

# Flow field analysis of turbojet combustion chamber

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**Abstract.** The paper presents some results regarding the identification of a turbojet engine’s optimal combustion chamber geometry, characterized by small dimensions, with enhanced possibilities for air and fuel mixture circulation in the primary combustion zone in order to obtain good residence time in the flame tube, higher turbulence and optimal radial temperature distribution. Also, it deals with the identification of some solutions of the differential equation for reduced temperature under imposed initial conditions. Some models of combustion numerical computations have been applied, as presented by the specialized documentation, to establish the combustion rate and flame speed for laminar combustion. The geometry of a combustion chamber, with twenty-four injectors and size comparable to a real combustion chamber, has been created in order to obtain the speed and temperature flow field within the flame tube. The major conclusion of the current research is that the distribution of holes within the liner does not need to be symmetric, which means that they have to be positioned in such a manner as to ensure a higher degree of turbulence in the combustion primary zone and a helical shape of stream lines in the proximity of the walls of the flame tube.

## 1 Introduction

The combustion chamber is one of the most important constructive elements of an aircraft engine and has an important role in the conversion of energy from chemical to kinetic. A reaction between oxygen in the air and fuel takes place upon the energetic collision between the molecules, which leads to a chemical reaction. The frequency of those collisions gives the rate of reaction, the time and length scale, and also the mixture properties. The curve of adiabatic temperature, regarded as a function of the equivalence ratio,  $\phi$ , has a maximum value at  $\phi = 1$ , but the actual temperature falls below the theoretical prediction, starting around an equivalence ratio of 0,4-0,5, due to the dissociation reactions [1]. This range of equivalence ratio corresponds to a fuel-to-air ratio of 2,5-3,5 and, taking into account the fact that gas temperature decreases after the point where  $\phi = 1$ , a burner exit temperature can be reached from either the fuel-lean or the fuel-rich side of the stoichiometric point. The combustion process depends on the degree of turbulence and energy release leads to large alteration in turbulence intensity [2, 3]. The current flame tubes are based on experimental data and less so on theoretical, analytical and CFD calculation because the old models of the combustion chamber were improved slowly due to their complexity, and the advanced combustion algorithms being developed now are based on powerful computers. The chemical process of combustion normally takes place very quickly but the rate falls roughly as the square of the pressure. The burning of liquid droplets requires the liquid to evaporate and then for the fuel and air to diffuse together to form locally a near stoichiometric mixture [4]. This process is much slower than the main chemical

process of combustion. A schemata of a combustion chamber airflow field is presented in Fig. 1. The air entering the dilution region creates a layer of cool air on the walls and changes the exit temperature so that it is suitable for the first turbine stage.

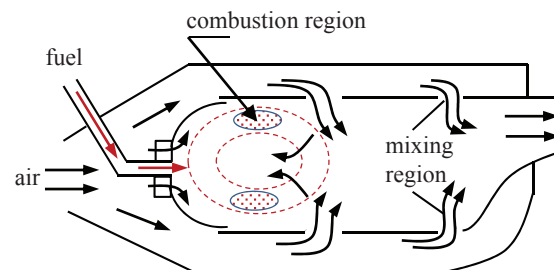


Fig. 1. Flow field model.

For the aircraft engine combustion chamber, the primary zone can be approximated with a premixed combustion, where the flame starts, propagating initially as a laminar flame and later developing into a turbulent flame. The experimental results presented in some publications [5] show a laminar flame speed of 0,5 m/s. The effect of turbulence consists in an enhancement of the energy transfer and an increase of the residence time in the flame tube volume. The performance of aircraft gas turbine engines depends extensively on the amount of energy release in the combustion chamber, as a result of air-fuel mixture burning, of the reaction rate, and of the time when combustion occurs, all of these being more or less determined by the combustion chamber’s geometry and size.

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Designing an aircraft engine involves knowledge in various academic areas such as fluid mechanics, thermodynamics, mathematics or materials science [6]. Controlling a system of this type implies an accurate understanding of each and every subsystem operation mode as well as the assembly of these sub-systems, regarded as a whole. The content of this study is based on the mathematical approach presented in reference [1].

