Multi-point ignition of air/fuel mixture by the initiated subcritical streamer discharge

Pavel Bulat[1], Pavel Chernyshov[1], Igor Esakov[2], Lev Grachev[2], Pavel Lavrov[2], Anzhelika Melnikova[1], Konstantin Volkov[3,*], Igor Volobuev[1]

[1]Baltic State Technical University, 190005, St Petersburg, Russia

[2]Moscow Radiotechnical Institute of Russian Academy of Sciences, 117519, Moscow, Russia

[3]Kingston University, SW15 3DW, London, United Kingdom

Abstract

An experimental study of ignition and combustion of a propane/air mixture is carried out, and the efficiency of two ignition systems is compared. The first one is the traditional technology with conventional spark plugs, and the second one is a system with microwave initiated streamer discharges. In both cases, the ignition sources, spark plugs or streamer discharges are distributed along the surface of the combustion chamber. A subcritical streamer discharge is initiated on the surface of the circular tube using a half-wave resonator when the intensity of the electric field is much smaller than the breakdown intensity because ability of electromagnetic vibrators to initiate air breakdown has a resonant character. For the initiated streamer discharge, intensity of microwave radiation is significantly lower than the breakdown intensity. The results obtained for a new microwave ignition system of a fuel/air mixture are presented and compared with an ignition system based on spark plugs. Comparative analysis is given for different initial pressures and composition of fuel/air mixture. The time of propagation of the flame front is compared, as well as the rate of pressure increase in the combustion chamber, depending on the initial pressure and the composition of the mixture. The optimal fuel/air equivalence ratio, which provides the highest pressure and the highest rate of pressure rise in the combustion chamber, is determined. A comparative assessment of the energy efficiency of each of the approaches applied to the ignition of the fuel/air mixture is performed. The results obtained could potentially be useful to improve reliability of plasma-assisted ignition systems and flight safety.

Keywords

Flight safety, microwave discharge, streamer discharge, spark plug, plasma-assisted technology, ignition, combustion, propulsion.

1 Introduction

Flight safety is significantly affected by the reliability of ignition systems. Development of high-speed ramjets, scramjets and more efficient lean burning engines requires design and optimization of advanced propulsion technologies [1–4]. The study of ignition, combustion and detonation processes is of interest for using their potential in propulsion systems [5]. Experimental measurements and numerical simulations are gaining importance in connection

*Corresponding author: k.volkov@kingston.ac.uk

with the need to establish the region of existence of a stable working process in detonation engines. In an engine with continuous detonation, the mixture is burned in a detonation wave propagates in tangential direction in an annular channel [6]. Detonation engines are theoretically 20–25% more efficient than traditional jet engines based on Brayton thermodynamic cycle [7–9]. The advantage is achieved due to the fact that the fuel burns in a detonation wave in a thin layer in a fairly short time interval [10].

For a stable propagation of the detonation wave, it is necessary that the state of the fuel mixture ahead of the travelling front does not change or change so insignificantly that it does not affect the speed and structure of the wave [11]. The tangential propagation of a detonation wave in an annular channel of finite curvature is accompanied by diffraction phenomena on the outer and inner cylindrical surfaces. In particular, due to the diffraction of the detonation wave, the maximum pressure on the outer wall of the cylindrical combustion chamber is 20–25% higher than on the inner one. This leads to the formation of transverse wave structures interacting with the intrinsic transverse waves of the detonation front. In places of collision of transverse waves of different structures, regions with reduced pressure arise, leading to the premature supply of fuel components to the detonation products. Numerical calculations carried out in [11] show that the detonation front acquires a W-shape with leading points on the inner and outer walls, as well as in the center of the gap. The development of a plane wave disturbance leads to the formation of a cellular detonation structure [12]. Rotating detonation have been studied experimentally and numerically in [13, 14]. Studies of continuous circular detonation show that the front of detonation combustion is a complex shock-wave structure consisting of at least two triple configurations. The triple configurations and the detonation combustion region are adjusted to each other so that the detonation front propagates along the annular gap with the minimum possible volume of detonation combustion.

A detonation wave can occur as a result of the transition from the slow combustion stage due to turbulence of the flame front (Deflagration to Detonation Transition, DDT). The advantage of creating a detonation by DDT is low initial energy consumption, and the disadvantage is the long development time of the process and its instability [15, 16]. For the direct initiation of detonation by a strong explosion under comparable conditions, energy costs are about 1000 times higher than with DDT. At the same time, there is a critical level of detonation energy, which depends on many factors [17]. An increase in the volume of a fuel mixture that can be ignited at the same time or multi-point ignition significantly reduces the transition time from deflagration to detonation [18]. The influence of the composition of combustible mixtures on the length of deflagration to detonation transition is discussed in [15].

The main problem of the development of ignition systems is the need to improve the reliability of ignition without significantly increasing the energy consumption for the ignition process [10]. The use of microwave radiation, high-power lasers and corona discharges seems to be unattractive, due to the low efficiency of such systems [19, 20]. Nevertheless, the volumetric plasma ignition of the fuel mixture has undeniable advantages [21–23], allowing it to be used not only in detonation engines, but also in traditional internal combustion engines for boosting the speed or reducing nitrogen oxide emissions due to significant increasing the combustion rate, as well as for stabilizing combustion in a supersonic flow [24].

The interaction of the electromagnetic field with gases has a pronounced threshold character. For the initiation of combustion and detonation, it seems promising to initiate a streamer discharge in a gas in a quasi-optical microwave beam, the energy of which is much lower than the electric breakdown energy of the gas [25] (subcritical streamer discharge). The modelling of the ionization-overheating instability of plasma formation and the nucleation of streamers is carried out in [26,27]. For sub-critical streamer discharge, breakdown conditions are created by special initiators within its local region, and the discharge propagates toward the source of electromagnetic beam.

Recent developments in diagnostics and simulations of streamers are reported in [28,29]. The corona discharge generates streamers coming from a star-shaped electrode, generally consisting of four or five tips.A statistical analysis of the streamer behavior was performed, by separately analyzing the streamers generated by each tip of the star-shaped electrode. Effects of varying applied voltage amplitudes on the characteristic parameters of the plasma-assisted planar shear flow combustion are analyzed in [30].

The minimum ignition energy characterizes the minimum amount of energy that must be supplied to the fuel/air mixture in order to ensure a self-sustaining combustion mode [31]. The minimum ignition energy depends on many factors, among which the composition of the fuel/air mixture, pressure and many others. The most studied, both theoretically and experimentally, is the minimum ignition energy when the mixture is ignited by a spark discharge. For most hydrocarbon fuels, the experimental values of the minimum ignition energy are in the range 0.2–0.3 mJ and above [32]. Air breakdown conditions in sub- and supersonic flows induced by the subcritical streamer discharge are reported in [31]. The ability of electromagnetic vibrators to initiate air breakdown has a resonant character.

For the case of ignition by a laser discharge, the values of the minimum ignition energy are higher than those for ignition by a spark discharge, and significantly depend on the duration, energy, wavelength of the laser pulse [19, 33]. Potential advantages of using combustion stimulated by non-equilibrium plasma of a pulsed discharge in various applications are discussed in [34, 35]. Despite the results achieved and the level of understanding of the structure of emerging flows, the diffraction of shock waves and the organization of shock-wave and detonation processes in propulsion systems remain the subjects of theoretical, experimental and numerical studies [36–41]. Previous experimental and numerical investigation of ignition and combustion of fuel/air mixtures have demonstrated a great potential and promising characteristics of the microwave streamer discharge and their ability to ignite lean fuel/air mixtures in long tube [42, 43], and sub- and supersonic flows [44, 45].

In this study, the rate of pressure rise and maximum pressures in the combustion chamber with different numbers of spark plugs are compared with the characteristics of the process that is realized with streamer ignition of the fuel/air mixture. The optimum fuel/air equivalence ratio for multi-point spark and streamer ignitions, which provides the highest pressure and the highest rate of pressure rise in the combustion chamber, is determined. The possibilities of an initiated streamer discharge for the ignition of a fuel/air mixture outside the ignition range under normal conditions are discussed.

2 Experimental setup

The experimental test rig, designed at the Moscow Radio-Technical Institute of Russian Academy of Sciences (MRTI RAS), makes it possible to carry out experiments with the ignition of combustible mixtures with a traditional ignition system using spark plugs (pulsed spark discharge) and the developed multi-focal microwave system. The experimental setup is shown in Figure 1, where P1 and P2 are propane and air valves, and V1, . . . , V6 are safety valves. The test rig includes a working chamber with channels for pumping and supplying gas and measuring equipment.

A series of experiments is carried out to study the ignition and combustion of a propane/air mixture in a circular tube. The diagram of the experimental setup is shown in Figure 2.

