BURNING OF THE SUPERSONIC PROPANE-AIR MIXTURE IN THE AERODYNAMIC CHANNEL WITH THE STAGNANT ZONE

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In the report the pulsed-periodical discharges created on an external surface of a flat plate being flown around of supersonic airflow and under condition of a stagnant zone, located on a wide wall of the aerodynamic channel of rectangular section were investigated. It was shown that the surface pulsed-periodical discharge results to ignition beforehand mixed supersonic propane-air fuel in the aerodynamic channel. In experimental conditions the combustion front speed reaches value of v_c=40-45 m/s, that well coordinates to the data which was got at investigation of burning into the fire-resistant channel. The kinetical model is working out for finding-out of influence of different channels on ignition of combustible mixtures in supersonic flow. The preliminary calculations demonstrate that at low initial gas temperature the induction time of H_2-O_2 mixture decreases on some orders of magnitude at taking into account of dissociation, active radicals and charged particles.

Introduction

During the last years the different type of gas discharge have gained the attention of scientists and engineers as a promising way for a supersonic combustor in scramjets. However till now there are the many unresolved problems connected to use of a gas discharge for improvement of a combustor work.

In previous our researches [1-5] various types of discharges were studied by us from the point of view of an opportunity of their application for ignition of a supersonic propane-air mixture. In experiments a direct current discharge, a freely localized microwave discharge, volumetric pulse-periodic transversal and longitudinal discharges in supersonic flow of gas were studied.

It is necessary to note that ignition of a propane-air mixture can be achieved with the help of any kind of the discharges at the corresponding energy contribution to supersonic flow. For various types of the discharges the ignition time of a supersonic propane-air mixture differs from each other.

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However the formation after ignition the stable long-time combustion of a mixture in free space is impossible, as a flame, moving together with a stream, exists in the fixed area of space only during discharge pulse duration. It is necessary to search and use the different ways for flame stabilization.

In report the ignition opportunity of a supersonic propane-air mixture with the use of the pulsed transversal surface discharge and stabilizing action of a stagnant zone in the aerodynamic channel of rectangular section on process of burning of a mixture were investigated.

Experimental technique

Experiments were carried out on the installation consisting of the vacuum chamber, the receiver of a high pressure of air, the receiver of a high pressure of propane, the system for mixing propane with air, the system for creation of a supersonic flow of a propane-air mixture, the aerodynamic channel, the discharge section, the source of high-voltage pulses, the synchronization unit, and the diagnostic system. Internal diameter of the cylindrical vacuum chamber – 105 cm, length – 300 cm. The vacuum system allowed to carry out researches in a wide range of air pressure p=1,0-760 torr.

The supersonic airflow with Mach number M=2 was formed at filling the chamber with air through specially profiled converging-diverging nozzle. The nozzle was made of a dielectric material. The nozzle was situated on the level of big transparent windows on the lateral surface of the chamber. The electric hydraulic valve operated with a power supply unit which was synchronised with the discharge power supply units.

The synchronization system allowed to input air, propane or air-propane mixture into discharge chamber with fixed delays under the relation to each other. The developed synchronization system allows to create also the surface discharge in a mode of a long single pulse (τ<1000 μs), or in a mode short periodical pulses (τ<100 μs), or in programmable regime. In the latter case the discharge is created in the mixed mode, that is the gas breakdown is carried out in a mode of short periodical pulses (τ<10 μs), and the basic energy pumping occurs during action of a long pulse. Thus it is possible to change in a wide range of the pulse duration, frequency of their following, a time delay between a pack of short pulses and a pumping pulse, number of pulses in a pack.

The aerodynamic channel of rectangular section with a stagnation zone in the form of rectangular cavity in a broad wall of the channel was made for investigation of a possibility of ignition of supersonic propane-air mixture with the help of a surface pulsed-periodical discharge.

