ASSESSMENT OF PLASMA FORMATIONS IMPACT ON ELECTROPHYSICAL, ACOUSTIC AND GASDYNAMIC CHARACTERISTICS OF THE COMBUSTION CHAMBER

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The processes in the combustion chamber of both subsonic and supersonic jet engines need to be optimized. What's more, the fundamental issue facing the developers of the supersonic combustion ramjet engine is acceleration the ignition of mixture to supersonic velocities. In conventional fuel-air mixtures combustion waves are associated with gas heating, so their distribution is determined by processes of heat transfer which even in the presence of strong turbulence can not provide the necessary velocity of wave propagation.

The idea of using the methods of plasma ignition of fuel is based upon the nonequilibrium generation of chemically active species, accelerating the combustion process. It is assumed that the gain in energy spent in accelerating the combustion with plasma methods is achieved due to nonequilibrium nature of plasma in the discharge which allows production of radical concentration that exceeds its equilibrium value. The effect is obviously highly dependent on the initial temperature, pressure, and composition of the mixture.

Choosing the type of plasma discharge, the use of which is most profitable for the optimization of combustion in the combustion chamber, it is necessary to analyze the existing types of such discharges, efficiency, energy generation costs, and the complexity of the technical implementation. Next, it is necessary to determine business environment of the test bench having analyzed methodology of assessment for plasma formation impact on the processes in the combustion chamber. It is necessary to determine the parameters of the working environment in the combustion chamber, as measured experimentally, and select (or develop in their absence) methods and apparatus for the measurement.

4.1 Selection the type of discharge for the optimization of combustion processes

The existence of plasma formations in the engine’s tract (before combustion chamber or directly in it) leads to three (3) major effects:

- increase of the initial temperature of the fuel mixture;
- formation of chemically active species whose composition depends on the type of fuel;
- increase in flow vorticity and better mixing of fuel and oxidizer.

The latter effect is characteristic of the unipolar nonequilibrium discharge in a magnetic field [1]. To correctly select the type of discharge, it is necessary to analyze which of the effects has the greatest influence on the processes of combustion. Obviously, the first two factors influence the speed and time of initiation of combustion. Indeed, the initial temperature increase significantly reduces the time of initiation of combustion due to less need for this energy, and increase in the number of reactive particles leads to increase in the rate of reaction occurring during combustion of fuel. The numerous papers on plasma initiation combustion [1-7] show that both mechanisms of combustion considerably influence both the process of combustion and the initiation as well depending on conditions of combustion. So, in [2] it is maintained that essential influence on combustion processes exerts operating time of chemically active particles in the discharge (see Fig.4.1, [2]). In [3] though, it is argued that the main reason for combustion process accelerating is heating of fuel mixture by plasma (see Fig.4.2, [3]). As mentioned in Chapter 1, for research in this area the following types of plasma discharges are typically used: longitudinal and transverse quasi-stationary unipolar self-discharges [4], nanosecond pulsed discharges [5], various types of microwave discharges [6], etc.

The main mechanism of influence of nanosecond pulsed discharges on reduction of initiation time and acceleration of combustion process is generation of chemically active radicals [5]. This is due to the fact that indicated type of discharge is significantly nonequilibrium, wherein the basic energy of the electric field goes to heating and the formation of electrons providing an effective electron-vibrational excitation of molecules of the combustible mixture. On the contrary, the main effect of using a microwave discharge is an effective investment of energy into the gas in the plasma region, i.e. heating the gas.

