NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF LASER IGNITION IN COMBUSTION CHAMBERS

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Abstract

In this paper the results of complex researches of the laser ignition in high-sized combustion chambers are presented. During this study the series of experiments and also the development of the numerical model of laser ignition were provided. Numerical simulations of mixing and ignition processes of non-hypergolic components of hydrogen-oxygen were integrated in a process of the development of the laser ignition system.

The results of this work confirmed the possibility of prediction of laser ignition process using the numerical simulation.

1 Introduction

One of the main problems of aerospace industry is the efficiency of energy system. This general problem divided by many other aspects, like an economy, viability, productivity and others. All of these tasks are correlate with each other and an advantage in one of them, even in one part of a big system, leads to increasing of the general efficiency of the entire system.

The problem of ignition in combustion chambers is very important for all performance of engine. It is strictly necessary to obtain a sustainable ignition in real conditions of engine life-cycle, and moreover, the ignition must be as efficient as possible. In addition to these requirements, the ignition must be economical and ready to multiple usages. The conventional ignition systems satisfy to these requirements in general, but they have many drawbacks and limitations, and for modern engine system it is necessary to use such system which will have all of its advantages and avoid its drawbacks. The laser ignition has the opportunities to be such system and replace the conventional systems in rocket space industry in nearest future.

This paper is divided into the several sections. Section 2 describes the general principles of laser ignition, its advantages and briefly describes recent investigations on this theme. In section 3 the series of experiments that were carried out in FSUE "Keldysh Research Center" will be described. Section 4 consists of the mathematical model construction and results of the numerical simulation of mixing and ignition processes. In sections 5 the conclusions will be discussed.

2 The fundamentals of laser ignition

Ignition occurs when the number of radicals in a medium is enough to start chain reactions until a sustainable combustion. In its turn, these reactions start when the energy of molecules exceeds some threshold value (which is called activation energy) [1, 2]. Here will be briefly described only one method, a non-resonant breakdown, which was used in current experimental investigations. The principle of this method is in laser energy focused in sufficiently small spot (several μm) and creating plasma with extremely high temperature (~10^6 K) due to the electron cascade mechanism. From plasma the energy is transferred to other molecules and ignition is starting. This ignition method requires a sufficiently small value of energy released from laser and permits to accurately locate the focusing point in a medium or on the surface of some solid body (even on the wall of the combustion chamber).

There are many investigations on the laser ignition were provided. Most of them investigate the laser ignition in small-sized rocket and internal combustion chambers in order to understand the main characteristics of such ignition method [3, 4, 5]. Also, the ignition for different propellants was tested (hydrogen-oxygen, methane-oxygen and biogas-air). In a part of numerical simulation, interesting work of LES simulation of the ignition process was provided [5], also one work with investigation of Pr_t and Sch_t influence on the mixing process was carried out [3]. In the research which carried out in [4], three types of ignition were observed: “smooth”, “transition” and “strong”.

On the results of these investigations it is possible to extract the main advantages of laser ignition method:

- Energy economy (the very small quantity of energy is required to create plasma source);
- Multiple usage and viability (much more working cycles than for conventional spark ignition systems);
- Large choice of locations of the focusing point in gas or on surface;
- Reliable ignition in a wide range of pressures and equivalence ratios.

3 Experimental investigations of laser ignition

In Russia the experiments on the laser ignition in rocket combustion chambers were provided by FSUE “Keldysh Research Centre”. The recent investigations were made for rocket engines of small thrust [6], for laser ignition in igniters [7] and for model combustion chambers [8]. This paper will describe the experiments that were made for model combustion chambers with non-hypergolic components of hydrogen-oxygen and methane-oxygen.

3.1 Experimental setup

The experiments on the laser ignition were carried out on the stand of FSUE “Keldysh Research Centre” with a fuel feed system for gaseous and liquid components. During the experiments the following parameters were measured: the pressure values of the components in a tank, mass flow rates at the exit of the tank and the overall mass flow of the components and equivalence ratio were calculated by the experimental measurement system.

There have been tested two possible locations of laser: on the injector head coaxial to the combustion chamber and normal to its axis on the wall of the chamber. At axial location the focusing point was located at the 8 mm from the bottom; with a normal positioning the laser was located at the 50 mm from the bottom and the focusing point had two locations: at the 5 mm from the wall and at the opposing wall of the chamber.

Figure 1 shows the general view of the model combustion chamber which was used in the experiments. The injector head and the wall of the chamber are water-cooling (except the laser section). The internal volume of the chamber is 2260 mm^3. On the figure 1a the normal location of the laser is presented and the figure 1b shows the axial location.

In the experimental scheme the coaxially-jet mixing scheme for gaseous components was used with the 24 jets of fuel and 3 jets of oxygen. Oxygen jets were located at 23° to the chamber axis. Two pairs of fuel and oxygen was tested: hydrogen-oxygen and methane-oxygen.

For the experiments was used the laser Yag:Nd with the passive Q-switching and the active element from aluminium-ytrium garnet, activated by neodymium. The series of 10 impulses was generated with the energy of the impulse E_i=35 mJ.

