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Electrodynamic model of combustion chamber using subcritical streamer discharge to ignite fuel mixture

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Various electrodynamic models of a combustion chamber, in which an initiated subcritical streamer discharge is used to ignite a combustible mixture, are considered. To localize the discharge in the working chamber, discharge initiators are used based on half-wave electromagnetic vibrators with resonant properties. The dependences of the structure of the electric fields that form the discharge on the geometric parameters of the discharge initiator are obtained on the basis of numerical calculations, and the issues of matching the chamber with the radiation generator are considered. Comparison of the calculation options for different positions of the initiator of the discharge in relation to the optical centreline of the camera. Possibilities for further enhancement of the field in the working zone at the poles of the microwave discharge initiator, which is required for the formation of discharges with a developed streamer structure at elevated gas pressures in the combustion chamber, are discussed. The ways of increasing the resulting electromagnetic field in the area of vibrators for the formation of discharges with a volumetric structure have been determined.

Keywords: microwave radiation, streamer discharge, electrodynamic model, plasma combustion, combustion chamber.

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Introduction

Use of initiated microwave discharges for ignition of combustible mixtures in the high-pressure chamber makes it possible to both create such discharges at significantly lower power of a microwave energy source, but also to localize them in the working chamber in the right place [1]. Comparative studies of the process of combustible mixture ignition by spark discharge from plugs of standard configuration and initiated microwave discharges were carried out in paper [2]. The study results demonstrated that ignition using a microwave discharge is much more energy efficient than the spark one [3]. Besides, efficiency of combustible mixture ignition by a microwave discharge depends on number of branches in the system of plasma channels it has [4]. The results obtained are of interest for the creation and application of nonequilibrium microwave discharges for ignition and intensification of fuel combustion in high-speed flows [5,6].

Properties of freely localized microwave discharges in a focused beam of quasi-optical radiation have been studied quite well [7,8]. Various approaches to modeling microwave radiation propagation in waveguides with different cross-sectional shapes have also been developed [9,10]. A wide range of theoretical, experimental, and numerical studies of a microwave discharge in air, including energy input to supersonic flow, are given in papers [11–15].

To localize a discharge in the working chamber, initiators based on half-wave electromagnetic vibrators are used. The most well-studied type of a microwave discharge initiator is a linear electromagnetic vibrator. Its advantages include design simplicity, known dependences of the field near the ends on various factors, as well as the possibility of providing a medium breakdown at high values of the initial field subcriticality index. The theory and methods to calculate initiators of various designs are given in paper [16]. Influence of conductivity, geometric dimensions and shape of the initiator and their group on the local properties of the induced electromagnetic fields are considered in paper [17].

Location of the discharge initiator near a metal screen or on the surface of a dielectric screen provides additional opportunities to amplify the field [18]. In this case, the discharge initiator is a piece of metal wire with rounded ends. In general, the smaller the end edge radius and the closer the resonator is to the screen, the greater the field gain [19,20]. In case of a dielectric screen, the resonator is placed directly on its surface. The maximum field intensity in this case is observed in the space formed by the screen surface and the radius end edge of the resonator [4]. Under conditions of resonance, high induced current arises in a conductor, and in the vicinity of the initiator gas ionizes, plasma channels are formed to heat the surrounding gas [21,22].

Conducted studies have shown that installation of an electromagnetic vibrator at a short distance from a metal screen makes it possible to achieve air breakdown at radiation power that is significantly lower than that required to implement a breakdown in unrestricted space [23] (deep subcritical streamer discharge). Paper [18] offers an energy efficient method of boundary layer control by creating a regular system of localized microwave discharges on the model surface, formed in the field of a quasi-optical electromagnetic beam of a remote microwave energy source.

The structure of microwave fields in the discharge chamber used to produce an electrode discharge is investigated in paper [19]. Numerical modeling makes it possible to quantify details of the discharge chamber design that would be optimal for discharge generation. Dependence of the structure of electric fields forming the discharge on the geometrical parameters of the discharge chamber has been obtained, and the issues of matching the discharge system with the generator have been considered.

Within applied scientific research a complex experimental setup consisting of a powerful pulse microwave generator and a high-pressure tube imitating a combustion chamber has been created [3]. The setup is equipped with a system for measuring pressure in the working chamber, which may measure both static pressure and the process of pressure variation in time with a resolution of less than $1\,\mu$s. In addition, it is possible to register optical radiation from the working chamber through a longitudinal window.

In the earlier experiments, microwave radiation was brought into the chamber with a flat rectangular flare through one of the side slits with a radio-transparent dielectric window. The same slit with a window on the opposite side of the tube served for visual observation and photographing of the discharges generated. Pulse power of the used microwave source was $P = 500\,\text{kW}$, operating frequency — $f_0 = 2.795\,\text{GHz}$ (wavelength — $\lambda = 10.7\,\text{cm}$), pulse duration — $\tau = 2{-}6\,\mu$s.