The surface pulsed-periodical discharge in supersonic flow was formed on a dielectric flat plane placed on a bottom of a cavity of aerodynamic channel at air pressure in the vacuum chamber **p**=150 torr, air pressure in the receiver-chamber (the high-pressure system) p_r=2 atm, voltage on the discharge gap U=10-20 kV, discharge current i=8-16 A, pulse duration τ=50-1000 μs.

The high-voltage pulses with the help of a high-voltage cable through the specially designed a vacuum cut-off point was lead to electrodes built-in flush into a dielectric plate.

The special measures for avoidance of an electrical breakdown on the opposite surface of a dielectric plate outside of supersonic flow were undertaken. It was possible to adjust the cavity depth from 0 up to 10 mm displacing a plate in direction perpendicular to supersonic flow one.

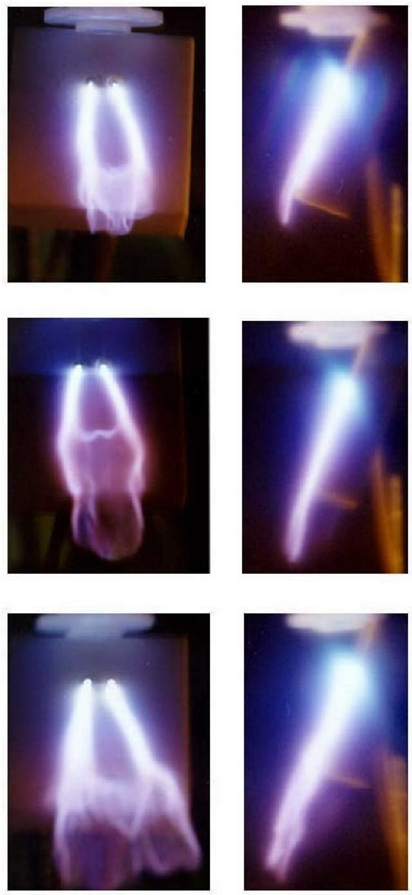
Experimental results

The surface pulsed-periodic discharge in supersonic free jet with flow Mach number of M=2 was created on a dielectric plate placed at the angle of approximately twenty degrees to the direction of supersonic airflow at air pressure into discharge chamber **p**=40 torr, voltage on the discharge gap U=15 kV, discharge current i=10 A, and different values of gas pressure p_o into the receiver-chamber.

The common view of the discharge in supersonic airflow on an external surface of a dielectric body is given in Fig. 1. This discharge does not differ from the common view of the volumetric discharge in supersonic airflow.

Without supersonic airflow the discharge represents the plasma channel existing on a surface of a dielectric body between two electrodes, fixed in a dielectric flush with a surface.

The supersonic flow leads to blowing of plasma jets from each of electrodes, which are overlapped among themselves downstream. The length of each jet depends on pulse duration, gas pressure, velocity of supersonic flow, and energy supplied into the discharge.



1

2

3

Front view Side view

Fig.1. The common view of the pulsed-periodic discharge in supersonic airflow on a surface of a flat plane at different values of air pressure in the high-pressure system p_o, atm: 1-1; 2-3; 3-6.

Dynamics of development of the surface pulsed-periodical discharge in supersonic stream M=2 of air in the aerodynamic channel has been investigated depending on discharge current, a stagnant zone depth (h=0-5 mm), distances from the beginning of a stagnant zone to electrodes. In Fig. 2-5 the common view of the pulsed-periodic transversal surface discharge in the aerodynamic channel are represented at various depth of a stagnant zone.

