Some Considerations about the Aircraft Engine Combustion Chambers Performances

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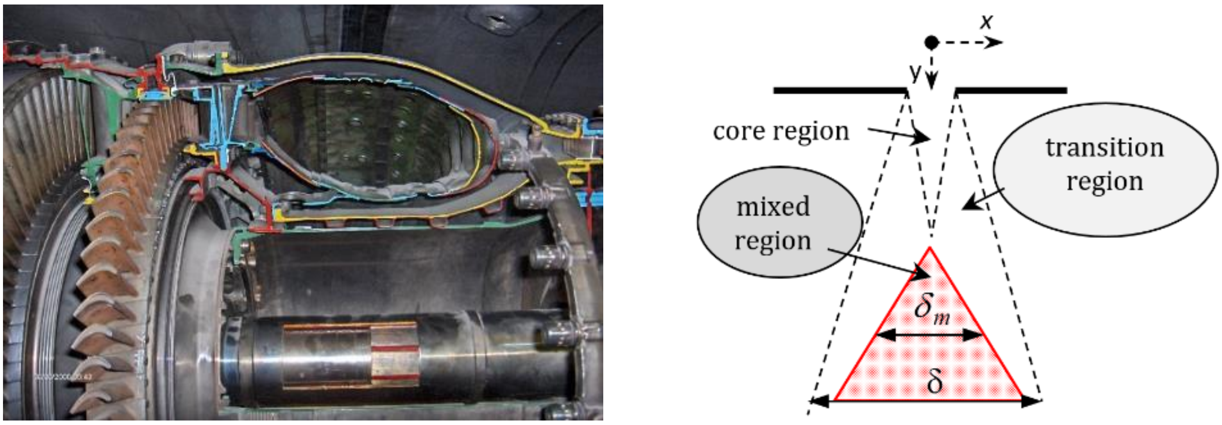
Abstract
The paper presents some results regarding the influence of the flame tube shape upon the combustion process in a turbojet engine. Also, it aims to present the results obtained following the research done for the identification of a turbojet engine's optimal combustion chamber geometry, characterized by as small as possible sizes with enhanced availabilities for air circulation in the primary combustion zone, in order to obtain a higher turbulence and an optimal radial temperature distribution at the entry to the stator of the first turbine stage in order to assure a minimal thermal load at the root of the blades. Similarly, the paper focuses on possibilities of positioning the holes of the flame tube to be more efficient, whereas its walls to be less thermally loaded and to obtain a low level of atmospheric pollution. The numerical results were obtained with Fluent CFD software and furthermore, there have been identified some solutions to the differential equation for reduced temperature (adimensional) under imposed initial conditions, by means of Maple software program.

Keywords
combustion chamber, flame tube, turbojet, noise and pollution

1. Introduction

The combustion chamber is one of the most important constructive element of the aircraft engines, which has an important role in the fuel chemical energy conversion and the engine noise and pollution effects. The pollution involves unburned hydrocarbons, smoke and oxides of nitrogen. Gradually steps have been taken to rein in these nuisances by international agreements with regulations both for combustion product emissions near airports and for noise during take-off and landing. The international limits on noise are above the noise produced by new aircraft with modern engines that the international limit serves merely as the benchmark from which the margin of lower noise is set. The effect of noise regulation has led to very significant alterations to the engine, with consequent reduction in aircraft performance and a larger fuel burn, because at take off the largest noise source is still produced by the jet, and no methods of jet noise reduction is more certain than reducing the jet velocity, this requiring bigger engines for the same thrust. Environmental issues are becoming more important, with the emphasis in regulation currently being around the airports. The potentially more important effects of emissions in the upper atmosphere will be the subject of the future regulation. Limiting noise during take-off and landing has already lead to the engine layout being modified so that it is no longer optimum for range or fuel consumption. To achieve smallest pressure lost and low emission in a small volume (like in the aero-engine combustion chambers) the flow must be turbulent (figure 1). The flow in same combustors is dominated by complex turbulent motions which cannot be fully described quantitatively.