In the experiments the following parameters were tested:

- components mass flow rate (48-54 g/s for hydrogen-oxygen and 41-58 g/s for methane-oxygen);
- equivalence ratios (0.6-0.8 for hydrogen-oxygen and 0.33-1.1 for methane-oxygen);
- laser frequency (10 and 20 Hz);

- delay in supply of fuel (from 0 to 0.2 s of oxygen supply before the start of the fuel supply);

3.2 Experimental results

Over 100 tests were made during the experiments. All of the ignition tests were successful. For the pair of hydrogen-oxygen, three types of ignition were observed: “smooth”, “transition” and “strong”, which are similar to [4]. The “strong” type of ignition was observed with the laser frequency of 10 Hz. After changing the frequency to 20 Hz the character of ignition became smoother. The cause of this effect may be in larger residence time of components in the combustion chamber before they has been ignited. We could assume that the ignition delay is equal to the interval between laser impulses, and the residence time is equal to:

$$\tau_{res} = \frac{V_{chamber}\rho_{chamber}}{G}, \qquad (1)$$

where $V_{chamber}$ is the chamber volume, $\rho_{chamber}$ is the mean components density in the chamber, G is the mass flow of the components. For the current experiments $\tau_{res} = 20 \div 50$ ms.

For this estimation we obtain that for the laser frequency of 10 Hz ignition delay is much more than the residence time, and for the laser frequency of 20 Hz this values are comparable.

But, unlike of [4], for the methane-oxygen components there always was only the “smooth” regime of ignition. All of the tests showed smooth ignition, and for equivalence ratio of 0.33 the ignition was obtained, but the flame in the combustion chamber didn’t reach to stationary state. For the normal focusing of the laser with the components pair of methane-oxygen after the ignition the flame exhausted from nozzle, but then it disappeared until stationary flame was established.

Due to the size of the combustion chamber and its proximity to real conditions the measurement of the experimental parameters, like the temperature, pressure and the concentration of the components, was impossible. In all of experiments the direct measurements insert its influence on the experimental process, which should be taken into account. But for experiments of combustion, the direct measurements of any parameter inside the chamber are very difficult because of high temperatures and chemical activity of the flow. The schlieren images of flame, like in experiment of [5], during current experiments were impossible, therefore the verification of the ignition and combustion processes as well as overall understanding of its principles and characteristics could be realized due to the numerical simulation under the real experimental conditions.

4 Numerical simulation of laser ignition in combustion chambers

4.1 Numerical model

At this study, the numerical simulation was integrated into the process of the development of the laser ignition in model combustion chambers. Firstly, the numerical model was constructed for parametric studies of mixing processes during the “filling phase” before ignition in order to investigate the most advantages focusing locations and moments of ignition. After the experiments, the numerical simulation of ignition was provided for investigating the characteristics of the ignition process.

For the both simulations, the Reynolds-averaged Navier-Stokes equations were solved numerically. For the ignition modeling, the model of the laser source called “Energy Deposition” [5] was used in addition to chemical kinetic scheme of hydrogen oxidation.

The Reynolds-averaged Navier-Stokes equations have the following view:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \qquad (2)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j + \delta_{ij} p - \tau_{ij}\right) = 0 \qquad (3)$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\left(E + \frac{p}{\rho}\right) + q_{\lambda,j} + \right.$$
$$\left. + \sum_s V_{s,j}\rho_s h_s - u_i \tau_{ij}\right) = S_E \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho Y_s)+\frac{\partial}{\partial x_j}\left(\rho u_j Y_s+\rho Y_s\cdot V_{s,j}\right)=\dot{w}_s \quad (5)$$

where τ_{ij} is the viscous stress tensor, $q_{\lambda,j}$ is the thermal heat flux, $V_{s,j}$ is the species diffusion velocity, S_E and $\dot{w}_s$ are correspondingly the energy and the component sources. These equations were used with the equations for turbulent kinetic energy and turbulent dissipation rate (the k-epsilon turbulence model was used) [9]:

$$\frac{\partial}{\partial t}(\bar{\rho}K)+\frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j K\right)=\frac{\partial}{\partial x_j}\left[\frac{\mu_T}{\sigma_K}\frac{\partial K}{\partial x_j}\right]+\mathrm{P}_K-\bar{\rho}\varepsilon \quad (6)$$

$$\frac{\partial}{\partial t}(\bar{\rho}\varepsilon)+\frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j\varepsilon\right)=\frac{\partial}{\partial x_j}\left[\left(\frac{\mu_T}{\sigma_\varepsilon}+\mu\right)\frac{\partial \varepsilon}{\partial x_j}\right]+ \quad (7)$$
$$+\frac{\varepsilon}{K}\left(C_{\varepsilon 1}\mathrm{P}_K-C_{\varepsilon 2}\bar{\rho}\varepsilon\right)$$

The following formulation was used for turbulent viscosity modeling:

$$\mu_T=C_\mu\rho\frac{k^2}{\varepsilon} \quad (8)$$

where C_μ is constant [9]. For the mixing simulation, the energy and the component sources were equal to zero. For the ignition simulation the energy sources was formulated as [5]:

$$S_E(x,y,z,t)=\frac{\varepsilon_i}{4\pi^2\sigma_r^3\sigma_t}\cdot\exp\left[-\frac{1}{2}\left(\frac{r}{\sigma_r}\right)^2\right]\cdot \quad (9)$$
$$\cdot\exp\left[-\frac{1}{2}\left(\frac{t-t_0}{\sigma_t}\right)^2\right]$$

where ε_i is the total amount of deposited energy from a laser, σ_t is the temporal thickness of deposition, σ_r is the spatial thickness of deposition, r is the distance between the center of the focusing point and a point of space and t_0 is the time of maximum deposited energy.