Initiators were half-wave linear vibrators in the form of metal wire segments with rounded ends and were located on the axis of the chamber and simultaneously parallel to the polarization vector of microwave radiation. The results of studies carried out in papers [1–3], demonstrated the possibility in principal to implement microwave ignition systems in high-pressure combustion chambers and their prospects. At the same time, the initiated microwave discharges were in the form of single streamers of limited length, which is explained by the short duration of radiation source pulses. One of the ways to increase the efficiency of the studied microwave ignition systems with the same energy parameters of the microwave radiation source is generation of discharges with a developed volume streamer structure [21,22].

Experience with microwave discharges in gases at atmospheric and elevated pressures in free space shows that the developed structure of the discharge can be realized with further increase in the electric field exciting the discharge on the poles of electromagnetic vibrator [1]. In this case, the nature and degree of change in the resulting electromagnetic field at the vibrator poles in process of discharge development are critical. To generate discharges with a developed streamer structure at increased gas pressures in the combustion chamber, it is necessary to further amplify the field in the operating area at the poles of the microwave discharge initiator.

From the physical point of view, two different approaches to creating a microwave ignition system in the working chamber are possible: location of the electromagnetic vibrator perpendicular to the optical axis of the chamber and parallel thereto with a corresponding change in the field polarization and design of the electromagnetic radiation input into the chamber. In this paper, we consider design of a three-dimensional electrodynamic model of the microwave ignition system in a cylindrical combustion chamber, where the vibrator is placed perpendicular to the optical axis of the chamber. Spatial distribution and amplitude of the electromagnetic field in the system both before and after the discharge generation are found. Based on the calculations performed, the ways of increasing the resultant field in the vibrator region to generate discharges with a volume structure are discussed.

1. Radiation input into chamber

Due to polarization of radiation (vector **E** is parallel to the linear vibrator axis), only two variants of radiation input into the chamber are possible: input by means of a flat flare and a flat waveguide through a side longitudinal window in the chamber.

The model of the working chamber with flare input of microwave radiation is shown in fig.1. The model applies a purely electrodynamic program technique common for such designs: the chamber walls, flanges and other metal elements are absent as useless, since under the outer space an ideal conductor is assumed. The model includes only internal parts of the design, which the electromagnetic wave can see. The electrodynamic model includes areas with dielectric permittivity equal to one (vacuum) and side windows made of Plexiglas (polymethylmethacrylate). The vibrator is a piece of metal wire with rounded ends.

One way to amplify the field in the vibrator region is to replace the flare with a regular waveguide with concentration of microwave radiation energy flux near the output aperture of the waveguide. In this case, waveguides with a circular cross section are practically not used, as it is difficult to maintain the required polarization of the electromagnetic wave therein. Such problem does not arise in a waveguide with rectangular cross-section. The type of electromagnetic wave propagating therein depends on the method of its excitation and the size of the cross section. In

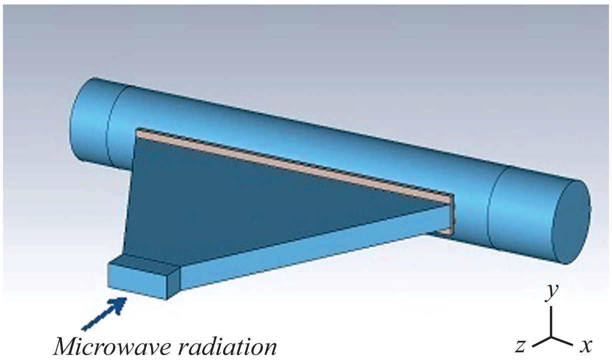

Figure 1. Flare input of microwave radiation.

practice, the simplest type of electromagnetic wave — H_{10} is most commonly used.

2. Mathematical model

To find the distribution of the electric field strength vector at the operating frequency, Maxwell's equations, written in frequency-dependent form, are solved inside a discharge chamber with conductive walls of all component parts of the structure. Using the definition of electric field strength through scalar and vector potentials and Lorentz-calibration linking the two potentials, we get the equation

$$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla(\nabla \cdot \mathbf{A}) - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2},$$

where c — speed of light, $\mathbf{E}$ — complex amplitude of electric field, $\mathbf{A}$ — complex amplitude of vector-potential defined by the ratio

$$\mathbf{A}(\mathbf{r}) = -\frac{1}{c}\int\limits_{V_1} \mathbf{j}(\mathbf{r}_1)\,\frac{\exp(iK|\mathbf{r}_1 - \mathbf{r}|)}{|\mathbf{r}_1 - \mathbf{r}|}\,dV_1,$$

where $\mathbf{j}$ — current density, $\mathbf{r}_1$, $\mathbf{r}$ — radius vectors of current element and a point, where the field is detected, V_1 — volume, where current density is different from zero, k — wave number.

