INVESTIGATION OF THE CHARACTERISTICS OF AN ELECTROGASDYNAMIC ENGINE

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This paper presents the results of a theoretical and experimental investigation of an electrogasdynamic (EGD) engine intended for developing thrust of aircraft. Calculated relations agreeing well with the experimental data are obtained. It is shown that the effectiveness of an EGD engine can be sufficiently high for practical use.

NOTATION

p, pressure; V, gas velocity; ρ, gas density; ξ, hydraulic loss coefficient; E, electric field strength; ρ_i, charge density; V_i, velocity of charge carriers; U, potential; j, current density; ε, dielectric constant; b, mobility of charge carriers; F, area; R, thrust; η, efficiency.

During passage of unipolar charges under the effect of an electric field through a dielectric medium (liquid or gas) the charges interact with neutral particles, thanks to which the energy of the electric field can be transformed to kinetic or potential energy of the entire medium.

At present there are a number of investigations into ion-convection pumps operating on this principle in which transfer of dielectric fluids is accomplished by a corona discharge [1, 2]. The use of the "corona wind" in gases permits creating a special engine which can operate in any nonconducting atmosphere. Such an engine can be called electrogasdynamic (EGD). Unlike the ion engine the thrust in the EGD engine is created by acceleration of a neutral working medium (for example, atmospheric gas) by means of ions, as a consequence of which it is possible to create an appreciable impulse sufficient for maintaining an aircraft in the atmosphere.

The scheme of the EGD engine, composed of parallel elements, is shown in Fig. 1. An individual element consists of two electrodes 1 and 2 having a substantially different curvature (for example, a needle and screen), and nozzle 3. We note that designwise it is more convenient that the noncorona electrode and nozzle have elements in common for the group, as shown in Fig. 1. When a sufficient potential difference is applied on the electrodes a corona discharge occurs between them. The unipolar ions formed in the outer region of the corona under the effect of the electric field between the electrodes move in the interelectrode space and as a consequence of their interaction with neutral molecules create a flow of the medium with a certain velocity V. The motion of the medium is transformed to thrust by means of nozzle 3.

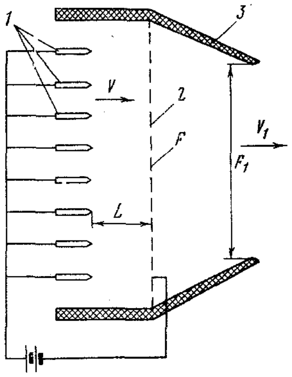

Fig. 1

The theoretical analysis of the operation of the EGD engine consists in calculating the head-flow and volt-ampere characteristics, which are determined from an examination of the processes in the outer region of the corona, and in a calculation of the thrust characteristics, which are determined from an examination of the gas flow in the nozzle.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 167-170, November-December, 1971. Original article submitted July 4, 1970.

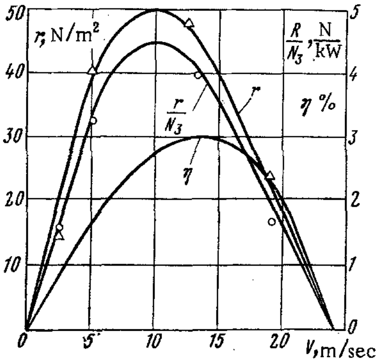

Fig. 2

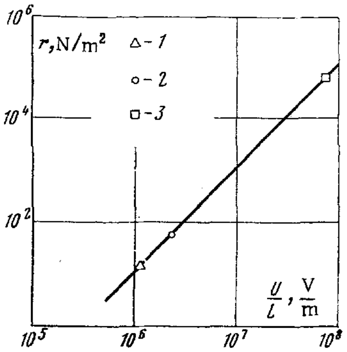

Fig. 3

The physical processes in the outer region of the corona under conditions of a moving medium can be described by means of the general system of electrogasdynamics [3]. An analytical solution of such a system is difficult. However, an EGD engine is a specific technical device, and for its calculation and prediction of characteristics it is desirable to have algebraic relations permitting a broad analysis. Such an analysis by means of numerical solutions is quite tedious and is not always effective. For this reason we will consider a quasi-one-dimensional approximation of the electrogasdynamic system of equations with the additional assumption of incompressibility of the working medium, ρ =const. This approach proved to be effective in solving the analogous problem of the operation of an ion-convection pump; the quasi-one-dimensional model of the EGD flow gave a good agreement with the experimental data.

