Development of mathematical model and numerical simulation of plasma ignition of flammable mixture with microwave subcritical streamer discharge

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Abstract

The study of ignition of flammable mixtures by a microwave discharge is of interest for the design of propulsion systems with increased reliability and possibility of the use of lean fuel/air mixtures. A mathematical model for estimating plasma heating and conversion caused by a microwave subcritical streamer discharge is developed. Pressure of the medium is 13.3 kPa, temperature is 300 K. Plasma is created by microwave discharge with flat mirror and initiator (thin antenna). The initiator is hollow, fuel mixture (propane/air) is pumped through it to the exterior medium. Power of microwave radiation is 1.5 kW. Air flows around the initiator with velocity varying from 11 to 500 m/s. The plasma region and its conductivity are set based on experimental statistics, this is a key feature that reduces the consumption of computing resources. The mathematical model consists of three main stages. At the first stage, the Boltzmann equation for the electron gas in unperturbed medium is solved. At the second stage, the Helmholtz equations and plasma domain are considered for microwave system under study. At the third stage, the Navier–Stokes and transport equations with external heat power and additional plasma reactions for a compressible medium are solved. The results of numerical calculations are compared with the data of a physical experiment. The proposed model gives approximate estimations of discharge parameters and flow quantities, while the requirements for computational resources and time are significantly reduced in comparison to traditional models.

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1. Introduction

The potential for the evolutionary development of aerospace technology has been largely exhausted. In this regard, an active search for new approaches and technologies is underway. Plasma technologies are considered one of the promising areas. For example, to create high-speed vehicles, it is required that their propulsion system can operate efficiently at high speeds. The higher the flow rate, the more difficult it is to ensure timely ignition of the fuel mixture. At the same time, at supersonic flow speeds, the traditional method of spark ignition stops working. One way to ignite the fuel mixture is to place spark plugs in a cavity in which the external flow velocity is significantly reduced [1]. However, such cavities create resistance to the external flow. It makes sense to investigate other types of discharges capable to provide ignition improvement with higher combustion efficiency at external conditions.

Hot plasma, which is widely used in spark ignition, is characterized by a relatively small volume the mixture is heated to the ignition temperature. After it chemical energy is released, and the combustion wave propagates throughout the combustion chamber. This ignition technique is complicated by the short time of mixture residence in the working chamber at supersonic flow speeds.

In a non-equilibrium plasma, in which the hot electron gas plays the main role, reactions of dissociation, excitation and ionization of particles take place at a low temperature of the medium [2]. It significantly increases the combustion rate [3] and the thrust of rocket engine [4]. In [5], the possibility of reducing emissions through the use of non-equilibrium plasma with an increase in the completeness of combustion of the fuel mixture was studied.

When studying the processes of combustion of hydrogen fuel under the action of non-equilibrium plasma using numerical simulation, it is necessary to consider branched hydrogen kinetics [2]. If hydrocarbon fuels are used, the kinetic scheme is supplemented by reactions with hydrocarbons. Data on the reactions of C_1–C_3 hydrocarbons with electrons are available in [6]. According to [2, 6], the Grimech 3.0 hydrocarbon combustion scheme and the reaction cross sections from `lxcat`, propane molecules can also enter into chain reactions in the presence of plasma.

The effect of increasing the speed of flame propagation in the presence of cold non-equilibrium plasma in the combustion area is identified and confirmed by many studies. It is used in advanced plasma ignition devices [3], when suppressing high-frequency oscillations in the combustion chamber (modes of vibrational combustion) [7], stabilization of combustion in lean fuel mixtures in low-emission gas turbine engines and power plants operating on organic waste [8], pre-ionization of the fuel components supplied to the combustion chamber, which reduces the ignition delay and makes the temperature gradient along the length of the chamber more favorable [9]. For these cases, numerical methods have been developed based on thermal effects and the presence of electron gas and free ions in the flow [10, 11].

In a number of problems, it is required to calculate not only the flow containing cold plasma, but also its source. For example, it is necessary to evaluate the total energy efficiency of the installation. Models are widely used in which systems of equations with the laws of conservation of the considered particles, electron energy and electrodynamics are solved. In practice, it is essential to take into account a large number of particles and reactions in order to obtain physically correct results. For the problem of heating pure nitrogen by a microwave discharge, at least 56 reactions and 15 types of particles are taken into account, together with a temperature of the medium, which describes the vibrational states of nitrogen during non-equilibrium excitation [12]. The complexity of a complete calculation of plasma in a medium even without fuel is also evidenced by the study [13], in which the results of a consistent calculation of a nanosecond inter-electrode discharge were obtained. In [14], various types of medium heating by plasma are considered. It was concluded that a significant number of particles and reactions should be taken into account for accurate estimations.

A number of studies have been carried out to obtain non-equilibrium plasma using an electrode system [11]. Such discharges reduce the ignition delay, making it possible to reduce the size of the combustion chamber of gas turbine engines [9] and increase the thrust of liquid rocket engines, which is confirmed by the results of numerical calculations [15]. In this regard, it is possible to use nanosecond voltage pulses to prevent the discharge from entering the hot phase. Note that the use of electrodes to create a high field strength requires only a voltage source of sufficient power. The use of sharp electrodes makes it possible to reduce the breakdown voltage and ensure the occurrence of a discharge at the tip.

Dielectric barriers increase the power supplied to the electrodes without damaging the installation [16, 17]. At the same time, it is necessary to ensure the discharge of the barriers, otherwise the flow of electric current stops. During the flow of a current of one polarity, the dielectrics are charged and the electric field strength in the plasma decreases. Such discharges are often used in emission reduction installations in power plants.

It is important to study the problems of creating detonation waves for advanced detonation rocket engines [18, 19, 20]. To obtain high energies and specific impulse, on the one hand, the use of high-calorie fuel is required, and, on the other hand, the fuel mixture must be able to detonate. In a thin layer of the detonation wave front, there is a rapid release of energy and combustion of the fuel mixture, which leads to the possibility of operating the propulsion system at high speeds with reduced heat loss through the chamber walls and reduced emissions. The use of non-equilibrium plasma makes it possible to increase the detonation ability of the fuel mixture. It was shown that microwave plasma ignites a propane/air mixture more efficiently and faster than a spark discharge [21].

Approximate models are much simpler than full models with a strict statement, and allow to perform calculations in less time with low resource costs. Such models have less accuracy and provide data, requiring the use of special approximations. These models allow to make preliminary estimations of the possibility of obtaining certain effects by choosing the most promising combinations of input parameters. In [4], the number of active particles in the flow was proposed, and in [22], the dimensions of the preheated region were given, which makes it possible to study the change in the parameters of the supersonic flow. In [3], the same approach was used to study plasma ignition using a one-stage reaction without taking into account plasma chemistry.