In the plane, through which radiation arrives in the system, in all calculations a transverse electromagnet wave (TEM) is excited at operating frequency f_0 at the specified capacity of the input signal. In the field of an external electromagnet wave along axis x there is a thin conductor of cylindrical shape with length l, radius $a \ll l$ and end conductivity s. Given that losses at the boundaries of the region, losses are small relative to other losses in the system, the Perfect Electric Conductor (PEC) boundary condition is used.

A particular type of microwave discharge requires an electromagnetic field with a certain amplitude $\mathbf{E}_0$. Value $\mathbf{E}_0$ makes it possible to estimate the electromagnetic energy flux density in the beam cross section for the linearly polarized TEM-wave $E_0^2/(2Z_0)$, where $Z_0 = 120\pi\Omega$.

Tangential components of the electric and magnetic field vectors at the interface are continuous. When studying AC electromagnetic field outside metallic conductors at the interface with metal, conductors are often replaced by a perfectly conductive medium. Such replacement is based on the fact that the perfectly conductive medium fairly correctly reproduces the effect of real metal conductors on the electromagnetic field outside them.

To solve the basic equations of electrodynamics, Finite Element Method (FEM) is used, which includes adaptive generation and division of mesh cells. Solutions for the electromagnetic field, found from Maxwell's equations, make it possible to accurately determine all characteristics of the microwave device, taking into account the occurrence and transformation of some types of waves into others, losses in the materials and on radiation, etc.

3. Results and discussion

Let us consider a variant with initiator location perpendicular to the optical axis of the chamber and a flare input of microwave radiation. Before modeling the ignition system as a complex, it is necessary to determine the presence of various heterogeneities and elements of real chamber design in the system and degree of influence on the initial structure of the electromagnetic field (its windows with dielectric inserts, „short-circuiting jumpers" of the chamber tube on the right and a sight dielectric window on the left, ends of the tube etc.).

Distributions of electric field strength along axes x and z are shown in fig. 2 for the chamber with one sight window (lines *1*). Presence of any heterogeneity in the working zone leads to a significant change in the field distribution in the chamber. As an example, the figure shows the electric field amplitude changes on the optical axis of the chamber tube x and along the flare axis z (coordinate z is counted from the opposite wall of the chamber tube to the flare) when the second sight window is introduced from the side opposite to the flare, and simultaneously dielectric inserts from polymethylmethacrylate are installed in the windows (lines *2*). Plexiglas inserts serve to separate the working volume of the high-pressure combustion chamber from the external environment and the waveguide path. There are not only abrupt changes in the field distribution, but also a periodic structure inherent in a standing wave in the right part of the graphs at the tube short-circuiting jumper on the right (Fig. 2, *a*) and a similar type of field graphs in the flare and waveguide (Fig. 2, *b*). Distributions shown in fig. 2, *a* testify to a substantially non-uniform axial field distribution in the model under consideration and its strong difference from the classical cosine field distribution in a flat rectangular waveguide excited on the lowest wave type H_{10}.

Diagram of electromagnetic field electric component in a real structure in the cross section $y = 0$ is shown in fig. 3. The above features of electromagnetic wave propagation in the system, including the spot nature of the field, mean

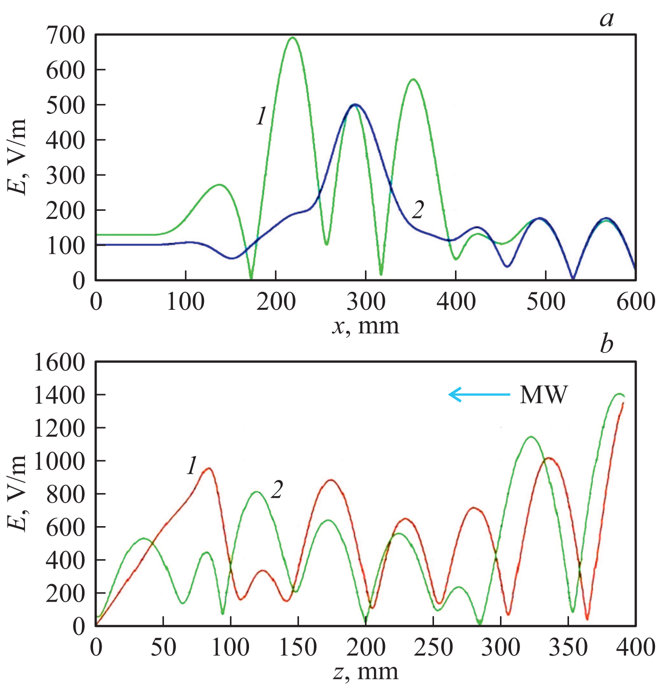

Figure 2. Distributions of electric field strength along axes x (a) and z (b). Lines *1* correspond to a chamber with one sight window, and lines *2* — to a chamber with a second sight window on the opposite side of the flare.

