PRINCIPAL ENERGY CHARACTERISTICS OF A LINEAR JET ENGINE

A. E. Voitenko UDC 621.454

A jet engien can be built in such an unusual way that the solid fuel is fixed along the trajectory of its motion. Examples of the design of a linear jet engine are known from the patent literature [1, 2]. The positioning of the fuel outside of the fuselage of the flight vehicle substantially alters its energy and dynamic characteristics. In this communication we consider the principal energy characteristics of linear jet engines.

1. Figure 1 shows a diagram of a linear jet engine, taken from [2]. The accelerated projectile 1 moves along the axis of the system clockwise inside a tubular charge 2 of detonating explosive. The device 3 for contact initiation of detonation, located on the projectile being accelerated, initiates a detonation wave 4 in the charge. The explosion products 5 expand in an annular nozzle, formed by a tail cone 6 and an outer tube 7. The excess pressure generated by the explosion products on the tail cone accelerates the projectile.

2. The operation of the linear jet engine can be considered normal only upon satisfaction of the conditions

$$D \leqslant u \ll (l/\delta)D \qquad (2.1)$$

where u is the velocity of the projectile, D is the detonation front velocity, ℓ is the nozzle length, and $\delta = R - r$ is the thickness of the charge wall. If the left side of the inequality is not satisfied, the detonation wave overtakes the accelerated projectile. If the right side is violated, the charge is transformed completely into gaseous explosion products, not in the initial part of the annular nozzle but in its wide part or altogether outside the nozzle, which is not acceptable.

The acceleration of the projectile from zero velocity to the detonation velocity, i.e., at $u < D$, is still possible but this requires that the average velocity of the explosion be reduced in the direction of the axis of the device, with the charge divided into sections each of which is detonated separately when it enters the initial part of the nozzle [1]. Condition (2.1) here is satisfied for the average explosion propagation velocity along the charge. If the sections of the charge are fairly short, then the relations given below are approximately applicable to the initial segment of acceleration as well.

3. The main equations for a linear jet engine in a fixed coordinate system in the quasi-steady approximation as

$$mdu + vdM = 0; \qquad (3.1)$$

$$mudu + (1/2)(v^2 + v_1^2)dM = \varepsilon k dM; \qquad (3.2)$$

$$v_1 \simeq (u - v)\,\mathrm{tg}\,(\alpha/2), \qquad (3.3)$$

where m is the mass of the accelerated projectile, M is the mass of fuel burned, v and v_1 are the axial and radial components of the average exit velocity of the explosion products, α is the divergence angle of the nozzle, ε is the specific energy of the explosion, and k is the thermal efficiency [3]. Equation (3.1) is the law of conservation of momentum in the direction of the axis of the device, Eq. (3.2) is the law of conservation of energy, and Eq. (3.3) is an approximate expression for the average radical velocity of the explosion products. It is assumed that the motion occurs in a vacuum and that the contribution made by the pressure at the nozzle exit section to the momentum transferred to the projectile.

Dnepropetrovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 118-120, March-April, 1990. Original article submitted July 20, 1986; revision submitted February 15, 1989.

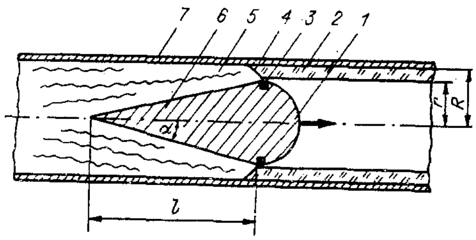

Fig. 1

The tail cone must be sufficiently acute, i.e., $\tan^2 \alpha \ll 1$, if the velocity of the projectile is to be substantially higher than the exit velocity of the detonation products. With this condition we neglect v_1 in comparison with v and reduce system (3.1)-(3.3) to one nonlinear differential equation for the function u(M):

$$(1/2)m^2(du/dM)^2 + mu(du/dM) - k\varepsilon = 0. \tag{3.4}$$

With the initial condition u(0) = 0 we have

$$\frac{u^2}{4k\varepsilon} + \frac{u}{2\,(2k\varepsilon)^{1/2}}\left(1 + \frac{u^2}{2k\varepsilon}\right)^{1/2} + \frac{1}{2}\ln\left[\frac{u}{(2k\varepsilon)^{1/2}} + \left(1 + \frac{u^2}{2k\varepsilon}\right)^{1/2}\right] = \frac{M}{m}. \tag{3.5}$$

At high velocity $u/(2k\varepsilon)^{1/2} \gg 1$, and, therefore, $M/m \gg 1$, the dependence u(M) simplifies to

$$u = (2k\varepsilon M/m)^{1/2}. \tag{3.6}$$

As the velocity of the projectile increases, the pressure on the tail cone falls off until the stream of explosion products breaks away from its surface, which stops further acceleration. In the coordinate system bound to the projectile the charge moves into the nozzle with velocity u and the explosion products fly apart radially with a velocity of the order of $(2k\varepsilon)^{1/2}$. The condition for flow without separation from the tail cone, therefore, is

$$(2k\varepsilon)^{1/2}/u \gtrsim \operatorname{tg}\alpha. \tag{3.7}$$

In the one-dimensional theory used here for a nozzle without violation of condition (3.7) the pressure on the cone abruptly drops to zero.

