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Combustion of lean fuel mixtures with subcritical streamer microwave discharge

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Abstract. A sub-critical microwave discharge is used to achieve a stable ignition and combustion of lean air-fuel mixtures in a long tube.The microwave discharge is burnt at the presence of initiator with the quasi-optical microwave beam. The resonance way of initiation of a microwave discharge is more effective compared to traditional plasma-assisted ways of ignition and stabilization of combustion. The experimental observations show that ignition and combustion of a lean air and propane mixture in a long tube is achieved at low ignition limit with fuel/air ratio lower than 0.55. The results obtained are useful for design of new and improvement of the existing plasma-assisted technologies in aviation industry.

1. Introduction

There are three main methods of organizing combustion: diffuse mixing of fuel and oxidizer, combustion of premixed mixtures and catalytic combustion [1]. The introduction of a catalyst makes it possible to reduce the combustion temperature to 1200–1500 K and thereby reduce NOx emissions by an order of magnitude.

The main way to improve fuel efficiency and reduce air emissions from conventional gas turbines in aviation industry is to switch to burning increasingly lean fuel mixtures with a large excess of oxidant. The air to fuel ratio value is limited to the region of unstable modes such as flame breakthroughs and vibrational combustion [1]. Methods for decreasing the concentration of nitrogen oxides are mainly reduced to a decrease in the temperature of fuel combustion, maximum depletion of the mixture, and a decrease in the residence time of combustion products at high temperatures [2, 3].

The use of microwave discharges makes it possible to expand the usually very narrow range of parameters for stable combustion of a lean fuel mixture [4, 5]. For this case, a series of consecutive pulses in a quasi-continuous mode or continuously burning corona discharges are used [6, 7].

Excitation of oxygen atoms in cold non-equilibrium plasma increases the diffuse flame propagation rate, which allows not only to stabilize the flame and expand the combustion limits, but also to increase the rate and completeness of fuel combustion, which also has a positive effect on the formation of nitrogen oxides NOx [8, 9]. Microwave discharges are very stable and do not extinguish in high-speed flows, which makes them promising for use in combustion stabilization systems, tubular flow-through combustion chambers, and burners of aircraft engines.

The main disadvantage of the methods for organizing combustion in the presence of plasma is the high energy consumption for electromagnetic breakdown and ionization of the medium. Micro- and nanosecond pulses of microwave and laser radiation used for ignition consume enormous powers due to the low efficiency of the sources and high threshold values of the breakdown of the gaseous medium [10, 11].

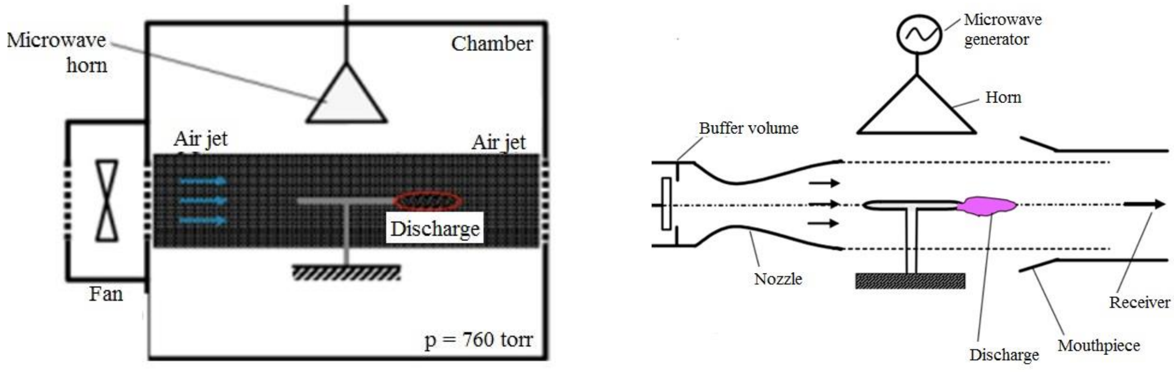
The method of initiating streamer discharges under resonance conditions at a sub-critical field level is more economical than other methodsin dozens or hundreds times [12]. Streamer discharges are discharges consisting of a plurality of plasma channels that form a bizarre net in space or on the dielectric surface. The breakdown energy depends on the pressure of the medium and the type of gas. If the similar energy of the radiation source is lower than the breakdown energy, then the discharge ignited in such a field is called sub-critical. The appearance and behavior of the discharge strongly depends on the strength of the electric field and can take the form of a tree-like formation or a diffuse cloud when streamers do not go beyond its limits. A streamer discharge has the ability to adhere even to a dielectric net, which allows it to be shaped to an arbitrary shape.