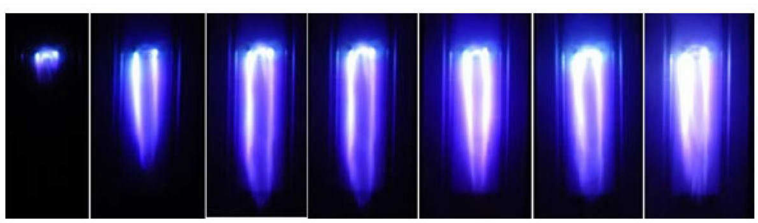
One can see that the transversal surface discharge represents two smooth plasma jets extended along a stream in the aerodynamic channel without a stagnant zone (Fig. 2). In wind tunnels the volumetric transversal discharge has the same structure. It testifies to uniformity of a supersonic stream in our channel without a stagnant zone.

The discharge structure starts to vary sharply at its creation in a cavity. It is observed a stream turbulization, the wall boundary layer separation (Fig. 2-5). At depth of a stagnant zone h=3 mm there are the opposites separated currents and the discharge is gone in two directions both upstream, and downstream.

The recirculation area with a vortex movement about a forward wall of a stagnant zone is formed. At use of a stagnant zone by depth h=5 mm the discharge exists only about a forward wall of a cavity and is not spread downstream. These circumstances are promising from the point of view of use of a cavity as a source of the active particles, promoting fast ignition and stable burning of a supersonic stream of a gas mixture.

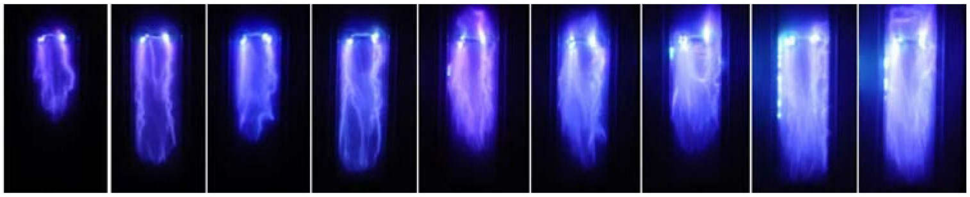
The use of the pulsed surface discharge results in an ignition of a propane-air mixture in the aerodynamic channel without a stagnant zone (Fig. 6). The flame jet, leaving the discharge, extends in a direction (x), perpendicular to a supersonic flow direction (z). Knowing a supersonic flow velocity v_f it is possible to estimate the combustion front speed $v_c=v_f tg\alpha$, where $tg\alpha=x/z$. In experimental conditions the combustion front speed v_c=40 m/s.

Under the condition of a propane-air mixture ignition the intensive radiation of CH band is registered from the area of the aerodynamic channel located on the distance z=30 cm downstream from electrodes through the time of t~600 μs after the switch on of a discharge current. It is necessary to note, that in the discharge area the intensive emission not only CH bands, but also bands of CN, C_2, OH, atomic lines of hydrogen H and oxygen O is observed. Thus the intensity of CN emission from the discharge in propane-air mixture approximately in 3-5 times more, than the one from the discharge in air. However already on distance some centimeters from the discharge in propane-air mixture the luminescence of CN band is not observed, then as the luminescence of CH bands does not decrease downstream.



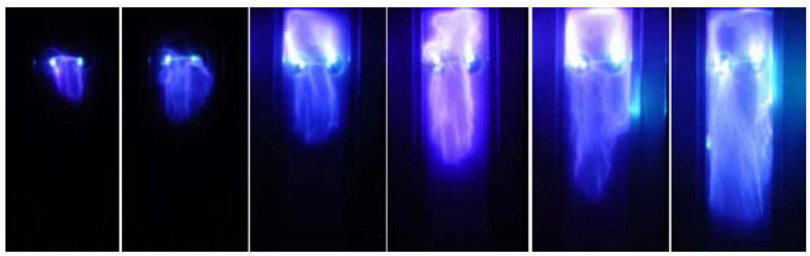
τ, μs: 100 200 300 400 600 800 1000

Fig. 2. The pulsed-periodic transversal surface discharge in supersonic airflow with M=2 in the aerodynamic channel of rectangular section 10x18 mm^2 without stagnation zone (h=0 mm). Front view. The supersonic airflow is directed from top to down. p=150 torr, p_o=2 atm, i=8 A.