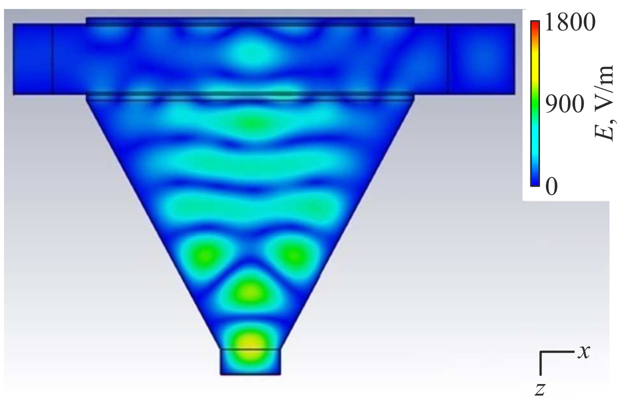

Figure 3. Initial distribution of electric field strength in cross section $y = 0$ without an electromagnetic vibrator.

excitation of higher wave types in the chamber and the strong reflection of microwave radiation in the path. Strong reflection of radiation in the studied design of the ignition system and working chamber is a characteristic feature of the considered methods of microwave energy input from the side and perpendicular to the chamber axis.

Installation of a half-wave electric vibrator of a microwave discharge initiator in the chamber leads to redistribution of electromagnetic fields in the system.

Development and experimental studies of the microwave ignition system are carried out at a fixed radiation frequency $f_0 = 2.795$ GHz. However, during the study of electromagnetic fields in model electrodynamic systems similar to the considered one, it is convenient to present the obtained results not only in space, but also in a certain frequency range. This makes it possible to visually describe the amplitude-frequency characteristics of the system and to predict the effect of certain changes therein.

Fig. 4, a shows a family of frequency dependences of the field amplitude at the electromagnetic vibrator poles at different vibrator lengths $L_v = 45-50$ mm in the frequency range 2.4–3.2 GHz. For convenience, the obtained results are given in a narrower frequency range — near the operating frequency (fig. 4, b). In all cases considered, the vibrator diameter is 1 mm.

The values of electromagnetic field indicated in the graphs correspond to the normalized value of microwave radiation power at the input to the system, equal to 1 W. To estimate true amplitude of the electric field in the desired point, it would suffice to multiply the value given in the graph by the square root of the ratio between real radiation power at the system input and normalized value of 1 W. So, for example, with microwave source power $P = 500$ kW the root of the ratio specified is approximately 707, and the field amplitude on the graph $E_A = 10^4$ V/m corresponds to the real field value in the regular units $E \approx 70$ kV/cm.

Amplitude of microwave electric field, which causes electrical breakdown of air and most real combustible mixtures at atmospheric pressure is approximately equal to 30 kV/cm. Therefore, in the entire interval of the vibrator length values of practical interest at the operating frequency

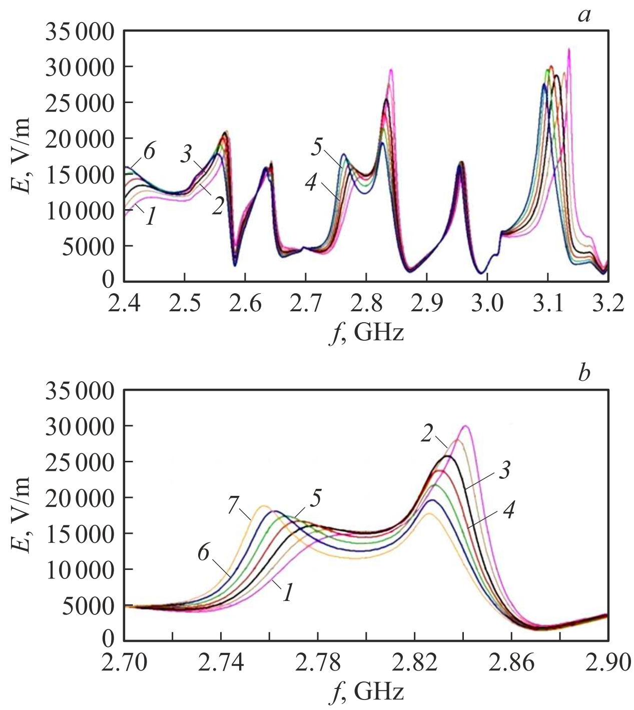

Figure 4. Distributions of electric field amplitude at vibrator poles at different vibrator lengths in wide (a) and narrow (b) frequency range with total tube length reduced by 120 mm at $L_v = 45$ (*1*), 46 (*2*), 47 (*3*), 48 (*4*), 49 (*5*), 50 (*6*), 51 mm (*7*).

