Ignition and combustion stabilization of multicomponent supersonic chemically active flows in low-temperature plasma conditions

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Abstract. An electrodeless freely localized microwave discharge, a surface microwave discharge, a non-equilibrium non-stationary transverse-longitudinal pulsating discharge were used for ignition and combustion stabilization. The induction periods for various discharges and the possibilities of their application for supersonic combustion stabilization inside the direct-flow aerodynamic channels are experimentally determined. A comparison of experimental results with the data of mathematical modeling is presented.

1. Introduction
Low-temperature plasma in a gas flow is widely used in scientific research and various technological applications [1-10]. The possible means of effective control of combustion processes via different physical actions has been discussed in the scientific literature for several decades. In recent years, the interest in the intensification of the combustion of gas-phase systems with the use of different forms of gas discharge considerably increased. The methods of control of the combustion of air–hydrocarbon supersonic flows based on the generation of electric discharges seem to be most promising at present.

The aim of this work is an experimental study of supersonic ignition and combustion of air-hydrocarbon mixtures initiated by low-temperature gas-discharge plasma. In the article transverse-longitudinal discharges [11-15], freely localized microwave discharges [2, 6, 16] and surface microwave discharges excited on a dielectric antenna [17-19] are used for the initiation of ignition and combustion stabilization of hydrocarbon fuels in supersonic air flows.

2. Experimental setup
Experiments were carried out on the installation consisting of a vacuum chamber, a receiver of a high pressure of air, a receiver of a high pressure of propane, a system for mixing propane with air, a system for producing a supersonic gas flow, two magnetron generators, two systems for delivering microwave power to the chamber, cylindrical and rectangular aerodynamic channels, two sources of high-voltage pulses, a synchronization unit, and a diagnostic system. A detailed description of the experimental setup is presented in [6, 9, 11, 18].

The basic component of the experimental setup is an evacuated metal cylindrical chamber, which serves simultaneously for supersonic flow creation, and as a tank for the expiration of gases or combustion products. The inner diameter of the vacuum chamber is 1 m, and its length is 3 m. A
supersonic flow was produced by filling the vacuum chamber with air through a specially profiled Laval nozzle mounted on the outlet tube of the electromechanical valve. In our experiments, we used cylindrical and rectangular nozzles.

The microwave source is a pulsed magnetron generator operating in the centimeter wavelength range. The parameters of the magnetron generator are as follows: the wavelength is \( \lambda = 2.4 \text{ cm} \), the pulsed microwave power is \( W_p < 200 \text{ kW} \), the pulse duration is \( \tau = 1-100 \text{ \mu s} \), and the period-to-pulse duration ratio is \( Q = 1000 \). Microwave power was delivered to the discharge chamber through a 9.5×19-mm rectangular waveguide. All the components of the microwave transmission line were sealed. To avoid electric breakdowns inside the waveguide, it was filled with an insulating gas (SF\(_6\)) at a pressure of 4 atm. The vacuum system of the chamber allows us to vary the pressure over a wide range from \( 10^3 \) to \( 10^4 \) Torr.

A transverse-longitudinal pulsating discharge was excited between two well streamlined electrodes. The design of the electrode unit was described in [9, 11, 12]. The minimum distance between the electrodes was varied from 0.1 to 3 mm. The electrodes were mounted inside the diverging wind tunnel. The discharge was produced using a power source with an output voltage of up to 4.5 kV and a discharge current of up to 20 A, the pulse duration being of up to 2 s. The air flow speed varied from 150 to 550 m/s. The second mass air flow rate in the experiment could vary from 25 g/s to 150 g/s, the second mass flow rate of propane varied from 3 g/s to 6 g/s.

Combustion was realized inside smooth (without stagnant zones) wind tunnels of rectangular cross section. Variable cross-section channels were used to prevent their thermal blocking. The electrode system of a special configuration was used to create a pulsating transverse-longitudinal discharge without additional initiation in a wide range of flow velocities of \( \nu = 100-600 \text{ m/s} \) and in a wide range of air pressures of \( p = 40-760 \text{ Torr} \). The electrical circuit consists of a series-connected stationary power source with an output voltage of \( U_0 = 2.0-4.5 \text{ kV} \) and an internal resistance of \( r = 100 \text{ \Omega} \), the ballast resistance, the value of which could be gradually switched to five fixed positions \( R_b = 145-675 \text{ \Omega} \), non-inductive resistance \( R_S = 0.32 \text{ \Omega} \) for measuring the discharge current. A non-inductive voltage divider with a division factor of \( k = 8760 \) was used to measure the voltage drop on the discharge.