The use of the electrogasdynamic system of equations for describing the flow of a compressible medium represents a certain assumption. However, a special analysis showed that consideration of compressibility at numbers $M \leq 0.7$ for actually realized cases changes the characteristics of the EGD flow by not more than 10-15%. With consideration of ρ =const the general system of equations in the quasi-one-dimensional case will have the following form:

$$\frac{dp}{dx} - \frac{x}{x_1} \rho_i E + \frac{\xi}{x_1} \frac{\rho V^2}{2} = 0, \qquad \frac{dV}{dx} = 0$$
$$\frac{d(V_i \rho_i x)}{dx} = 0, \quad V_i = V + bE, \quad \frac{d(Ex)}{x\,dx} = \frac{\rho_i}{\varepsilon} \tag{1}$$

Solving system (1) by a method analogous to that presented in [2] for the same boundary conditions, we obtain the expressions:

for the volt-ampere characteristic of the corona in a moving medium

$$j = \frac{U}{L^2} \varepsilon b \left(\frac{U}{L} + \frac{V}{b} \right)$$

for the head-flow characteristic of the EGD engine

$$\Delta p = \varepsilon \frac{U^2}{L^2} - \xi \frac{\rho V^2}{2}$$

for the consumed electric power

$$N_3 = Uj = \frac{U^2}{L^2} \varepsilon b \left(\frac{U}{L} + \frac{V}{b} \right) \tag{2}$$

for the useful hydrodynamic power

$$N_n = \Delta p V = \varepsilon V \frac{U^2}{L^2} - \xi \frac{\rho V^3}{2} \tag{3}$$

Here U is the voltage at the corona electrode; L is the space between electrodes.

The stage efficiency of the EGD engine is determined as the ratio of the useful power to the consumed power. Optimizing N_n with respect to velocity V, we obtain an expression for the flow velocity V_* at which the maximum fluid power is provided:

$$V_* = \frac{U}{L} \left(\frac{2\varepsilon}{3\xi\rho} \right)^{1/2} \tag{4}$$

With consideration of (4) we obtain from (2) and (3) the value of the optimal efficiency of the EGD engine

$$\eta_* = \frac{2}{3}\left[\left(\frac{3}{2}\xi\frac{\rho b^2}{\varepsilon}\right)^{1/2} + 1\right]^{-1}$$

We see from this expression that the optimal value of η_* depends only on the set of parameters of the working medium $\rho b^2/\varepsilon$ and the hydraulic resistance coefficient ξ.

To calculate the thrust characteristic we will consider the forces (Fig. 1) acting on nozzle 3. The thrust R, which is directed opposite to the direction of the velocity, is determined from the following balance of forces:

$$R = pF - p(F - F_1) + \rho V_1^2 F_1 - \rho V^2 F - p_1 F_1 \tag{5}$$

Taking the pressure at the nozzle end face to be equal to the pressure of the ambient medium, i.e., $p_1 = p_0$, and denoting $p - p_0 = \Delta p$, we obtain from (5) after transformations

$$R = F_1 \Delta p + \rho V_1^2 F - \rho V^2 F \tag{6}$$

Hence, using the Bernoulli equation and the equation of continuity

$$\rho V_1^2 = 2\Delta p + \rho V^2, \qquad F_1 V_1 = FV$$

we can obtain the dependence of the thrust referred to a unit area of the active zone of the EGD engine F on the flow velocity in the active zone V and magnitude of the head Δp being produced:

$$r = \frac{R}{F} = (3\Delta p + \rho V^2)\left(\frac{\rho V^2}{2\Delta p + \rho V^2}\right)^{1/2} - \rho V^2 \tag{7}$$

Equation (7) permits determining from the known heat-flow characteristic (3) the "midsection" thrust of the engine r, in which case the relationship of the diffuser areas necessary for accomplishing the given operating regime is determined from the relation

$$\frac{F_1}{F} = \left(\frac{\rho V^2}{2\Delta p + \rho V^2}\right)^{1/2}$$

Substituting (4) into (7), we obtain the relation for the optimal thrust

$$r_* = \frac{2}{3}\varepsilon\frac{U^2}{L^2}\frac{1}{\xi}\left[\frac{3\xi + 1}{(2\xi + 1)^{1/2}} - 1\right]$$

