Study of propane-air mixture combustion initiation by the formation of microwave plasma in a flow

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Abstract. This study confirmed propane ignition by microwave discharge upon varying the proportion of fuel in a mixture for difficult ignition conditions, such as high altitude launch of an aircraft engine and combustion in a supersonic flow. Then study was carried out experimentally in a test channel with a central body. The mixture was ignited by a deep-subcritical streamer discharge with a wavelength of 12.4 cm.

1. Introduction

Traditional methods of ignition with spark plugs have a low conversion efficiency of electrical power into energy released for ignition. Such discharges are inherent to problems associated with the instability of the ignition when fuel covers the electrodes, with the formation of a scorching layer, and the pulsed ignition of the discharge.

The use of a microwave discharge (MWD) to ignite fuel mixtures under relatively low pressures may be more preferable. The area of influence on the gas mixture is wider than with a spark discharge. Electrodes for the realization of a MWD are less susceptible to material erosion. Meanwhile, the requirements for the stability of the generation parameters for devices that are needed in this technology are very low. Additionally, there is a widespread of availability of microwave equipment due to its application in various technology fields. The high energy efficiency of MWDs is the main advantage for creating ignition systems in combustion chambers and jet flight control systems.

Numerous experimental studies have demonstrated the possibility of organizing a working process using microwave plasma generators to initiate surface and volume plasma discharges in flows before the tear zone or in it to stabilize the flow in model channels tested in a free flow and under the conditions of an attached air duct [1–4].

The purpose of this work was to test the ignition possibility of a fuel mixture by a MWD in difficult combustion conditions.

2. Experimental setup and conditions

The experiments were conducted on a test vacuum chamber at the Moscow Radiotechnical Institute of Russian Academy of Science (MRI RAS). The stand (Figure 1) includes a gas-dynamic channel with a high-speed EPV\(_A\) air valve at the entrance, a microwave generator waveguide, fuel supply lines, a pressure and temperature measurement system and an exhaust system placed in a vacuum chamber.
Before the air valve, a manifold for injection and further mixing of fuel in the test channel was installed, the flow rate of which was controlled by an EPV_F fuel valve and the pressure in the tank, P_F. If supersonic velocities were to be reached in the channel, a supersonic diaphragm nozzle with a Mach number M = 2 was installed. The magnetron was outside the chamber with a power of 4 kW and a wavelength of \(\lambda = 12.4 \text{ cm}\). This wavelength is one of the most common for microwave generating devices.

The gas-dynamic channel is a cylinder with a diameter of 14 mm with a constant cross-section. Behind the section of the supersonic nozzle installation was a straightened section with a length of 15 calibers to which a working radiocarbon caprolon section of 8 caliber lengths was installed. The discharge ignition occurred in the working section of the channel on a duralumin electrode, which was installed along the axis of the channel. The diameter of the electrode, d_el, was 4 mm, and the length, l_el, that was selected in preliminary tests was 57 mm and mounted on a pylon that was 2 mm thick and 10 mm wide. The total obstruction of the pass was 14.7%.

There are known [6] types of MWDs, which have been realized depending on the pressure and electric intensity for different wavelengths. The limitations of source power supplies and pressure levels in aviation technology make it necessary to use a deep subcritical streamer discharge. The main positive point of these studies is the high temperature in the discharge, which ranges from 1000 to 2000 °C. Such discharges are tied; therefore, installation of antennas is required - electrodes that receive microwave radiation and initiate air breakdown at their ends. For electrodes, there is an optimal geometric dimension ratio depending on the thickness, length, and height of the installation above the metal screen that provides the maximum electric field strength at which a stable breakdown is possible even at atmospheric pressure.

Static pressure receivers P_{st1} and P_{st2} are located before the working section. The receiver of total pressure P_tot and temperature T_tot are located in the outlet of the working channel. The thermocouple and the pressure sensor signals were recorded using an Instek GDS-830 oscilloscope.

Propane (C_3H_8) was resting in a fuel tank at a (P_F) pressure of 1.8 to 2.2 atm before the start of the test cycle at which the EPV_F fuel valve was opened. The fuel under pressure P_F was sprayed through collector holes with a diameter of 1 mm. By varying the number of open holes from 1 to 5, a change in fuel consumption was achieved. The propane flow was measured by the pressure drop in the P_F tank during this time. Consumption of the air or the fuel mixture, which had different excess fuel ratios, \(\phi = L_0 \cdot G_F / G_A\), where L_0 for propane was assumed to be 15.6, was measured according to the parameters in the critical section of the supersonic nozzle.

The experiment was conducted in a pulsed regime. The triggering signal started the oscilloscope measurement, and after 0.2 s, the EPV_A and EPV_F valves were opened. Due to the pressure drop between the atmosphere and the vacuum in the chamber, P_{ch}, the flow of gas or fuel mixture was achieved. After 0.1 s, the MWD was initiated, which burned for 0.4 s. The tests were conducted in
three regimes: 1 – "cold", i.e., without fuel and MWD, 2 – with MWD but without fuel, 3 – with MWD and fuel (Figures 2–5). The experiments were conducted at different $P_{ch}$ in the chamber from 30 to 150 Torr and at $T_{tot} = 300$ K. The value of $\phi$ was varied from 0.65 to 1.16. In some experiments, the combustion duration of the discharge and fuel supply varied.