The diagnostic complex consists of monochromators and spectrographs with digital recording of the spectrum; a probe diagnostics block with digital recording of the volt–ampere characteristics; pressure sensors; thermocouples; strain sensors; a shadow system; refracting laser sensors; an electric probe incandesced in the flame flow; a system of flame conductivity measurement; electron sensors measuring the concentration of propane and carbon dioxide, temperature, and absolute and relative humidity; digital photo cameras; a high-speed digital video camera; digital oscilloscopes; and computers.

The completeness of hydrocarbon fuel combustion under plasma-assisted combustion was determined via measurements of the gas temperature in the closed chamber immediately after switch off of discharge with help of a calibrated thermocouple and electron thermometer placed near walls of the chamber far from the hot flow.

Simultaneously with the temperature measurement, the time behavior of the pressure change in the closed chamber in the process of air injection without a discharge, with a discharge without combustion, and as a result of hydrocarbon fuel combustion were also recorded. This made it possible to determine the fraction of the burned propane.

The concentration of water vapors in the closed chamber after propane burning was also recorded. Knowing the amount of propane introduced into the flow, one can calculate the water vapor concentration that must be formed in the process of complete fuel combustion. Comparison of this value with the measured water vapor concentration that forms in the experiment makes it possible to calculate the completeness of propane combustion.

The combustion completeness was also estimated by the time dependence of the thrust force appearing under the plasma-assisted combustion of a supersonic propane–air flow in a 60-cm-long aerodynamic channel equipped with an outlet nozzle.
3. Experimental results

It is known, that self-sustained microwave discharges, as well as high-voltage nanosecond electrode discharges, exist at high values of the reduced electric field. However as against the nanosecond high-voltage discharge, high value of the reduced electric field under conditions of a microwave discharge can be supported during long (hundreds microseconds) time. Therefore, features of self-sustained microwave discharges are very perspective from the point of view of the fast reliable ignition of high speed air-hydrocarbon flows. However, as well as for other types of the gas discharges, combustion of high speed combustible flow under condition of microwave discharges stops, as soon as the supply of microwave energy is switched off.

For stationary work of the engine under condition of non-stationary low-temperature plasma for ignition of hydrocarbon-air mixture it is necessary to optimize a mode of initiation of the pulsed discharge, i.e. the value of energy put into plasma, pulse duration and pulse repetition rate. This can be done using the discharge in a programmable mode. In a programmable pulse mode gas breakdown and creation of plasma is carried out with the help of a short powerful pulse, and maintenance of the formed plasma and energy input occur during the long low-power pulse.

A gas discharge is usually considered only as a source of thermal energy introduced into the system. But a different degree of gas ionization is achieved for different types of gas discharges at the same input power. In this case, the electrical energy is redistributed in various ways along the internal degrees of freedom of the molecular gas. This redistribution in a very strong degree depends on the reduced electric field, which, in turn, is determined by the electrodynamics of the discharge. Different results can be achieved using the same power source. For example, to ignite a high-speed propane-air flow with a Mach number \( M = 2 \), we used a direct current electrode discharge, a freely localized electrodeless microwave discharge, a surface microwave discharge, a transverse-longitudinal discharge.

Figure 1 presents a photograph of the general views of the ignition and combustion of fuels in high-speed air flows under conditions of freely localized microwave discharge (1), surface microwave discharge (2), (3) and transverse-longitudinal pulsating discharge (4), (5).

![Figure 1. General view of the ignition and combustion of fuels in high-speed air flows under conditions of freely localized microwave discharge (1), surface microwave discharge (2), (3) and transverse-longitudinal pulsating discharge (4), (5).](image)

The experiments show that under conditions of pulsed microwave discharges with pulse duration of 100 \( \mu s \) (photo 1, 2, 3 in Figure 1) the combustion completeness of propane is low, since when the pulsed discharge is turned off, combustion stops. Pulsed discharges can be used to quickly ignite; however, in
order to maintaining stationary combustion it is necessary to use mechanical stabilizers. The maximum completeness of fuel combustion reaches ~90% in the conditions of a quasi-stationary pulsating transverse longitudinal discharge (photo 4, 5 in Figure 1).

Figure 2 shows the experimentally obtained dependence of the induction period on the reduced electric field for a supersonic propane-air flow $M = 2$.

![Figure 2. Dependence of the induction period on the reduced electric field. Transverse-longitudinal discharge (1), freely localized microwave discharge (2), surface microwave discharge (3).](image)

4. Mathematical modeling

Numerical model has been developed to study C$_3$H$_8$-air plasma-stimulated combustion. In the article, the ignition of gas fuel mixtures was simulated under the conditions of non-equilibrium gas discharge plasma of microwave discharges. Simulation was performed for a stationary propane-air mixture.