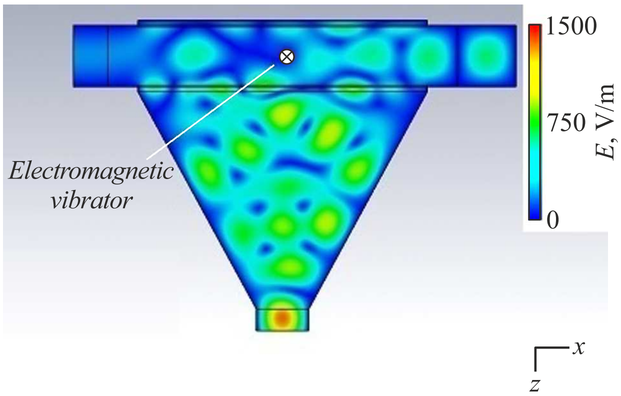

Figure 5. Distribution of microwave electric field in cross section $y = 0$ in a chamber with an electromagnetic vibrator

of 2.8 GHz the pulse amplitude of the electric field at the vibrator poles is more than sufficient for the gas breakdown both at atmospheric and at increased chamber pressure even in the initial conditions (without any-optimization of the geometry and size of the system).

An important feature, which should be noted when analyzing the graphs in fig. 4, is the multiresonance nature of the electromagnetic field in the system on the frequency axis, which is fundamentally different from the usual form of the resonance curve of a half-wave vibrator in free space. In contrast to the electromagnetic vibrator in free space, its length in the interval of interest weakly affects both the field amplitude at the poles and the characteristics of the system as a whole.

From the electrotechnical point of view, the considered system with the vibrator is no longer a single LC-contour, but a system of connected contours with their resonances, determined by a set of system parameters — diameter and length of the working chamber, shape and size of windows in the chamber, size and permeability of dielectric inserts in the windows and, naturally, size and location of the electromagnetic vibrator in the chamber. The mentioned feature of the studied electrodynamic system practically excludes the possibility of its usual setup by changing the geometrical dimensions of the vibrator. It is necessary to adjust and optimize the whole design.

The diagram of microwave field in a system with a vibrator in the cross section $y = 0$ is presented in fig. 5. At the location of the vibrator (indicated with a cross in the figure) near its center, the amplitude of the electric field at given polarization is zero.

Another important issue is to determine the possible variations in the amplitude of the electromagnetic field at the vibrator poles after occurrence and development of the streamer microwave discharge. Construction of the exact physical model of the vibrator with the developed volume discharge is hardly possible or reasonable from the point of view of the time costs for modeling due-to the structure, size and other parameters of the discharge that always change in time, as well as lack of exact data on conductivity of individual structural elements in the discharge. A reasonable way out for qualitative analysis and quantification of the discharge model is to replace the Perfect Electric Conductor (PEC) with a metal with finite conductivity.

Equivalent conductivity of the streamer microwave discharge in process of development may vary widely, therefore the effective resistance of the equivalent LCR-contour (R means a resistor element) also changes. The required range of conductivity variation in an electromagnetic vibrator with length of $L_v \sim 5$ cm and diameter of 1 mm is determined based on the range of equivalent resistance variation of such a contour that is of real physical interest.

The corresponding graphs of field amplitude dependence at vibrator poles with length $L_v = 48$ mm selected in fig. 2 are shown in fig. 6. In this series of calculations, the tube length is again increased by 57 mm to its real size, and the length of its right-hand section with the short-circuiting jumper at the end is increased by 70 mm. Drops of the curves $E(f)$ in the central part became more drastic, but the dip and amplitude near the operating frequency $f_0 = 2.795$ GHz changed insignificantly. Effect of vibrator conductivity (equivalent resistance of streamer discharge plasma), as well as of the vibrator length, in fig.6 is also insignificant.

The family of parameter $S_{1,1}$ (reflection coefficient) graphs of the same model is shown in fig. 7. Parameter $S_{1,1}$ represents the radiation reflection coefficient by the field at the input of the system. In this case, at the operating frequency — $S_{1,1} = 0.7–0.8$. The energy reflection coefficient by power is -still a characteristic of the entire system, not of an individual vibrator in front of the flare aperture, and at f_0 frequency this coefficient exceeds the value of $(S_{1,1})^2 \geq 0.5$.