The aim of the study is to create an approximate mathematical model of plasma and analyze its effect on fuel mixtures. This model is applied to calculate plasma combustion in the presence of a microwave subcritical streamer discharge. The subscritical streamer discharge represents an electric plasma discharge obtained on a thin initiator under the influence of microwave radiation. To reduce the power consumption of the emitter, focusing systems and thin antennas are used, which focus the radiation, locally increasing the electric field strength generated by the radiation. For a given electrical strength (minimum field strength to create a plasma), it is possible to obtain a plasma having radiation with insufficient strength before focusing. The seed electrons are accelerated in the electromagnetic field and accumulate energy for ionization reactions. An important feature of the developed model is the dependence of plasma effects on the parameters of the microwave system (heating and an additional set of reactions), which is achieved through additional preliminary simulation steps. A microwave subcritical streamer discharge is characterized by volumetric action, reaching high electron concentrations [23]. The use of propane is explained by the presence of reliable detailed combustion schemes (using Grimech 3.0).

The environmental conditions, under which the combustion features of propane/air mixtures, are studied are determined by experiments [3]. Medium parameters are fixed at air pressure 0.13 bar and temperature 150 K. External flow speed is up to 500 m/s around a special hollow initiator. A fuel mixture is supplied through the cavity with a given gauge pressure and composition (stoichiometric mixture with a pressure of 1 bar and pure propane pressure of 0.2 bar). Microwave radiation has a wavelength of 12.5 cm and a power of 1.5 kW).

The three-stage model of microwave subcritical streamer discharge plasma heating and conversion has been considered and verified. It is necessary to provide to the model information about common plasma region and typical size, conductivity. There is a plasma properties correction tool based on electron reaction balance in the model. It makes possible to use specified properties at different external conditions. The main output model data are temperature, pressure, velocity, medium composition fields. The results show that combustion process of pure propane in a supersonic air flow in considered conditions creates noticeable amount of hydrogen, oxygen, hydroxyl radicals in a flame trace. It should be important as an liquid fuel ignition tool for case of supersonic flows. The proposed model gives approximate estimations and perform fast calculations on modern personal computers.

2. Mathematical model

The model for calculating the plasma ignition of gas mixtures of hydrocarbon/air mixtures with a pulsed microwave discharge and a non-equilibrium plasma near the initiator is based on the scheme of splitting by physical processes and consists of three stages (Figure 1). The stages of the model proposed are explained below.

Stage 1. Calculation of the electron energy distribution function (EEDF), dependencies of the coefficients of reactions involving electrons as functions of the amplitude of the external electric field at the given frequency, quantitative density of the medium, composition of the medium, and dependencies of the cross sections of such reactions on the electron energy.

Stage 2. Calculation in a three-dimensional formulation of the propagation of microwave radiation in the presence of focusing systems, an antenna, a given conducting plasma region near the antenna. The Helmholtz equations for monochrome radiation are solved. The main quantity is the distribution of the electric field in the plasma. It and the data from the first stage make it possible to estimate the local values of the reaction coefficients, as well as the Joule heating power. The values are averaged over the plasma region and used in Step 3. Plasma effects depend on the specific power of microwave radiation, geometry and the state of the medium.

Stage 3. Calculation of gas dynamics in the presence of the plasma region with an additional set of reactions and a given specific heating power, calculated during post-processing of the results of stage 2. The equations of gas dynamics for a compressible flammable medium and the laws of conservation of particle types are solved.

The division of the model into different stages significantly reduces the consumption of computing resources, computation time and is implemented through the use of special approximations.

2.1. Main assumptions

The microwave discharge plasma is non-equilibrium. Most conductance-enhancing ionization reactions are driven by low-density hot electron gas. The external power supply is pulsed, the plasma does not have time to go to the equilibrium stage.

The plasma is formed and acquires a stable conductivity value and shape within a few microseconds and then maintains it. Due to this, it is possible to specify the plasma from the outside with parameters based on experimental statistics.

The state of the electron gas is determined by the local value of the electric field amplitude. The composition of the medium is assumed to be constant. Small changes in the composition of the medium (less than 1% before ignition) negligibly change the EEDF and the values of the coefficients of plasma reactions.

At this stage of the development of the model, photoionization reactions are not taken into account. Plasma effects without photoionization are expected to be less intense. It is suggested that about half of the plasma effect

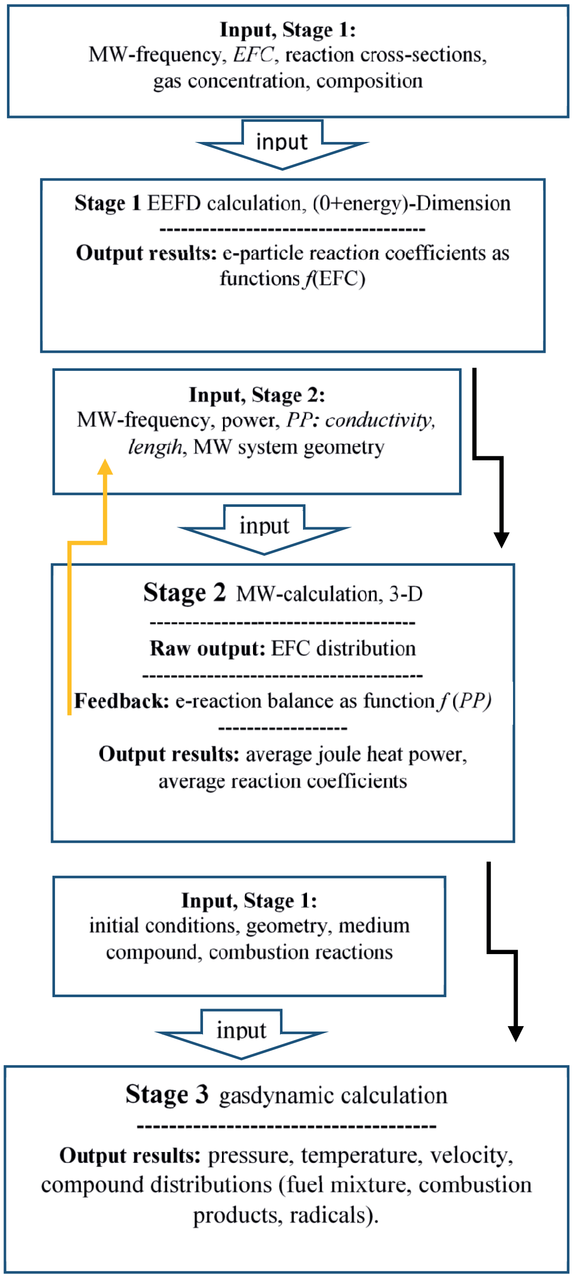


Figure 1: Three-stage mathematical model (EFS is electric field strength, PP is plasma parameters). The input parameters and the results of the calculation of the stages to be used in the next stages and the final results of the calculations are indicated in bold. The parameters that need to be sorted out during the solution stages are indicated in italic.

is due to photoionization. To compensate for the absence of photoionization, the heating power value and plasma reaction coefficients are doubled.