The component source was defined as:

$$\dot{w}_S=W_C\sum_{k=1}^{K}\left(\nu_{kl}''-\nu_{kl}'\right)R_k \quad (10)$$

where W_C is the species molecular mass, ν_{kl}',ν_{kl}'' - stoichiometric coefficients of the species in the forward and backward reaction and R_K is the rate of reaction.

For current investigation, the kinetic scheme of Conaire [10] which consists of 19 reactions for 8 species: H_2, O_2, H, O, H, OH, HO_2, H_2O_2 (see table 1) has been used. The rates of the reactions 9 and 15 were taken depending on the pressure: for low pressure levels the first expressions were taken and for high pressure the second expressions were used for the simulation.

In the equations (4) and (5) Pr_t and Sc_t numbers were set to 0.7 in both of simulations – for mixing and for ignition processes.

4.2 The results of numerical simulation

The results of modeling of mixing phase were published in [11]. There will be presented a short review of this work as a part of entire development process.

The computational domain represented 3-D angular sector of 60° with symmetrical conditions on the cut planes. During the numerical simulation of the mixing all two pairs of components (hydrogen-oxygen and methane-oxygen) were simulated. Also, several locations for ignition points were probed during the simulation. At the figure 2 two charts of the equivalence ratio changing are presented (the ignition locations are the same as in the experiments). At the figure 2a the components of hydrogen-oxygen in two locations of the laser are presented and figure 2b shows the same conditions for methane-oxygen. It may be noticed that after 0.1÷0.15 seconds of filling phase the value of equivalence ratio establishes. Also, on these figures one could see that equivalence ratio in the normal location is closer to stoichiometric conditions than in axial location. After the numerical simulation of the mixing the recommendations on the possible location of the focusing point and on the moments of ignition were developed.

For the simulation of the ignition the following conditions have been used:

- hydrogen-oxygen components were simulated;
- oxygen delay in supply: 0.07 s from the simulation start;
- start of ignition: 0.12 s after simulation start;

- the focusing point was located at 8 mm from the chamber bottom on the axis of the chamber;
- the laser frequency is 20 Hz;
- the spatial width of energy deposition: 0.001 m;
- the temporal width of energy deposition: 25 μs;

The boundary conditions are presented in the table 2. At the start moment $(t_0 = 1\,s)$ the chamber is filled by the air with 0.232 mass fraction of oxygen and 0.768 mass fraction of nitrogen.

On the figure 3 the streamlines and vectors of the flow at the ignition moment are presented. The focusing point located in the backflow region, where the velocity of the flow in about 100 m/s. In this region the ignition is "separated" from the outer flow by the angular streams of the oxygen and ignition could grow without flame separation. The mean chamber pressure at the moment of ignition is about 2.5 atm. As we could see on the figure 4, the equivalence ratio at the ignition moment is not yet stabilized and equal to 0.35. There is some contradiction between initial mixing modeling and modeling of ignition which can be explained by the different mesh density. At the figure 5 the computational meshes for mixing and ignition simulation are presented. The computational mesh for the mixing simulation is coarsened and for ignition simulation it was refined in order to calculate the flame growth more precisely.

The simulation shows that to ignite the mixture within the combustion chamber it is enough just one laser impulse. The figure 6 shows the pressure changing at two locations: in the ignition point and on the chamber wall near the diffusor. At the moment of ignition at the focusing point there is a peak of pressure which is repeated again with double force. After some time this peak is observed at the second probe, and this means that the flame front have reached to diffusor. The value of the third peak is much smaller than the second, and it shows that the pressure field is smoothing.

The figure 7 shows the temperature distribution in the combustion chamber during the flame expansion. With these figures, the ignition process could be separated on the several regimes:

1) the flame kernel formed and become grow, saving it initial rounded form;
2) the form of flame is distorting, the flame moves upstream and anchors to the jet outlets;
3) the flame front is formed, and the flame is expanding downstream; the reactions are taking place into the thin region of flame front and near the jet outlets; within the flame the equilibrium state is reached (see figure 8);
4) the flame exhausted from the nozzle and is reaching to its stationary state.

During the ignition process the flame is anchoring to jet outlets and there are some backflows into the jet channels. This effect has been observed before [5], and because of it the computational domain was prolonged to the injector head.

The analysis of flow character should include a comparison with other researches of the laser ignition, and it is obviously that the regimes obtained in the simulation very good correlate to experiments and simulations of [3, 4, 5]. One can see that in all of these researches there are such regimes like spherical flame growth, flame kernel distortion and flame anchoring to the jets. In such researches like ignition and combustion investigations, where the measurements are difficult, the comparison with the investigations which were validated by obtained measurement data is a good path to verify the physical character of the numerical simulation.

Since 0.1 ms after the ignition the flame expanding velocity is greatly increases; it can be illustrated by the difference between figures 7d and 7e. And on the figure 8 the equivalence ratio distribution is presented. From this figure one can see that in the "outer" region of the flow the ratios of the components are stoichiometric. This is because after expanding beyond the "internal" region between the chamber bottom and jets flow the velocity of the flame propagation and the intensity of the chemical reactions are increased.