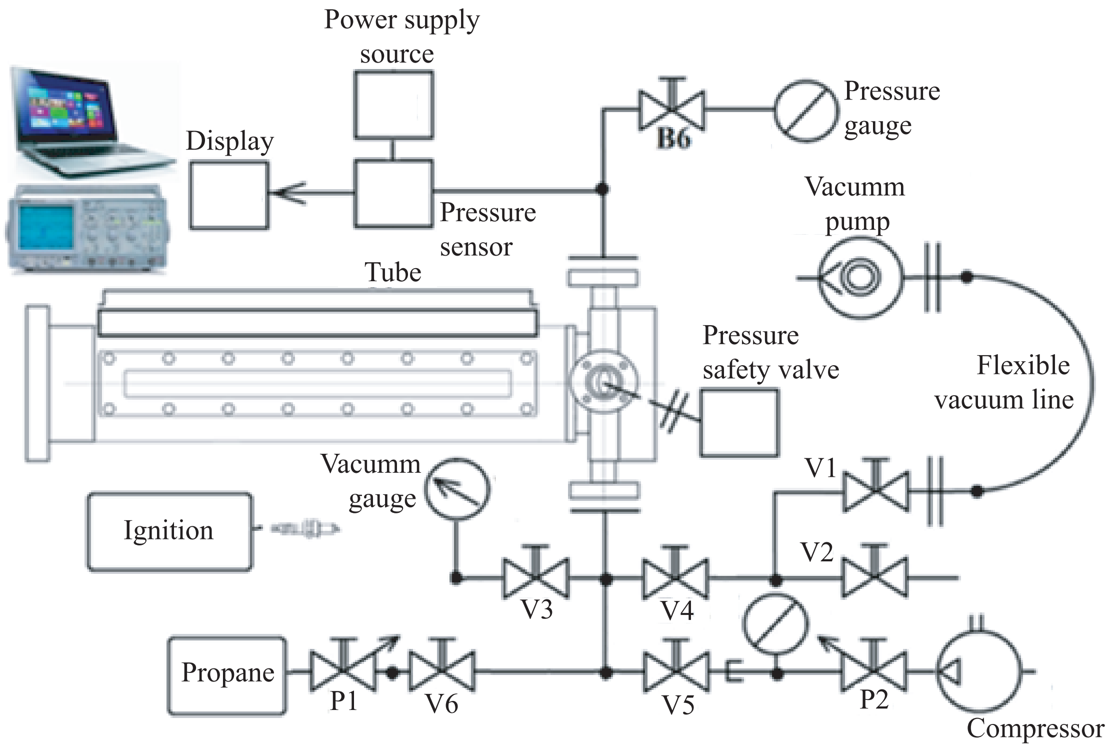

Figure 1. Experimental test rig

The combustion chamber is roughly the size of a commercial vehicle engine cylinder. The length of the cylindrical combustion chamber is 280 mm and its radius is 40 mm. The spark discharges are installed at regular intervals. When using 8 spark charges, the distance between them is 40 mm. The combustion products are pumped out after the completion of the combustion processes. The installation has two viewing windows (side and face), through which video recording of the ignition and combustion processes is made on a high-speed camera at a speed of 400 frames/s. Thanks to these videos, it is possible to estimate the speed of propagation of the flame front and the burning time.

Microwave radiation with a wavelength of $\lambda = 12.3$ cm is fed into the combustion chamber through a horn from the magnetron of the microwave generator, developed and manufactured at the MRTI RAS (Figure 2). Dimensions of the generator are $1800\times800\times2200$ mm. The generator has the following technical characteristics: microwave frequency is 2795 MHz, pulse repetition rate is 1–800 Hz (or single pulses), pulse durations are 2, 4 and 6 μs, output pulse power is 50–600 kW. The cross section of the waveguide supplying radiation at the horn input is 72×34 mm, and the aperture at the output is 370×25 mm. Horn length is 330 mm. At a radiation frequency of 2.8 GHz, which corresponds to the radiation frequency of the generator used, the reflection coefficient of the horn is 12 dB, which indicates a fairly good quality of its manufacture.

In the working combustion chamber, 8 streamer discharge initiators are installed with a distance of 40 mm from each other. The initiators are attached to a 10 mm quartz tube using high-temperature cyacrine glue. A quartz tube is installed in the center of the chamber along the centreline of the tube using special supports made of a radio-transparent heat-shielding material with a dielectric constant close to unity. The layout of the initiators is shown in Figure 3.

The pressure in the experiments is measured with two differential electronic pressure sensors (Figure 2). The installation allows to ignite the fuel/air mixture with 8 streamer microwave discharges. Microwave initiators are made of Ni-Cr wire with a diameter of 0.5 mm.

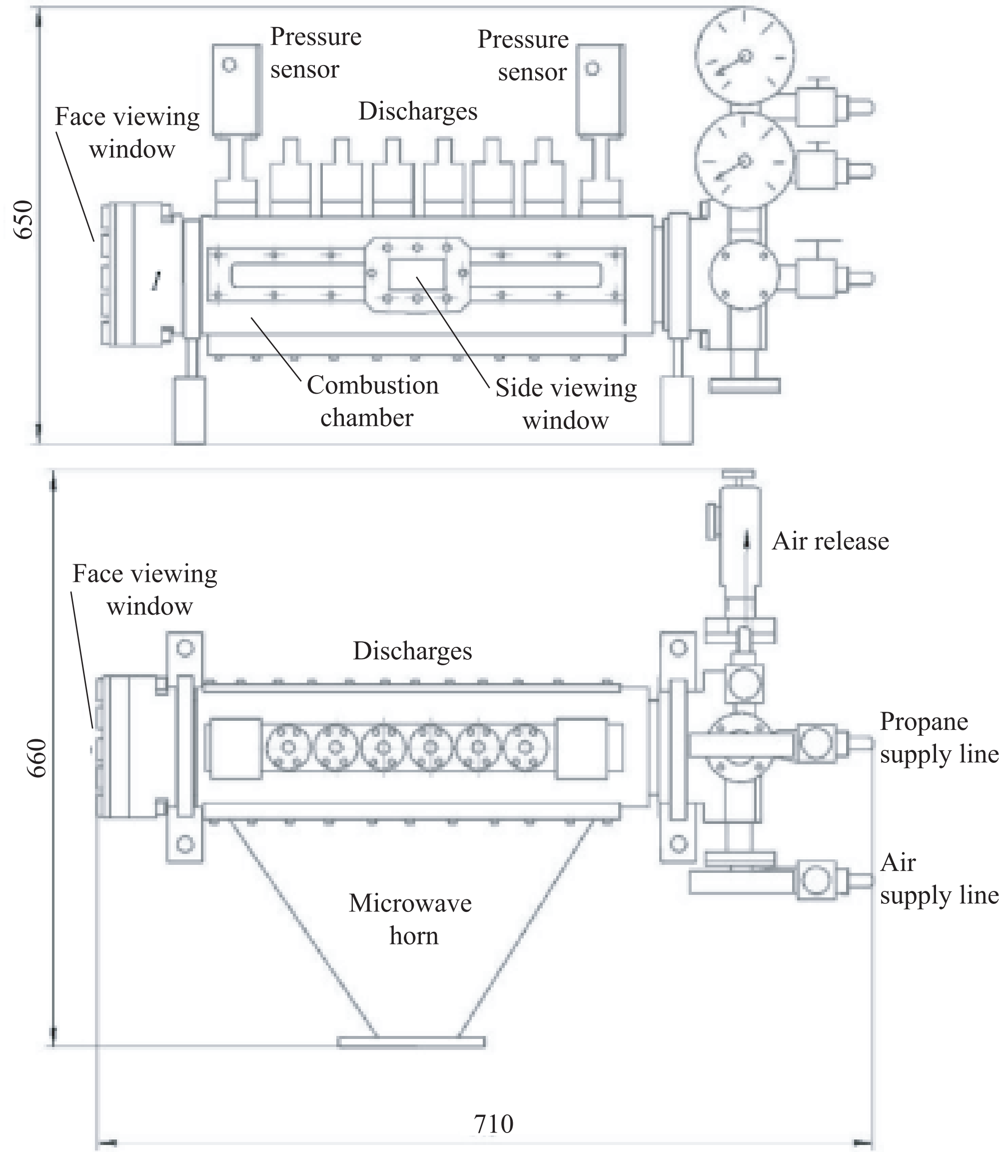

Figure 2. Diagram of the experimental setup

The optimal (resonance) length of initiators is calculated and additionally determined experimentally. An initiator with an initial length of 60 mm is installed in the tube. Microwave radiation is fed into the tube from the generator through the horn from the magnetron with the lowest possible power. The air from the pipe is evacuated by a vacuum pump and pumped in by a high pressure pump. The dependence of the pressure at which the discharge occurs at the ends of the initiator on the length of the initiator is presented in Figure 4. The graph shows that the optimal initiator length is about $L = 51$ mm.

In experiments, pressure is measured with a differential electronic pressure sensor, the signal from which is recorded and stored using an oscilloscope connected to a computer. The signals of the pressure sensor are recorded and stored every 80 μs or 160 μs, depending on the selected oscilloscope sweep limit. Then, graphs of the dependence of the pressure in the tube on time are plotted. The use of high-speed video recording of the process with a high-speed camera allows to visually observe the propagation of the flame front inside the tube through special viewing windows.