2.2. Stage 1

The stationary Boltzmann kinetic equations for a homogeneous electron gas in a medium in an external oscillating electric field with a given amplitude to search for an equilibrium EEDF are solved. The finite element method is used. A grid of basis functions in a one-dimensional space of electronic energy is constructed.

The Boltzmann equation for the electron energy distribution function has the form

$$\frac{\partial}{\partial \varepsilon}\left(W F_e - D\frac{\partial F_e}{\partial \varepsilon}\right) = \sum S_{in}, \tag{1}$$

$$\gamma = \sqrt{\frac{2\left|e\right|}{m_e}}, \tag{2}$$

$$W = -\gamma \varepsilon^2 \sum \sigma(\varepsilon), \tag{3}$$

$$D = \frac{\gamma}{3} E_N^2 \frac{\varepsilon}{\sigma(\varepsilon)} + \frac{\gamma k_B T_g}{\left|e\right|}\varepsilon^2 \sigma(\varepsilon), \tag{4}$$

where E_N is the reduced magnitude of the electric field amplitude; ε is the electron energy; F_e is EEDF; W and D are the mobility and diffusion coefficients of electron energy in the energy space; S_{in} are the powers of electron gas cooling by inelastic reactions involving electrons; γ is the electronic parameter; $\sigma(\varepsilon)$ are the dependencies of the reaction cross sections on the kinetic energy of electrons; T_g is the medium temperature; k_B is the Boltzmann constant; $|e|$ is the elementary charge; m_e is the electron mass.

The electron gas is heated by an external oscillating electric field. The electrons collide with the particles of the medium. The right side of equation (1) takes into account the energy losses of electrons due to reactions in the medium. The molar fractions of propane, nitrogen and oxygen molecules corresponding to the mixtures under consideration are set. The reactions of elastic collision with them are taken into account. Excitation and ionization reactions of nitrogen and oxygen are considered. The above reactions are from the `lxcat` database. They are supplemented by reactions of electrons with hydrocarbons (dissociation and ionization) from [6].

It is possible to take into account reactions with particles with zero molar fractions, for example, a hydrogen molecule. It is assumed that they are small enough not to distort the electronic energy distribution function. Such reactions are considered in order to be able to calculate their reaction coefficients for subsequent stages.

The coefficient of mobility of electron energy is determined using the collision cross sections, and diffusion is determined by heating the external electric field and interaction with the medium.

The natural boundary conditions are applied to calculate the EEDF. It is assumed that there are no electrons with negative kinetic energy and, therefore, their interaction with electrons with an energy greater than zero is impossible, and there are also no electrons with infinite energy. Then

$$\left.\frac{\partial F_e}{\partial \varepsilon}\right|_{\varepsilon=0} = 0,\ F_e\big|_{\varepsilon=\varepsilon_{max}} = 0. \tag{5}$$

In the numerical calculation, it is considered that there are no electrons with a very high energy ε_{max} (the value of 150 eV is chosen).

When calculating the EEDF, the reduced parameters of the external electric field, normalized to the quantitative density of the medium N_g, calculated from the equation of state of an ideal gas, are applied

$$N_g = \frac{p_g}{k_B T_g}, E_N = \frac{E}{N_g}, f_N = \frac{f_{MW}}{N_g}, \tag{6}$$

where p_g is the medium pressure; E and f_{MW} are the amplitude modulus and frequency of the electric field; f_N is the reduced modulus of the electric field frequency.

To solve equation (1) numerically, a grid of 3000 linear elements in the energy space from 0 to 150 eV with an element size increase factor of 10 is constructed. Iterative correction of the stationary energy distribution of electrons is made. The total source of electron energy and the fluxes in the energy space are equal to zero. The iterative process is started with a Maxwell distribution with an average energy of 2 eV. The sequence of approximations is be performed according to the Newton–Raphson method until the specified residual level of 10^{-8} is obtained.

To calculate the reaction coefficients, k_{ei}, for the given cross sections and EEDF the following equation is used

$$k_{ei} = \gamma \int_0^{\varepsilon_{max}} \varepsilon \sigma(\varepsilon) F_e(\varepsilon) d\varepsilon. \tag{7}$$

The coefficients are calculated from (7) for a number of values of the electric field amplitude, which turn out to be tabular dependencies on this field. These coefficients are necessary for the post-processing of the solution at stage 2.

2.3. Stage 2

The Helmholtz equations are solved for monochrome microwave radiation in the presence of a conductive region

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \left(1 - \frac{i\sigma_{cond}}{2\pi f_{MW}\varepsilon_{)}}\right) \mathbf{E} = 0, \tag{8}$$

$$\mathbf{B} = -\frac{1}{2\pi i f_{MW}} \left[\nabla \times \mathbf{E}\right], \tag{9}$$

where $E(x, y, z)$ is the electric field strength vector; $B(x, y, z)$ is the magnetic induction vector; k_0 is the wave vector in open space; i is the imaginary unit; σ_{cond} is the conductivity of the medium (not equal to zero in plasma); ε_0 is the electrical constant.

The plasma area could be set based on experimental statistics, while it is clearly visible where the plasma occurs, what its shape is and the approximate value of the conductivity or charge concentration. The model takes into account a tool for checking plasma on the possibility of its existence. Comparing reactions that increase and decrease conductivity is made. It is advisable to enumerate several parameters of the plasma such as the length and concentration of electrons in it. The tool corrects the properties of the plasma, it choose the best considered properties values.

Based on the given concentration of electrons in the plasma, as well as their mobility at a known quantitative density of the medium and a known composition of the plasma, the determine of its conductivity for equation (8) is made

$$\sigma_{cond} = |e| \left(b_e n_e + \sum_i |z_i|^2 b_i n_i\right) \approx |e|\, b_e n_e, \tag{10}$$

where b_e and b_i are the mobility of electrons and ions in an electric field in the medium; z_i is the charge number of the ion. The ions are two orders of magnitude less mobile and have a comparable concentration (the plasma is quasi-neutral), so their contribution can be neglected.