On the figures 6 and 7 one can see that the processes of flame kernel growth and flame expanding are very fast, and it is very difficult to observe it in real conditions (even if measurements wouldn't distort the process). The analysis of such effects like pressure peaks, flame anchoring and jets backflow is very important for researches of ignition and for combustion chamber design. Therefore the numerical simulation is the essential part of developing such systems like the system of laser ignition. The analyzing of the results of the numerical simulation in addition to experimental works has the great advancement which permits to realize the purposes of the research much faster and precise.

5 Conclusions

In the process of experimental and numerical investigations of laser ignition in combustion chambers the general characteristics of the investigated processes were analyzed. Particularly, the parametric investigations were provided, with an account of several types of propellants, focusing points, parameters required for the laser were defined. Also the presence of three types of ignition was confirmed.

In a part of numerical simulation the numerical model of mixing and ignition of the propellants of hydrogen-oxygen and methane-oxygen was constructed. It has been shown that the results of the numerical simulation permits allow:

- to choose the optimal zones for the focusing points of the laser;
- to obtain the data of the temporal characteristics of the investigated processes, including the delay of supply;
- to predict the pressure peaks, arising during the ignition process.

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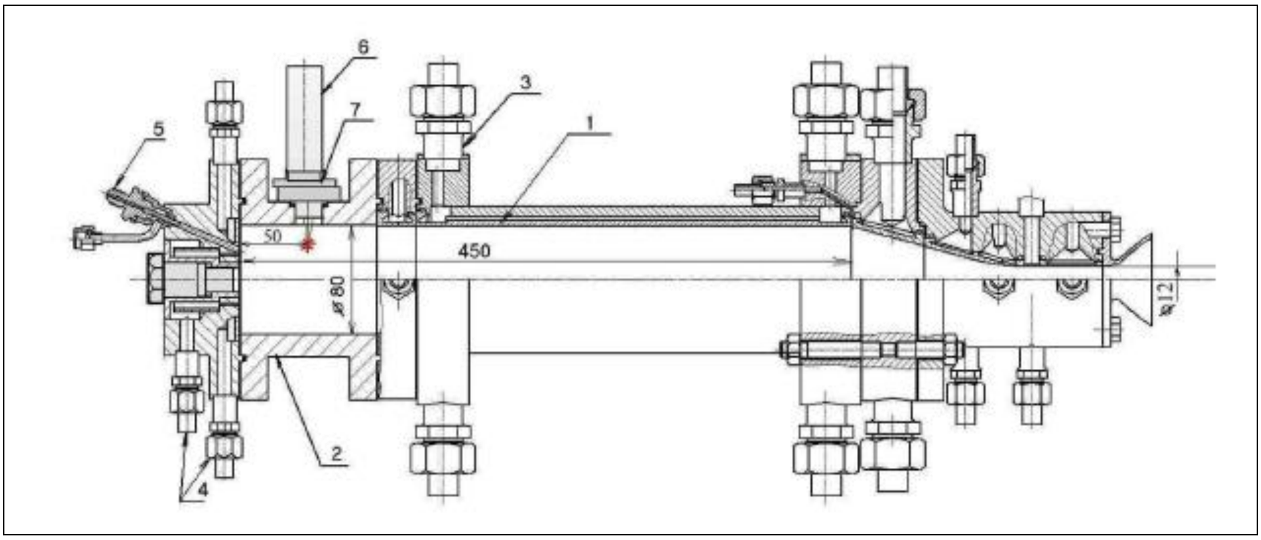
6 Figures and tables

Boundary	Component mass fraction	Mass flow rate, g/s	Total Temperature, K	Pressure, atm
H2_inlet	1.0 H_2	7.8	293	
O2_inlet	1.0 O_2	47.9	293	
Opening	0.232 O_2; 0.768 N_2		293	1.0

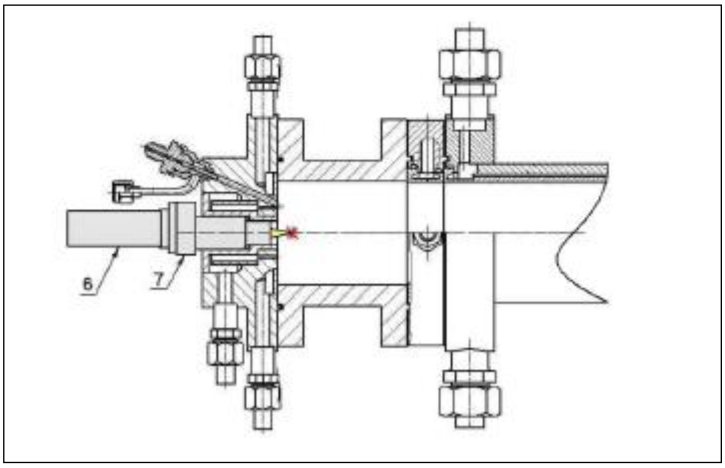
Tab. 1. Boundary conditions for ignition simulation.

