Comparison of energy efficiency of ignition of fuel/air mixture with spark and streamer discharges

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An increase in fuel efficiency and efficiency of combustion processes in power plants is discussed based on the data of physical and computational experiments. Two systems for ignition of a fuel mixture are considered, one of which uses a multi-point pulsed spark discharge, and the other uses a multipoint streamer discharge. A comparative assessment of the energy efficiency of each approach to the ignition of the air/fuel mixture is carried out, and conclusions are drawn about their effectiveness and prospects for use.

Keywords: spark discharge, streamer discharge, microwave discharge, plasma-assisted combustion, engine.

The use of several ignition sources distributed along the length of the combustion chamber (multipoint ignition) increases the total surface of the flame, ensuring the reliability of ignition, an increase in the combustion rate in the volume of the chamber, and the completeness of combustion of the combustible mixture [1, 2]. Multipoint ignition of the fuel mixture also significantly shortens the deflagration to detonation transition. Various types of plasma combustion, such as combustion in a corona discharge or nanosecond discharge and a laser method for creating a plasma combustion center, are used in engines of various designs [3, 4].

The performed theoretical, experimental, and numerical studies indicate promising characteristics and broad prospects for the practical application of a subcritical streamer discharge [5–9].

In this paper, we study the ignition of a premixed propane–air fuel mixture in a constant-volume cylinder using multipoint spark ignition and multipoint ignition by streamer microwave discharges. The advantage of ignition with a streamer discharge in comparison with others is an increase in the fuel combustion rate at a constant volume from 20–30% by several times at a significant decrease in energy consumption for ignition of the mixture.

In experimental studies, a stand designed and developed at the Moscow Radiotechnical Institute, Russian Academy of Sciences, which allows investigating the ignition of combustible mixtures using a classical ignition system using automotive spark plugs and a new ignition system based on subcritical streamer discharges, is used. The measurements are performed using a setup with a microwave radiation wavelength of lambda = 12.3 cm at a quasi-optical beam power of P = 1 kW and a microwave pulse duration of tau = 0.2 s. Details of the experimental setup are given in [6, 7].

Eight initiators with a pitch of 40 mm are installed in the operating combustion chamber. The initiators are attached to a quartz tube with a diameter of 10 mm using high-temperature cyacrine glue. The quartz tube is installed in the center of the chamber along the pipe axis with the help of special supports made of radiotransparent heat-shielding material with a dielectric constant close to unity. The setup allows igniting the fuel mixture with one, four, or eight car spark plugs or eight streamer microwave discharges. Microwave initiators are made of Ni–Cr wire with a diameter of 0.5 mm. The setup has two viewing windows (side and end), through which the ignition process is video recorded by a Nikon D1 high-speed camera at a speed of 400 fps. Using these videos, it is possible to estimate the propagation velocity of the flame front and the burning time of the flame.

A computational experiment is performed to check and identify the effect of various physical factors on the results. In the calculations, the development of the flame when the mixture is ignited with one, four, and eight spark plugs, as well as with one and eight microwave discharges, is studied. The duration of the microwave discharge is assumed to be 6 ìs, and the energy supplied to the plasma is 1.6 J. When calculating the spark ignition, a standard spark model with a discharge duration of 4 ms and the amount of energy released by one spark plug of 0.5 J are used. The power of energy release changes linearly: from the maximum at the initial moment up to 0.5 of the maximum at the moment of 4 ms.

To numerically simulate the formation and propagation of a streamer discharge in the field of an electromagnetic pulse of microwave radiation, as well as the subsequent ignition of the fuel mixture by plasma channels and its combustion, the unsteady threedimensional Navier–Stokes equations, Maxwell's equations, and equations of chemical kinetics for thermodynamically nonequilibrium plasma are used. A model of absorption of microwave radiation by a streamer discharge, as a result of which it is heated, is used. To calculate the chemical kinetics of combustion of a propane–air mixture, a quasi-global combustion model, which includes elementary reactions between 12 components of the mixture and one global reaction [9], is used. Some details of the mathematical model are given in [8]. The discharge shape is assumed to be spherical with a uniform coverage over the volume with a grid of streamers. The energy supplied to the discharge is released on streamers. For simplicity, it is assumed that the main energy is released at the nodes of the streamer in spherical formations, the diameters of which are about three times the diameter of the streamer.