## 2 Premixed flame model

The simplified conservation equations for laminar one-dimensional premixed flames are [1]

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} &= 0; \\ \frac{\partial \rho Y_k}{\partial t} + \frac{\partial}{\partial x} [\rho(u + V_k)Y_k] &= \dot{\omega}_k; \\ \rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) &= - \sum_{k=1}^N h_k \dot{\omega}_k + \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) - \\ &\quad - \rho \frac{\partial T}{\partial x} \left( \sum_{k=1}^N C_{p,k} Y_k V_k \right), \end{aligned} \quad (1)$$

where  $Y_k$  is the mass fraction of species  $k$  in the reaction mixture,  $V_k$  is the diffusion velocity,  $\dot{\omega}_k$  is the reaction rate,  $C_p$  and  $C_{p,k}$  are the heat capacities at constant pressure of the mixture and of the species  $k$  respectively,  $h_k$  the enthalpy,  $\lambda$  – heat diffusion coefficient,  $\rho$  – mixture density,  $T$  – temperature,  $u$  – axial velocity.

Typical inlet conditions are  $u|_{x=0} = u_1$ ,  $T|_{x=0} = T_1$  and also the flame must be ignited and the temperature must reach the adiabatic flame temperature at the outlet of the flow domain.

The basic model configuration for one-dimensional reactive flow is presented in Fig. 2.

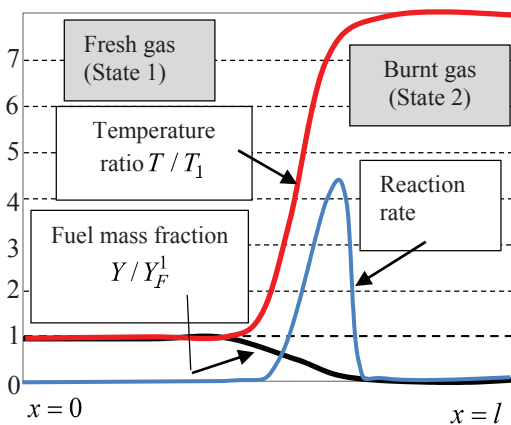


Fig. 2. Combustion computation model.

After some assumptions, the system of equations (1) can be transformed in the reference frame of the flame moving at speed  $s_L$  to the resolution of a single equation for the variable  $\theta = (T - T_1)/(T_2 - T_1)$ . The link between the reduced temperature,  $\theta$ , and reduced fuel mass fraction  $Y = Y_F / Y_F^1$  is  $\theta + Y = 1$ , so  $\theta$  varies from 0 where  $T = T_1$

to 1 in the burnt gases, and  $Y$  goes from 1 in the fresh gases to 0 in the burnt gases. The frequency of the collisions per unit volume contributes to the reaction rate in the form proposed by Arrhenius,  $p^n f(T) e^{-E_a/(RT)}$ , where  $p$  is the pressure,  $T$  is the reactant's absolute temperature,  $E_a$  is the activation energy and  $R$  is the universal gas constant [7].

In the aircraft engine combustion chamber, the pressure is approximately constant along the flame tube, so gas density can be expressed by the equation  $p = \rho RT$  (the law of perfect gases) as follows:

$$\rho = \rho_1 \frac{T_1}{T} = \rho_1 \frac{1}{1 + \alpha \theta / (1 - \alpha)}, \quad (2)$$

where  $\alpha = (T_2 - T_1)/T_2$ .

The exponential expression of the reaction rate,  $e^{-E_a/(RT)}$  can be transformed into  $e^{-\frac{\beta}{\alpha} \frac{\beta(1-\theta)}{1-\alpha(1-\theta)}}$  with  $\beta = \alpha T_{a1}/T_2$ , where  $T_{a1}$  is the activation temperature; therefore the reduced reaction rate can be expressed as

$$\frac{\dot{\omega}_F}{\rho_1 Y_F^1 B_1} = T^{\beta_1} e^{-\frac{\beta}{\alpha} \frac{\beta(1-\theta)}{1-\alpha(1-\theta)}} \frac{1 - \theta}{1 + \frac{\alpha \theta}{1 - \alpha}}, \quad (3)$$

where subscript  $F$  refers to the fuel,  $B_1$  is the reaction rate pre-exponential constant and  $\beta_1$  is the temperature exponent. Fig. 3 presents four lines corresponding to  $\alpha = 0,75$ ,  $\beta_1 = 0$  and different  $\beta$  exponents for a fuel inlet temperature of 300 K. The reduced reaction rate, expressed by  $\dot{\omega}_F / (\rho_1 Y_F^1 B_1)$ , has a maximum value for  $\theta = 1 - 1/(\alpha + \beta)$ . The four curves correspond to  $\beta = 6$ ,  $\beta = 6,5$ ;  $\beta = 7$  and  $\beta = 7,5$ .