The level of emission of a pollutant can be considered important for two different points of view. One relates to the effect on the environment, such as global warming, climate change and ozone depletion, being a problem during cruise when most of the fuel is burned and the other relates to the immediate surroundings of the airports [2]. At present legislation applies only to operation near the airports, even though the consequences of aviation emissions during cruise are potentially far more important. This level of emission and pollutant is expressed in terms of emissions index, which is the emissions in grams for each kilogram of fuel burned. The CO_2 and H_2O are unavoidable consequences of the burning of hydrocarbon fuel, which can be reduced by making the engine more efficient and reducing the drag of the aircraft. The oxides of sulphur SO_x are determined wholly by the amount of sulphur in the fuel after refining rather than by the engine, the level of sulphur being normally kept very low. Oxides of nitrogen, NO_x, unburned hydrocarbons, CO and particulates (mainly soot, which is unburned carbon) depend on the performance of the combustion chamber and in an ideal one would be virtually zero. There is growing concern about the effect of CO_2 and NO_x introduced by air traffic into the upper atmosphere. Currently about 2 – 3 % of the CO_2 is produced by aviation. The influence of NO_x is upon the ozone and the greenhouse effect. The allowable amount of NO_x is proportional to the pressure ratio to compensate for the additional difficulty in reducing this pollutant when compressor outlet temperature increases.



(a) (b)

Fig. 1. Combustion chamber shape (a) and the mixing flow model (b)

The emission index used in the regulations by the International Civil Aviation Organization, which is the specialized agency that has global responsibility for the establishment of standards, recommended practices and guidance on various aspects of international civil aviation, including environmental protection, provides scaling for engine size.

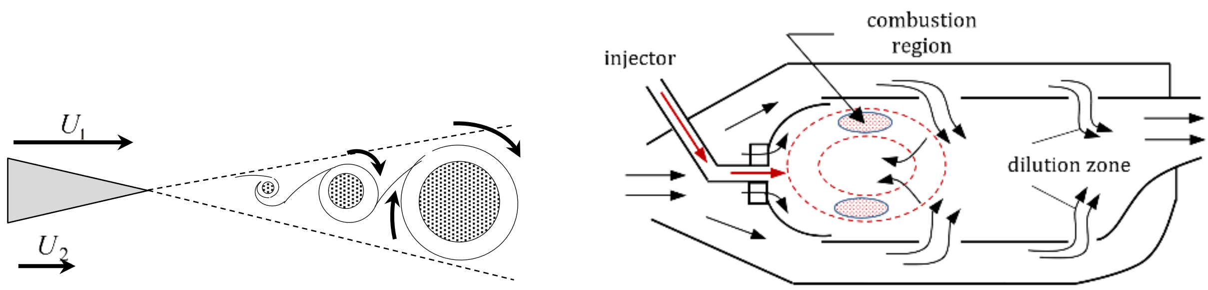
2. Aircraft Engine Combustion Chamber

The power that results from gas pressure and shear stress produces a moment about the axis of rotation that can be assessed. On the other hand, this moment of rotation can be estimated based on the parameters of the combustion gases in the inlet and exit sections of the turbine. Since the tangential stresses outside and inside the flow volume are low, the work of the blades can be calculated from measuring the gas velocity components in the inlet and exit sections [2, 3].

Gas temperature at the turbine inlet is important because its increase can lead to a higher pressure ratio. Also, reducing air temperature at the compressor inlet has the same effect as the increase of temperature at the turbine inlet. Turbine blades can operate at higher temperatures if they are cooled with compressor air. Their thermal fatigue doesn't depend as much on operation time as on the number of times they have been started, accelerated and stopped.

There is a balance between turbine inlet temperatures and the cooling air flow rate because the decrease of the air flow rate that reaches the combustion chamber reduces the efficiency and thrust of the engine. Inside the flame tube of a combustion chamber for an aero-jet-engine a great amount of energy release takes place per volume unit; moreover, the combustion chamber volume has to be as small as possible in order to reduce the distance between compressor and turbine, and, implicitly, to shorten the shaft. The high rate of energy release within a small volume is possible due to high air pressure and an increased level of turbulence. In the area where the fuel is injected into the flame tube, the ratio between fuel flow rate and air flow rate is close to the stoichiometric ratio and, through the holes situated on the flame tube, supplementary air is admitted in order to decrease gas temperature at the turbine inlet to admissible levels for the blades to resist. The blade stress is higher at the root, therefore, it is necessary for the temperature to be lower here than on the tip [4, 5].

The flow field model in an aircraft engine with an axial turbine is based on streamlines, surfaces and flow tubes. Fluid streamlines and paths coincide in the case of steady flows which is a supplementary hypothesis in the study of gas turbine engines. If two streams of fluid have different molecular characteristics the shear layer between these flows is a mixed layer generated at the interface between surfaces with different speeds (figure 2). The force of the vortex generated by the surfaces depends on the amount of speed and the thermodynamic characteristics of the working fluid.