№	Reaction	№	Reaction
1	H+O2 = O+OH	11	HO2+H = OH+OH
2	O+H2 = H+OH	12	HO2+O = OH+O2
3	OH+H2 = H+H2O	13	HO2+OH = H2O+O2
4	O+H2O = OH+OH	14	HO2+HO2 = H2O2+O2
5	H2+M = H+H+M	15	H2O2 +M = OH+OH+M
			H2O2 = OH+OH
6	O+O+M = O2+M	16	H2O2+H = H2O+OH
7	O+H+M = OH+M	17	H2O2+H = H2+HO2
8	H+OH+M = H2O+M	18	H2O2+O = OH+HO2
9	H+O2+M = HO2+M	19	H2O2+OH = H2O+HO2
	H+O2 = HO2		
10	HO2+H = H2+O2		

Tab. 2. Kinetic scheme of hydrogen oxidation used for numerical simulation of ignition [10].

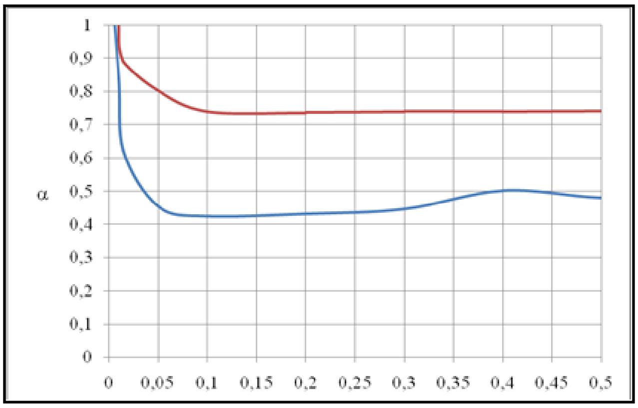


a)

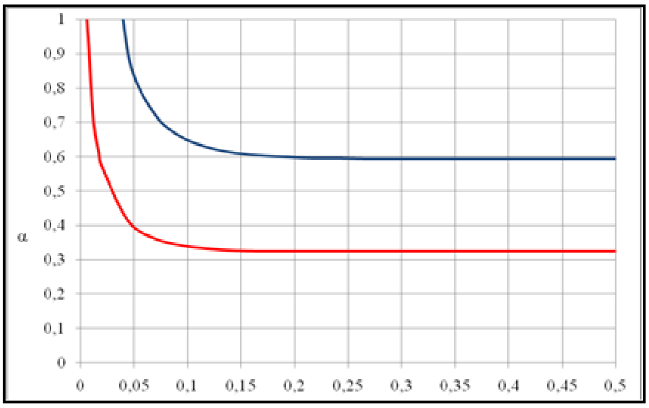


b)

Fig. 1. The general view of the experimental combustion chamber: a) normal location of the laser; b) axial location of the laser. 1 – combustion chamber, 2 – cylindrical insert; 3 – water supply for engine cooling, 4 – propellant supply in the injector head, 5 – orifice static tap, 6 – laser, 7 – laser focusing unit. [8]

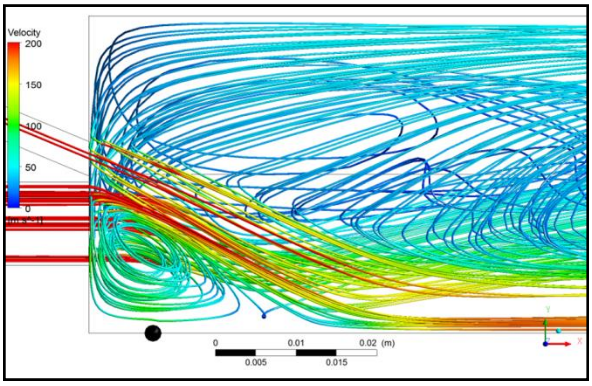


a)

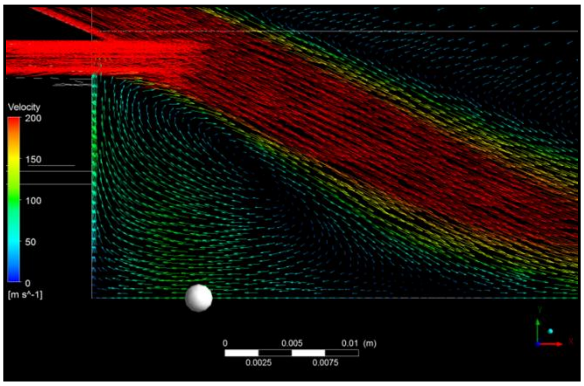


b)

Fig. 2. Values of the equivalence ratios during the filling phase at the focusing locations: a) hydrogen-oxygen components, normal location to the axis (red line) and axial location (blue line); b) methane-oxygen components, normal location to the axis (blue line) and axial location (red line). [11]