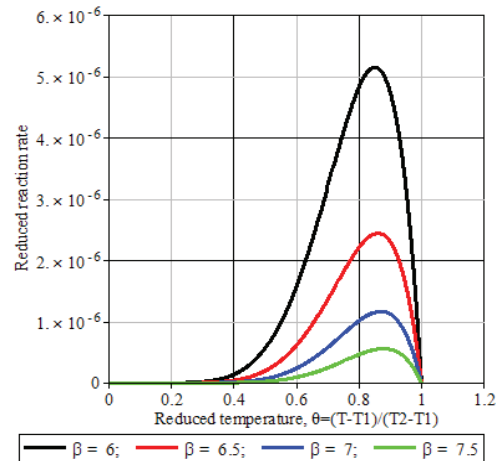


Fig. 3. The reduced reaction rate.

The combustion process of hydrocarbon fuels in air involves the collision of molecules (oxygen and fuel) and near stoichiometric combustion, and the reaction time takes a minimum of about 0,3 milliseconds. The reaction time scale may be approximated as

$$t_{reaction} = p^{-n} T^{-m} e^{\frac{E_a}{RT}}. \quad (4)$$

The residence timescale in an aircraft gas turbine combustor is longer compared with the reaction timescale.

### 3 Diffusion flame model

In a gas turbine engine, the fuel and oxidizer enter the combustion chamber separately; therefore, to solve the problem of the diffusion flame it is necessary to decouple these two main processes, namely the mixing and the combustion. In addition, some assumptions are made: the heat capacities of chemical species are equal and independent of temperature; the pressure is constant; the chemical species have the same heat capacities [8, 9]. The balance equation for the case that involves only fuel and oxidizer has the expression:

$$\frac{\partial \rho z_k}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i z_k) = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial z_k}{\partial x_i} \right), \quad (5)$$

where  $z_k$  has the expressions  $z_1 = s Y_F - Y_O$ ,  $z_2 = \frac{C_p T}{Q} + Y_F$  and  $z_3 = s \frac{C_p T}{Q} + Y_O$ , according to the conservation equations for fuel,  $F$ , and oxidizer,  $O$ , and temperature  $T$ ,  $s = \left( \frac{Y_O}{Y_F} \right)_{st}$ ,  $Y_F$  and  $Y_O$  are the mass fractions of fuel and oxidizer,  $D$  – diffusion coefficient [ $\text{m}^2/\text{s}$ ],  $Q$  – heat of reaction, [ $\text{kJ}/\text{kg}$ ],  $C_p$   $C_p$  – the mixture heat capacity [ $\text{J}/(\text{kg}\cdot\text{K})$ ],  $x_i$  – spatial coordinates and  $u_i$  – velocities spatial projections.

The normalized variables  $z_i$  for the scalars  $Z_i$  are defined by the expression

$$z_i = \frac{Z_i - Z_i^0}{Z_i^F - Z_i^0} \quad (6)$$

for  $i = 1, 2, 3$ , and they have the same boundary conditions and follow the same balance equation, which means that the mixture fraction measures the local ratio between the fuel and oxidizer and has the same boundary. The expression of the mixture fraction is

$$z = \frac{1}{\varphi + 1} \left( \varphi \frac{Y_F}{Y_F^0} - \frac{Y_O}{Y_O^0} + 1 \right), \quad (7)$$

where  $\varphi = s Y_F^0 / Y_O^0$ .

Equation (5) can be simplified for the case that corresponds to the aircraft turbojet engine, where the pressure in the combustion chamber is approximately constant, having the form

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x_i} (u z) = \frac{\partial}{\partial x_i} \left( D \frac{\partial z}{\partial x_i} \right) \quad (8)$$

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

The above equation (8) is reduced to

$$\frac{\partial z}{\partial t} = D \frac{\partial^2 z}{\partial t^2}, \quad (9)$$

assuming a constant diffusion coefficient and not moving before ignition.