Electric field distribution diagrams in the two cross sections of the model at $y = 0$ and $x = 0$ with vibrator conductivity $\sigma = 10^3$ Cm/m (equivalent resistance is 100 Ω) are shown in fig. 8. Compared to the diagram in fig. 5, changes in the field distribution in fig. 8 are very insignificant. The lower diagram also illustrates a sharp

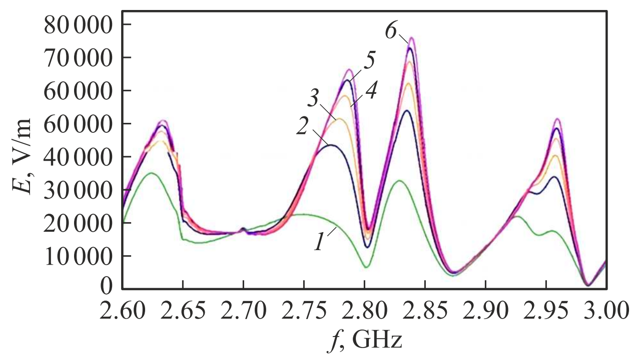

Figure 6. Distributions of electric field amplitude at vibrator poles at vibrator length of $L_v = 48$ mm and different conductivity values $\sigma = 10^2$ (*1*), 10^3 (*2*), $3 \cdot 10^3$ (*3*), 10^4 (*4*), $3 \cdot 10^4$ (*5*), 10^5 Cm/m (*6*).

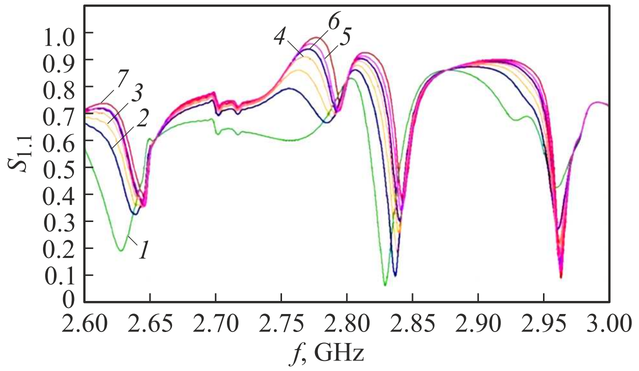

Figure 7. Distributions of parameter $S_{1,1}$ in waveguide path of microwave radiation input to chamber at vibrator length $L_v = 48$ mm and different conductivity values $\sigma = 10^2$ (*1*), 10^3 (*2*), $3 \cdot 10^3$ (*3*), 10^4 (*4*), $3 \cdot 10^4$ (*5*), 10^5 Cm/m (*6*). Line *7* corresponds to PEC.

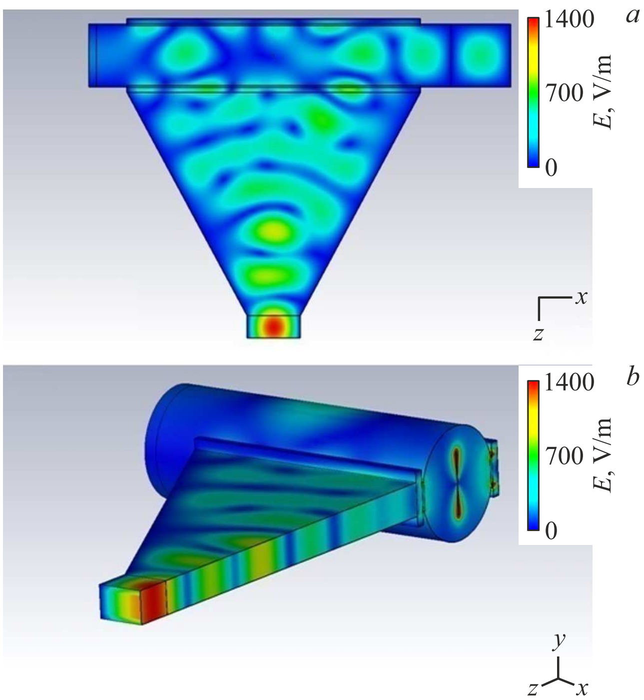

Figure 8. Distributions of electric field intensity in cross sections of model $y = 0$ (*a*) and $x = 0$ (*b*) with electromagnet vibrator with length of $L_v = 48$ mm and conductivity $\sigma = 1000$ Cm/m.

enhancement of the resultant field in the area of the vibrator location near its poles.

As in the previous case, a standing wave is formed in the system, and a pure traveling-wave mode cannot be achieved. However, after occurrence and development of the streamer discharge, the field amplitude at the vibrator poles and, obviously, at the streamer ends decreases not so quickly as in the case of electromagnetic vibrator in free space. In other words, generation and development of the streamer volume structure of the discharge during the microwave pulse should occur with a practically invariable rate. To form the volume streamer microwave discharge, you only have to find a way to increase the electric field at the electromagnetic vibrator poles.