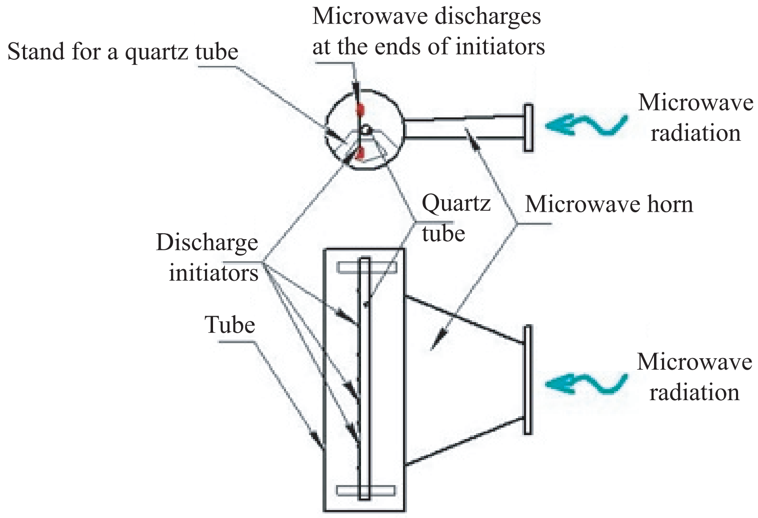

Figure 3. Layout of initiators in the tube

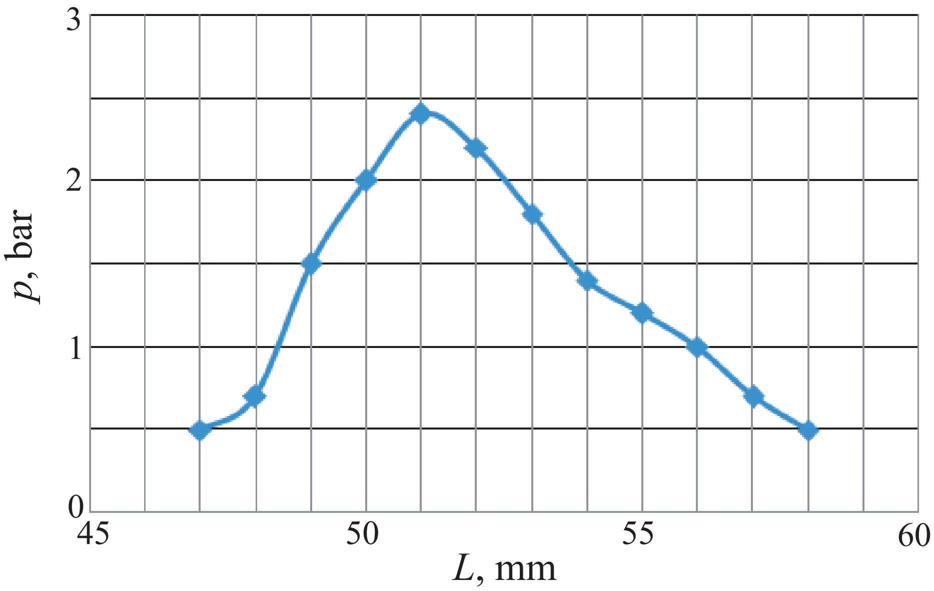

Figure 4. Dependance of breakdown pressure on the length of discharge initiator

3 Structure of discharges

The moment of ignition of a streamer discharge in a tube filled with air is shown in Figure 5. The dimensions of the streamer discharge significantly exceed the dimensions of the spark, and discharges have a spatially developed structure. Pictures of the development of combustion fronts during spark and streamer ignition are presented in Figures 6–8.

The development of combustion process with spark plug ignition, from the moment of ignition to the moment when the combustion occupies the entire volume of the tube, is shown in Figure 6. The flame has a characteristic blue color.

The development of combustion during streamer ignition, starting from the moment of ignition of the discharge up to the moment when combustion covers the entire volume of the tube, is shown in Figure 7. The flame has a pinkish character, and the combustion front, in general, has a structure that is observed with spark ignition in Figure 6. The discharge begins to branch, streamer channels appear, the length of which does not exceed 1.5 cm.

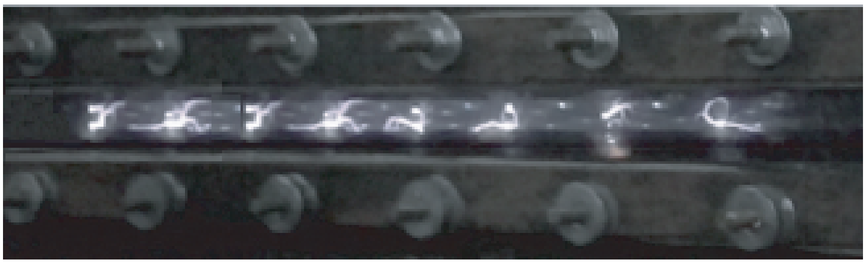

Figure 5. Streamer discharge in the tube filled by air

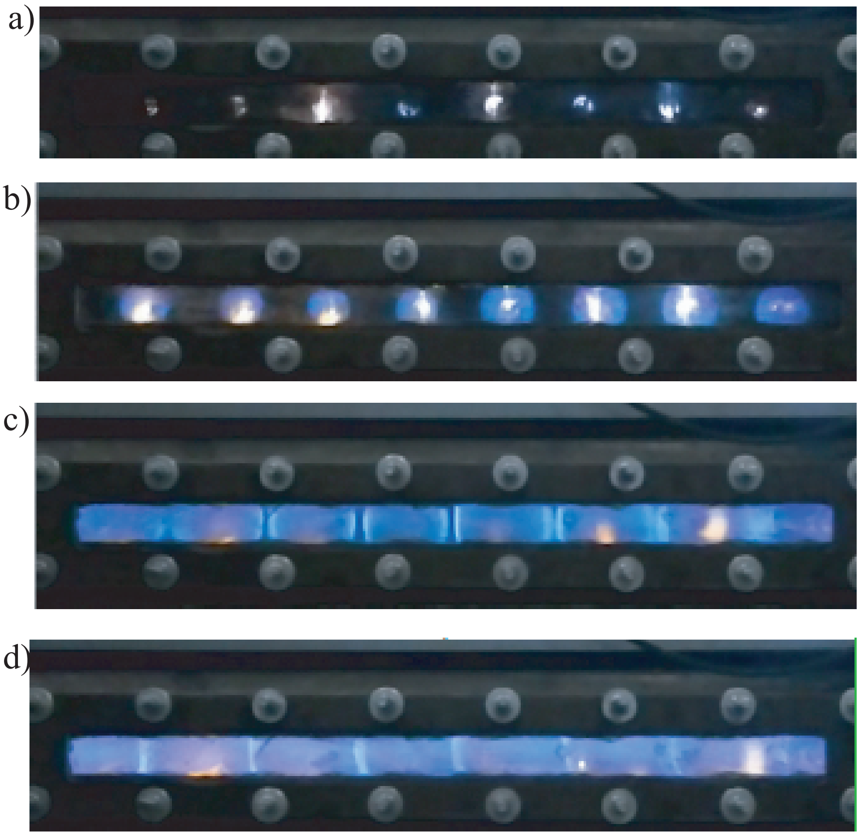

Figure 6. Flame with spark ignition of the mixture at $\eta = 1$ and $p_0 = 2$ bar at the moments of time corresponding to ignition of the mixture (a) and 3/400 s (b), 6/400 s (c), 9/400 s (g) after ignition

This is due to the fact that the duration of microwave radiation is limited to 6 μs, and the propagation velocity of the streamer is about 2 km/s. In this case, multi-point ignition occurs and it is not volumetric. Discharges also occur on a quartz tube on which initiators are attached. The rate of development of combustion in the case of streamer ignition of the mixture is almost three times higher than in the case of spark ignition.

The development of combustion through the end glass of the installation is shown in Figure 8. It is clearly seen that ignition occurs immediately in a significant volume (as in a volumetric explosion). The flame during spark ignition from the moment of spark formation (Figure 6a) to the moment of time 3/400 s (Figure 6b) smoothly increases in size from zero. With streamer ignition at the moment of time 1/400 s the flash of the fuel mixture immediately has the size shown in Figures 7b and 8b.

Comparison of two family of experimental results obtained with spark plugs and streamer discharges is shown in Figure 9 (half of the tube is shown). The upper fragments in each

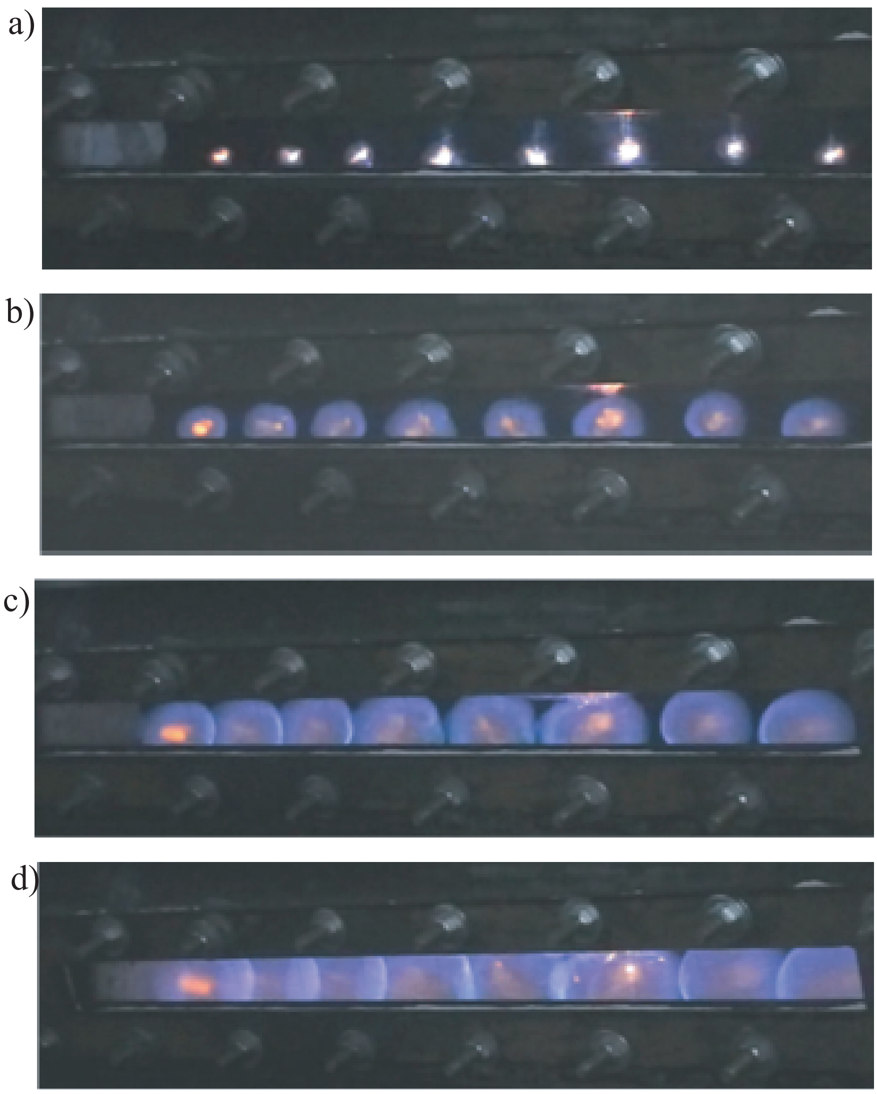

Figure 7. Flame with streamer ignition of the mixture at $\eta = 1$ and $p_0 = 2$ bar at the moments of time corresponding to ignition of the mixture (a) and 1/400 s (b), 2/400 s (c), 3/400 s (g) after ignition

series show the development of combustion with spark ignition, and the lower fragments show the results of the experiment with streamer ignition. The duration of the microwave discharge is assumed to be 6 μs, and the energy supplied to the plasma is about 1.6 J. Duration of spark discharge is 4 ms, and the amount of energy released by one spark plug is 0.5 J. The power of energy release varies linearly from the maximum at the initial time moment to 0.5 at 4 ms.