To calculate the propagation of microwave radiation (8) in the focusing system, the following elements are taken into account in the model: an initiator and a mirror surface under it, a plasma with desired properties, and an entry zone for microwave radiation. The geometry for calculating the microwave field is shown in Figure 2. In this case, the plasma represents six cylinders located at the end of the initiator (a circle with a uniform distribution over it). The diameter of each cylinder is 0.3 mm. Thus, the effect of spontaneous quenching, the formation of thin streamers at the end of the initiator in the presence of microwave radiation is modelled. A single wide streamer is not used (a superposition of many small streamers). The estimated heating of the medium by the plasma would be less local. Taking into account the temperature non-linearity of combustion reactions, this would lead to completely different results.

The equations (8) are supplemented with boundary conditions. The initiator and the mirror ideally reflect the radiation, therefore

$$\mathbf{n} \times \mathbf{E} = 0, \tag{11}$$

where **n** is the surface normal vector.

To save computational resources, a half of the model is considered. On the plane of symmetry, the condition for the zero tangential component of the electric field is set. It has the form

$$\mathbf{n} \times \mathbf{B} = 0. \tag{12}$$

Above the initiator, the entry condition for radiation through an area of 100 cm^2 (for half of the model 50 cm^2) with a given polarization and power is considered. The electric field is directed along the initiator and has an amplitude E_0, therefore

$$\mathbf{E} = E_0 \mathbf{e}_x. \tag{13}$$

On the remaining boundaries, the second-order scattering condition is defined

$$\mathbf{n} \times (\nabla \times \mathbf{E}) - ik_0 \mathbf{n} \left(\mathbf{E} \times \mathbf{n}\right) - \frac{1}{2ik_0} \nabla \times \left[\mathbf{n}\mathbf{n} \left(\nabla \times \mathbf{E}\right)\right] = 0. \tag{14}$$

To solve equations (8) of stage 2, a grid is constructed with the following parameters. At a distance from small objects, the sizes of elements with a characteristic length of up to 0.2 of the wavelength are chosen. Near small

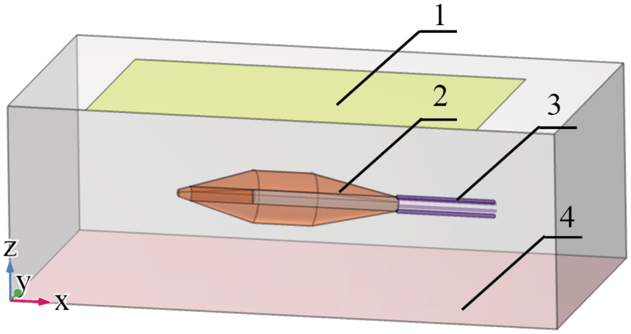


Figure 2: The geometry for microwave field calculations (1 corresponds to microwave radiation input zone, 2 corresponds to initiator, 3 corresponds to plasma domain, 4 corresponds to mirror-plane, xz plane symmetry corresponds to a condition of zero tangential magnetic field, the rest boundaries are related to a condition of open boundary, second order).

objects, the grid is condensed so that at least six elements are located in narrow gaps such as the diameter of the plasmoid. Second order elements are chosen (600 thousand elements). A geometric multigrid method is applied for solving difference equations based on the V-cycle. An additional grid with a halved number of elements is created.

The average values of the reaction coefficients, k_{je}^{n}, with the participation of medium particles j and electrons e, the specific Joule heating power W_{joule} over the plasma region Ω_{plas} and the integration operator $\hat{I}[A]$ are found from

$$\hat{I}[A] = \int_{\Omega} A\mathbf{dx}, \tag{15}$$

$$W_{joule} = \frac{\hat{I}\left[(\mathbf{j}, \mathbf{E})\right]}{\hat{I}(1)}, \tag{16}$$

$$k_{je}^{n} = \frac{\hat{I}\left[k_{je}^{n}\left(|\mathbf{E}|, \mathbf{E}\right)\right]}{\hat{I}(1)}, \tag{17}$$

where A is some field function to which the integration operator is applied; $\mathbf{dx}$ is the elementary volume; j is the conduction current density.

The region is checked for the possibility of plasma existence. Different plasmoids are studied and the criterion of electron balance, the difference between all rates of ionization, recombination and attachment reactions is introduced. If under given conditions the balance of electrons B is less than zero, then the plasma does not exist. If it is significantly greater than zero, the plasma develops. If the plasma has a positive balance close to zero, then it is maximally developed and should be selected. So, the reaction rate of particles i, j with given molar fractions w is

$$S_{ij}^{n} = k_{ij} n_i n_j, \ n_i = N_g w_i. \tag{18}$$

Then, the total rates of all ionization reactions S^{σ^+} involving electrons and attachment are estimated

$$S^{\sigma^+} = \sum_{n \in \sigma^+} S_{ie}^{n}, \tag{19}$$

$$S^{e^-} = \sum_{n \in e^-} S_{ie}^{n}, \tag{20}$$

where σ^+ and e^- are the sets of ionization and attachment type reactions, respectively. The recombination reaction, S^{σ^-}, are found from the known recombination coefficient, C^{σ^-}, in the quasi-neutrality approximation

$$S^{\sigma^-} = C^{\sigma^-} n_e n_i = C^{\sigma^-} n_e^2. \tag{21}$$

The typical value of the recombination coefficient is 10^{-13} m^3/s.

As a result, the balance is

$$B = S^{\sigma^+} - S^{e^-} - S^{\sigma^-}. \tag{22}$$

2.4. Stage 3

The equations of gas dynamics are solved in the Ansys FLUENT package for a compressible medium in an axisymmetric formulation. To verify the ignition model, the results are compared with the experimental data [3]. The environment contains particles of air, propane, intermediate and final products of combustion. To calculate combustion, Grimech 3.0 reaction schemes are set along with the accompanying transport and thermal properties. The species transport model with volumetric responses is used. The k–ε turbulence model with the parameters standard for the Ansys FLUENT package is applied. In the third stage the average Joule heating power (16) is set uniformly in the plasma region. The plasma is assumed stationary, which means that the known number of electrons and ions in the plasma, previously obtained in stage 2, are preserved. In order not to introduce new particles (electrons and ions) and not to significantly alter the scheme of reactions,

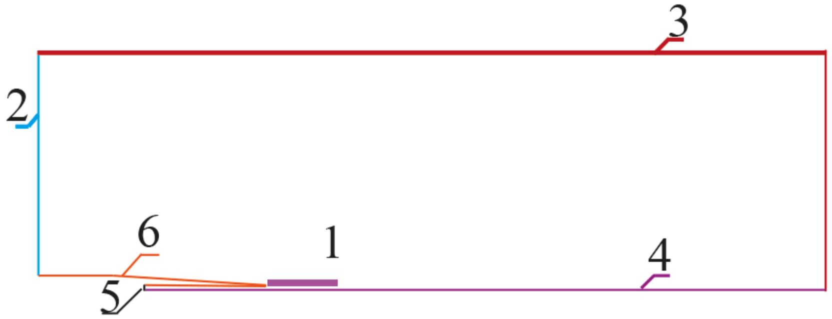


Figure 3: Geometry to study gas dynamics of propane–air flame in case of plasma domain (1). Boundary conditions include inlet and exterior flux of air (2), outlet (3), centreline (4), inlet of fuel mixture (5), wall condition for initiator (6).

and also not to adjust their sources, they are not considered explicitly. Instead, the reaction coefficients are multiplied by the concentrations of such particles, and the reactions from this stage forward are considered formally one-particle rather than two-particle. They occur only in the plasma domain. From a technical point of view, this is a simplified analogue of frozen particles in a medium.