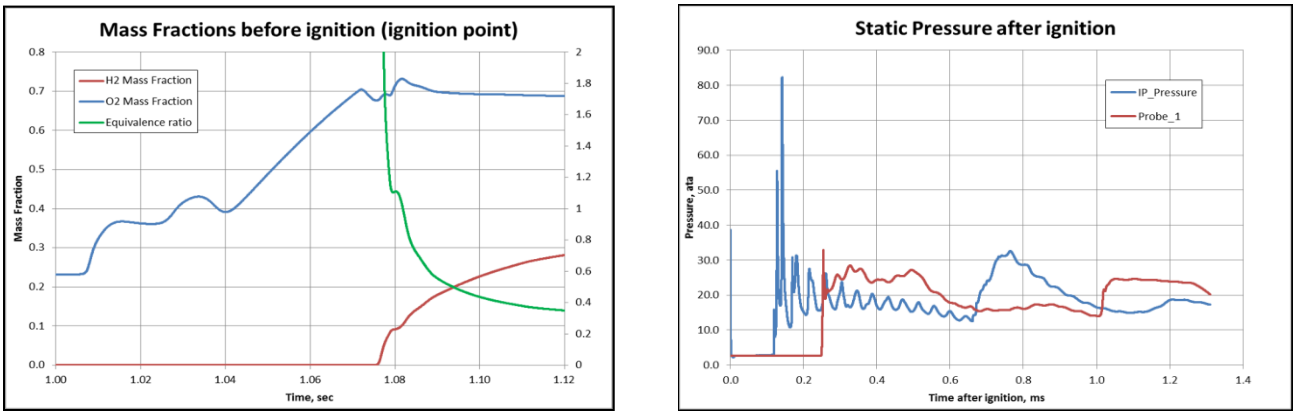


a)



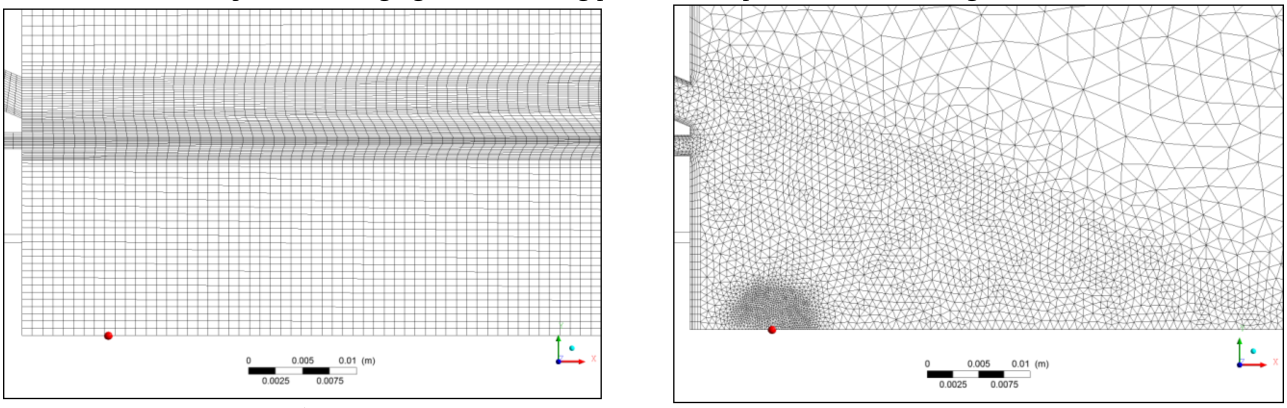
b)

Fig. 3. The streamline and vector distribution of the flow before ignition near the ignition location (the black and white spheres shows the focusing point location).



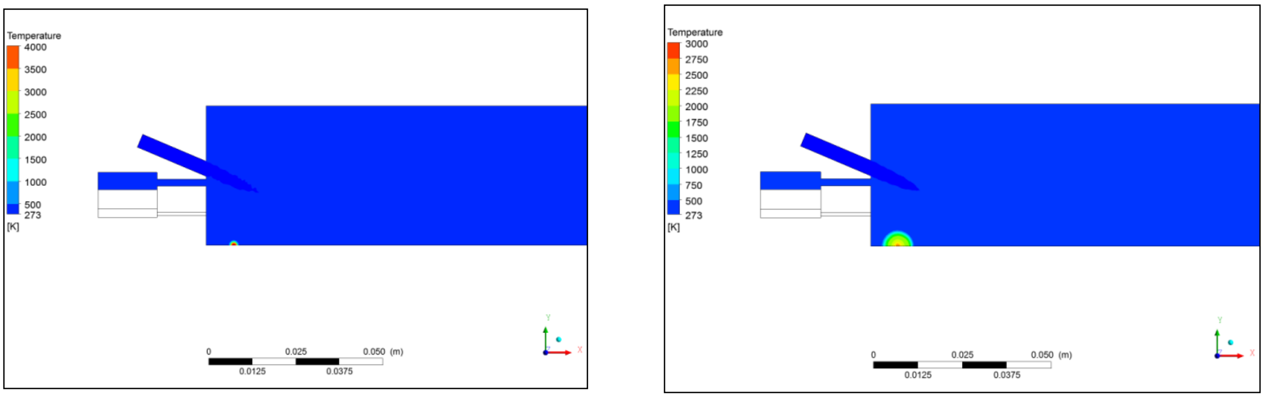
a) b)

Fig. 4. a) Chart of species mass fractions and equivalence ratio in the focusing point before ignition; b) Chart of the pressure changing in the focusing point and the probe location after ignition.