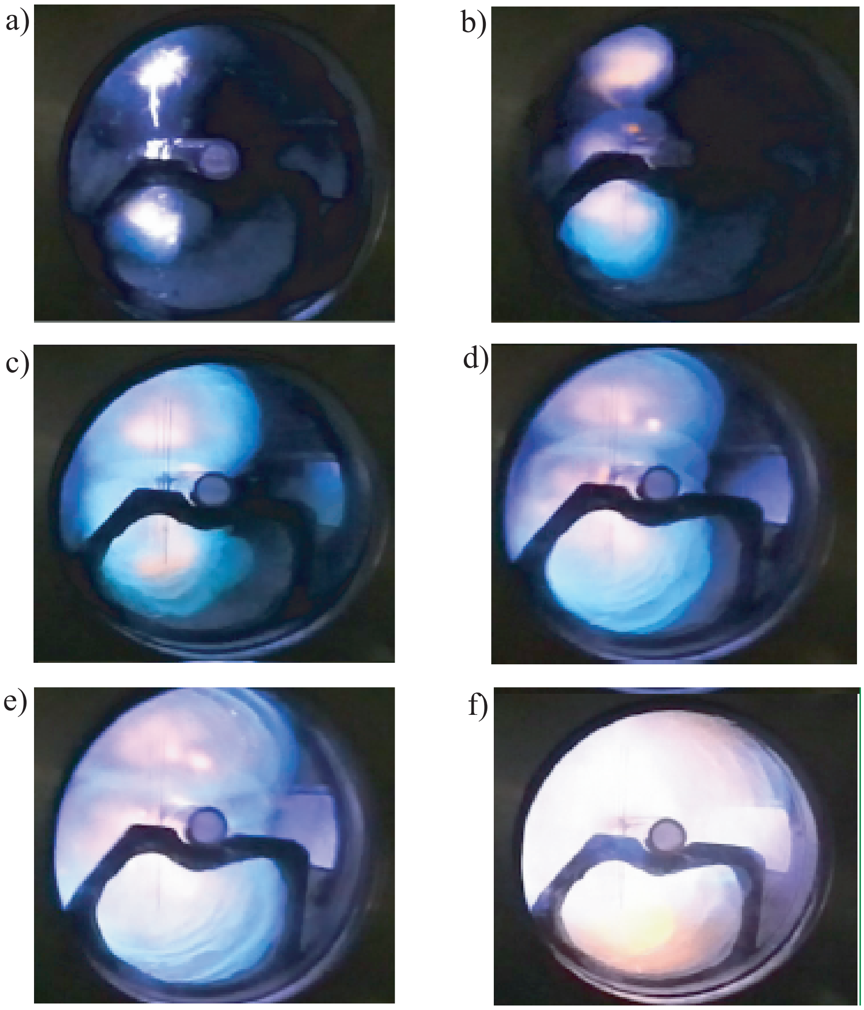

Figure 8. Flame through the end window with streamer ignition of the mixture at $\eta = 1$ and $p_0 = 2$ bar at the time instant corresponding to the ignition of the mixture (a) and 1/400 s (b), 2/400 s (c), 3/400 s (d), 4/400 (e), 5/400 s (e) after ignition

4 Results and discussion

Initial pressure of the mixtures varies from 1 to 2.5 atm. The experiments are carried out with fuel/air ratios in the range from 0.6 to 2. At other values of fuel/air equivalence ratio, the mixture is not ignited. These values are close to the upper and lower limits of ignition of a propane/air mixture.

4.1 Initial pressure $p_0 = 1$ atm

The time dependencies of the pressure in the tube are shown in Figure 10. The results obtained make it possible to find the values of the maximum pressure during combustion of the fuel/air mixture, the time of pressure rise and the rate of pressure rise. High-speed video recording allows to measure the time of filling the entire volume of the tube with the flame and the time of combustion of the mixture (the end of the glow).

The dependencies of the maximum pressure in the combustion chamber on the composition of the fuel/air mixture are shown in Figure 11. For comparison, this figure also shows a similar graph of the combustion process induced with a spark plug. The maximum pressure

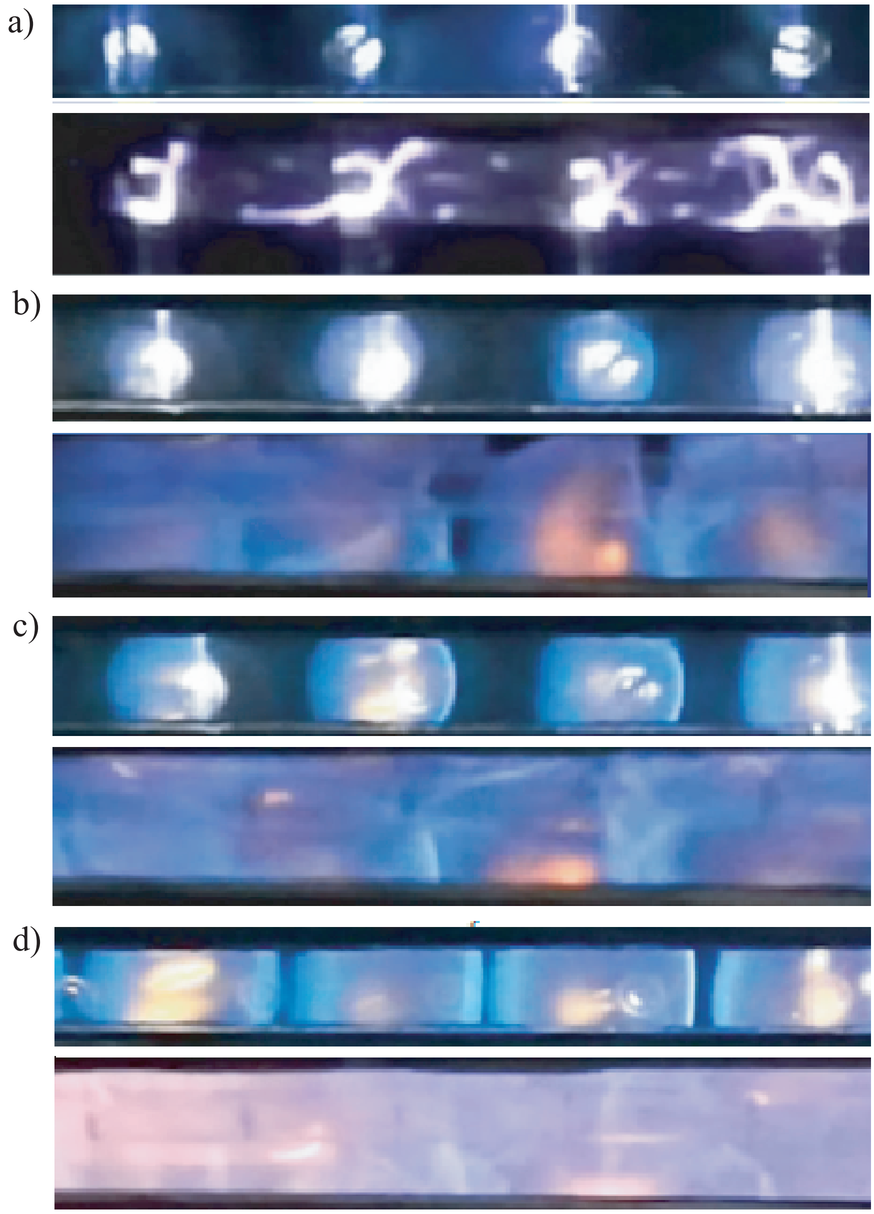

Figure 9. Comparison of the results of experiments with the spark ignition (upper photo) and experiment with streamer ignition (lower photo) in the case of 4 ignition centers at times corresponding to the discharge ignition (a) and 3/400 s (b), 6/400 s (c), 9/400 s (d) after ignition

values for microwave ignition are 10% higher than when using a spark plug. The similar pattern is observed when comparing the graphs of the pressure rise rates shown in Figure 12. The maximum speed with with microwave ignition is 160 atm/s, and the maximum speed with spark plug ignition is 140 atm/s.