In this study, the ignition of a stationary lean mixture by a pulsed discharge on the inner cylindrical surface is considered, as well as the ignition of the flow of the fuel mixture and the jet of the fuel mixture in the co-current air flow by a quasi-continuous discharge connected to the initiator.

2. Test rig

For the experiments, equipment is used that made it possible to ignite microwave discharges in a moving fuel mixture (case 1) and in a stationary medium (case 2).

A microwave generator based on a magnetron is used. The working radiation wavelength λ=12.5 cm. The radiation power could be adjusted stepwise from P_{gen}=200 W to 2 kW. The operating mode is quasi-continuous, the pulse duration is limited only by the requirements of the experiment and could be adjusted from 0.1 s or more. To study combustion initiated by an attached discharge in a slow blowing air flow, the setup shown in figure 1a is used. It allows to conduct unlimited research at an air flow rate of up to 50 m/s, which is created by a fan at atmospheric pressure.

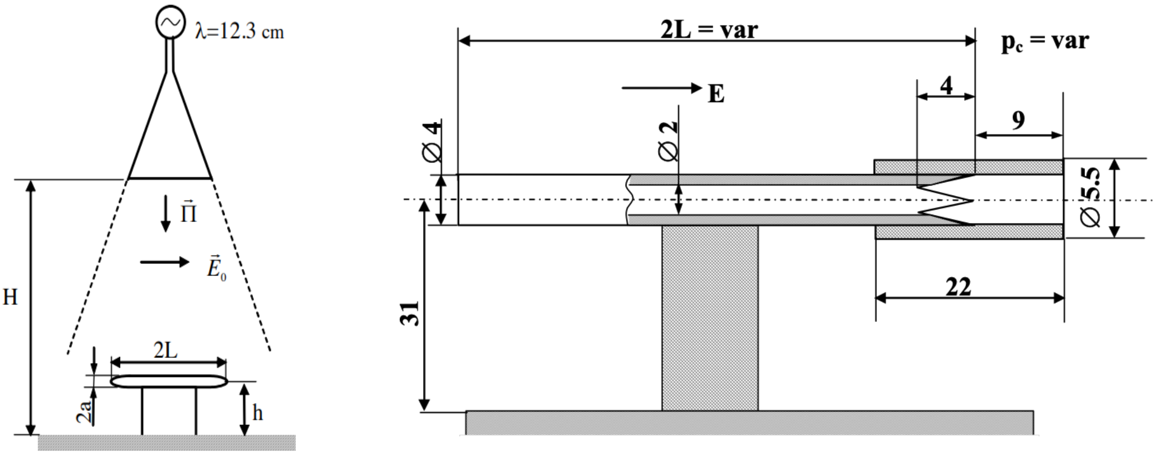


a) b)

Figure 1. Schematic diagram of experimental test rig designed to study the initiation of combustion in slow subsonic (a) and high-speed transonic flows (b).

The installation shown in figure 1b is a vacuum-type impulse wind tunnel. It allows creating a flow of a premixed fuel mixture at a speed of 10 to 500 m/s within a few seconds. The jet velocity of the fuel mixture is controlled by the total mixture pressure in the receiver.

In both cases, a cylindrical vibrator with rounded ends is used to ignite the discharge (figure 2a). In addition, a tubular initiator with a quartz packing is used (figure 2b), through which it is possible to pump a pre-prepared fuel mixture of propane and air with a given total pressure. The tube itself is placed in an external co-current air flow generated by a fan.



a) b)

Figure 2. Tube with a quartz discharge initiator (a) and a thermocouple for temperature measurement (b).

The temperature in the flame or discharge field is measured by a thermocouple installed in the tube at a distance of 30 mm from the initiator trailing edge. The equipment allows to change the intensity of the electro-magnetic field in focus, ignite discharges of different intensities, blow these discharges with air, a prepared fuel mixture or a compact jet of a fuel mixture in a co-current air flow, which simulated different schemes of combustion chambers.

3. Results and discussion

In the analysis of processes in gas microwave discharges, the concept of the critical field E_c is introduced. This is the minimum gas breakdown field at a given pressure. To burn a discharge at the level of the initial field $E_0<E_c$, the gas breakdown must be initiated. It uses a linear electro-magnetic vibrator to initiate breakdown. For the initiator of the discharge, the conditional geometry of which is shown in figure 2a, the breakdown energy in free space is calculated (figure 3), and then the breakdown pressure at a field strength E_0=25 V/mm in free space and in the presence of a screen located at a variable distance *h* (figure 4). For a vibrator of resonance length, the field at its vertices is hundreds of times larger than the original field. This allows efficient breakdown at the initial field level $E_0<E_c$.