The considered reactions involving ions are charge exchange reactions accompanied by dissociation of particles; in this case, the reaction coefficients are taken from [24].

A grid with a characteristic element size of 0.1 mm and elements of the second order is used with an implicit time integration scheme of the first order. The transition problem is solved until a stationary solution is obtained. The time step is 2 μs.

The geometry and boundary conditions are shown in Figure 3. A propane/air fuel mixture is supplied through the nozzle initiator, the nozzle itself is blown with clean air.

3. Result and discussion

The three-stage mathematical model of microwave ignition of gaseous mixtures with air using the available experimental data is verified and validated against experimental data.

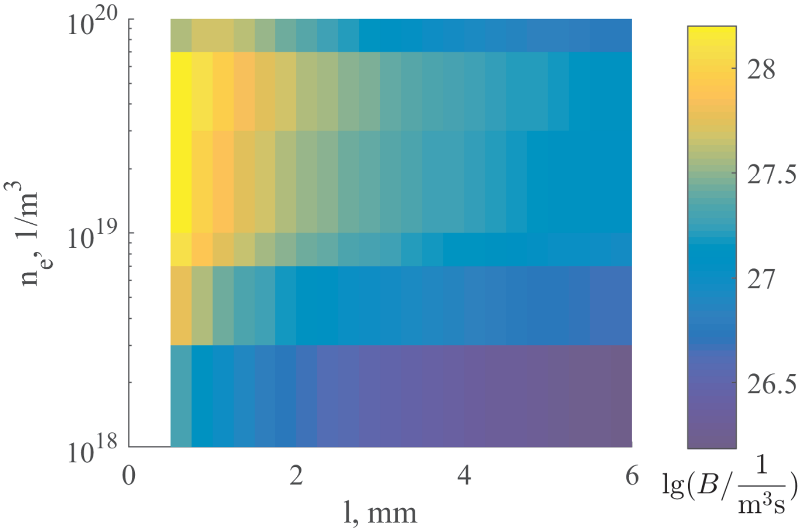


Figure 4: The balance decimal logarithm values at different plasma lengths and electron concentrations.

3.1. Stages 1 and 2

At stage 1, calculations of kinetic equations (1) for electrons in energy space are performed. Electrons are heated by an external microwave field, their amplitude changes parametrically and can perform elastic collisions, as well as reactions of excitation, dissociation and ionization of medium particles.

The main plasma reactions are the dissociation of oxygen and propane with the formation of individual atoms, a hydrogen molecule, an entire methane molecule or its radical. In this case, ionization of particles is possible simultaneously with dissociation. Such reactions lead to a noticeable plasma conversion of propane, to plasma ignition (together with the dissociation of the oxygen molecule), and to the maintenance of plasma conductivity. In stage 2, the propagation of microwave radiation in the presence of an antenna is calculated. After obtaining the results for different plasma conductivity and its length, the reaction balance is checked (Figure 4). As a result, the balance has decreased and has a negative value with increasing plasma length and conductivity (not shown in Figure 4), since it is more difficult to maintain it at a given microwave power.

A plasma has the following parameters: length is 6 mm, electron concentration is 10^{20} m^{-3}. The reaction coefficients are estimated and a total specific heating power is 220 GW/m^3. Note that only 67% of the Joule heating power of ions and electron gas will be applied to the medium, since part of the energy is dissipated. The total heating power of the plasmoid is calculated, it is equal to 240 W when the microwave power of 3 kW is applied. In the work [3] it is reported that with a microwave power of 1 kW, 80 W of plasma heating power is obtained. At the second stage, the model has a linear dependence of the heating power at constant conductivity on the external radiation power. Thus, when recalculating the heating power, one can obtain comparable values of the plasma heating power.

3.2. Stage 3

At stage 3, the results of the calculation of gas dynamics in the presence of the plasma region were compared with the experimental data from [3]. As a result of this experiment, various series of data were obtained. There are two series of them.

The first series contains data on the flame diameter depending on the composition of the propane/air mixture at an external flow of 11 m/s. The medium pressure is 13 kPa, the temperature is 150 K. The gauge pressure for supplying the mixture is 101 kPa. The flame diameter of the region near the initiator is estimated. It is a transverse size of region with a temperature of more than 743 K (ignition temperature of propane).

In the second series, photographs of the flame under the following conditions: medium pressure is 13 kPa, temperature is 150 K, external air flow speed varies between 85 and 500 m/s, which is supplied through the antenna. At the output, a stoichiometric mixture of propane–air with an excess pressure of 101 kPa or pure propane pressure of 20.2 kPa is obtained. Photographs of the flame under these conditions were compared with the results of numerical simulations performed under the same conditions, and description was added on the observed features of the flame.

The simulation results are compared with the first series of the indicated experimental data. Figure 5 shows two dependencies of the flame diameter on the excess fuel ratio. The dependence marked with red squares is the experimental data from the work under consideration. The blue circles are the calculated flame diameter from the simulation data. The region near the initiator with a temperature of more than 747 K is considered as the flame region (the ignition temperature of propane). The flame diameters calculated from the simulation results are quantitatively close to the experimental ones. The difference is 12–25% for the considered values of the fuel excess coefficients. The model, taking into account its approximation and high calculation speed, is suitable for use as a method for obtaining a preliminary estimate of the flame parameters before calculating with a detailed model. The latter may require a significant amount of computing resources and time. Also, an approximate model can be used when planning an experiment (search for a microwave power range sufficient for ignition, etc).

The model underestimates the size of the flame in all considered cases of the excess fuel coefficient. This may be due to the approximations used. The presence of ions outside the plasma region is not taken into account, which limits the scope of ionic chemistry. Plasma heating in the presence of microwave radiation also occurs only in the plasma region with fixed dimensions. Electrons, ions could leave the initial region of the plasma, which would expand it and increase the ability to receive external radiation. Photonics is not taken into account, when photons are formed in plasma, they would spread in all directions and increase the area of plasma action. Thus, the model estimates from below the plasma effect of the microwave discharge on the fuel mixture, namely, the flame size.