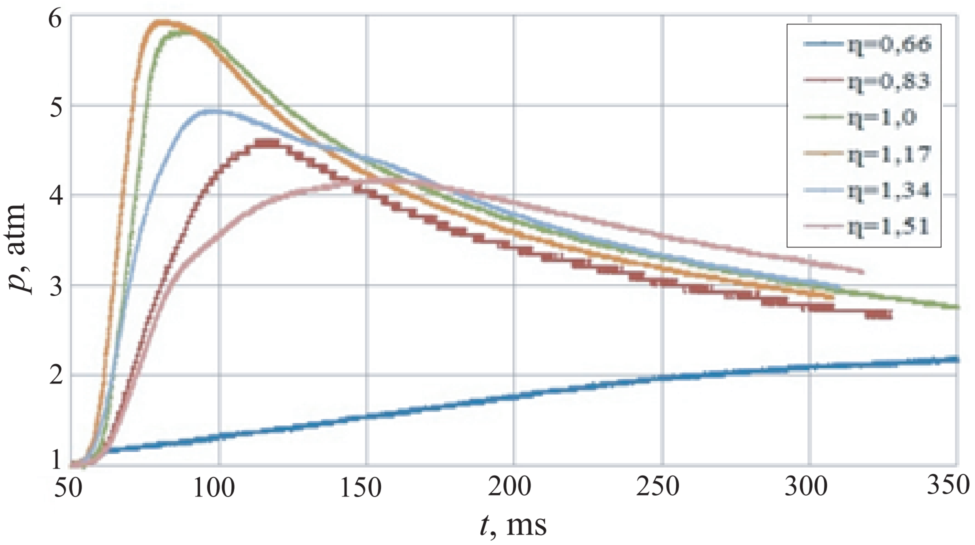

Figure 10. Dependencies of pressure in the tube on time at an initial pressure of $p_0 = 1$ atm

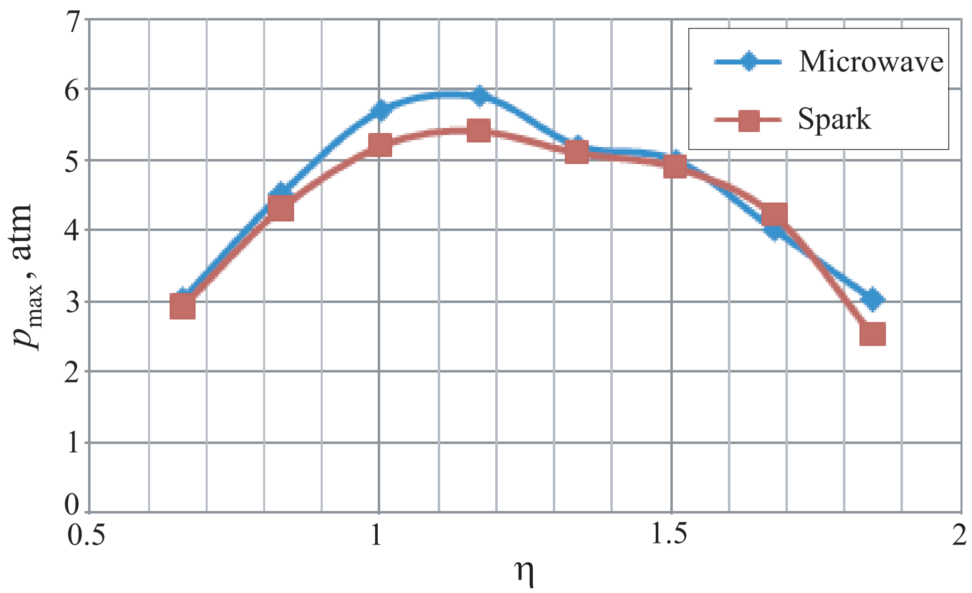

Figure 11. Dependence of the maximum pressure on the composition of the fuel/air mixture for $p_0 = 1$ atm. The blue line corresponds to ignition by multi-microwave discharge system, and the red line corresponds to the ignition with spark plugs

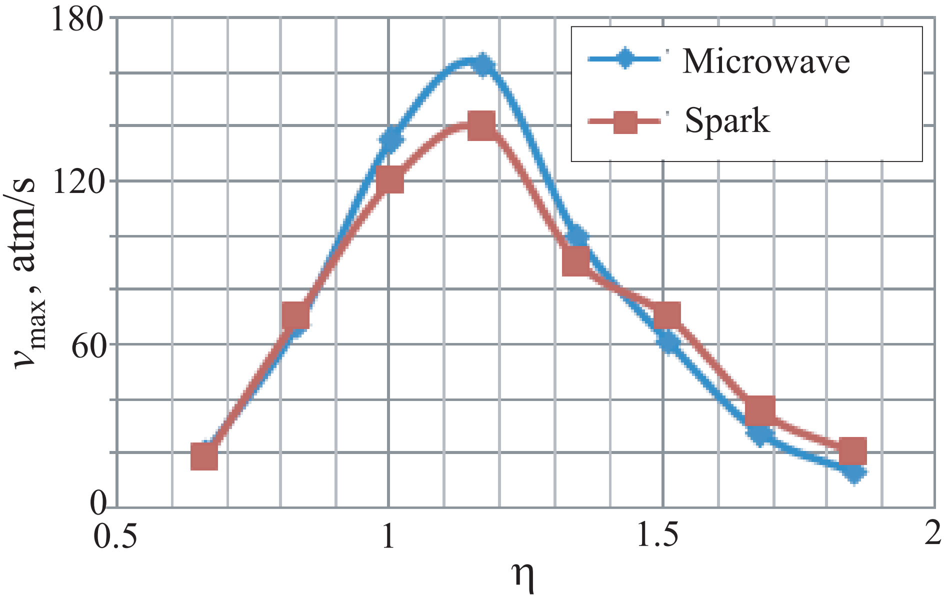

Figure 12. Dependence of the rate of pressure rise on the fuel/air equivalence ratio for $p_0 = 1$ atm. The blue line corresponds to ignition by multi-microwave discharge system, and the red line corresponds to the ignition with spark plugs

The main characteristics of the combustion process of a propane/air mixture in an experimental tube are given in Table 1 at initial pressure of $p_0 = 1$ atm. Here, η is the fuel/air equivalence ratio, $p_{\max}$ is the maximum pressure in the tube, t_p is the time of pressure rise to the level of $p_{\max}$, v_p is the rate of pressure rise from p_0 to $p_{\max}$, t_v is the time of filling the entire volume with flame, t_b is the burning time of mixture.

Table 1. Dependencies of combustion parameters on the fuel/air equivalence ratio with ignition induced by microwave discharges at $p_0 = 1$ atm

No	η	$p_{\max}$, atm	t_p, ms	v_p, atm/s	t_v, ms	t_b, ms
1	0.55	—	—	—	—	—
2	0.66	3	100	20	90	250
3	0.83	4.3	50	67	75	250
4	1	5.7	35	135	80	305
5	1.17	5.9	30	163	85	290
6	1.34	5	40	100	10	175
7	1.51	4.3	70	61	90	400
8	1.67	4.2	120	27	70	500
9	1.84	3	150	13	140	550
10	2	—	—	—	—	—

4.2 Initial pressure $p_0 = 2.5$ atm

The time dependencies of the pressure in the tube are shown in Figure 13. The maximum pressure reaches 19.2 atm with a fuel/air equivalence ratio of 1.51. The increase in pressure relative to the initial one is $p_{\max}/p_0 = 19.2/2.5 = 7.7$. If the fuel mixture is ignited with spark plugs, the maximum pressure increase reaches 5.6 times relative to initial pressure.

The dependencies of the maximum pressure in the tube on the composition of the fuel/air mixture are shown in Figure 14 for various ignition systems. With an increase in the

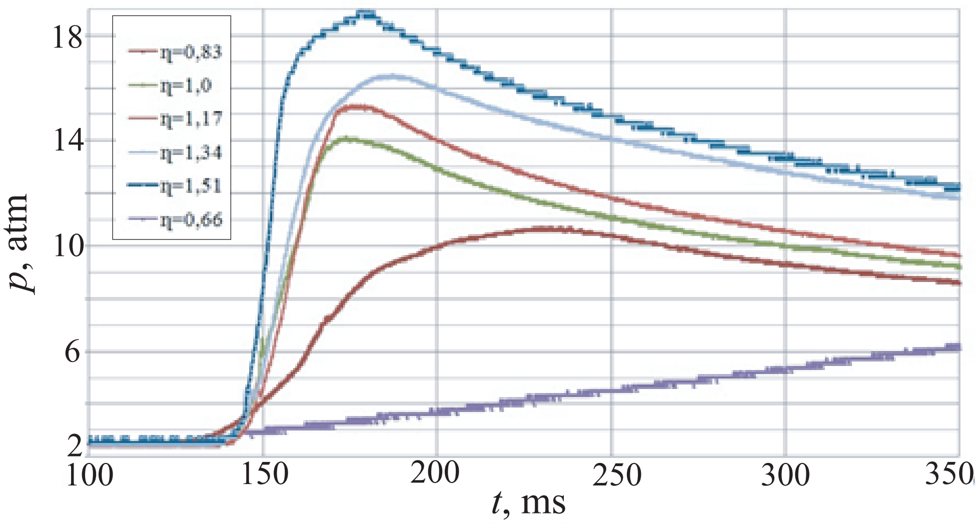

Figure 13. Dependencies of the pressure in the tube on time at an initial pressure of $p_0 = 2.5$ atm

initial pressure to $p_0 = 2.5$ atm, the pressure in the tube increases by 2 atm or about 10% when using microwave ignition. The dependencies of the rate of pressure rise for different mixture compositions are shown in Figure 15. The maximum rate of pressure rise reaches 420 atm/s, and the maximum rate of pressure increase with spark plugs is 340 atm/s. With an increase in the initial pressure in the tube, the rate of pressure rise increases, and this dependence in the studied pressure range is linear $p_{0,2.5}/p_{0,1} = v_{m,2.5}/v_{m,1} = 2.5/1 \sim 416/160$.