(a) (b)

Fig. 2. Streams mixing (a) and flame tube geometry (b)

A very important issue in the design of a flame tube is the asymmetric distribution of holes through which air enters the tube. Currently used engines have a symmetric linear and circumferential distribution which doesn't provide a high turbulence level, especially in the first area, that of mixture between air and fuel [6].

In order to prevent the flame from blowing out, the speed of the air-fuel mixture must be lower in the recirculation area where the fuel is evaporated and mixed with the air coming from the compressor, approaching the stoichiometric mixture. A few simplifications of flow conditions are necessary in order to generate the process of combustion: the air flow rate that transits the compressor equals the rate of gases through the combustion chamber.

3. Diffusion Flame Model

In order to solve the problem of diffusion flame in gas turbine engines, where the fuel and oxidizer enter the combustion chamber separately, it is necessary to decouple the two main processes: the mixing and the combustion (once the mixing is achieved). The idealized case for diffusion flames corresponds to the following assumptions: thermodynamic pressure is constant; all the diffusion coefficients of chemical species are equal; the heat capacities of chemical species are equal and independent of temperature [1]. For the case that involves only fuel, oxidizer and product of reactions, the balance equation, without source terms, has the following expression:

$$\frac{\partial \rho z_k}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i z_k\right)=\frac{\partial}{\partial x_i}\left(\rho D \frac{\partial z_k}{\partial x_i}\right) \tag{1}$$

where z_k is the scalar which follows the conservation equations for fuel, F and oxidizer, O, and temperature T, $z_1 = sY_F - Y_O$; $z_2 = \frac{C_P T}{Q} + Y_F$; $z_3 = s\frac{C_P T}{Q} + Y_O$; s – mass stoichiometric ratio, $s = \left(Y_O/Y_F\right)_{st}$; Y_F and Y_O – mass fractions of fuel and oxidizer; C_p – the heat capacity at constant pressure of the mixture, J/(kg·K); Q – heat of reaction, kJ/kg; ρ – mixture density, kg/m^3; D – diffusion coefficient m^2/s; x_i – spatial coordinates, m; and u_i – velocity projections on the spatial coordinates, m/s.

Taking into account the boundary conditions for the scalars Z_i, one could define the normalized z_i variables by the expression

$$z_i = \frac{Z_i - Z_i^0}{Z_i^F - Z_i^0} \tag{2}$$

for $i = 1, 2, 3$ which follow the same balance equation and have the same boundary conditions (z_i = 1 in the fuel flow stream and z_i = 0 in the oxidizer stream). The mixture fraction z measures the local ratio between fuel and oxidizer. For the simplified case where there is no fuel in the oxidizer stream and no oxygen in the fuel stream, the mixture fraction z could be expressed as

$$z = \frac{1}{\varphi + 1}\left(\varphi \frac{Y_F}{Y_F^0} - \frac{Y_O}{Y_O^0} + 1\right) \tag{3}$$

where $\varphi = sY_F^0 / Y_O^0$ represents the equivalence ratio which corresponds to the fuel and oxidizer mass fractions in pure fuel and oxidizer streams.

In a constant pressure flame case (like in the aircraft turbojet engine), density ρ and temperature T are linked by $\rho(z) = \rho_1(z) \cdot T_1(z) / T(z)$ and the equation (1) becomes

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x_i}(uz) = \frac{\partial}{\partial x}\left(D\frac{\partial z}{\partial x}\right) \tag{4}$$

with the initial conditions $z(x, t=0) = 1 - H(x)$, $z(-\infty, t) = 1$ and $z(+\infty, t) = 0$, which correspond to pure fuel for negative *x* and pure oxidizer for positive *x*.

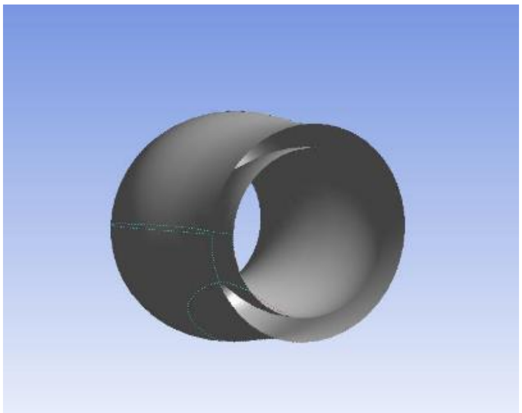
Assuming a constant diffusion coefficient D and not moving flow before ignition, the z balance equation (4) reduces to

$$\frac{\partial z}{\partial t} = D\frac{\partial^2 z}{\partial t^2} \tag{5}$$

The aircraft combustion chamber is fed by fuel mass flow rate $\dot{m}_F$ and oxidizer mass flow rate $\dot{m}_O$, therefore, the global equivalence ratio obtained if all fuel and oxidizer flow rates would mixt perfectly is $\varphi_g = \varphi \cdot \dot{m}_F / \dot{m}_O$.