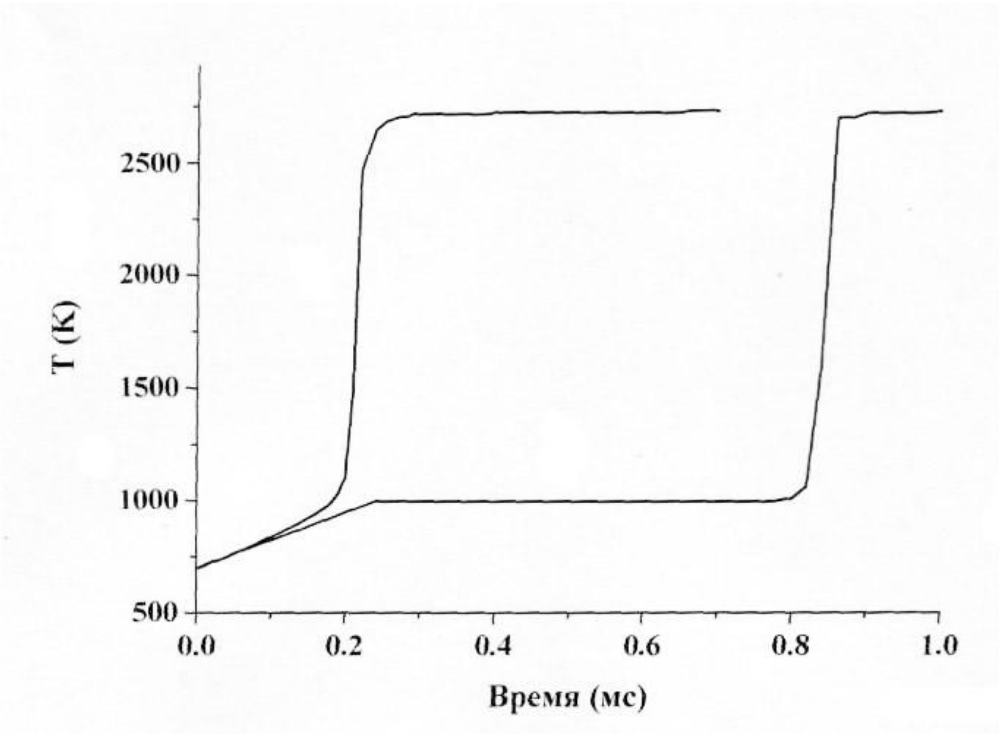

Fig. 4.1 — Dependence of gas temperature on time. P = 1 atm, T0 = 700K; discharge duration – 0.24 m/s; mixture $H_2 : O_2 : N_2$ = 0.28: 0.14: 0.58. Left-hand line – discharge initiation; right-hand line – heating