3. Results

Figure 2 shows the total pressure ($P_{tot}$) change in the outlet of the working part with the supersonic nozzle installed. As measured by $P_{st2}$ and $P_{tot}$, the speed at the entrance to the working section reached a Mach number of $M = 1.6$. Ignition of a discharge in the flow decreased the $P_{tot}$ by a value of 8% to 11%. This is due to the increase in air temperature. From the pressure distributions, there is a slight decrease in the $P_{tot}$ by 2% when fuel is added to the stream. The flowing chemical reaction of fuel combustion also caused an increase in $T_{tot}$ and, as a consequence, a decrease in the $P_{tot}$. The change ($P_{ch}$) had little effect on the magnitude of the $P_{tot}$. The realized critical drop provided a supersonic jet outflow; therefore, the variation in $P_{ch}$ affected only the stability of the MWD ignition and had no effect on the gas-dynamic flow parameters. Additionally, a slight change in $P_{tot}$ by 0.5% was observed with a variation of $\phi$.

The $T_{tot}$ measurements were confirmed by the deductions made earlier. Slight changes in the $T_{tot}$ by 10–15 °C were observed when $P_{ch}$ was varied from 60 to 150 Torr (0.08–0.2 at). Immunity to the change ($P_{ch}$) was observed both for the air flow with a MWD and for the combustion of the fuel mixture in the presence of a MWD. An increase ($\phi$) in the flow (Figures 3 and 4) from 0.7 to 0.98 caused an increase in $T_{tot}$ by 60–80 °C. A further increase ($\phi$) (Figures 4 and 5) to the level of 1.16 increased the $T_{tot}$ to 350 °C, which is almost 100 °C higher than for $\phi = 0.98$.
Figure 6. Photo of the propane flame at $P_{ch} = 0.12$ at and $\phi = 0.75$.

Figure 7. Photo of the second type of MW antenna after tests.

When the microwave power was disconnected, the glow in the channel ceased. Thus, it was possible to achieve ignition of the fuel mixture, but there was no stabilization of the combustion. This fact was confirmed by the distribution of $P_{tot}$ in Figure 2, where it is shown that after disabling the discharge, $P_{tot}$ is restored to its initial value. By increasing the burning time of the MWD to 1 s and the feeding fuel to 0.8 s, it was possible to increase the $T_{tot}$ to 380 °C. Flame stabilization was also not observed in this case. The burning fuel mixture is shown in Figure 6.

The maximum theoretical flame temperature for propane is 2200 K. In the experiment, the $T_{tot}$ was ≈ 500 K. According to the heat balance of energy and the known temperature, it was roughly estimated that the completeness of fuel combustion under these conditions was 0.21 and that 15 MJ of energy was released during the chemical combustion reaction. Such low combustion parameters were apparently obtained because of the small contact area of the fuel mixture with a high-temperature discharge. For example, the discharge diameter reached 5-7 mm according to visual estimates and occupied 18% of the cross-sectional area, and there was a low initial temperature of the reagents (300 K), which decreased with Mach number from 1.6 to 200 K at a low pressure (0.1 atm). To implement ignition under these conditions in another way is seen as problematic.

An attempt was made to increase the completeness of combustion by increasing the contact surface of the fuel mixture with a hot MWD. An electrode with a diameter of 5 mm and a branched tail was developed in which the discharge was to be ignited on four ends (Figure 7) and installed like an electrode with a pointed tail onto a 2-mm-thick pylon. Tests showed that the MWD appeared only on one of the four points with increased erosion and a lower luminescence intensity. The position of the plasma formation was not stationary, and the desired effect of increasing the completeness of combustion was not obtained. On the contrary, a decrease in $T_{tot}$ to 100–120 °C was observed. In addition, the electrode was made of stainless steel; therefore, there were traces of the strongest erosion (burnout) of the tail material where the MWD (Figure 7) was initiated.

In the case of supersonic nozzle removal, the flow pattern considerably changed. The pressure sensor readings indicated a subsonic flow with large losses caused by throttling and blocking of the path by the central body. In this case, the initiation of the MWD less frequently occurred and only at low $P_{ch}$ because in the subsonic flow compared with supersonic in which the level of static pressure is higher. $T_{tot}$ in these experiments did not exceed 100 °C, and the variation of $P_{ch}$ only affected the probability of ignition of the discharge.

4. Conclusions

To confirm the possibility of a propane-air mixture ignition by microwave discharge in the difficult conditions of a high-altitude launch of a gas turbine engine or supersonic flow, experiments were conducted under conditions of gas outflow under a pressure drop between atmospheric pressure and $P_{atm}$ of 30 to 150 Torr and for various $\phi$ from 0.65 to 1.18.

Under supersonic flow conditions, flame temperatures ($T_{tot}$) of the fuel mixture at a level of 150–
200 °C were achieved. An increase of $\phi$ from 0.7 to 0.98 increased $T_{tot}$ by 60–80 °C. A further increase in $\phi$ to the level of 1.16 increased the $T_{tot}$ to 350 °C, which is almost 100 °C higher than for $\phi = 0.98$. $P_{tot}$, $P_{st1}$ and $P_{st2}$ changed little for any changes in $P_{ch}$ and $\phi$. By increasing the burning time of the MWD to 1 s and the fuel supply time to 0.8 s, it was possible to increase the $T_{tot}$ to 380 °C. The completeness of fuel combustion under these conditions was 0.21. Such low combustion parameters were obtained because of the small contact area of the fuel mixture with the high-temperature discharge and the initial temperature of the reagents. The attempt to use a branched stainless steel electrode did not increase the completeness of combustion.

Under subsonic flow conditions, the initiation of the MWD occurred less frequently and only at low $P_{ch}$. $T_{tot}$ in these experiments did not exceed 100 °C.

Electrodes from duralumin are subject to erosion to a much lesser extent. It is necessary to organize fuel injection through holes at the leading edge of the electrodes to concentrate fuel on the surface to increase the contact of the fuel mass with the MWD.

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