4. Numerical Results

The CFD simulation for an inner combustion chamber with 24 injectors gave the following pictures (figures 3 ... 7).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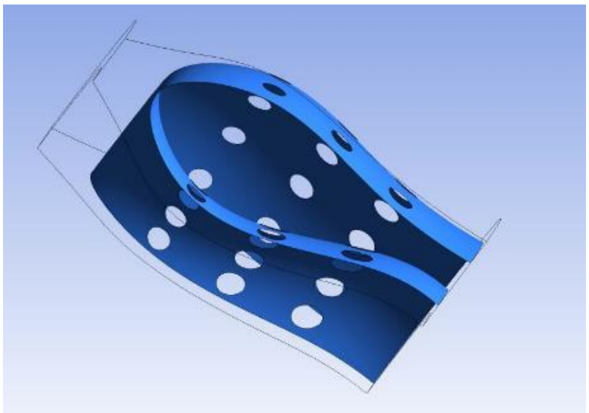
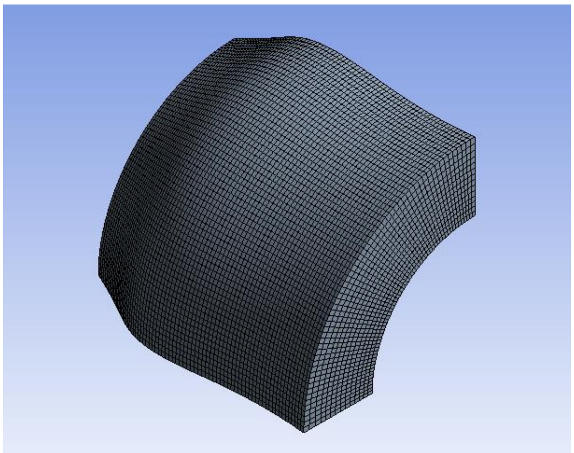

(b)

Fig. 3. The CFD geometry for the flame tube (a) and holes distribution (b)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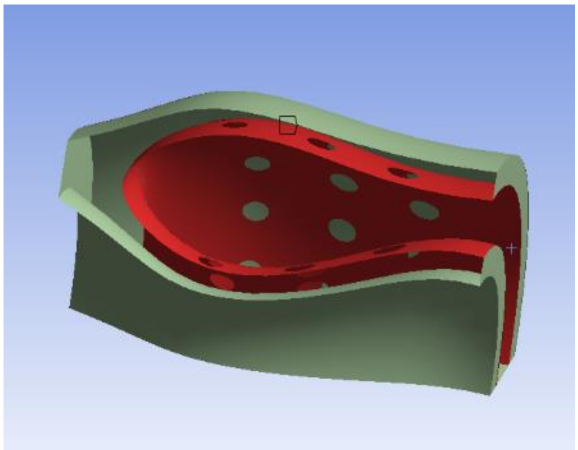
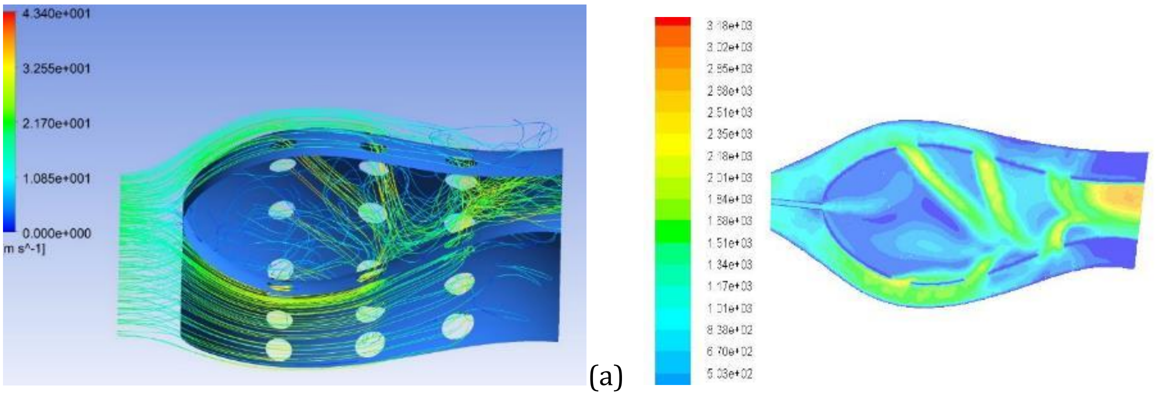
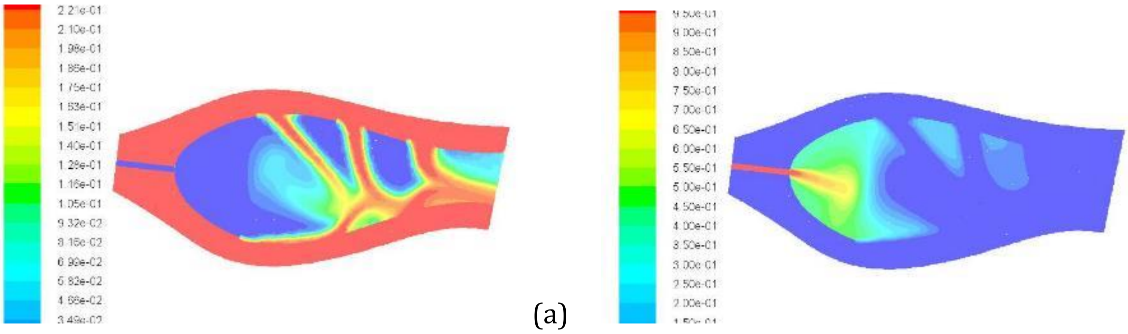