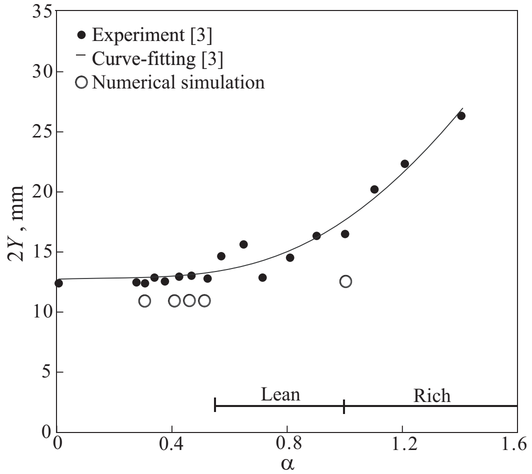


Figure 5: Dependence of the diameter $2Y$ of the region with the flame on the coefficient of fuel/air ratio α. Red squares are experimental data from [3], blue circles are based on simulation data.

In the second series of data, there are three situations that differ from each other by the composition of the fuel mixture and the speed of the external flow.

Case 1 corresponds to external air flow velocity 85 m/s, a stoichiometric mixture is fed through the initiator. The photograph of the flame and the results of the calculation (fields of temperature and modulus of movement speed) are shown in the Figure 6. The photograph shows that there is a glow region due to the presence of excited particles. The glow has a bright purple due to emit particles with a high level of excitation, characteristic of non-equilibrium plasma. Such particles can be formed in plasma and then propagate by diffusion. The scattering of the glow in the medium is also observed. In other words, the area of the violet glow visible in the experiment must be no less than the area of action of the plasma, and presumably the flame. From the photograph, it can be seen that its length is approximately half the height of the conical rear part of the initiator. The propane flame (blue glow) is not visible, which means that the combustion area is inside the purple glow area.

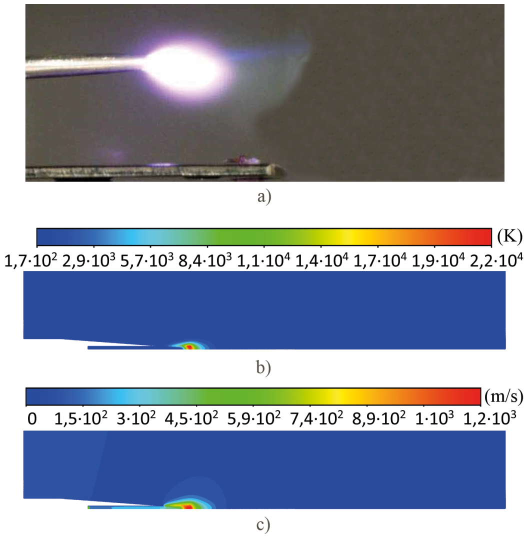
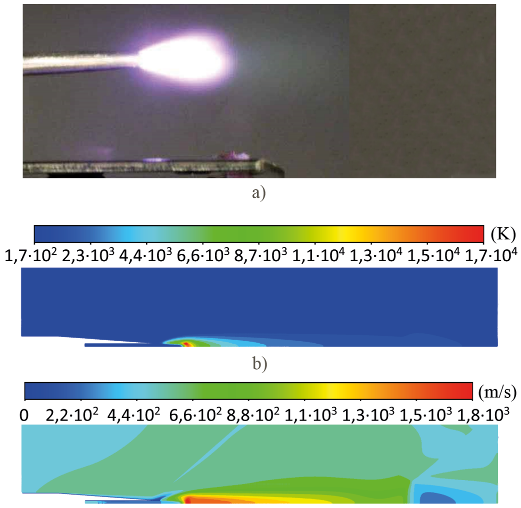


Figure 6: Model validation and calculation results for the case of stoichiometric mixture and external flow velocity 85 m/s: a) photos from the experiment [3], b) temperature (K), c) velocity magnitude (m/s).

The temperature and velocity fields of the medium are obtained with features suitable for the experiment: at the output of the initiator, combustion occurs with an increase in temperature up to 20000 K and with the expansion of the medium at a speed of up to 1.2 km/s. These areas have a size of about 1/3, 1/2 of the height of the conical part of the initiator, and their shape is close to oval. The calculation results for the described conditions do not contradict the experiment.

Case 2 corresponds to a stoichiometric mixture and pure propane at an external flow velocity of 500 m/s. Results for case 2 presented in Figure 7 show that in a supersonic flow the glow region is shifted from the initiator, otherwise the features are similar to the case of a flow velocity of 85 m/s. The calculation results agree with the experiment: there is a flame, the region of elevated temperature is smaller than the region of bright glow.



a)

b)

c)

Figure 7: Model validation and calculation results for the case of stoichiometric mixture and external flow velocity 500 m/s: (a) photos from the experiment [3], b) temperature (K), c) velocity magnitude (m/s).

Case 3 corresponds to combustion when pure propane is supplied at an external flow velocity of 500 m/s (Figure 8). Propane is enough to clearly see the flame in a large volume outside the area of violet glow. The length of the flame is comparable to the height of the initiator cone. Temperature distribution according to the simulation data: there is a long jet with a high temperature of about 2000 K, which decreases as the gas moves away from the plasma towards the outlet. In the experiment, the intensity of the flame glow decreases in the same direction.