This equation can be transformed by replacing variables  $x$  and  $t$  with  $\eta = x / (2\sqrt{Dt})$ , which leads to

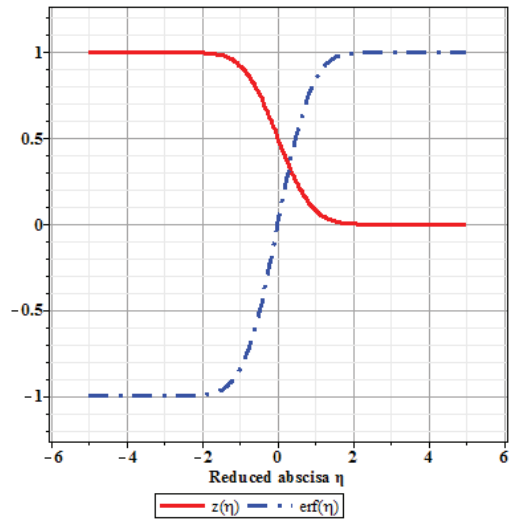
$$\frac{\partial^2 z}{\partial \eta^2} + 2\eta \frac{\partial z}{\partial \eta} = 0. \quad (10)$$

The MapleSoft solution of Equation (10) is:

$z(\eta) = \frac{1}{2} - \frac{1}{2} \text{erf}(\eta)$ , where the exponential error function  $\text{erf}(\eta)$  is defined as

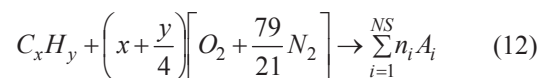
$$\text{erf}(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta e^{-x^2} dx. \quad (11)$$

Fig. 4 shows the plotting of  $z(\eta)$  and  $\text{erf}(\eta)$  for  $\eta$  from  $-5$  to  $5$ .

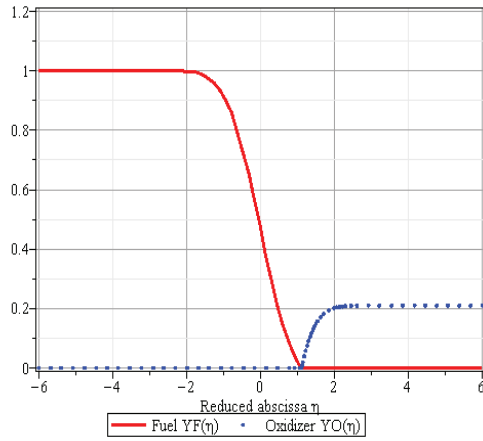


**Fig. 4.** The mixture fraction  $z(\eta)$  and the exponential error function  $\text{erf}(\eta)$ .

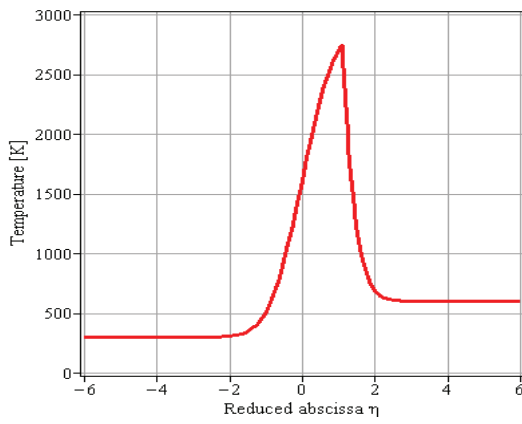
For the assumption of infinitely fast chemistry, where the fuel and oxidizer cannot be found together, functions  $T(z)$ ,  $Y_F(z)$  and  $Y_O(z)$  for a one-dimensional flame of jet fuel ( $\text{C}_{12}\text{H}_{23}$ ) and air with  $Y_F^0 = 1$  and  $Y_O^0 = 0,21$  are presented in Fig. 5. Fuel and air temperatures are 300 K and 600 K and the fuel heat of the reaction is 43000 kJ/kg. The curve of the temperature is presented in Fig. 6. The atom-balance equation for an ideal mixture of fuel and air



gives the following mass stoichiometric and equivalence ratios for jet fuel:  $s = 3,4$ ;  $\varphi = 16,19$ ;  $z_{st} = 0,0581$ .