(b)

Fig. 4. Mesh domain (a) and main sections (b)



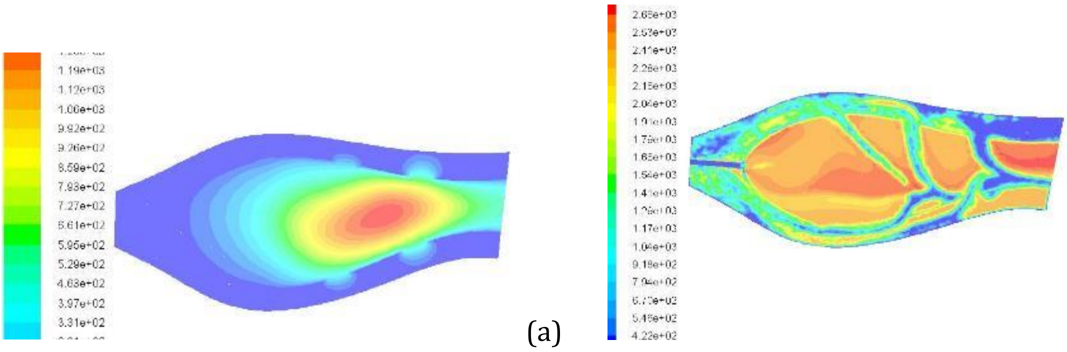
(a) (b)

Fig. 5. Stream lines (a) and velocity distribution (b)



(a) (b)

Fig. 6. O_2 mass fraction (a) and fuel mass fraction (b)



(a) (b)

Fig. 7. Turbulent kinetic energy (a) and temperature distribution (b)

5. Conclusions

The design of the flame tubes therefore continues to relay to a considerable extent on insight and experience, the CFD software being a very important tools in the combustion modeling. The problem of reducing NO_x is important because it is formed in chemical reactions which are much slower than those leading to the formation of CO_2 and H_2O but the rate of formation of NO_x increases rapidly with temperature, which means that the amount created depends on both the temperature and the residence time at that temperature. The long residence time which would reduce CO, unburned hydrocarbons and smoke would favor the formation of NO_x. The standard approach to reducing NO_x is to minimize the residence time at high temperature as much as possible, with necessity to burn off soot, unburned hydrocarbons and CO, and also to keep an acceptable level of combustion efficiency at high altitude and low fuel flow rate. The strong dependence of NO_x formation on temperature means that there is a tendency for the level to increase as the temperature of air entering the combustion chamber increases and as the temperature leaving the combustor increases. For very low level of emissions one solution could be the use of different injectors in different locations of the flame tube. Another solution could be the arrangement of premixed combustion, where the fuel and the air are mixed and partially vaporized before entering the combustion region. A potential advantage of premixed is that it avoids the near-stoichiometric burning which takes place in most present-day flame tubes as fuel and air diffuse together and burn with high local temperatures.

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