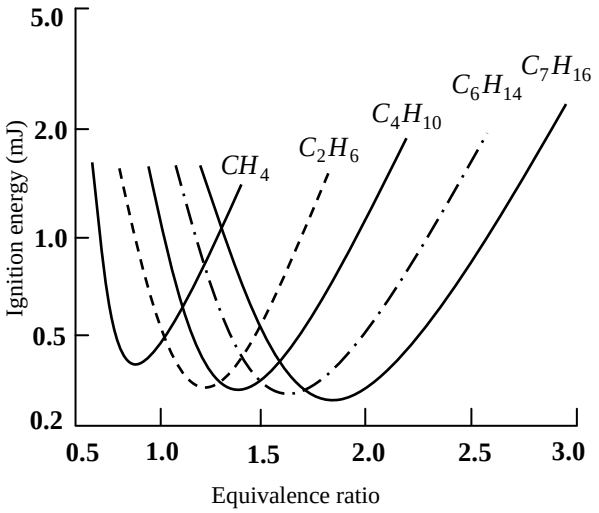

Fig. 4 Minimum ignition energy

Assuming an isentropic compression process, the total density at state 3 (the station behind the compressor) is proportional to the total pressure at this state, $\rho_{t3} \propto (p_{t3})^{1/\gamma_C}$ and the residence time, t_{res}, is proportional to the reaction time, so, the length of burner could be estimated by

$$L \approx \frac{A_4}{A_{ref}\sqrt{T_{t4}}}(p_{t4})^{\left[n-\frac{\gamma_C-1}{\gamma_C}\right]} \quad (12)$$

where station 4 is the high pressure turbine stator inlet and γ_C is the ratio of specific heats.

The reaction timescale, t_{re}, is inversely proportional to reaction rate, which may be written as

$$t_{re} \approx p^{-n}T^{-m}e^{\frac{E_a}{RT}} \quad (13)$$

The pressure and temperature exponents in a turbojet combustor have values around 1-2 for *n* and 1.5-2.5 for *m* [3].

III. Results

The combustion chamber geometrical model of a turbojet engine is presented in Fig. 5 and it is similar to a real model with 24 injectors.

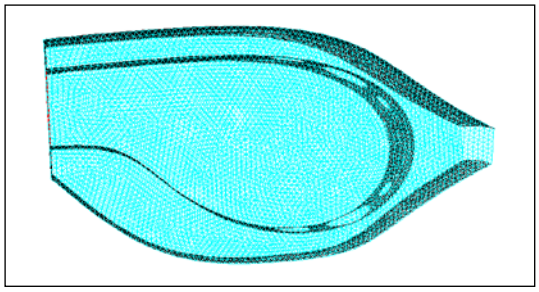

Fig. 5 Combustion chamber geometrical model

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 length of combustion chamber is 37 cm and the flame tube has the shape presented in Fig. 6.

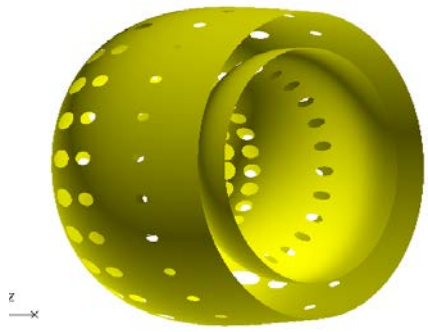

Fig. 6 Flame tube

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 [9, 10].

In the second step was calculated the Nonadiabatic System Chemistry with 0,3 Fuel Rich Flamability Limit.

The simulations were made in Fluent software [11]

- Segregated implicit sover;
- K-epsilon viscous model;
- Injection Type: group;
- Number of Particle Steam: 10;
- Particle Type: Dropelt;
- Diameter Distribution: linear;
- Stochastic tracking Model: 10 Number of Tries.

Some results are presented in the following pictures (Figs. 7-9].