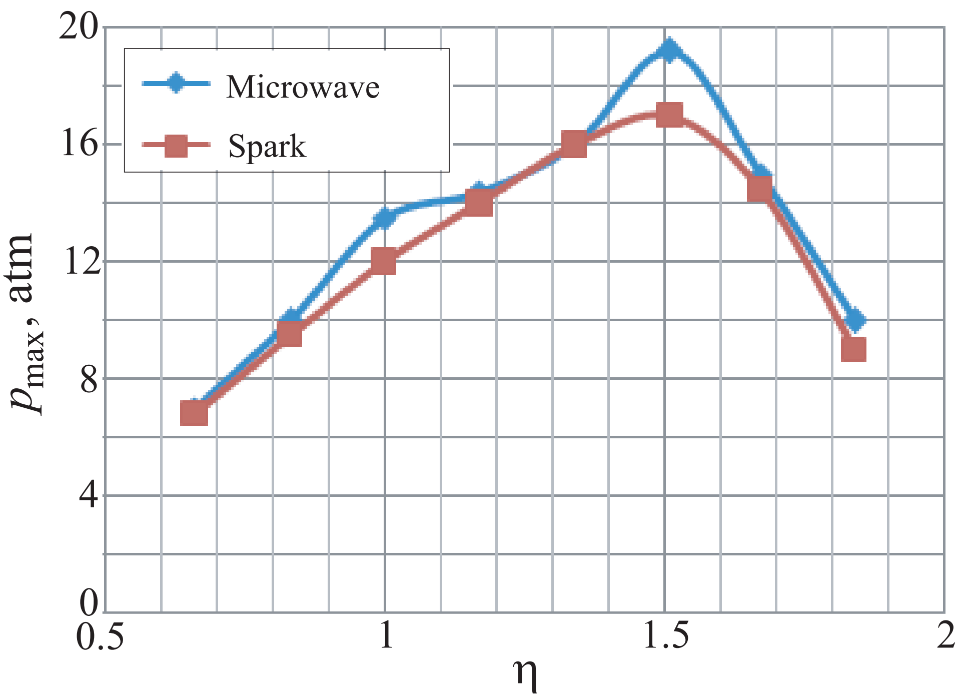

Figure 14. Dependence of the maximum pressure on the fuel/air equivalence ratio for $p_0 = 2.5$ atm. The blue line corresponds to the ignition with the multi-point microwave discharge, and the red line corresponds to the ignition with spark plugs

The main characteristics of the combustion processes at the initial pressure of the propane/air mixture in the experimental tube are given in Table 2 (ignition with one spark

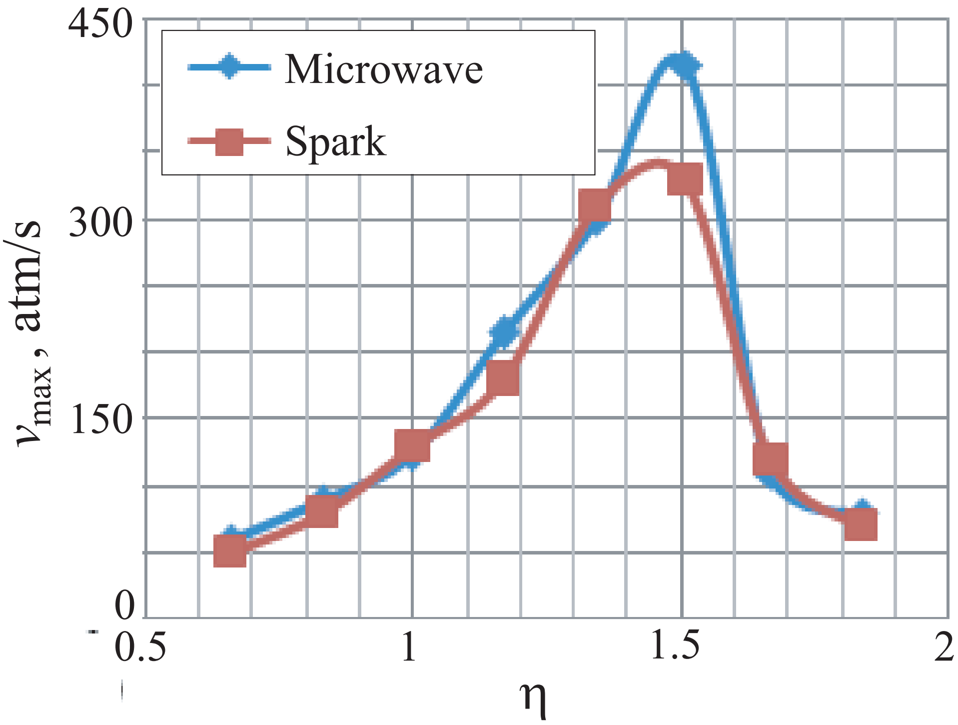

Figure 15. Dependence of the rate of pressure rise on the composition of the mixture for $p_0 = 2.5$ atm. The blue line corresponds to the ignition with the multi-point microwave discharge, and the red line corresponds to the ignition with spark plugs

plug), Table 3 (ignition with four spark plugs), Table 4 (ignition with eight spark plugs) and Table 5 (streamer ignition).

Table 2. Dependencies of combustion parameters on the fuel/air equivalence ratio at an initial pressure of $p_0 = 2.5$ atm when the mixture is ignited with 1 spark plug

No	η	$p_{\max}$, atm	t_p, ms	v_p, atm/s	t_v, ms	t_b, ms
1	0.66	3.7	160	23	100	230
2	0.83	6	120	50	85	240
3	1	7.15	120	60	78	305
4	1.17	8.5	120	71	75	290
5	1.34	8.5	140	60	78	450
6	1.51	9.7	140	70	85	400
7	1.67	6.9	160	43	78	500
8	1.84	6.5	160	40	132	550
9	2	—	—	—	—	—

Table 3. Dependencies of combustion parameters on the fuel/air equivalence ratio at an initial pressure of $p_0 = 2.5$ atm when the mixture is ignited with 4 spark plugs

No	η	$p_{\max}$, atm	t_p, ms	v_p, atm/s	t_v, ms	t_b, ms
1	0.66	3.7	180	21	45	275
2	0.83	5.8	110	53	33	275
3	1	8.5	90	94	35	350
4	1.17	9.2	90	103	33	425
5	1.34	9.3	80	116	30	450
6	1.51	9.7	70	139	33	440
7	1.67	7.8	100	78	45	475
8	1.84	6.9	120	58	45	575
9	2	6.8	120	45	48	590

Table 4. Dependencies of combustion parameters on the fuel/air equivalence ratio at an initial pressure of $p_0 = 2.5$ bar when the mixture is ignited with 8 spark plugs

No	η	$p_{\max}$, atm	t_p, ms	v_p, atm/s	t_v, ms	t_b, ms
1	0.66	5	160	31	30	260
2	0.83	7	120	70	25	250
3	1	9.1	80	113	20	350
4	1.17	11.1	75	145	20	350
5	1.34	11.6	50	216	20	470
6	1.51	10.4	45	231	24	450
7	1.67	8.1	80	101	27	470
8	1.84	7.8	120	65	40	490
9	2	6.9	140	50	45	500

Table 5. Dependencies of combustion parameters on the fuel/air equivalence ratio at an initial pressure of $p_0 = 2.5$ bar when the mixture is ignited with 8 microwave discharges

No	η	$p_{\max}$, atm	t_p, ms	v_p, atm/s	t_v, ms	t_b, ms
1	0.55	—	—	—	—	—
2	0.66	6.5	150	160	90	250
3	0.83	10	85	120	75	250
4	1	13.5	90	123	80	305
5	1.17	14.4	51	215	85	290
6	1.34	16	53	300	10	175
7	1.51	19.2	35	416	90	400
8	1.67	14.5	90	120	70	500
9	1.84	10	110	75	140	550
10	2	—	—	—	—	—

4.3 Comparison of ignition systems

In the case of spark plug ignition, the speed of propagation of the flame front is about 4 m/s. This rate is weakly dependent on the composition of the mixture. The maximum speed is reached with the fuel/air equivalence ratio of $\eta = 1.2$. The main difference is that in a lean mixture, the brightness of the flame is very weak (little energy is released). In a mixture close to the stoichiometric ratio at η from 0.7 to 1.6, the flame front speed remains practically unchanged and up to 3.5–4 m/s, while in rich mixtures at $\eta = 1.7$ and above, the speed drops to 2 m/s (the entire combustion time increases). In addition, when rich mixtures are burning at $\eta > 1.2$, the flame is orange. This indicates that the propane is not completely burned out. In the case of lean mixtures at $\eta < 0.6$, no slower combustion is observed, the mixture ceases to burn in principle. The pressure rise time is practically independent on the fuel/air equivalence ratio and is about 150 ms. When the composition of the mixture changes, the maximum pressure of the combustion process changes, which reaches its maximum value at $\eta = 1$–1.5. Consequently, the rate of pressure rise is maximum at these values of the fuel/air equivalence ratio.