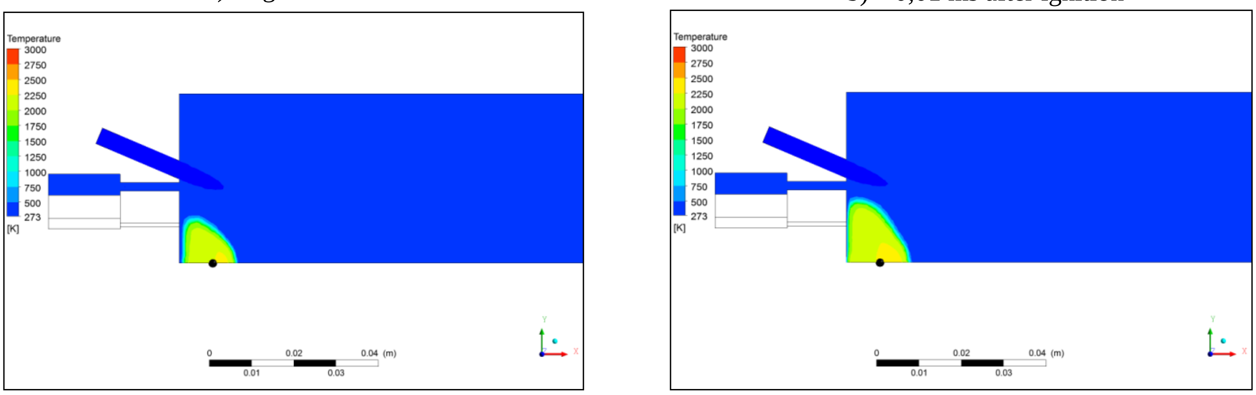
a) b)

Fig. 5. The computational meshes for mixing (left) and ignition (right) simulation. Red point shows the focusing point location.