**Fig. 5.** Flame structure for  $C_{12}H_{23}$  fuel.



**Fig. 6.** The gas temperature.

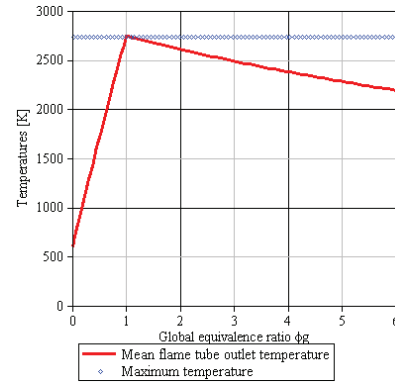
The aircraft combustion chamber is fed by fuel mass flow rate  $\dot{m}_F$  and oxidizer mass flow rate  $\dot{m}_O$ ; therefore, the global equivalence ratio obtained if all fuel and oxidizer flow rates are perfectly mixed is  $\varphi_g = \varphi \dot{m}_F / \dot{m}_O$ . The mean temperatures after complete combustion,  $T_m$ , and maximum temperature,  $T_{ad}$ , are

$$T_m = \frac{T_F^0}{1 + \frac{\varphi}{\varphi_g}} + \frac{T_O^0}{1 + \frac{\varphi_g}{\varphi}} + \frac{QY_F^0}{C_P(\varphi + \varphi_g)} \min(\varphi_g, 1); \quad (13)$$

$$T_{ad} = \frac{T_F^0 + \varphi T_O^0}{1 + \varphi} + \frac{QY_F^0}{C_P(\varphi + 1)}. \quad (14)$$

The effect of the initial temperature on the adiabatic temperature is that only a half of the inlet temperature rise appears as rise in the final flame temperature.

Fig. 7 shows the variation of these temperatures versus the global equivalence ratio,  $\varphi_g$  for the aircraft fuel kerosene ( $C_{12}H_{23}$ ) and air. Both temperatures are equal for  $\varphi_g = 1$ . Regarding aircraft engine pollution, the nitric oxide  $NO_x$  is mainly controlled by temperature and regardless of the  $\dot{m}_F$ ,  $\dot{m}_O$  and  $\varphi_g$  parameters the diffusion flame always reaches the same maximum temperature  $T_{ad}$ , and generates high  $NO_x$  pollutant in the stoichiometric regions, namely, in the vicinity of  $z = z_{st}$ .



**Fig. 7.** Mean outlet and maximum temperatures.

The flame position  $x_f$  can be determined from the mixture fraction equation

$$z_{st} = \frac{1}{2} [1 - \text{erf}(\eta_f)] \Rightarrow \eta_f = \text{erf}^{-1}(1 - 2z_{st}) = 1,110$$

therefore,  $x_f = 2\sqrt{D \cdot t}$ ;  $\eta_{st} = 2.220\sqrt{D \cdot t}$ .

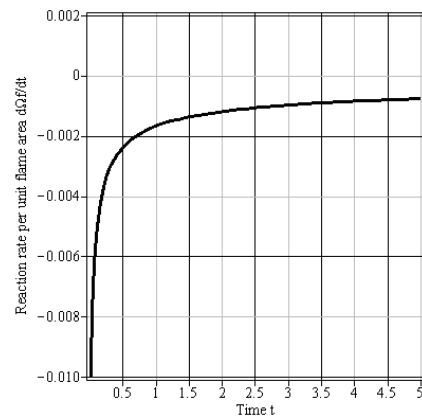
For stoichiometric conditions, the flame velocity remains at  $x_f = 0$  and is moving toward the fuel for  $\varphi < 1$  and toward the oxidizer for  $\varphi > 1$ . Taking into account the conservation equation for fuel,

$$\frac{\partial \rho Y_F}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i Y_F) = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial Y_F}{\partial x_i} \right) + \dot{\omega}_F \quad (15)$$

in the case of constant density and zero velocity flow, the fuel reaction rate per unit flame area  $\dot{\Omega}_F$ , can be obtained by integrating  $\dot{\omega}_f$  between two points located on both sides of the flame front, delimited by  $x_f$  on the right and the left hand sides [1]:

$$\dot{\Omega}_f = - \int_{x_f^-}^{x_f^+} \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial Y_F}{\partial x_i} \right) dx = - \frac{\rho}{2} \frac{Y_F}{1 - z_{st}} \sqrt{\frac{D}{\pi}} e^{-\eta^2}. \quad (16)$$

Fig. 8 displays  $\dot{\Omega}_F$ , where one can see that it goes to zero like  $1/\sqrt{t}$ , thus for keeping a diffusion flame burning, the reactants must be pushed against each other.