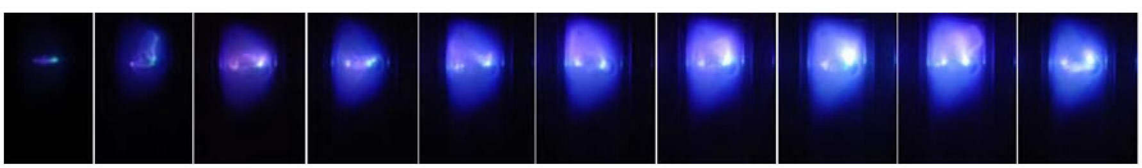
τ, μs: 150 200 250 300 400 500 600 800 1000

Fig. 3. The pulsed-periodic transversal surface discharge in supersonic airflow with M=2 in a stagnant zone (h=2 mm) of aerodynamic channel of rectangular section 10**x**18 mm^2. Front view. The supersonic airflow is directed from top to down. Spacing interval from beginning of a cavity up to electrodes z_e=15 mm. p=150 torr, p_o=2 atm, i=8 A.



τ,μs: 75 150 300 600 800 1000

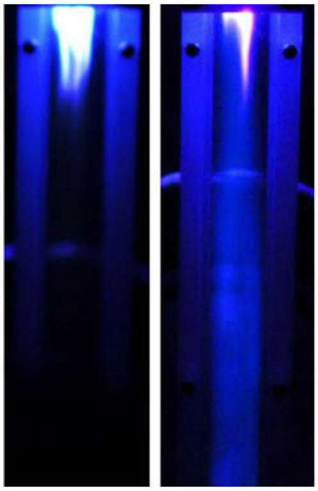
Fig. 4. The pulsed-periodic transversal surface discharge in supersonic airflow with M=2 in a stagnant zone (h=3 mm) of aerodynamic channel of rectangular section 10**x**18 mm^2. Front view. The supersonic airflow is directed from top to down. Spacing interval from beginning of a cavity up to electrodes z_e=15 mm. p=150 torr, p_o=2 atm, i=8 A.



τ,μs: 100 200 300 400 500 600 700 800 900 1000

Fig. 5. The pulsed-periodic transversal surface discharge in supersonic airflow with M=2 in a stagnant zone (h=5 mm) of aerodynamic channel of rectangular section 10**x**18 mm^2. Front view. The supersonic airflow is directed from top to down. Spacing interval from beginning of a cavity up to electrodes z_e=15 mm. p=150 torr, p_o=2 atm, i=8 A.

Therefore we identify a luminescence of CH band as the indicator of burning of a propane-air mixture (Fig. 7).



a b

Fig. 6. The common back view of the aerodynamic channel with the discharge in supersonic flow of air (a) and propane-air mixture (b). Air pressure in the vacuum chamber **p**=150 torr, air pressure in the receiver-chamber (the high-pressure system) p_o=2 atm, flow Mach number M=2, discharge current i=16 A, pulse duration τ=500 μs.

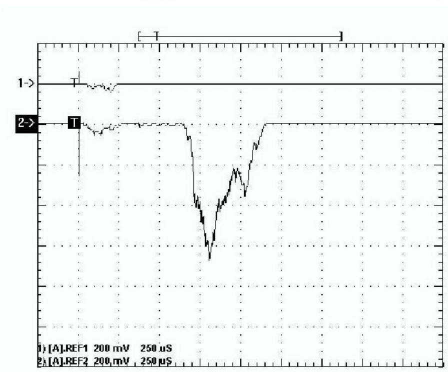


Fig. 7. Typical temporal behaviour of CH^* emission (the transition A-X, the band (0,0), the wavelength λ=4315 A^o). 1 – discharge in supersonic flow of air; 2 – discharge in supersonic flow of propane-air mixture. Air pressure in the vacuum chamber p=150 torr, air pressure in the receiver-chamber (the high-pressure system) p_o=2 atm, flow Mach number M=2, pulse duration τ=200 μs, discharge current i=16 A, the area of the aerodynamic channel, from which the CH^* emission was registered, located on the distance z=30 cm downstream from electrodes