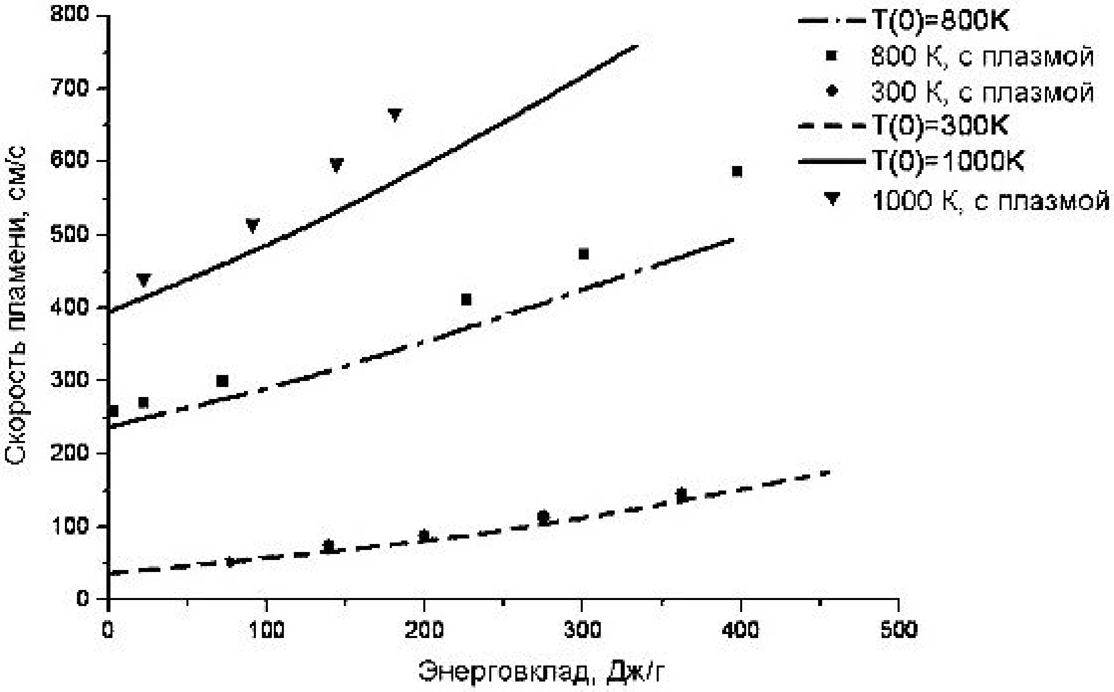

Fig. 4.2 — Dependence of flame rate on energy input at different initial temperatures (300K, 800K, 1000K) with plasma influence and without it

As is well known, the unipolar self-discharge is nonequilbrium at low and mean pressures, though under pressure increase from hundreds of Torr to atmospheric one the degree of its non-equilibrium significantly drops [7].

Thus, when using suchlike discharge, there appears an opportunity to investigate the influence on the combustion process of both above-mentioned factors. Apart from that, there is a good possibility of the arbitrary orientation of the vector of the electric field in the plasma of this discharge with respect to the mass velocity of the reacting components in the combustion chamber. That is why, in our opinion, when studying the influence of plasma on the processes of combustion, it is worth while to use this type of discharge. The main disadvantage of unipolar quasi-stationary discharge in this case is the low conversion efficiency of consumed energy of the generators of such discharge, as well as the low stability of the parameters produced by the plasma. These problems were successfully solved (see below).

4.2 Selection of the experimental setup parameters

To investigate the influence of plasma formations on the combustion processes, the experimental setup must comply with certain requirements:

1. Continuous cycle setup is a must, since a reduction of time of continuous operation of the stand (bench) leads to complication of diagnostic devices and data processing algorithms;
2. Provision should be made for continuous pumping and removal to a safe place of combustion products;
3. Provision should be made for the ability to change parameters of the combustible mixture in the combustion chamber in a wide range;
4. Provision should be made for distance precision displacement of sensors along the combustion chamber volume during combustion of fuel with the control panel outside of combustor;
5. Provision should be made for the input of electrical connections from the outside into combustion chamber, while some of them must be of high voltage (up to 10 kV);

6 Provision should be made for the combustor placed in a hermetically sealed chamber of larger size sufficient to accommodate diagnostic equipment complete with a function of combustion yields pumping (see par 2).

Installation that meets the above requirements is the wind tunnel VU-1 wherein the experiments have been conducted up till now, including ones in plasma aerodynamic flow.

4.3 Brief characteristic of VU-1

VU-1 is a supersonic wind tunnel originally designed to simulate the flow of bodies when they enter the Earth’s atmosphere and that of other planets.

Basic flow parameters:

- flow Mach numbers $\boldsymbol{M} = 0.8 \div 7$;
- simulated altitude range 15 ÷ 100 km;
- maximum Knudsen number Kn = 1.5;
- Reynolds number range $Re_o = 10 \div 10^3$;
- stagnation temperature $\boldsymbol{T}_o = 1300^o$ C (ohmic/resistive gas heating);
- plasma gas heating $\boldsymbol{T}_o = 2500^o$ C;
- temperature factor 0.1 ÷ 1;
- working gas air, $\boldsymbol{N}_2$, $\boldsymbol{CO}_2$, propane;
- maximum non-computation of jet flows $\pi \approx 10^3$;
- peak power - 65 kW.

The scheme of installation is presented in Fig.4.3. VU-1 was one of the first aerodynamic tunnels (ADT) in the country capable of simulating flight conditions at altitudes in the range 15 ÷ 100 km.

Distinctive features of research on VU-1:

1 The installation is equipped with apparatus of “electron-beam” method that allows studying of the density fields in the flow of sharp and blunt bodies. This technique allows determination of parameter evolution in the flow field with varying degrees of rarefaction, studying of relaxation processes in the gas at various temperatures, as well as the structure of the jets with combustion.