The total energy for powering the spark-plug system is calculated taking the following data into account: power supply Vp = 14.5 kV, power-supply efficiency is etap = 50%, wire resistance Rw = 5 kOhm (VAZ 2101-06 silicone wires are used), and limiting resistance Rb = 10 kOhm (provide simultaneous ignition of several spark plugs from a common power source). The total resistance in the circuit of each spark plug is Rt = Rw + Rb = 15 kOhm. The current in the circuit is Imax = Vp/Rt = 0.98 A (maximal value), and the measured current is 0.9 A. The total storage capacity is Ct = 1.85 ìF. The energy that is stored in the container and is released in all eight spark plugs is W = Ct /2 = 208 J. Then, Wt = W/etap = 416 J.

We find the energy released on one spark plug. Spark-plug arc voltage V1 = 300 V (measured). Eight spark plugs connected in parallel are installed in the circuit. The current that flows in all the spark-plug supply circuits is Imax = Vp/RSum = 7.7 A, where RSum = Rt/8 = 1.87 kOhm. The time constant of the discharge process is tau = Ct RSum = 3.46 ms. The running time is also measured with an oscilloscope using a resistive probe, which yields ts = 2.4ô = 5 ms. The current has an exponential form with time, decreasing from the maximal value Imax to zero for a time of 2.4tau.

The energy that is released in the discharge in all eight spark plugs is considered as the area of a triangle with sides Imax and 2.4tau since the current is not constant, but falls from Imax to zero. The estimate yields Ws = Ps ts = V1 Imax 2.4tau/2 = 6.4 J. The efficiency of the system is etas = Ws/Wp = 1.5%. When using one spark plug, the storage capacity is reduced by eight times. The spark-plug operation time does not change and is ts = 8.5 ms.

We consider the estimate of the efficiency of mixture ignition using a microwave discharge system. 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 Um = 30 kV (measured by a voltmeter built into the power supply), and the current flowing through the magnetron is Im = 40 A (measured with a shunt and an oscilloscope). The power that is spent to power the magnetron is Pm = Um Im = 1200 kW. The operating time of the magnetron (the time of emission of microwave energy or the lifetime of the discharge) is tm = 6 ìs (a value that is maximum for the given microwave generator). The energy required to power the magnetron is Wm = Pm tm = 7.2 J.

The modulator has an efficiency of less than 80%, and, taking into account the heating, cooling, and starting system, the efficiency is etam = 50%. The energy supplied to the entire microwave source is WSum = Wm/etam = 14.4 J.

We calculate the energy released in the microwave plasma. Microwave power Ps = 600 kW. The measured reflection coefficient of microwave radiation from the horn is 12 dB; therefore, the efficiency of the magnetron-tube system is etamt = 94%. Microwave power reaching the initiator system Pmt = Ps etamt = 550 kW. The initiators and the chamber itself are not completely optimized in design; therefore, it can be concluded that the energy released in the discharges is 50% of the total supplied energy: etats = 50%.

We find the energy released in the plasma produced by eight initiators (this plasma ignites the propane–air mixture): Ws = Pmt tm etats = 1.6 J. The efficiency of the microwave system is etas = Ws/WÓ = 14.4 J, or 11%. This efficiency can be increased up to 20% if the system is optimized tubes–initiators–waveguide.

A comparison of the results of calculation with the experimental ones is shown in Fig. 1. Each fragment above shows the development of combustion at spark ignition; in the middle, the results of modeling combustion at streamer ignition; and, below, the results of the experiment at streamer ignition. The results of calculations and experiments in terms of the rate of combustion development at streamer ignition are in rather good agreement with each other.

Calculations show that the energy released on streamers leads to the formation of high-intensity shock waves, which decay rather quickly, since the initial diameter of the plasma formation is of the order of 1 mm. Heating by shock waves and thermal diffusion lead to a gradual heating of the fuel mixture to ~1000 K. At this moment, a flash, in which the average temperature is already 2000 K, occurs. Detonation waves run through the ignition area and immediately ignite the mixture in a significant volume. Next, the combustion front propagates in the same way as when the gas is ignited in the tube in the volume at one of the bottoms. In this case, the flame velocity is significantly higher than that at spark ignition.