Other types of discharges do not possess such properties, although at present the efficiency of energy use at supercritical nanosecond pulses is 85-90%. To ignite the fuel mixture, it is necessary to initiate chemical chain reactions, which does not require heating, but the dissociation of gas molecules. A powerful electron avalanches develops at the nodes of a streamer discharge even if there is one free electron in the gaseous medium. The plasma temperature in the streamer nodes reaches tens of thousands of degrees. Shock waves with a compression ratio of at least 10 are initiated in the nodes. Shock waves propagate in the discharge plasma region at speeds of 6-8 km/s.

The high speed of the streamer discharge, which reaches 5 km/s in free space and 15 km/s on the dielectric surface, makes it possible to consider the ignition as instantaneous and multipoint. The induction time (30–60 ms) is 3 orders longer than the pulse time (10-40 μs).

The results of ignition initiation by a streamer discharge on the inner surface of a cylindrical tube are considered. Air is evacuated from the tube to the pressure of 3 torr. Then propane is fed into the tube up to the specified pressure. After that, the tube is filled with air to atmospheric pressure. The discharge is ignited in the fuel mixture. The increase in pressure is recorded by a pressure sensor (figure 5). Black line corresponds to the readings at the start of a streamer discharge in a tube filled with air. The fuel excess coefficient α=0.53 corresponds to a partial propane pressure of 15 torr, α=0.67 - to a pressure of 18 torr, α=0.78 - to a pressure of 21 torr, α=0.89 - to a pressure of 24 torr.A stoichiometric mixture with α=1 at a pressure of 27 torr is an olive line. No ignition occurs at α<0.5.

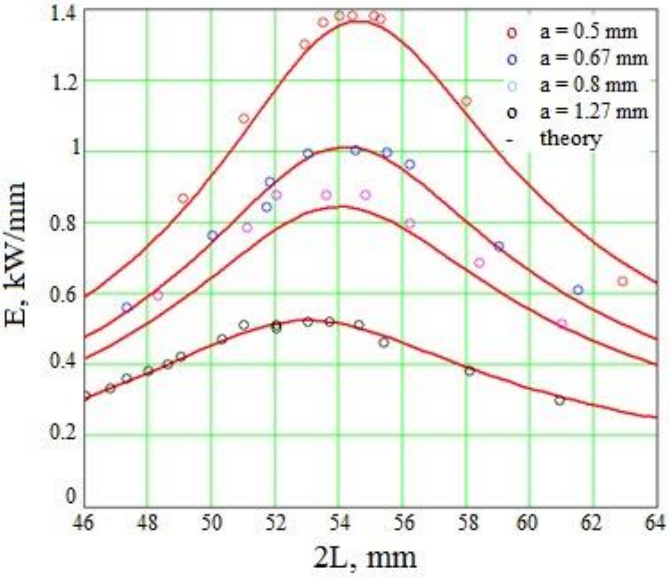


Figure 3. Breakdown in free space. Resonance curves for cylindrical vibrators in free space with given values of the radius, λ=12.3 cm, E_0=25 V/mm.

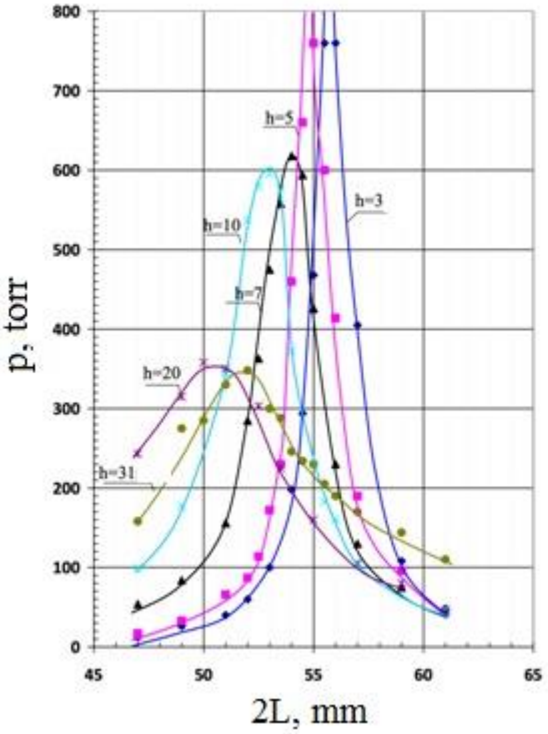


Figure 4. Breakdown near the screen. Resonance curves for cylindrical vibrators in free space with given values of the radius, λ=12.3 cm, E_0=25 V/mm.