2 To study combustion in supersonic flows, a special stand at VU-1 has been developed, a distinctive feature of which is the use of special dispenser which allows introduction into the flow of gaseous particles of cesium, thus opening up wide opportunities for the study of combustion in supersonic flows.

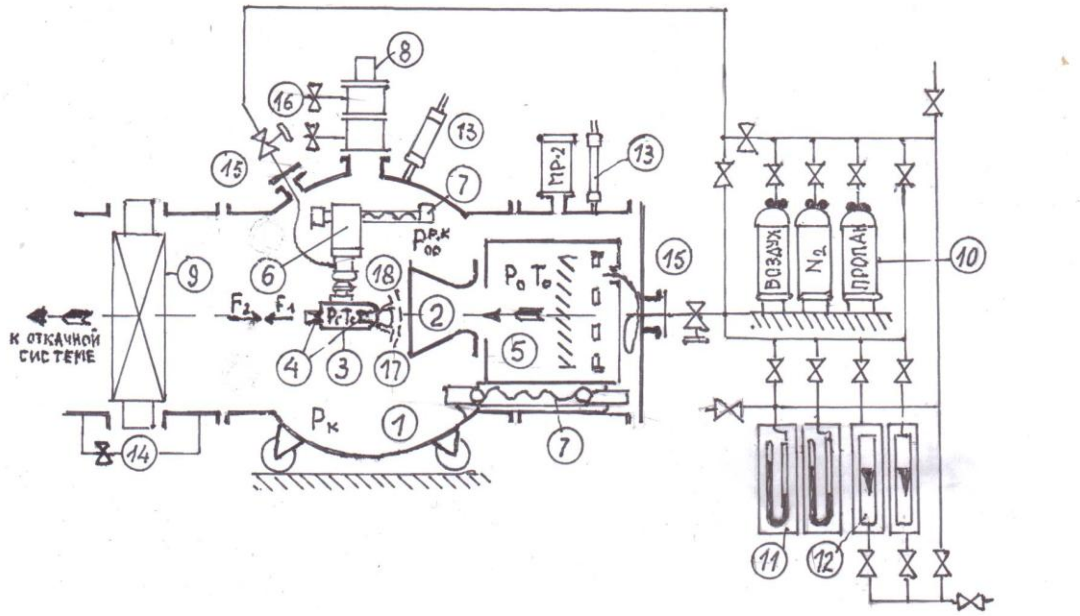

Fig. 4.3 — VU layout: 1 - processing chamber; 2 – supersonic nozzle; 3- model; 4 – supersonic nozzles; 5 – pre-combustion chamber; 6 – aerodynamic balance; 7 – coordinate arrangements; 8 – electric gun; 9 – vacuum valve; 10 – gas cylinders; 11 – U-shaped manometer; 12 – flow meter; 13 – pressure sensor; 14 – bypass pipeline; 15 – gas flow rate control; 16 – repress pumps of electron gun; 17 – flow deceleration area; 18 – shock waves; Po, To – stagnation parameters of supersonic flow; Ṕo, T́o – ́stagnation parameters of the jet; Ps – static pressure at the nozzle exit; n – off-design jet; F1, F2 – off-design reactive power and reactive forces of the jet in the base area of the model; F – drag force acting on the model

For combustion in supersonic flows special dispensers have been manufactured and installed in the principal pre-ignition chamber creating sypersonic flow. A dispenser contains a glass sealed-off ampoule/vial with liquid cesium. Each ampoule containing 1g of cesium is intended for a single use. During the experiment the ampoule is broken with a special knife, cesium is poured into the housing of dispenser having a heater. By adjusting the temperature cesium is transferred to the gaseous state. At a temperature of 200º C the vapor pressure makes about 15 Torr, so cesium is fed into the pre-ignition chamber of the flow. The resulting supersonic mixture of propane, cesium with the air oxidant, and oxygen lights up creating a supersonic combustible mixture.