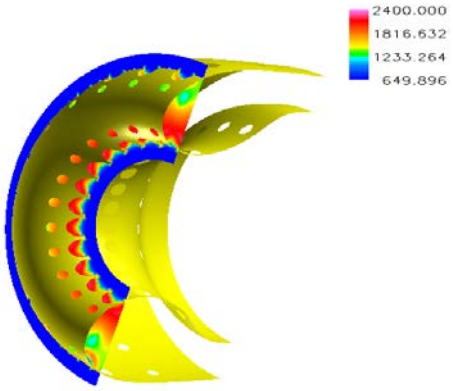

Fig. 7 Temperature

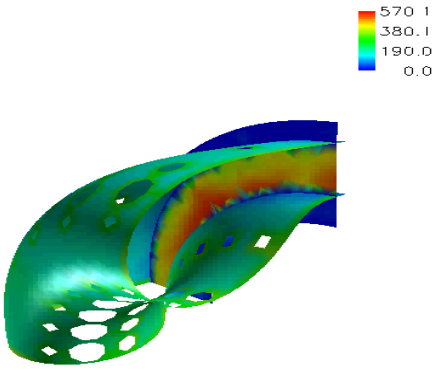

Fig. 8 Velocity magnitude

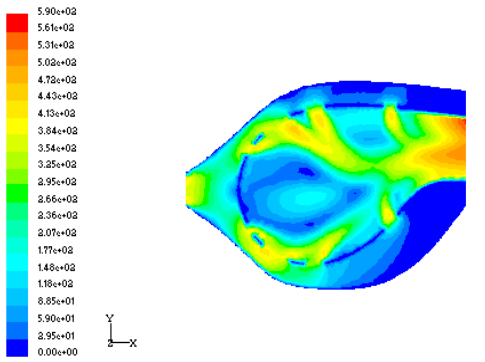

Fig. 9 Contours of velocity magnitude

IV. Conclusion

A low turbulence intensity environment in a fuel-air mixture flow of 50-100 m/s results in a root mean square of the turbulence fluctuation speed of 2.5-5 m/s. In a high turbulence intensity in a flow with a mean speed of 100 m/s, the turbulence contribution to flame propagation speed may be as high as 30 m/s.

In order to approach new constructive solutions for complex systems like the aircraft engines, it is necessary to use software codes to study the behavior or performances of these systems. For an aircraft engine the experimental validation is expensive, so the first step in this study is the simulation of the virtual model of constructive elements, like combustion chamber. In this study are obtained some results regarding the 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.

It is important to emphasize the inherent limitation in the use of the chemical reactor network approach in the simulation of combustion as the result of the simplification on the fluid mechanics equations, in contrast to the more elaborate description of the kinetic of combustion and the lower computational burden. A good alternative in the modeling and simulation of turbojet combustion systems could be the adoption of sophisticated approaches, such as the CFD, to get a better prediction of the thermodynamic performances of the turbojet combustion chambers.

References

[1] J. D. Mattingly, "Elements of Propulsion. Gas Turbines and Rockets", AIAA, Reston Virginia, USA, 2006.
[2] L. C. Jaw, J. D. Mattingly, "Aircraft Engine Controls – Design, System Analysis and Health Monitoring", AIAA, Reston Virginia, USA, 2009.
[3] S. Farokhi, "Aircraft Propulsion", John Wiley & Sons Inc., USA, 2009.
[4] Rotaru Constantin, Arghiropol Adrian, "Numerical Computation of Internal Flow for Turbojet Engine Combustion Chamber", 16th International Conference The Knowledge-Based_Organization: Applied Technical Sciences and Advanced Military Technologies, Proceedings 3, pag. 117-122, Romania, 2010.
[5] Rotaru, C., Safta, D., Barbu, C., "Aspects regarding internal flow in combustion chamber of turbojet engines", Proceedings of the 5th IASME/WSEAS International Conference on Fluid Dynamics and Aerodynamics, Greece, 2007.
[6] R. F. Huang, H. F. Yang, C. M. Hsu, "Flame Behavior and Thermal Structure of Combusting Nonpulsating and Pulsating Plane Jets", Journal of Propulsion and Power, Volume 29, number 1, 2013, pag. 114-124.
[7] Ronald D. Flack, "Fundamentals of Jet Propulsion with Applications", Cambridge University Press, 2005.
[8] Rotaru Constantin, "Aspects Regarding Combustion Chamber Dynamics for Turbojet Engines", ICMT'09 International Conference on Military Technologies, Brno, Czech Republic, Proceedings, pag. 342-349, 2010.
[9] J. D. Mattingly, W. H. Heiser, D. T. Pratt, "Aircraft Engine Design",second edition, AIAA, Reston Virginia, USA, 2002.
[10] Rotaru, C., Arghiropol, A., Barbu, C., "Some aspects regarding possible improvements in the performances of the aircraft engines", Proceedings of the 6th IASME/WSEAS International Conference on Fluid Dynamics and Aerodynamics, Greece, 2008.
[11] FLUENT Documentation.