In comparison with one spark plug, when the mixture is ignited with four spark plugs, the time during which the flame front occupies the entire volume of the tube is 15/400 s (38 ms), which is 2.7 times faster than with one spark plug. The time does not increase proportionally an increase in the number of ignition points. Most likely, this is due to the fact that the flame, which has already begun from the neighboring ignition points, increases the pressure in the tube, and therefore the speed of the flame front decreases. With an increase in the initial pressure in the tube, the maximum pressure of the combustion process also increases, and this dependence is close to linear. For example, the maximum pressure at $p_0 = 0.5$ atm is $p_{\max} = 2.5$ atm, and at $p_0 = 2.5$ atm one has $p_{\max} = 13.5$ atm. The linear dependence remains at all initial pressures used in experiments. In this case, only the value of the maximum pressure itself changes, which depends on the composition of the mixture. When using eight spark discharges, the time it takes for the flame to fill the entire volume of the tube decreases even more in comparison with four spark plugs and drops to $9/400 = 23$ ms, which is 1.5 times faster. The pressure rise time is reduced approximately 1.5 times compared to experiments using four ignition points, and approximately three times faster than in the case of a single ignition point.

5 Energy efficiency

Minimum energy required to ignite a propane/air mixture with spark plugs and multi-point streamer discharges are estimated and compared n]based on experimental measurements.

5.1 Spark ignition

The total energy for powering the spark plug system is estimated using parameters from experiments. The power supply is $V_p = 14.5$ kV, the power supply efficiency is $\eta_p = 50\%$, the wire resistance is $R_w = 5$ kOhm (silicone wires are used), the limiting resistance is $R_b = 10$ kOhm (it provides simultaneous ignition of several spark plugs from a common power source). The total resistance in the circuit of each spark plug is $R_t = R_w + R_b = 15$ kOhm. The current in the circuit is $I_{\max} = V_p/R_t = 0.98$ A (maximum value), and the measured current is 0.9 A. The total storage capacity is $C_t = 1.85$ μF. The energy that is stored and released in eight spark plugs is $W = C_t V_p^2/2 = 208$ J. It gives $W_t = W/\eta_p = 416$ J.

The energy released on one spark plug is found. The voltage in the arc of the spark plug is $V_1 = 300$ V (it is measured). Eight spark plugs working in parallel are installed in the circuit. The current that flows in circuits is $I_{\max} = V_p/R_\Sigma = 7.7$ A, where $R_\Sigma = R_t/8 = 1.87$ kOhm. Time constant of the discharge process is $\tau = C_t R_\Sigma = 3.46$ ms. The running time is also measured with an oscilloscope using a resistive probe, which gives $t_s = 2.4\tau = 5$ ms. The current has an exponential form in time, decreasing from the maximum value $I_{\max}$ to zero in 2.4τ (Figure 16).

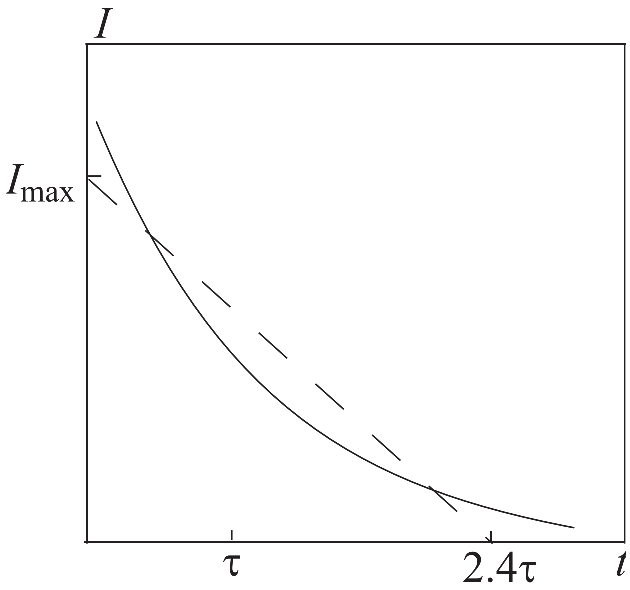

Figure 16. Change in current strength over time

The energy that is released in the discharge in eight spark plugs is considered as the area of a right triangle with sides equal $I_{\max}$ and 2.4τ, since the current is not constant, but falls from $I_{\max}$ to zero. The estimation gives $W_s = P_s t_s = V_1 I_{\max} 2.4\tau/2 = 6.4$ J. The efficiency of the ignition system is $\eta_s = W_s/W_p = 1.5\%$. When one spark plug is used, the storage capacity is reduced by 8 times. The operating time does not change and equals $t_s = 8.5$ ms.

5.2 Streamer ignition

The assessment of the efficiency of propane/air ignition with multi-point streamer discharges is considered. The efficiency of the entire system depends on the efficiency of the modulator, the efficiency of the magnetron and the efficiency of energy absorption by the initiators. The voltage on the magnetron is $U_m = 30$ kV (it is measured by a voltmeter built into the power supply), and the current flowing through the magnetron is $I_m = 40$ A (it is measured with a shunt and an oscilloscope). The power that is used to power the magnetron is $P_m = U_m I_m = 1200$ kW. The operating time of the magnetron (the time of emission of microwave energy or the lifetime of the discharge) is $t_m = 6$ μs (this value is maximum for the microwave generator used in experiments). The energy required to power the magnetron is $W_m = P_m t_m = 7.2$ J.

The modulator has an efficiency less than 80%, and its efficiency is $\eta_m = 50\%$ (the estimation takes into account the heating, cooling, starting). The energy supplied to the entire microwave source is $W_\Sigma = W_m/\eta_m = 14.4$ J.

Then, the energy that is released in the microwave plasma is calculated. Microwave power is $P_s = 600$ kW. The measured reflection coefficient of microwave radiation from the horn is 12 dB, therefore, the efficiency of the magnetron and tube system is $\eta_{mt} = 94\%$. The power of microwave radiation that reaches the initiator system is $P_{mt} = P_s \eta_{mt} = 550$ kW. The initiators and the chamber itself are not fully optimized in design, so it could be conclude that the energy released in the discharges is 50% of the total supplied energy and equals $\eta_{ts} = 50\%$.

The energy that is released in the plasma created by eight initiators (this plasma ignites the propane/air mixture) is estimated as $W_s = P_{mt} t_m \eta_{ts} = 1.6$ J. The efficiency of the microwave system is $\eta_s = W_s / W_\Sigma = 14.4$ J or 11%. This efficiency can be increased to 20% if the pipe-initiator-waveguide system is optimized.

5.3 Efficiency comparison

Estimations show that the energy released on streamers leads to the formation of shock waves of sufficiently high intensity, which decay rather quickly, because the initial diameter of the plasma filaments is of the order of 1 mm. Heating by shock waves and thermal diffusion lead to a gradual heating of the fuel/air mixture to a temperature of about 1000 K. At this moment, a flash occurs, in which the average temperature is already 2000 K. Detonation waves run through the ignition region, which immediately ignites the mixture in a significant volume. In this case, the flame speed is significantly higher than that with spark plug ignition.

Comparison of the energy efficiency and features of two systems for ignition of a propane/air mixture is given in Table 6. Line 2 of the table gives a comparison of the energy supplied to ignite the propane/air mixture. The energy released in a spark discharge is 4 times more than the energy released in a microwave discharge. Line 3 shows a comparison of the efficiency of both ignition systems. The efficiency of the microwave ignition system is 8 times higher than the efficiency of the spark plug ignition system.

Table 6. Energy efficiency of two ignition systems

Parameter	Spark plug ignition	Streamer ignition
W, J	6.4	1.6
Efficiency, %	1.5	11
P, J	416	14.4

With about 30 times less energy consumption, microwave ignition provides an advantage in the rate of increase in pressure in the tube and the rate of combustion of the fuel/air mixture by about 25–30% compared to the ignition with eight spark plugs. In this case, the efficiency of microwave ignition is about 11%. Eight spark plugs supply 4 times more energy directly to the fuel/air mixture than eight streamer discharges. The multi-point microwave ignition system surpasses the traditional spark plugs in terms of efficiency and energy consumption. In addition, the rate of pressure rise is higher in the case of using a multi-point microwave discharges, although this increase is not so significant, amounting to about 10%.

In one of the experiments with streamer discharges at an initial pressure in the tube of $p_0 = 2.5$ atm, it was possible to obtain direct detonation of the fuel mixture when only 1.6 J was supplied to it. Under similar conditions, from 1 to 3 g of trinitrotoluene (TNT) is required, which corresponds to about 4 kJ, for the direct initiation of detonation of a propane/air mixture.

The experiments and calculations performed at various fuel/air ratios show that moderately rich mixtures are optimal for microwave ignition, in terms of the rate of pressure rise in the tube, as well as for spark ignition, at $\eta = 1$–1.1. This allows to conclude that the main factor affecting the character of ignition with streamer ignition is its volumetric character, while the main ignition mechanism is thermal. Expansion of the range of ignition of the mixture in terms of the fuel/air equivalence ratio with microwave ignition in comparison with spark ignition is not observed.

6 Conclusion

Ignition of a propane/air mixture with spark plugs and multi-point streamer discharges is compared, and combustion of the mixture in a closed tube is studied. A streamer microwave discharge is ignited inside a metal combustion chamber, and its efficiency as an ignition source is higher than both a point and multi-point pulsed spark discharges.

The rate of pressure rise during microwave ignition is one third higher than with a multi-point spark discharges and three times higher than with standard ignition with one spark plug, and the energy input is almost 30 times lower. This makes it possible to significantly increase the specific characteristics of both internal combustion engines and gas turbine engines. Multi-point ignition with streamer discharge allows several times to increase the rate of fuel combustion and the pressure in the combustion chamber in comparison with traditional spark plug ignition. The advantage in the combustion rate and pressure increase is obtained due to the volumetric nature of ignition initiated by streamer discharges with a developed spatial structure.

The results obtained show the great potential of ignition with multi-point streamer discharges to be used in propulsion systems and can be applied to ignite fuel/air mixtures in high-speed flows as well as in pulsed and rotating detonation engines.