**Fig. 8.** The fuel reaction rate per unit flame area.

## 4 Numerical results

In order to simulate gas flow, a combustion chamber was built with a flame tube perforated with three rows of holes. The dimensions of the combustion chamber are close to those of a real combustion chamber, with 24 injectors. The range for the injectors' distribution is 0.35 m, whereas the supplied mass flow rate is 75 kg/s at maximum rev of the engine. Computational Fluid Dynamics calculations have been made for two cases, firstly for a flame tube with three rows of holes of the same diameter, and secondly for a flame tube with three rows of holes of various diameters. Some of the results and combustion chamber shapes are presented in the following images.

Fig. 9 illustrates the geometry of the flame tube and Fig. 10 shows the mesh domain. The first simulation of the flow through the flame tube was achieved for a uniform distribution of holes on the flame tube surface, in order to compare it with a flame tube with asymmetrically positioned holes.

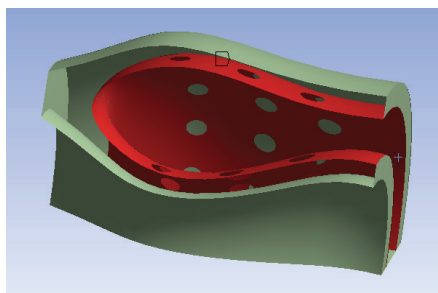


Fig. 9. The 3D view of the flame tube.

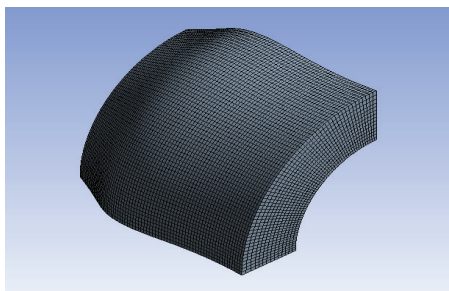


Fig. 10. The mesh domain.

Figures 11 and 12 show the current lines contour for the combustion chamber with six injectors in cases of symmetric and asymmetric distribution of holes. In the primary area of the flame tube the turbulence degree must be much higher.

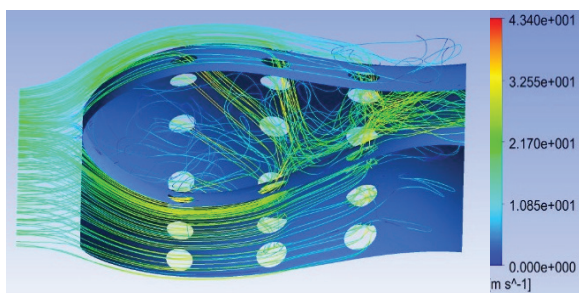


Fig. 11. The flow field lines contour.

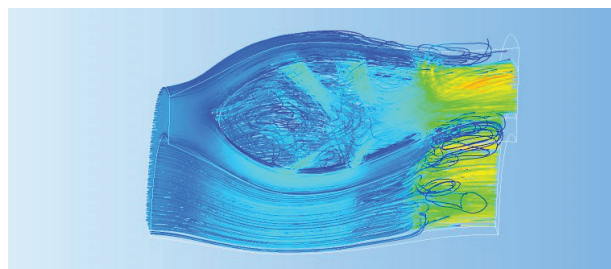


Fig. 12. The inner flow.

## 5 Conclusions

The prototype of the flame tube with asymmetric distribution of holes on its surface ensures a higher turbulence in the secondary area. Therefore, the residence time of the air-fuel mixture in the combustion chamber is higher, which allows for the complete burning of the mixture. The asymmetric distribution of the holes may lead to a helicoidal movement with a similar rotation direction to that of the turbine engine, which leads to a decrease in pressure losses in the stator of the first stage of the turbine.

The results obtained allow for the evaluation of the temperature field in the radial direction at the combustion chamber exit, in order that there are not high temperatures at the base of the rotor blades because they are subjected to mechanical stress in this root section. Similarly, the possibility of fuel injection through the stator blades can be further analysed, so that the maximum temperature in the flame tube can be reduced, and this difference in temperature be compensated by burning a certain amount of fuel through the stator wall of the first stage of the turbine.

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