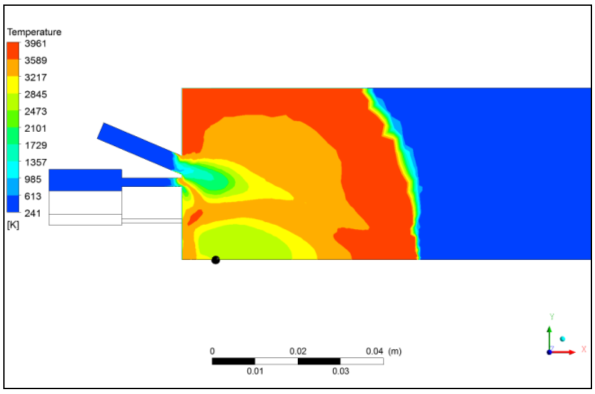
a) Ignition moment

b) 0,01 ms after ignition

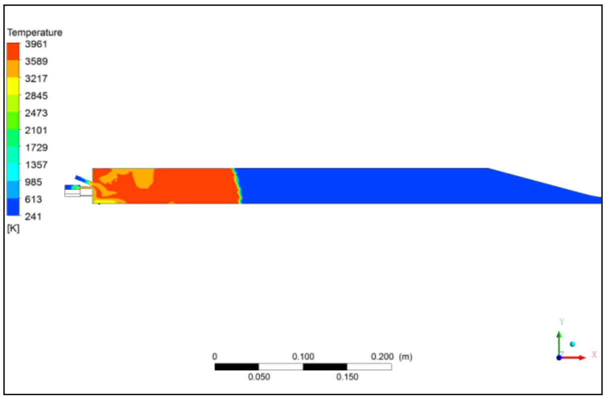


c) 0,05 ms after ignition

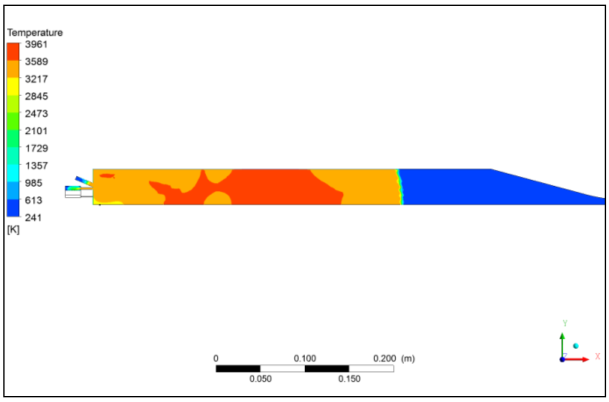
d) 0,08 ms after ignition



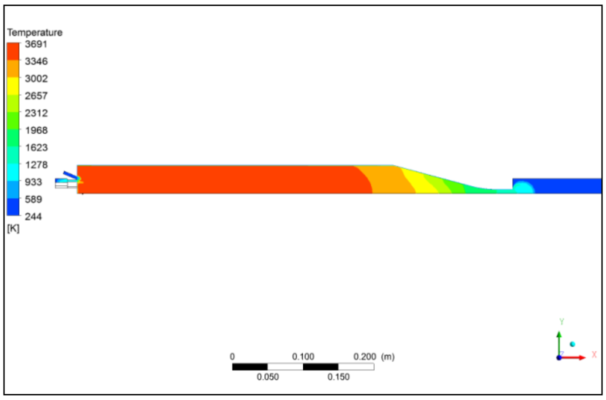
e) 0,12 ms after ignition



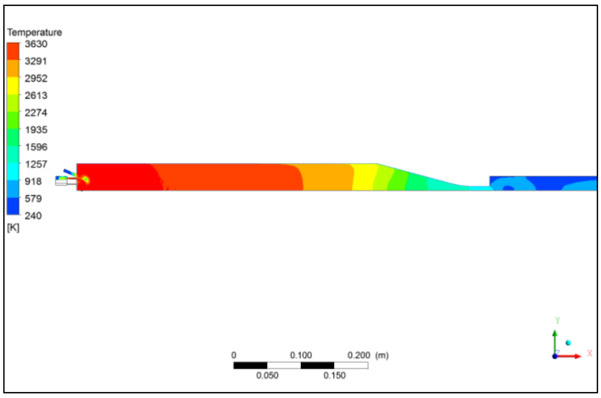
f) 0,15 ms after ignition



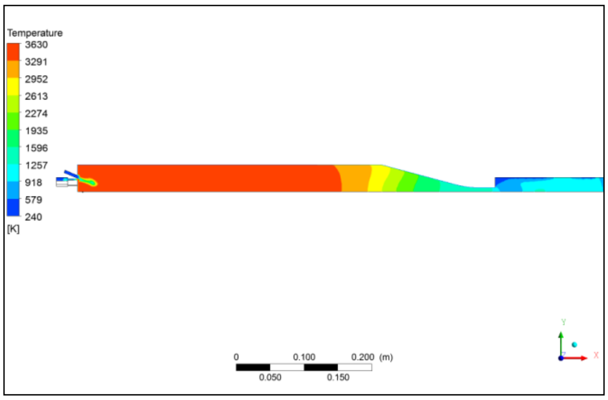
g) 0,2 ms after ignition



h) 0,4 ms after ignition



k) 0,8 ms after ignition



l) 1,32 ms after ignition

Fig. 7. The temperature distribution on the computational domain after ignition.

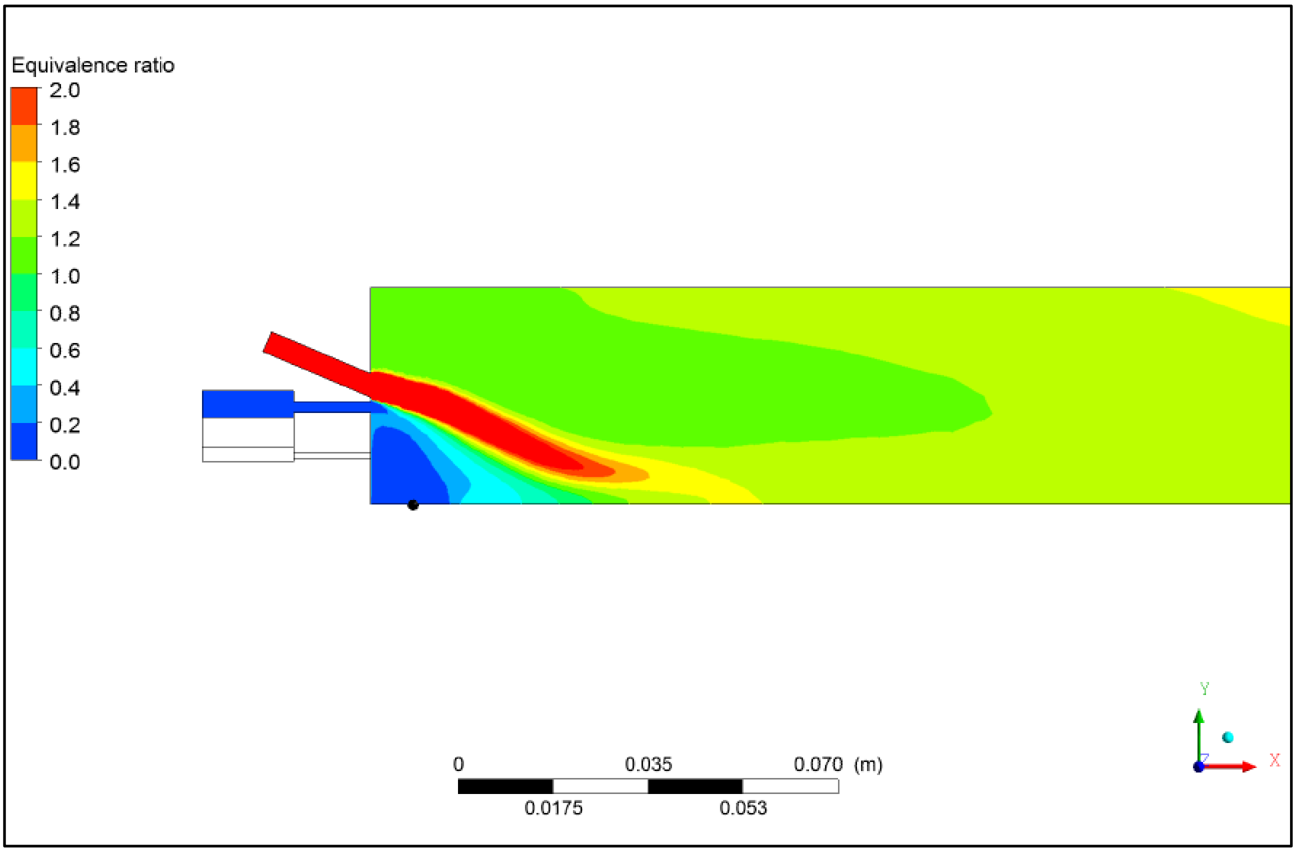


Fig. 8. The equivalence ratio distribution on the domain at t=0.08 ms after ignition.

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