Laser air-jet engine

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We discuss a concrete variant of a laser air-jet engine, in which the working medium is only atmospheric air, and the heating "fuel" is electromagnetic radiation transmitted to the flying craft via a laser beam from the earth or from another flying craft.

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The idea of producing a jet thrust by using a laser-energy source located outside the accelerated craft has already been discussed in the literature.[1,2] There, however, the subject was principally an evaporation thrust mechanism, resulting from evaporation of the working medium of the rocket under the influence of the radiation incident on its surface. The principal interest in the development of such devices lies in the solution, on their basis, on the problem of multiple utilization of high-power energy installations, that ensure that a space craft will be launched on a specified trajectory: the large number of carrier rockets is replaced by a single stationary laser installation located on earth. To effect such a program, it is necessary to have a laser with "superparameters"—a continuous power $P \gtrsim 10^9$ W and a beam divergence angle $\phi \lesssim 10^{-5}$ rad.[1,2]

In this article we consider a much more modest problem, but one easier to realize. We have in mind the development of laser-driven air-jet engines (LAJE), intended for the acceleration of flying craft (FC) within the confines of the earth's atmosphere, and in which the only working medium would be atmospheric air. Thus, the difference between the LAJE and the traditional air jet engines (AJE) is that instead of chemical fuel, which the FC with ordinary AJE carries, it is proposed to heat the air in the LAJE by electromagnetic radiation transmitted to the FC by a laser beam from the surface of the earth (or from another craft).

To realize the main idea of the LAJE—namely, the use of laser radiation to heat the atmospheric air drawn into the engine—it is necessary that the intensity of the radiation in the heating region be high enough, and that the air have an appreciable (nonlinear) absorption with an effective photon free path not exceeding the dimensions of the heating region. On the other hand, in the laser beam itself, as it propagates through the atmosphere, the intensity must, to the contrary, be lower than the nonlinear absorption threshold. This means, in particular, that the LAJE must of necessity include a focusing system.

The required high level of absorption of the laser radiation inside the heating region can be realized only by producing and maintaining during the entire irradiation time an optical discharge in the air contained in this region. There exist several regimes of self-maintaining optical discharges in gases,[3] but not all of them can be used for an effective and stable operation of the LAJE.

We consider now only one concrete variant of the LAJE, which was investigated by us both theoretically and experimentally.[1)]

In this variant, the LAJE operates in a pulsating (periodic-pulse) regime in conformity with the similar character of the laser operation. Each radiation pulse passes without substantial absorption through the atmosphere and strikes a parabolic reflecting surface, which is located in the tail part of the FC and is rigidly connected to it. The pulsed intensity of the radiation in the focal region of this surface should exceed the optical-breakdown threshold of the air in this region. In practice, it is most advantageous to use CO_2 lasers (or others operating in the far infrared, if such can be developed with the necessary average power level and with the required efficiency), inasmuch as in the far infrared the breakdown threshold of air (and of gases in general) can be greatly reduced by placing in the focal region an auxiliary solid target that induces a few-threshold breakdown (see[4,5]). At atmospheric pressure, the breakdown threshold of air at the wavelength $\lambda = 10.6\ \mu$ is reduced thereby to 10^6—10^7 W/cm^2 (at a pulse duration $\tau \sim 10^{-5}$—10^{-6} sec).[4,5] The optical breakdown of the air inside the focal region, having explosive properties excites in the surrounding air a shock wave that exerts, as it propagates, a pressure on the reflecting surface, which serves thus simultaneously also as a pressure receiver. If the region near the reflecting surface manages to become filled with cold air having the initial parameters by the time the next pulse arises, then the periodic pulsed irradiation should result in a sequence of shock waves with an average pressure force (thrust) $F_{av} = I/T$, where I is the total mechanical momentum transferred to the FC by one shock wave, and T is the radiation-pulse repetition period.