The kinetic model includes 166 components and 1168 direct and reverse reactions. In the simulation takes into account the following components: neutral particles: H, H$_2$, N$_2$, N, NH, NH$_2$, NH$_3$, N$_2$H, N$_2$H$_2$, N$_2$H$_3$, N$_2$O$_4$, NO, NO$_2$, NO$_3$, NHO, HNO, HNO$_2$, HNO$_3$, NO, O, O$_2$, OH, H$_2$O, H$_2$O$_2$, H$_2$O$_3$, O$_3$, C, C$_2$, CH, CH$_2$, CH$_3$, CH$_4$, C$_2$H, C$_2$H$_2$, C$_2$H$_3$, C$_2$H$_4$, C$_2$H$_5$, C$_2$H$_6$, CO, CO$_2$, HCO, CH$_2$O, CH$_3$O, CH$_2$OH, CH$_3$OH, CH$_3$O$_2$, CH$_3$OOH, C$_2$HO, C$_2$H$_2$O, CH$_2$CO, CH$_2$CO, CH$_2$CHO, CH$_3$O, CH$_3$O$_2$, CO, CH$_4$, CN, C$_2$N, C$_2$N$_2$, HCN, NCO, C$_2$H$_2$, CH$_3$, CH$_4$, n-C$_3$H$_7$, iso-C$_3$H$_7$, n-C$_3$H$_8$, iso-C$_3$H$_8$, O, H, H$_2$, C, C$_2$, C$_3$, C$_4$, C, O, O$_2$, OH, H, H$_2$, O, H$_2$O, H$_2$O$_2$, H$_2$O$_3$, O$_3$, O$_4$, CO, CO$_2$, HCO, CH$_2$O, CH$_3$O, CH$_2$OH, CH$_3$OH, CH$_3$O$_2$, CH$_3$OOH, C$_2$HO, C$_2$H$_2$O, CH$_2$CO, CH$_2$CO, CH$_2$CHO, CH$_3$O, CH$_3$O$_2$, CO, CH$_4$, CN, C$_2$N, C$_2$N$_2$, HCN, NCO, C$_2$H$_2$, CH$_3$, CH$_4$, n-C$_3$H$_7$, iso-C$_3$H$_7$, n-C$_3$H$_8$, iso-C$_3$H$_8$, O, H, H$_2$, C, C$_2$, C$_3$, C$_4$, C, O, O$_2$, OH, H, H$_2$, C, C$_2$, C$_3$, C$_4$, C

\[ \frac{dR}{dt} = G_i - \gamma_i \sum_{j \neq i} G_j, \quad G_i = \sum_{q \in \mathbb{R}} \frac{a_{iq}^+ - a_{iq}^-}{N} \left[ R_q^+ - R_q^- \right], \]

\[ R_q^\pm = k_q \prod_{j \neq k} \left( N \right)^{a_{qj}^\pm}, \quad \frac{dN}{dt} = \sum_{k \in \mathbb{R}} G_k, \quad p = NRT_0. \]

The calculation of the kinetic coefficients of the electrons was carried out based on the solution of the Boltzmann equation for the spherically symmetric component of the EEDF.
The dependences of the propane-air induction periods on the reduced electric field are presented in Figure 3 under conditions of microwave discharges.

\[ E/n, \text{Td} \]

\[ 10^4 \quad 10^5 \]

\[ 120 \quad 140 \quad 160 \quad 180 \quad 200 \]

**Figure 3.** Dependences of the induction period on the reduced electric field.

In addition to the experimental data (1), the graph shows the results of calculating the dependence of the induction time of the propane-air mixture on the reduced field for several cases. First, the discharge was calculated at a constant value of the amplitude of the electric field (2). Secondly, a similar calculation was performed in the case of a preliminary breakdown of the gas by a microwave pulse with a reduced field of 150 Td, and the pulse duration 1.3 μs, which led to an increase in the electron concentration up to \( 10^{12} \text{ cm}^{-3} \) (3). Thirdly, the discharge was calculated with a constant amplitude of the electric field with the electron concentration limited to \( 4.2 \times 10^{12} \text{ cm}^{-3} \) (4). It can be seen from the Figure 3 that such a limitation affects the ignition times for large values of the reduced electric field and gives dependence better consistent with the experiment. In plasma of microwave discharges, generated in a focused beam of electromagnetic radiation, the electric field is screened. This electrodynamic effect leads to a decrease in the electron concentration behind the leading front of the propagating discharge.

**5. Conclusions**

It is shown, that the all types of the discharges result in a reliable ignition of hydrocarbon fuel. The stationary plasma-assisted combustion of a propane–air mixture in aerodynamic channels without the use of different dead zones is realized under condition of a nonstationary transvers-longitudinal pulsating discharge. Mathematical modeling confirmed the strong influence of the reduced electric field on the induction period.

**Acknowledgments**

This work was supported by the Russian Foundation for Basic Research, project # 18-02-00336-a.

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