Acknowledgements

This work was financially supported by the Ministry of Science and Higher Education of Russian Federation during the implementation of the project "Creating a leading scientific and technical reserve in the development of advanced technologies for small gas turbine, rocket and combined engines of ultra-light launch vehicles, small spacecraft and unmanned aerial vehicles that provide priority positions for Russian companies in emerging global markets of the future", No. FZWF-2020-0015.

References

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

[2] Betelin V.B., Nikitin V.F., Mikhalchenko E.V. 3D numerical modeling of a cylindrical RDE with an inner body extending out of the nozzle. Acta Astronautica, 2020, 176, pp. 628–646.

[3] Liu X., Chen Y., Xia Z., Wang J. Numerical study of the reverse-rotating waves in rotating detonation engine with a hollow combustor. Acta Astronautica, 2020, 170, pp. 421–430.

[4] Wang Y., L J. A rotating detonation engine using methane-ethylene mixture and air. Acta Astronautica, 2021, 188, pp. 25–35.

[5] Rankin B.A., Fotia M.L., Naples A.G., Stevens C.A., Hoke J.L., Kaemming T.A., Theuerkauf S.W., Schauer F.R. Overview of performance, application, and analysis of rotating detonation engine technologies. Journal of Propulsion and Power, 2017, 33(1), pp. 131–143.

[6] Xie Q., Wang B., Wen H., Wolanski P. Enhancement of continuously rotating detonation in hydrogen and oxygen-enriched air. Proceedings of the Combustion Institute, 2019, 37, pp. 3425–3432.

[7] Wolanski P. Detonative propulsion. Proceedings of the Combustion Institute, 2013, 34, pp. 125–158.

[8] Zhao N.B., Zheng H.T., Wen X.Y., Zhao N.B., Zheng H.T., Wen X.Y., Xiao D.M. Thermodynamic performance enhancement of marine gas turbine by using detonation combustion. ASME Paper, 2018, GT2018-75493.

[9] Sousa J., Paniagua G., Morata E.C. Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor. Applied Energy, 2017, 195, pp. 247–256.

[10] Koch J., Kutz J.N. Modeling thermodynamic trends of rotating detonation engines. Physics of Fluids, 2020, 32, 126102 (12 pages).

[11] Dubrovskii A.V., Ivanov V.S., Frolov S.M. Three-dimensional numerical simulation of the operation process in a continuous detonation combustor with separate feeding of hydrogen and air. Russian Journal of Physical Chemistry B, 2015, 9, pp. 104–119.

[12] Levin V.A., Manuylovich I.S., Markov V.V. Numerical simulation of spinning detonation in circular section channels. Computational Mathematics and Mathematical Physics, 2016, 56(6), pp. 1102–1117.

[13] Bluemner R., Bohon M.D., Paschereit C.O., Gutmark E.J. Experimental study of reactant mixing in model rotating detonation combustor geometries. Flow, Turbulence and Combustion, 2019, 102, pp. 255–277.

[14] Weiss S., Bohon M.D., Paschereit C.O., Gutmark E.J. Computational study of reactants mixing in a rotating detonation combustor using compressible RANS. Flow, Turbulence and Combustion, 2020, 105, pp. 267–295.

[15] Polezhaev Yu.V., Stonik O.G. From deflagration to detonation: three modes of combustion. High temperature, 2010, 48(4), pp. 534–540.

[16] Karlin V. Radiation preheating can trigger transition from deflagration to detonation. Flow, Turbulence and Combustion, 2011, 87, pp. 511–523.

[17] Baklanov D.I., Golub V.V., Ivanov K.V., Krivokopytov M.S. Transition of combustion into detonation within a channel with the diameter less than the critical diameter of the existence of stationary detonation. High temperature, 2012, 50(2), pp. 238–243.

[18] Denissenko P., Bulat M.P., Esakov I.I., Grachev L.P., Volkov K.N., Volobuev I.A., Upyrev V.V., Bulat P.V. Ignition of premixed air/fuel mixtures by microwave streamer discharge. Combustion and Flame, 2019, 202, pp. 417–422.

[19] Volkov K. Laser-induced breakdown and detonation in gasparticle and gas-droplet mixtures. Horizons in World Physics, 2015, 284, pp. 127–178.

[20] Saifutdinov A.I., Kustova E.V., Karpenko A.G., Lashkov V.A. Dynamics of focused pulsed microwave discharge in air. Plasma Physics Reports, 2019, 45(6), pp. 602–609.

[21] Starikovskaya S.M., Aleksandrov N.L., Kosarev I.N., Kindysheva S.V., Starikovskii A.Yu. Ignition with low-temperature plasma: kinetic mechanism and experimental verification. High Energy Chemistry, 2009, 43(3), pp. 213–218.

[22] Starikovskiy A., Aleksandrov N. Plasma-assisted ignition and combustion. Progress in Energy and Combustion Science, 2013, 39, pp. 331–368.

[23] Vasilieva O.B., Kumkova I.I., Kuznetsov V.E., Rutberg A.Ph., Safronov A.A., Shiryaev V.N. Possibilities of applying plasma technologies for processing organics-containing substances: the effect of the shape of the voltage curve on the working mode of the plasma torch. High temperature. 2015, 53(4), pp. 470–475.

[24] Medvedev R.N., Drozhzhin A.P., Teslenko V.S. Thrust generation by pulse combustion of gas in a submerged chamber. International Journal of Multiphase Flow, 2016, 83, pp. 232–238.

[25] Aleksandrov K.V., Grachev L.P., Esakov I.I., Fedorov V.V., Khodataev K.V. Domains of existence of various types of microwave discharge in quasi-optical electromagnetic beams. Technical Physics, 2006, 76(11), pp. 1438–1456.

[26] Khodataev K.V. The initial phase of initiated undercritical microwave discharge. AIAA Paper, 2005, 2005-598.

[27] Esakov I., Khodataev K.V. Applicability of ionization overheating instability theory for a microwave gas discharge. AIAA Paper, 2012, 2012-1163.

[28] Cruccolini V, Grimaldi CN, Discepoli G, Ricci F, Petrucci L, Papi S. An optical method to characterize streamer variability and streamer-to-flame transition for radio-frequency corona discharges. Applied Sciences, 2020, 10(7), 2275 (22 pages).

[29] Nijdam S., Teunissen J., Ebert U. The physics of streamer discharge phenomena. Plasma Sources Science and Technology, 2020, 29(10), 103001 (49 pages).

[30] Pan J., Meng W., Li S., Du J. Numerical investigations on methane-air nanosecond pulsed dielectric barrier discharge plasma-assisted combustion. ACS Omega 2020, 5(49), pp. 31891–31901.

[31] Bulat P.V., Esakov I.I., Grachev L.P., Volkov K.N., Volobuev I.A. Experimental study of air breakdown induced by subcritical streamer microwave discharge. IEEE Transactions on Plasma Science, 2021, 49(3), pp. 1041–1049.

[32] Ko Y., Anderson R.W., Arpaci V.S. Spark ignition of propane-air mixture near the minimum ignition energy. Part 1. An experimental study. Combustion and Flame, 1991, 81, pp. 75–87.

[33] Phuoc T.X., White F.P. Laser-Induced spark ignition of CH4/air mixtures. Combustion and Flame, 1999, 119, pp. 203–216.

[34] Ju Y., Sun W. Plasma assisted combustion: dynamics and chemistry. Progress in Energy and Combustion Science, 2015, 48, pp. 21–83.

[35] Adamovich I.V., Lempert W.R. Challenges in understanding and predictive model development of plasma-assisted combustion. Plasma Physics and Controlled Fusion, 2015, 57(1), 014001 (12 pages).

[36] Reeves J., Skews B. Unsteady three-dimensional compressible vortex flows generated during shock wave diffraction. Shock Waves, 2012, 22(2), pp. 161–172.

[37] Krassovskaya I.V., Berezkina M.K. Mechanism of formation of reflection configurations over concave surfaces. Shock Waves, 2017, 27(3), pp. 431–439.

[38] Soni V., Hadjadj A., Chaudhuri A., Ben-Dor G. Shock-wave reflections over double concave cylindrical reflectors. Journal of Fluid Mechanics, 2017, 813, pp. 70–84.

[39] Smirnov N.N., Penyazkov O.G., Sevrouk K.L., Nikitin V.F., Stamov L., Tyurenkova V. Detonation onset following shock wave focusing. Acta Astronautica, 2017, 135, pp. 114–130.

[40] Smirnov N.N., Penyazkov O.G., Sevrouk K.L., Nikitin V.F., Stamov L. Onset of detonation in hydrogen-air mixtures due to shock wave reflection inside a combustion chamber. Acta Astronautica, 2018, 149, pp. 77–92.

[41] Li X., Yu Q., Zhou N., Liu X. The influence of pipe length on explosion of flammable premixed gas in 90° bending pipe and dynamic response of the thin-walled pipe. Advances in Mechanical Engineering, 2019, 11(5), pp. 1–9.

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

[43] Bulat M.P., Bulat P.V., Denissenko P.V., Esakov I.I., Grachev L.P., Volkov K.N., Volobuev I.A. Ignition and combustion of air/fuel mixture in a long tube induced by microwave subcritical streamer discharge. Acta Astronautica, 2019, 163, pp. 33-43.

[44] Bulat M.P., Bulat P.V., Denissenko P.V., Esakov I.I., Grachev L.P., Volkov K.N., Volobuev I.A. Numerical simulation of ignition of premixed air/fuel mixtures by microwave streamer discharge. IEEE Transactions on Plasma Science, 2019, 47(1), pp. 62–68.

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