ELECTRIFICATION OF NOZZLE
IN A LIQUID ROCKET ENGINE

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A method of electrical-physical diagnostics is developed and experimental studies are conducted of the process of nozzle electrification in a liquid rocket engine operating on a hydrocarbon fuel. The highest electric potential is shown to be realized at about a stoichiometric ratio of the components, i.e., when the flow velocity, temperature, and, hence, ionization of combustion products are maximum. Recommendations for practical application of the information obtained are given.

Previous experimental and theoretical studies show that, with the use of engines of different designs, the electrization of combustion chambers and nozzle units is observed [1–4]. Thus, it is shown in [2] that as the combustion products flow around the parts of a solid-fuel engine, the latter acquires a high negative potential $\varphi_n \approx 1$ kV. The higher the temperature (and, consequently, electrical conductivity) of combustion products, the smaller the value of $\varphi_n$. As a result, the charge is carried away by the flow. In laboratory tests [3] of a model air-feed jet engine with an electrically insulated nozzle, the largest value of $\varphi_n = -400$ mV was obtained at a stoichiometric ratio of fuel components, and ranges of the coefficient of excess of the oxidizer $\alpha$ were found where the nozzle potential changes the sign to positive. In our opinion, the quantitative difference in the experimental data is due to the fact that the whole engine was insulated in [2], whereas in [3] only the nozzle was insulated and the charge leakage to the grounded frame of the combustion chambers was significantly higher.

The electrization of the engine parts occurs because of the fact that a double electric layer consisting of ions oriented in a certain way forms at the ionized-gas–wall interface during outflow of high-temperature ionized combustion products. This layer causes a corresponding rearrangement of the ion structure of the surface layer in the material of the wall and as a result, the latter was electrified [5]. This type of electrification was termed motor or inside electrification. Note that when flying machines move in the upper strata of the atmosphere, outside electrification becomes possible because of the interaction between the parts of the combustion chamber and flows of charged particles generated by the Sun or Galaxy [6].

Since a correlation between the process variables and the electric potential of the combustion chamber and nozzle parts has been registered, it seems possible to design systems of electrophysical diagnostics and control for the engines. In addition, it is necessary to study the mechanism of accumulation of electric charges on the parts of flying machines in order to prevent emergencies and exclude the influence of the charges on the operation of airborne equipment (in particular, in objects used in space technology).

In this connection, the aim of the present work was to study the process of nozzle electrification in a model liquid rocket engine. Standard procedures were used for the experiments. They were conducted on a special testbed that allowed a controlled feed of fuel components into the combustion chamber. These components were gaseous oxygen and a 80% (by volume) water solution of ethyl alcohol. The ratio between the mass consumption of fuel and oxidizer, characterized by the oxidizer-excess coefficient, was taken as the main variable.
To determine the regularities and characteristics of the electrification process, a special nozzle head was made, which was electrically insulated from the combustion chamber by means of a P5-7 Plexiglas spacer 10 mm thick (Fig. 1). The head was designed so as to ensure an undetached stream at the end of the liquid rocket engine nozzle and maintain expansion of the flow of combustion products up to value of $D_a/D_{th} = 1.8$. Here, $D_a = 18$ and $D_{cr} = 10$ mm are the diameters of the nozzle-head section and critical section, respectively. Since the head (a wall 6–8 mm thick made of high-temperature 1Ch18N10T steel) is heated during the course of the experiment, a Chromel–Nickel thermocouple (the junction is located at a depth equal to half of the wall thickness) was built into the head wall for measuring the temperature. The signals from the thermocouple and the nozzle potential, measured across the head and grounded combustion chamber, come to a R009 limit selector via a Topaz-3 universal amplifier and are registered by a N-117 loop oscillograph. The systematic error in measuring the parameters did not exceed 4.5%.

Potapov and Dregalin [1] obtained a theoretical relationship between the parameter $\varphi_n$ and the gas dynamic and electrophysical characteristics of the flow of combustion products

$$\varphi_n \sim D_a q_e n_e w_a \sigma.$$  

Here, $q_e$ is the electron charge, $n_e$ is the equilibrium value of electron concentration at the boundary of the double layer, $w_a$ is the flow velocity at the nozzle section, and $\sigma$ is the electric conductivity of the layer. The parameters $w_a$, $n_e$, and $\sigma$ are interrelated. For instance, a decrease in the degree $D_a/D_{th}$ of geometric expansion of the nozzle leads to an increase in the outflow velocity. At the same time this is responsible for a decrease in $n_e$ and $\sigma$, since the flow of combustion products cools on expansion.

In accordance with the method in [7], thermodynamic calculations of the outflow characteristics with reference to the conditions realized in experimental studies have been conducted to study how the operation regimes of liquid rocket engine and nozzle geometry are related to the change of temperature $T_a$ and the flow velocity of combustion products along the nozzle duct at various $\alpha$. The data obtained indicate that the use of the additional nozzle head leads to a 6–15% decrease in the temperature of the combustion products and 16–18% increase in the flow velocity. However, despite the large expansion of combustion products, the temperature values are sufficiently high in all cases, and the combustion products contain positive and negative ions, and free electrons, the molar concentration of which depends on the temperature of the combustion products and reaches a maximum value at a stoichiometric ratio of components (Tables 1 and 2). Hence the electrification of the heat head in this case will be the greatest.

The experimental studies conducted confirmed this assumption. Figure 3 shows the temporal change in values of $\varphi_n$ and of the head temperature $T_a$ in three operation regimes of liquid rocket engine (combustion