Condition (3.7) enables us to estimate the limiting velocity obtainable with the aid of the device under consideration:

$$u_* \simeq (2k\varepsilon)^{1/2} \operatorname{ctg}\alpha. \tag{3.8}$$

A more pointed cone ensures a higher limiting velocity of the projectile. The charge mass

$$M_* \simeq m \operatorname{ctg}^2\alpha \tag{3.9}$$

corresponds to the limiting velocity. A further increase in the charge mass above M_* by building up its length does not result in a rise in velocity.

4. Let us define the overall efficiency as the ratio of the kinetic energy of the accelerated projectile to the total energy of the exploded charge. Using (3.5), we obtain

$$\eta = \frac{mu^2}{2M\varepsilon} = \frac{2k}{1 + \left(1 + \frac{2k\varepsilon}{u^2}\right)^{1/2} + \frac{2k\varepsilon}{u^2}\ln\left[\frac{u}{(2k\varepsilon)^{1/2}} + \left(1 + \frac{u^2}{2k\varepsilon}\right)^{1/2}\right]}. \tag{4.1}$$

At the onset of acceleration, when $u/(2k\varepsilon)^{1/2} \ll 1$ and $M/m \ll 1$, the efficiency $\eta \to 0$. At a higher velocity, when $u/(2k\varepsilon)^{1/2} \gg 1$ and $M/m \gg 1$, the efficiency $\eta \to k$. For example, at $u/(2k\varepsilon)^{1/2} = 5$ we have $\eta = 0.95\,k$. At $M/m \gg 1$ the overall efficiency approaches the thermal efficiency and, therefore, the propulsion efficiency of the linear jet engine tends to unity. For an ordinary rocket the propulsion efficiency tends to zero at $M/m \gg 1$ [3].

Using (4.1) and the well known Tsiolkovskiî formula [3], we can show that at the same thermal efficiency of the nozzle the energy efficiency of a linear jet engine is substantially better than that of an ordinary rocket. For example, at $M/m = 100$ the overall efficiency of the linear engine is ~5 times that of the rocket.

5. As an example of the application of the relations obtained here we evaluate the linear jet engine parameters necessary for accelerating a mass $m = 1$ kg to the satellite velocity $u = 8$ km/sec. Setting $\varepsilon = 4$ MJ/kg [4] and $k = 0.5$, we obtain a charge mass $M = 20$ kg and efficiency $\eta = 0.4$. Assuming that the charge has inside and outside radii of 27 and 25 mm and a density of 10^3 kg/m^3, we have an acceleration path of ~60 m, an average tail cone pressure of ~230 MPa, and a projectile acceleration of ~$5 \cdot 10^5$ m/sec^2. Conditions (2.1) and (3.7) are satisfied, e.g., at $\tan \alpha = 0.1$ and $D = 3$ km/sec. The important problems of the stability of motion and strength of a device of this type should be considered separately.

The feasibility of a direct launch of projectiles into space by means of an electromagnetic railgun launcher powered by magnetic-cumulative explosive generators, i.e., using the energy of an explosion. The energy characteristics of a linear rocket engine for achieving this are substantially better and the device is simpler.

6. The relations given here describe the main energy characteristic of a linear jet engine, which can be determined on the basis of the laws of conservation and the one-dimensional nozzle theory. More exact calculations, which are associated primarily with the refinement of condition (3.7), require numerical solution of the equations for the two-dimensional flow of explosion products in an annular nozzle with allowance for the motion of the tail cone and with boundary conditions given at the detonation wave front. It is also desirable to take the friction and thermal conductivity into account in this treatment.

The fact that the efficiency of a linear jet engine is substantially higher than that of an ordinary rocket is not surprising since this is predetermined by the fundamental features of its design. In an ordinary rocket the fuel is on board and it is imparted a high velocity relative to the takeoff point. For example, if the final velocity of the rocket is 8 km/sec, the considerable mass of the fuel must be imparted a velocity of more than 7 km/sec. A large amount of energy must be expended on accelerating the fuel. In a linear jet engine this large expenditure of energy is eliminated and this is unquestionably an advantage.

LITERATURE CITED

1. W. K. Kern and F. E. Null, Explosive Linear Acceleration, USA Patent No. 3,031,933,F 41 41 f 1/00.
2. A. L. Korr and E. H. Walker, Muzzle Attachment for Accelerating a Projectile, USA Patent No. 3,880,044, F 41 f 1.00.
3. V. I. Fedos'ev and G. V. Snigirev, Introduction to Rocket Engineering [in Russian], Oborongiz, Moscow (1969).
4. F. A. Baum, K. P. Stanyukovich, and B. I. Shekhter, Physics of an Explosion [in Russian], Fizmatgiz, Moscow (1969).
5. R. S. Hawke, A. L. Brooks, C. M. Fowler, and D. R. Peterson. "Electromagnetic railgun launcher: direct launch feasibility," AIAA J., 20, No. 7 (1982).