The most important characteristic of LAJE, which determines the feasibility of their production and utilization, is the amount of thrust, equal to the ratio P_{av}/F_{av}, where $P_{av} = E/T$ is the average radiation power (E is the energy in one pulse). According to the general conceptions, $F_{av} = \dot{m}_{av} u$, where $\dot{m}_{av}$ is the air-mass flow averaged over the period, and u is a certain effective escape velocity of the heated air. So long as we can neglect the counterpressure of the surrounding air we have $\dot{m}_{av} \sim \rho R^3/T$ and $u \sim (E/\rho R^3)^{1/2}$, where R is the focal distance of the reflecting surface and ρ is the density of the initial air in the heating region. From this we obtain

$$F_{av} \sim \frac{\rho R^3}{T}\left(\frac{E}{\rho R^3}\right)^{1/2} = \left(\frac{\rho}{p_e}\right)^{1/2} (R/R_0)^{3/2} P_{av}, \tag{1}$$

where p_e is the external pressure of the air, and $R_0 = (E/p_e)^{1/3}$. It is seen from (1) that the per-unit thrust P_{av}/f_{av} is proportional $(R/R_0)^{3/2}$, i.e., it decreases with increasing R/R_0. Formula (1), however, is valid only if $(R/R_0) \ll 1$, when the counterpressure is in fact negligible. At $(R/R_0) > 1$, it becomes significant, the shock wave is attenuated before reaching the receiver, and the per-unit thrust begins to increase again. At $(R/R_0) \sim 1$, a minimum should be observed, corresponding to the optical (with respect to the thrust) operating regime of the LAJE. On the basis of the theory of point-centered explosion using dimensionality theory (see, e.g.,[6]), we can obtain the following general formula

$$P_{av}/F_{av} = c_0 \sqrt{p_e/\rho} \Big/ [(R/R_0)^{3/2} f(R/R_0,\ R/D)], \tag{2}$$

where $c_0=\sqrt{\gamma p_e/\rho_e}$ is the speed of sound in the surrounding air and D is the diameter of the pressure receiver. The dimensionless function f takes into account the geometry of the problem and the influence of the counterpressure, when the parameter R/R_0 changes from zero to infinity (and at a fixed geometrical parameter R/D), the function f decreases monotonically. Thus, the optical parameter value $(R/R_0)_{opt}$ corresponding to the maximum of the denominator in (2) depends in general on the geometrical parameter R/D, and given R_0 (i.e., given E and p_e), the optimal focal length R_{opt} depends on the parameter D. It can be shown that

$$R_{opt} \approx \frac{R_0}{\psi}\left[1-\sqrt{1-(D/R_0)^2}\right], \qquad (3)$$

and that the optimum exists only in the diameter interval $0 \leq D \leq R_0$. It is seen from (3) that the optimal focus always lies inside the pressure-receiving paraboloid (or on its section at $D_{max}=R_0$).

Our experiments (CO_2 laser with pulse duration $\tau \approx 10^{-6}$ sec) have confirmed these theoretical conclusions. We measured in them the specific confirmed of the pressure I/E on targets with different geometrical shapes (paraboloid, hemisphere, cone, disk at $\rho/\rho_e=1$), resulting from optical breakdown of air by one laser pulse. By the same token, we determined the per-unit thrust $P_{av}/F_{av}=(I/E)^{-1}$, which should be produced by periodic pulsed irradiation; the experimental values of P_{av}/F_{av} lie in the range 20—50 kW/kgf, depending on the geometric parameter R/D. These values of the per-unit thrust turned out to be of the same order of magnitude as reached at the present time in the better variant of electro-jet engines. To produce a thrust $F_{av} \approx 500$ kgf, it is necessary to have an average laser power $P_{av} \approx 10$ MW at an individual pulse duration $\tau \sim 10^{-5}$—10^{-6} sec and at a repetition frequency on the order of 300 Hz.

The main advantage of LAJE over all the presently existing rocket engines (and also AJE with evaporation thrust mechanism) lies obviously in the fact that the final weight of the flying craft coincides in this case with its starting weight. If, furthermore, it becomes possible to bring the payload of the craft close to its total weight, one can hope that LAJE can ensure unprecedented values of accelerations acquired by the flying craft over the entire trajectory of their active motion.

[1)]The results of these investigations will be published elsewhere.

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