4.4 Development of measuring and assessment techniques of the influence of plasma formations on the combustion chamber characteristics

As stated above, the main influence of plasma formations on the processes of ignition and combustion of the fuel mixture in the combustion chamber consists in, firstly, temperature increase of the fuel mixture within a short time, secondly, in generation of chemically active particles speeding up the reactions in the combustion chamber, and, thirdly, when adopting additional measures (say, MHD effects on plasma formation) in a significant increase in the turbulence of fuel mixture, thus providing better mixing of fuel with oxidizer. The above is illustrated in Fig.4.4 [1].

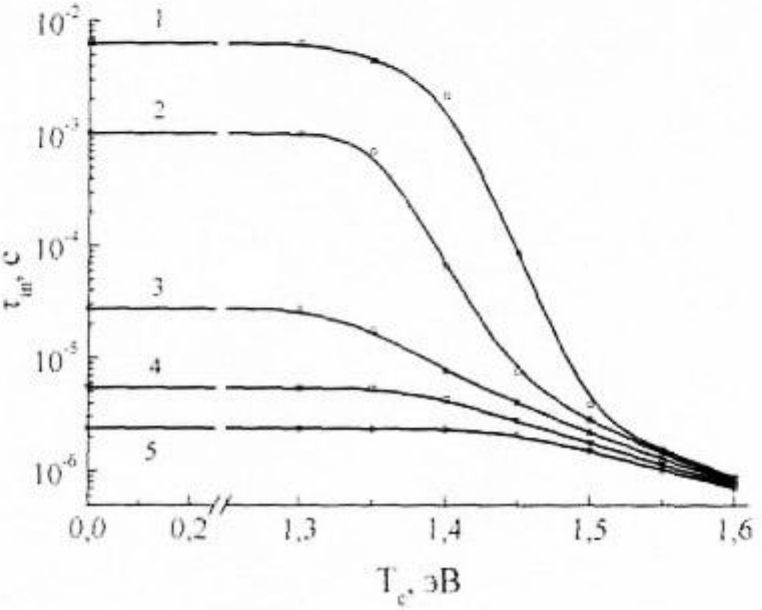

Fig. 4.4 — Dependence of induction period of H2 – O2 mixture at P = 105 Pa and instantaneous heating of gas up to various temperatures To (1 – 800K; 2 – 900K; 3 – 1000K; 4 – 1100K; 5 – 1200K) on the electron temperature

Conclusion

Thus, basic physical quantities determining positive effect of plasma formations are as follows:

1. time of combustion initiation;
2. propagation velocity of combustion wave (burning front);
3. high conversion efficiency of consumed energy for generator of plasma transformations;
4. a degree and rate of mixing for fuel and oxidizer.

As is evident from the foregoing, the main parameters influencing these physical quantities at the fixed composition of the fuel mixture are:

- temperature of gas;
- temperature of electrons in the region of plasma formations;
- a degree of turbulence of the fuel mixture (including one before combustion initiation).

To experimentally determine these parameters and other ones required for calculation of efficiency of the developed techniques, it is necessary to define (measure) the following quantities:

- temperature of gas;
- stagnation temperature;
- current in the region of plasma formation;
- electrical field in the region of plasma formation;
- static and dynamic pressure;
- time of combustion initiation;
- propagation velocity of combustion wave (burning front).

The degree of turbulence of the fuel mixture can be determined with the help of shadowgraphs. Assessment of the impact of plasma formations is carried out in several stages. At first, this impact on the temperature of neutral particles is studied. Maximum heating of the fuel mixture is to be reached in a short time (up to 1ms). Then it is necessary to start optimization of the parameters of plasma formations in order to maximize electron temperature, as this dramatically increases the number of chemically active species. After that it is necessary to carry out modification of the discharge in order to accelerate the processes of fuel and oxidizer mixing in the presence of plasma formations. Of no less importance is the increase in conductivity of plasma, as one of the possible efficient impacts on the structure of plasma formation is MHD effect [1]. The methods of measurements of the above enumerated parameters and necessary apparatus are presented below.

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