It follows from this expression that the optimal midsection thrust of the EGD engine is determined mainly by the quantity U/L, i.e., by the ratio of the applied voltage to the interelectrode space. The value of U/L is limited by the region of existence of the corona with respect to the applied voltage. The upper limit of U/L corresponds to the change of the corona to a spark breakdown, in which case operation of the EGD engine is impossible. Limitation of U/L means that a power not greater than a certain value determined by the breakdown voltage can be applied physically per unit active surface. In connection with this, the most acceptable atmosphere for operation of the EGD engine will be gases with an increased density and media containing halogen-fluorine compounds which, as is known, are distinguished by a high breakdown voltage. We note that an increase of density leads to a decrease of the mobility of ions and accordingly to an increase of η.

Figure 2 shows the calculated dependences of thrust r, efficiency η, and ratio of applied power R/N_3 on velocity V for operation of the EGD engine in air under normal conditions. As we see from Fig. 2, all quantities have maxima at a certain velocity and vanish when $V = 0$ and when $V = V_{\max}$ corresponding to a zero head $\Delta p = 0$.

The level of the characteristics of the EGD engine in air under normal conditions is low:

$$\eta \approx 3\%, \qquad r \approx 50 \ \mathrm{N/m^2}$$

In the atmosphere of Venus, which according to the latest data consists of carbon dioxide at a pressure of about 100 bar, the thrust and η of the EGD engine can reach respectively

$$r \approx 10^5 \ \mathrm{N/m^2} \qquad \eta \approx 40\%$$

This is due to the considerably higher pressure of the working medium of the EGD engine.

Figure 3 shows the dependence of the optimal midsection thrust of the stage of the EGD engine on the dielectric properties of the medium – more exactly, on the ratio of the breakdown voltage to the corresponding interelectrode space U/L. Figure 3 determines the design expediency of using the EGD engine under various conditions. In particular, point 1 corresponds to conditions of the earth's atmosphere, point 3 to the Venusian atmosphere, and point 2 to conditions in dielectric fluids.

A flying model of the EGD engine was fabricated and tested to check the theoretical conclusions. The model represented two parallel frames (area 100 cm^2) fastened together by an insulator to which an adjustable potential difference of the order of 10-15 kV was supplied. Fifty needles spaced 10 mm apart were attached on the upper frame perpendicular to its plane. A metal screen was stretched on the lower frame. The holes of the screen served as a nozzle, since its cross section was less than the total area of the frame. The operating regime of the EGD engine with respect to velocity was regulated by using screens with different cross sections.

In the experiments we measured the volt-ampere and thrust characteristics of the EGD engine. The thrust was determined on the basis of the weight of the model in regimes where the lift was balanced completely by the earth's gravitational force and the model hung in the air, not rising and not descending.

In Fig. 2 the experimental points are plotted on the theoretical curves. The satisfactory agreement of the theoretical and experimental data shows the suitability of the quasi-one-dimensional theory for calculation and prediction of the characteristics of an EGD engine.

EGD engines have specific properties which determine their area of use. In the earth's atmosphere the EGD engine cannot compete with other types of engines owing to the smaller values of η and the developable midsection thrusts. However, in the atmosphere of planets with a high pressure and composition of gases having a high dielectric strength, the EGD engines are completely competitive, considering their simplicity, absence of moving parts, no need for a fuel reserve, etc. In addition, the EGD engines can be used for transporting parts of instruments, sensors, etc., in dielectric fluids.

LITERATURE CITED

1. O. M. Stuetzer, "Ion drag pumps," J. Appl. Phys., 31, No. 1 (1960).
2. Yu. S. Bortnikov, V. A. Nesterov, and I. B. Rubashov, "Investigation of the characteristics of the stages of an ion-convection pump," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 4 (1968).
3. Yu. S. Bortnikov and I. B. Rubashov, "Some problems of an investigation of the system of equations of electrogasdynamics," Magnitn. Gidrodinam., No. 2 (1968).