Figure 9 shows the dependencies of the integral fluxes of a number of

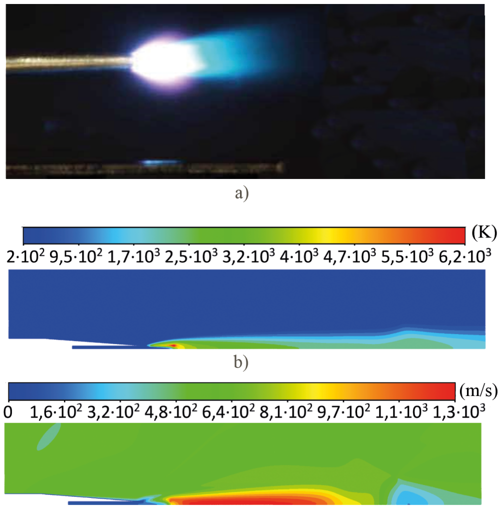


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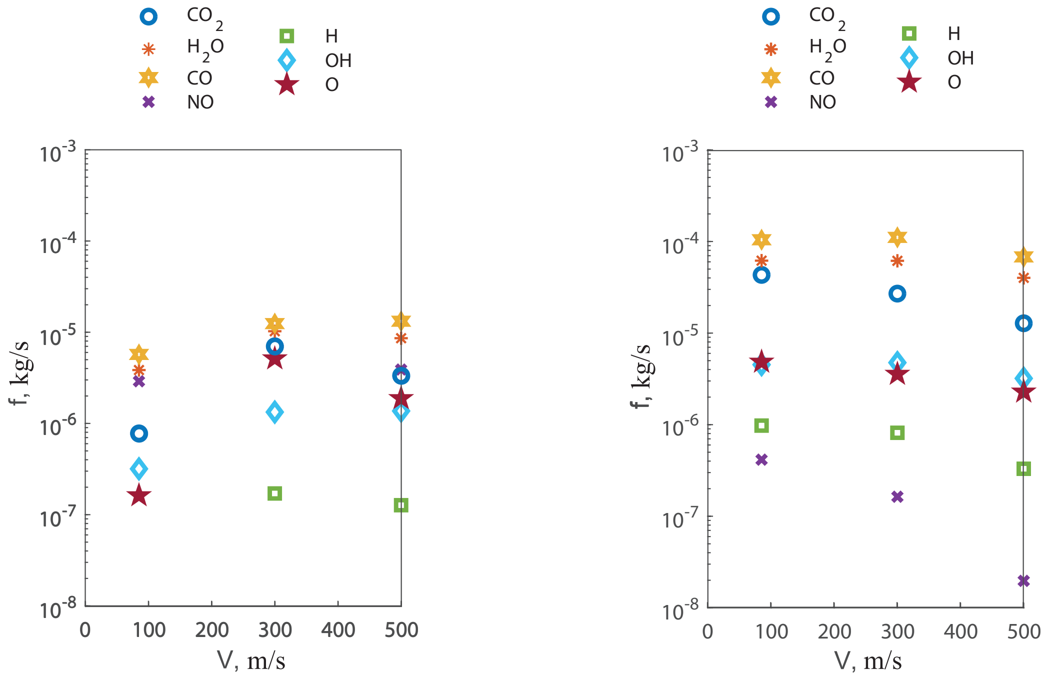
Figure 8: Model validation and calculation results for the case of pure propane and external flow velocity 500 m/s: a) photos from the experiment [3], b) temperature (K), c) velocity magnitude (m/s).

combustion products and active radicals through the rightmost boundary of the model on the external flow velocity are shown. Data are presented for a stoichiometric mixture and pure propane with excess pressures of 1 and 0.2 bar, respectively.

In the case of a stoichiometric mixture, with an increase in the external flow rate, the fluxes of combustion products and radicals also increase. However, their concentrations in the medium decrease. An increase in fluxes by a factor of 2—5 is obtained with an increase in velocity by almost a factor of 6. Note that there is an ejection effect, at a higher speed at a given mixture supply pressure, more of it should fall into the external environment. Consequently, the mixture does not have time to burn out, but the fact of combustion is observed.

With an increase in the velocity of the external flow, an increase in the flow of atomic oxygen and hydrogen by an order of magnitude is obtained. This feature can be useful for using the system as a plasma-flame torch for heating and plasma, thermal conversion of complex fuel mixtures.

When the stoichiometric mixture is replaced with pure propane, then combustion is achieved again, as well as an order of magnitude more atomic hydrogen in the stream. But to a lesser extent, the amount of atomic oxygen



a) b)

Figure 9: The dependence of the mass flux of a number of combustion products through the most right boundary of the model on the speed of the external air flow: a) stoichiometric mixture, b) pure propane.

and the hydroxyl group are increased. Such an effect is due to the fact that more propane containing hydrogen enters the computational domain. Plasma, on the other hand, acts only on it, heating it and carrying out the conversion at a greatly reduced oxygen content in the flow of the fuel jet. Activated propane (propane radicals, hydrogen) at the boundary of two streams (fuel jet, external air stream) react with oxygen. Hydrogen chain-like reactions take place, oxygen is atomized, a hydroxo group is formed, but this takes time, so for these two substances the fluxes did not increase by more than an order of magnitude relative to the case of a stoichiometric mixture.

For water, carbon monoxide and carbon dioxide, their flows increased when the mixture changed to pure propane, since it is more in the computational region. In this case, nitric oxide is formed in a smaller amount: the plasma no longer acts on the external air flow, does not form atomic oxygen, nitrogen, which then combine into oxide. From the point of view of creating the hottest flame in a significant volume with a decrease in the emission of nitrogen oxide, with an increase in the number of active radicals, the combustion of pure propane in an external air flow is more promising than a stoichiometric propane-air mixture.

As a result of the combustion of a jet of pure propane in an oxygen-deficient air stream inside the jet of propane in the combustion products, there is a highly heated activated synthesis gas with a high content of active radicals. It makes sense to further study the combustion of pure gaseous fuels in a flow with an oxidizer to ignite mixtures with liquid fuel (kerosene) by non-equilibrium plasma through an intermediary. According to [25], kerosene actively interacts with the hydroxyl group (hydrogen atoms). Direct ignition is impossible because the electrons quickly stick to the fuel droplets.

It can be concluded that the simulation results are in reasonable agreement with the experimental data. The missing region of the violet glow as a result of the experiment is explained by photons not taken into account in the calculation, the remaining visible features of the flame and plasma are consistent.

4. Conclusion

Calculations are performed on the basis of a three-stage approximate model for the ignition of propane in air using a microwave subcritical streamer discharge. The simulation results are close to the experimental data. The model was validated by comparing the temperature fields and concentrations of different types of particles with photographs from the experiment of other authors. For all considered cases, the fuel mixture was ignited.

A microwave system is used with the following parameters: radiation power is 1.5 kW, radiation wavelength is 12.5 cm. At the same time, the parameters of the medium are fixed at pressure of 13 kPa and temperature of 150 K. It moves at a given speed relative to the initiating antenna up to 500 m/s. Various propane/air mixtures are fed through the initiator: a stoichiometric mixture (excess pressure 101 kPa), pure propane (20 kPa), lean mixtures (101 kPa) with different fuel excess coefficient from 0.3 to 0.5.

The model makes it possible to analyze the combustion products of the fuel mixture, to make initial estimates before setting up an experiment or numerical simulation, where the complete system of equations of plasma, gas dynamics and combustion will be more strictly and consistently solved.

The model tends to underestimate the dimensions of the flame due to the approximations used. The diameter of the high temperature region of more than 743 K (the ignition temperature of propane) according to simulation data is 12–20% less than the diameter of the flame region from experimental data for verification from other authors.

One of the interesting results is the combustion of pure propane in an external air stream with the formation of hot syngas with a significant amount of radicals: hydrogen, oxygen, hydroxyl group atoms. Such a fuel mixture can be used for plasma ignition of mixtures with liquid fuel, and this requires further research.