The flame luminescence time is 350 μs (Fig. 7) whereas discharge pulse duration is equal 200 μs. Knowing the geometrical sizes of the channel and the supersonic flow velocity it is possible to estimate the combustion front speed v_c. In our conditions v_c=45 m/s, that well coincides with the combustion front speed v_c=40 m/s, that we have received earlier.

A probe method was also used for diagnostic of process of ignition and combustion of a propane-air mixture. Probe current and typical temporal behaviour of CH^* emission (the transition A-X, the band (0,0), the wavelength λ=4315 A^o) is given in Fig. 8. Probe located on the distance of z=32 cm downstream from electrodes. The area of the aerodynamic channel, from which the CH^* emission was registered, located on the distance z=30 cm downstream from electrodes. One can see that that as well as an optical method the probe method is a reliable way of diagnostic of process of combustion of a propane-air mixture.

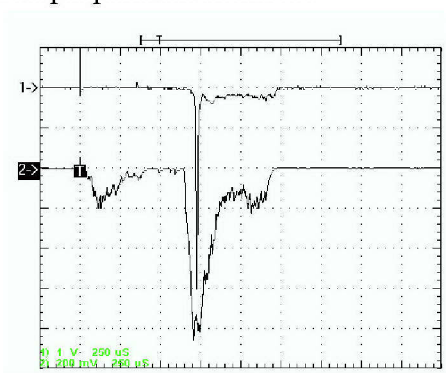


Fig. 8. Ignition of the supersonic propane-air mixture at **p**=150 torr, p_o=2 atm, i=16 A, τ=350 μs. The area of the aerodynamic channel, from which the CH^* emission (2) was registered, located on the distance z=30 cm downstream from electrodes. Probe (1) located on the distance z=32 cm downstream from electrodes.

Use of stagnant zone results in stabilization of burning of a supersonic propane-air mixture. For example (Fig. 9), even a stagnant zone by depth of 2 mm results in sharp increase of a burning time up to 1000 μs at duration of discharge pulse τ=200 μs.

It is necessary to note, that in experiments the optimum variant of a stagnant zone, stoichiometry of a propane-air mixture, pressure and a mode of excitation of the surface discharge were not used. Optimization of these parameters should lead to burning time increase of the supersonic propane-air mixture ignited with the use of the pulsed transversal surface discharge.

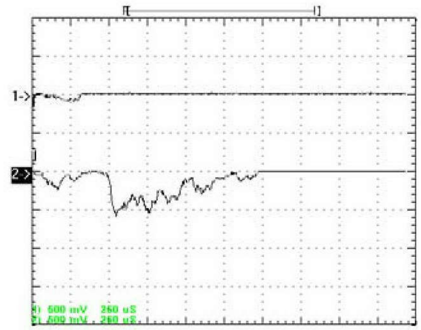


Fig. 9. Typical temporal behaviour of CH^* emission (the transition A-X, the band (0,0), the wavelength λ=4315 A^o). 1 – discharge in supersonic flow of air, 2 – discharge in supersonic flow of propane-air mixture. Stagnant zone depth h=2 mm.

The kinetical model which is taking into account creation of active radicals and charged particles under conditions of a non-equilibrium plasma of gas discharge is working out for finding-out of influence of different channels on ignition of combustible mixtures in supersonic flow. The preliminary calculations demonstrate that at low initial gas temperature of H_2-O_2 mixture the induction time decreases on some orders of magnitude at taking into account of dissociation, active radicals and charged particles.

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