Let us consider a variant with initiator location perpendicular to the optical axis of the chamber and a waveguide input of microwave radiation.

Families of the electric field amplitude curves at the electromagnetic vibrator poles and parameter $S_{1,1}$ at different lengths of the vibrator are shown in fig. 9,*a*; similar dependences at the optimal length of the vibrator $L_v = 45$ mm and different values of its conductivity — in fig. 10. The obtained frequency dependences retain,

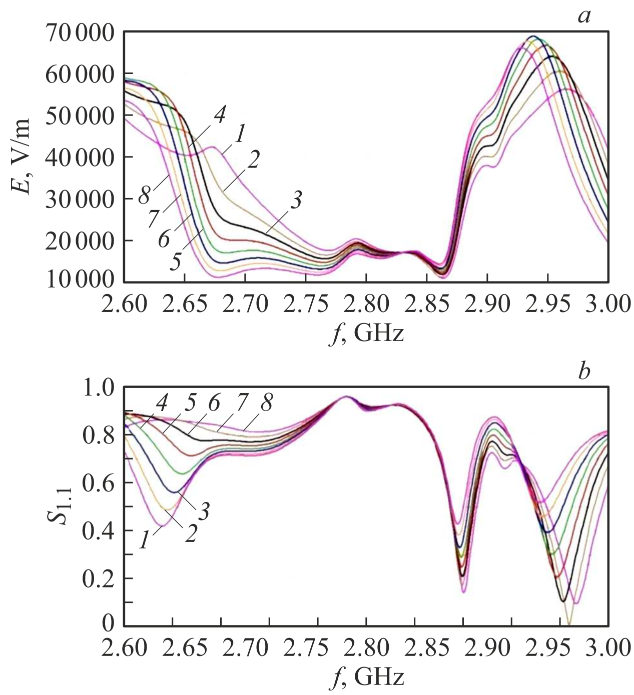

Figure 9. Distributions of electric field amplitude at vibrator poles (*a*) and parameter $S_{1,1}$ (*b*) for waveguide microwave radiation input at $L_v = 45$ (*1*), 46 (*2*), 47 (*3*), 48 (*4*), 49 (*5*), 50 (*6*), 51 (*7*), 52 mm (*8*).

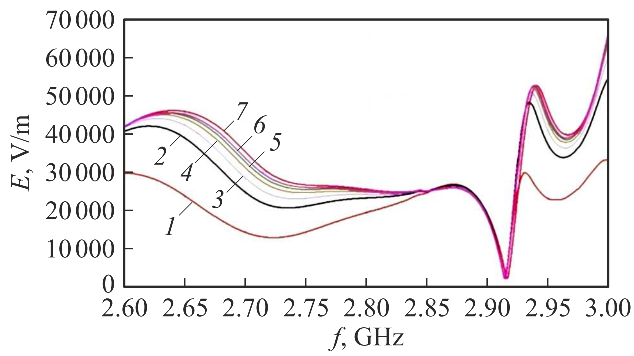

Figure 10. Distributions of electric field amplitude at vibrator poles at vibrator length of $L_v = 45$ mm and different conductivity values $\sigma = 10^2$ (*1*), 10^3 (*2*), $3 \cdot 10^3$ (*3*), 10^4 (*4*), $3 \cdot 10^4$ (*5*), 10^5 Cm/m (*6*). Line *7* corresponds to PEC.

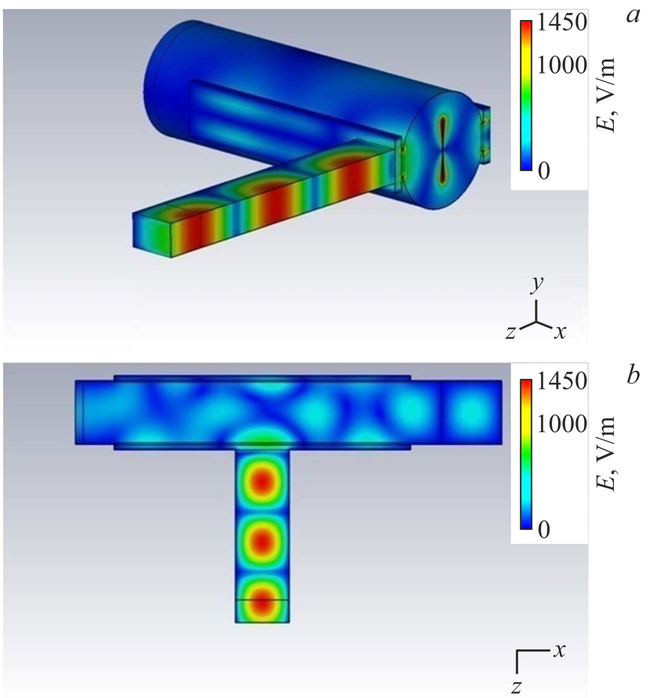

Figure 11. Distributions of electric field intensity in cross sections of model $y = 0$ (a) and $x = 0$ (b) with electromagnet vibrator with length of $L_v = 48$ mm and conductivity $\sigma = 1000$ Cm/m.