A key approximation used in the work is the parameters and geometry of the plasma are assumed to be known. This leads to a significant reduction in the resource consumption of the model and the calculation time, since numerous particle transfer equations are not considered at the stage of calculating microwave fields, which require compliance with stability criteria. It is allowed to reuse the results of the proposed stages 1 and 2 of the simulation for new problems. In the future, it is planned to add an additional stage for evaluating the effects of photon interaction with the medium, add a streamer growth model, and use a simplified model for preliminary estimates of the possibility of creating a detonation wave in a round tube due to intense plasma ignition.

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References

[1] R. Feng, Z. Wang, M. Sun, H. Wang, Y. Huang, Y. Yang, X. Liu, C. Wang, Y. Tian, T. Luo, J. Zhu, Multi-channel gliding arc plasma-assisted ignition in a kerosene-fueled model scramjet engine, Aerospace Science and Technology **126** (2022) 107606.

[2] S. M. Starikovskaia, Plasma assisted ignition and combustion, J. Phys. D: Appl. Phys. **39** (2006) R265–R299.

[3] M. P. Bulat, P. V. Bulat, P. V. Denissenko, I. I. Esakov, L. P. Grachev, P. V. Lavrov, K. N. Volkov, I. A. Volobuev, Plasma-assisted ignition and combustion of lean and rich air/fuel mixtures in low- and high-speed flows, Acta Astronautica **176** (2020) 700–709 .

[4] Q. Chen, J. Ge, T. Zheng, X. Che, W. Nie, The role of non-equilibrium plasma kinetic effect on GCH4/GOX rocket engine combustion performance, J. Phys.: Conf. Ser. **1707** (2020) 012015.

[5] V. A. Kotel'nikov, M.V. Kotel'nikov, G. s. Filippov, Electrical and Physical parameters of plasma fluxes in exhaust from a liquid-propellant rocket engine, J. Mach. Manuf. Reliab. **47** (2018) 488–494.

[6] R. K. Janev, D. Reiter, Collision processes of C2,3Hy and C2,3Hy+ hydrocarbons with electrons and protons, Physics of Plasmas **11** (2004) 780–829.

[7] S. Zhou, W. Nie, Y. Tian, High frequency combustion instability control by discharge plasma in a model rocket engine combustor, Acta Astronautica **179** (2021) 391–406 .

[8] M. P. Bulat, P. V. Bulat, P. V. Denissenko, I. I. Esakov, L. P. Grachev, K. N. Volkov, I. A. Volobuev, Ignition of lean and stoichiometric air–propane mixture with a subcritical microwave streamer discharge, Acta Astronautica **150** (2018) 153–161.

[9] W. Kim, J. Cohen, Plasma-assisted combustor dynamics control at ambient and realistic gas turbine conditions, Volume 4A: Combustion, Fuels and Emissions. Charlotte, North Carolina, USA: American Society of Mechanical Engineers, (2017) V04AT04A037.

[10] M. Bulat, P. Bulat, P. Denissenko, I. Esakov, L. Grachev, K. Volkov, I. Volobuev, Numerical simulation of ignition of premixed air/fuel mixtures by microwave streamer discharge, IEEE Trans. Plasma Sci. **47** (2019) 62–68.

[11] A. Sharma, V. Subramaniam, E. Solmaz, L. Raja, Fully coupled modeling of nanosecond pulsed plasma assisted combustion ignition, J. Phys. D: Appl. Phys. **52** (2019) 095204 .

[12] A. I. Saifutdinov, E. V. Kustova, Dynamics of plasma formation and gas heating in a focused-microwave discharge in nitrogen, Journal of Applied Physics **129** (2021) 023301.

[13] V. A. Bityurin, A. N. Bocharov, A. S. Dobrovolskaya, T. N. Kuznetsova, N. A. Popov, E. A. Filimoniva, Numerical modeling of pulse-periodic nanosecond discharges, J. Phys.: Conf. Ser. **2100** (2021) 012032.

[14] N. A. Popov, S. M. Starikovskaia, Relaxation of electronic excitation in nitrogen/oxygen and fuel/air mixtures: fast gas heating in plasma-assisted ignition and flame stabilization, Progress in Energy and Combustion Science **91** (2022) 100928.

[15] T. Zheng, X. Che, L. Li, C. Chen, W. Nie, X. Li, Numerical study of plasma assisted combustion for a rocket combustor using GCH4/GOX as propellants, J. Phys.: Conf. Ser. **1064** (2018) 012013.

[16] Z. Zheng, W. Nie, S. Zhou, Y. Tian, Y. Zhu, T. Shi, Y. Tong, Characterization of the effects of a plasma injector driven by AC dielectric barrier discharge on ethylene-air diffusion flame structure, Open Physics **18** (2020) 58–73.

[17] J. Deng, L. He, X. Liu, Y. Chen, Numerical simulation of plasma-assisted combustion of methane-air mixtures in combustion chamber, Plasma Science and Technology **20** (2018) 1–11.

[18] J. Z Ma, M. Y. Luan, Z. Xia, J. Wang, Recent progress, development trends, and consideration of continuous detonation engines, AIAA Journal **58** (2020) 1–59.

[19] N.N. Smirnov, V.F. Nikitin, L.I. Stamov, E.V. Mikhalchenko, V.V. Tyurenkova, Three-dimensional modeling of rotating detonation in a ramjet engine, Acta Astronautica **163** (2019) 168–176.

[20] N. N. Smirnov, V. F. Nikitin, L. I. Stamov, Different scenarios of shock wave focusing inside a wedge-shaped cavity in hydrogen-air mixtures, Aerospace Science and Technology **121** (2022) 107382.

[21] P. V. Bulat, P. S. Chernyshov, I. I. Esakov, L. P. Grachev, P. Lavrov, A. I. Melnikova, K. N. Volkov, I. A. Volobuev, Multi-point ignition of air/fuel mixture by the initiated subcritical streamer discharge, Acta Astronautica **194** (2022) 504–513.

[22] Y. V. Dobrov, V. A. Lashkov, I. Ch. Mashek, R. S. Khoronzhuk, Investigation of heat flux on aerodynamic body in supersonic gas flow with local energy deposition, AIP Conference Proceedings **1959** (2018) 050009.

[23] P. V. Bulat, I. I. Esakov, L. P. Grachev, P. V. Denissenko, M. P. Bulat, I. A. Volobuev, Modeling and simulation of combustion and detonation by subcritical streamer discharge, Scientific and technical journal of information technologies, mechanics and optics **17** (2017) 569–592.

[24] I. A. Kossyi, A. Yu. Kostinsky, A. A. Matveyev, V. P. Silakov, Kinetic scheme of the non-equilibrium discharge in nitrogen-oxygen mixtures, Plasma Sources Sci. Technol. **1** (1992) 207–220.

[25] N. Zettervall, C. Fureby, E. J. K. Nilsson, A reduced chemical kinetic reaction mechanism for kerosene-air combustion, Fuel **269** (2020) 117446.