We compare the energy efficiency and features of the two systems for ignition of a propane–air combustible mixture (see Table 1). The first row of the table shows a comparison of the energies that are spent on the ignition of a propane–air mixture. The energy released in a spark-plug discharge is four times more than the energy released in a microwave discharge. The next row shows a comparison of the efficiency of both ignition systems. The efficiency of the microwave ignition system is eight times higher than the efficiency of the spark-plug ignition system. The last row shows a comparison of the amount of energy from the power line. In the case of microwave ignition, almost 30 times less energy is needed.

In terms of all the indicators of the efficiency and energy consumption, the multipoint microwave ignition system surpasses the traditional spark discharge system. In addition, the rate of pressure rise is higher in the case of using a multisystem of microwave discharges, although this increase is not so significant (~10%).

On the basis of the experimental and numerical studies that have been carried out, it was shown that a subcritical discharge initiated inside a model combustion chamber allows igniting both lean and rich fuel mixtures. In this case, the efficiency of ignition of the fuel mixture by a streamer discharge turns out to be higher than that by point and multipoint ignition of the mixture with a pulsed spark discharge. In this case, the rate of pressure increase at multipoint streamer ignition is one-third higher than that at a multipoint spark discharge and three times higher than that at standard ignition with one spark plug, while the energy input is almost 30 times less.

The use of streamer ignition of a fuel mixture allows to significantly increase the specific indicators of both internal combustion engines and engines of constant volume. The ignition system of the fuel mixture using a subcritical streamer discharge seems promising for engines in which combustion at a constant volume is used and in high-speed sub- and supersonic flow of the fuel mixture, as well as for pulsating and rotary detonation engines.

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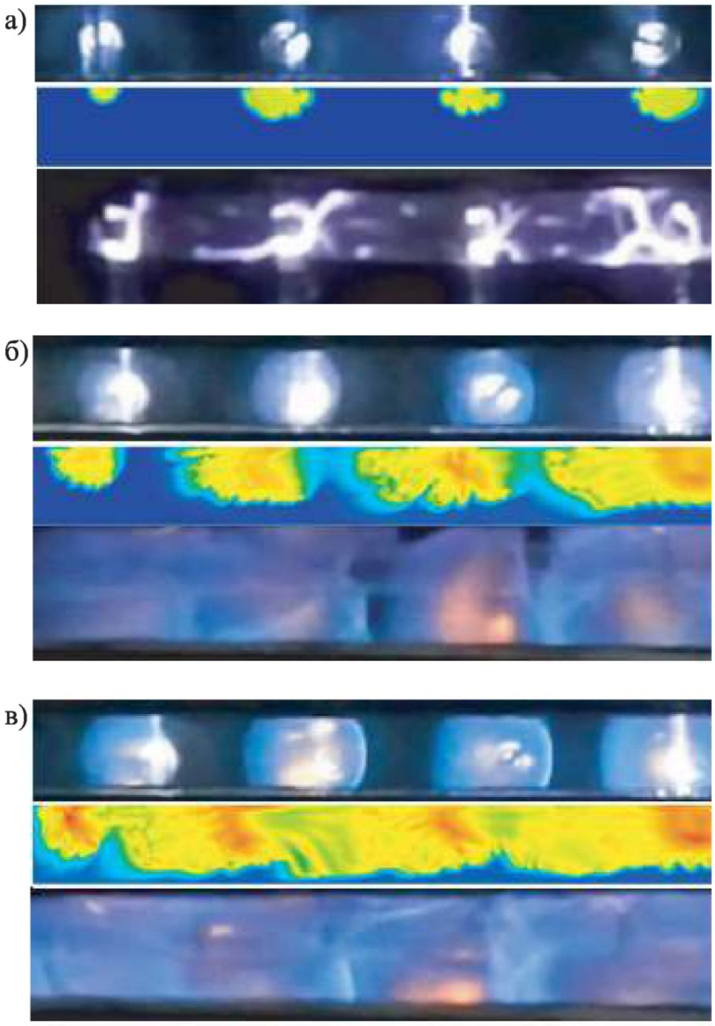

Fig. 1. Comparison of the results of experiments with spark ignition of the mixture (upper part of each fragment) with the results of modeling streamer ignition (middle part) and experiment with streamer ignition (lower part) in the case of eight ignition centers (half of the tube is shown) at times corresponding to (a) the occurrence of a discharge, (b) 3/400, and (c) 6/400 s.

Parameter	Spark dicharge	Streamer discharge
W, J	6.4	1.6
Efficiency, %	1.5	11
P, J	416	14.4

Tab. 1. Energy efficiency of two propane–air combustible mixture ignition systems