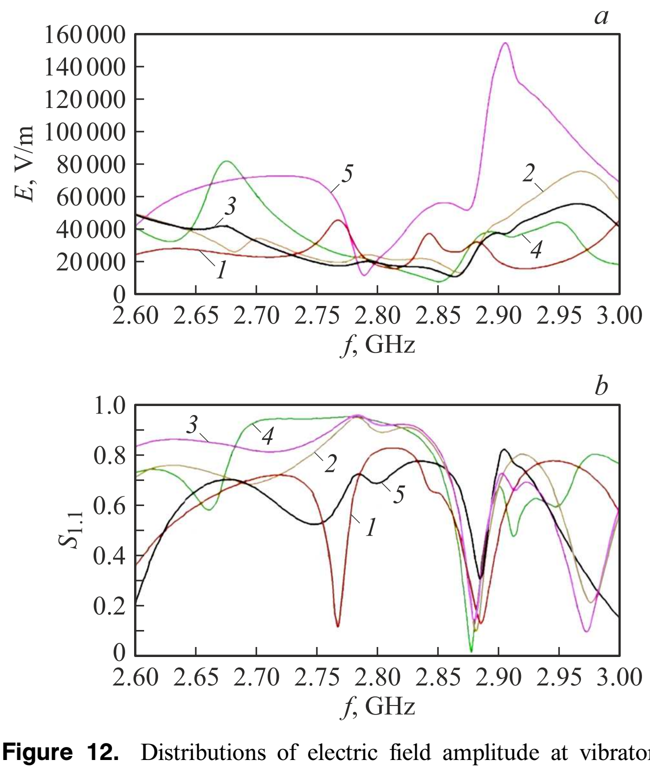

Figure 12. Distributions of electric field amplitude at vibrator poles (a) and parameter $S_{1,1}$ (b) at vibrator length of $L_v = 45$ mm and different value of its bias $s = -30$ (*1*), -10 (*2*), 0 (*3*), +15 (*4*), +30 mm (*5*).

although less pronounced, but still the same multiresonance nature, formed by the equivalent system of coupled contours with distributed parameters L and C.

The reflection coefficient of microwave radiation in the input waveguide path is greater by power and exceeds 80%. Effect of vibrator parameters as such on the characteristics of the system is still low. In a variant of the system with waveguide microwave energy input, the field amplitude at operating frequency in conventional units is about $2 \cdot 10^4$ V/m, and at input path power of 500 kW it reaches 140 kV/cm. At such electric field strength and given parameters of the vibrator, it is possible to generate a microwave discharge at gas pressure in the chamber $p = 4$ atm and more.

At the same time because- of a highly inhomogeneous field distribution on the chamber axis near the flare aperture (compared with uniform cosine distribution) and amplitude amplification in its central part, the gain from using waveguide input of microwave radiation is not as great as could be expected.

Availability of a clearly pronounced standing wave mode in the path and formation of an inhomogeneous field on the chamber axis is confirmed by the electromagnetic field diagrams shown in fig. 11 in two cross sections of the model — $x = 0$ and $y = 0$ (nonlinear scale is used).

Attempts to further tune and improve the characteristics of the system by displacing the vibrator along the z axis by s in the range from -30 to $+30$ mm were unsuccessful (fig. 12). The obtained families of curves (parameters E_A and $S_{1,1}$) are even more indented, and no gain in the field amplitude at the vibrator poles is obtained.

4. Conclusion

Simulation and comparison of a number of ways of practical interest to generate initiated microwave discharges with a developed volume structure and limited duration of pulses of electromagnetic radiation were performed. The available results confirm the possibility and prospects for using new effective ignition systems in high-pressure combustion chambers based on initiated microwave discharges with a developed volume structure. The option of placing electromagnetic vibrators in the working chamber parallel to its axis with a corresponding change in the microwave radiation input and chamber design is of the greatest interest.

The obtained results are important for investigating the effect of microwave discharges of different types on the characteristics of propane-air gas mixture combustion at increased pressure.

Before making a final decision on modification or radical upgrade of the working chamber with the ignition system, it seems necessary to study and determine the possibility of applying other discharge initiator designs, in particular, quarter-wave vibrators with the base on the working chamber wall and a pole in its central part; circular vibrators with a cut, excited by the magnetic component of the electromagnetic field; curvilinear initiators in the form of an arc segment, placed near the walls of the cylindrical chamber with microwave radiation input from the chamber end.

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Conflict of interest

The authors declare that they have no conflict of interest.

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