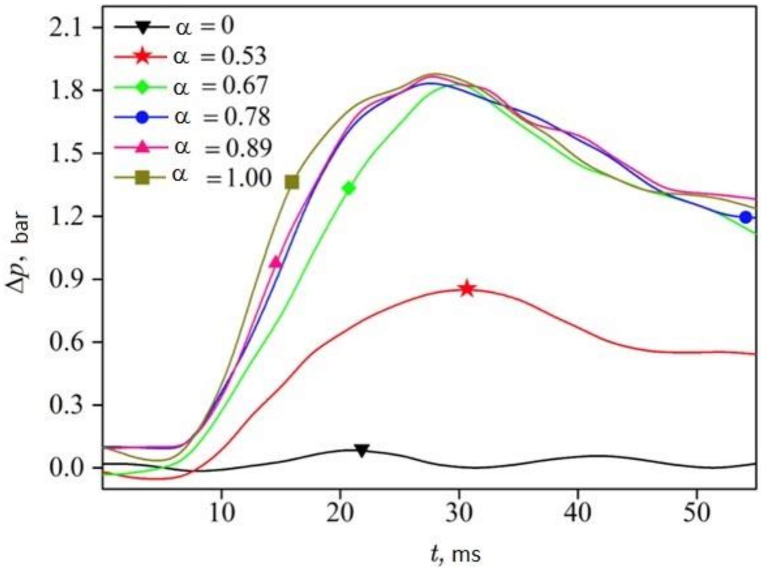


Figure 5. Pressure sensor readings during ignition of a propane-air mixture in a quartz tube.

At a pressure of 15 torr, the pressure rise is higher than in a discharge in air. This indicates the presence of combustion in the tube. In this case, the flame is not visible, i.e. combustion is flameless. An increase in fuel to air ratio leads to appearance of a flame front.

To assess the nature of flame propagation at different α, the temperature is measured across the jet cross section. Measurements show that even at α=0.57, the flame front propagates in the transverse direction, and already visible at at α=0.52 (below the flammable concentration limit under normal conditions, the mixture burns only in the trail of the discharge).

The use of a streamer discharge in a tube gives a significant gain in the flame propagation speed. The cumulative effect also makes its contribution, since ignition occurs in a thin layer on the wall, after which the flame front propagates towards the axis and is significantly accelerated. After the front closes on the axis, the flame is ejected towards the open edge of the tube. In this case, the front speed reached 200 m/s in some experiments. With the thermal method, the ignition is of a point nature, the flame front develops smoothly and gradually. Its speed is not exceeded 1 m/s. Combustion induced by the streamer discharge is faster and more complete than thermal spot ignition.

4. Conclusion

The problem of improving fuel efficiency and reducing harmful emissions from gas turbines is considered. Usually, the problem is solved by burning especially lean fuel mixtures, which are difficult to ignite, burn poorly, often with the occurrence of emergency phenomena such as flame breakthrough and vibrational combustion. For stable combustion of such mixtures, volumetric ignition and combustion support are used with the help of a resonant subcritical microwave streamer discharge.

The discharge is ignited in the presence of an initiator by a quasi-optical microwave beam with a wavelength of 12.5 cm. For ignition, a resonant method of initiating a discharge is used, which is 20-100 times more economical than the known plasma ignition and combustion stabilization methods. The experiments performed show that guaranteed ignition of a lean fuel mixture is achieved at the lower theoretical ignition limit with a propane excess ratio of less than 0.55. A flameless combustion mode is discovered, when the flame is not visible, but heat release is recorded as a result of an exothermic reaction. Stable combustion of a lean mixture in a subsonic flow at a speed of up to 30 m/s is obtained using a setup simulating a tubular combustion chamber. It is found that radiation pulses with a short wavelength of the order of 2.5 cm are not capable of creating a developed spatial structure of the discharge; therefore, they are unpromising for volume ignition. In experiments with an equal supplied energy, an increase in the flame propagation velocity from 2.5 to 4 times is obtained in comparison with spark ignition.

Traditional low-emission combustion chambers are large and complex in design. The application of the method used makes it possible to create significantly more compact combustion chambers for power micro-turbines.

Acknowledgements

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