12. V. I. Kondrat'ev and E. E. Nikitin, Kinetics and Mechanism of Gas-Phase Reactions [in Russian], Nauka (1974).
13. A. B. Petersen, C. Witting, and S. R. Leone, Appl. Phys. Lett., 27, 305 (1975).
14. A. E. Belyanko, Yu. B. Konev, I. K. Krasyuk, et al., Kratk. Soobshch. Fiz., No. 3, 41 (1977).
15. E. B. Gordon, V. D. Sizov, S. A. Sotnichenko, and V. L. Tal'roze, in: Ninth All-Union Conf. on Coherent and Nonlinear Optics, Abstracts, Leningrad (1978), part 2, p. 24.
16. S. C. Brown, Basic Data of Plasma Physics, MIT Press (1959).
17. T. Holstein, Phys. Rev., 72, 1212 (1947).
18. R. J. Donovan and D. Husain, Chem. Rev., 70, 489 (1970).
19. A. S. Biryukov, Yu. A. Kulagin, and L. A. Shelepin, Fiz. Inst. Akad. Nauk, Preprint No. 105 (1975).
20. S. A. Losev, Gasdynamic Lasers [in Russian], Nauka (1977).
21. V. N. Kondrat'ev, Rate Constants of Gas-Phase Reactions [in Russian], Nauka (1970).
22. A. B. Petersen, L. W. Braverman, and C. Witting, J. Appl. Phys., 48, 230 (1977).

PISTON ENGINE DRIVEN BY A cw LASER

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The construction and operating principles of a piston laser engine driven by a cw laser and its indicator diagrams are considered under various operating conditions. Equations are given for the indicator efficiency of the engine as a function of the opening angle of the obturator that controls the entry of the laser energy into the cylinder, and recommendations are made for the choice of the optimal regime. Engines with working volumes 2.5 and 45 cm^3 driven by a 1-kW CO_2 laser were constructed. The former reached 3600 rpm.

1. Introduction

The question of conversion of laser energy into mechanical energy is now becoming vital. Thus, the possibility of launching a rocket with the aid of a laser was demonstrated in [1], and the feasibility, in principle, of a piston laser engine based on resonant absorption of laser radiation by a working gas was considered for the first time ever in [2]. Assuming that the piston laser engine (PLE) can be realized only with a pulsed laser, the authors have considered just this case. Soon after, the startup of a PLE driven by a pulsed laser with average power 20 W was reported [3]. The engine was made of Plexiglas and its efficiency was 2%. We have reported [4, 5] a two-cycle PLE driven by a cw CO_2 laser of 25-W power. The engine shaft efficiency was 6% in terms of the laser radiation fed to the cylinder.

The possible fields of application of the PLE are determined by two characteristic features: 1) it can receive energy from a laser located at a considerable distance from the engine (more than 100 km) [2], and 2) the PLE operates with a closed gas cycle, so that the engine needs no air and does not exhaust to the atmosphere [4].

In the future, when high-power laser sources are developed, such as, e.g., an atomic-reactor laser [6, 7] or a solar laser [8], the laser motor may be a convenient intermediate link in the conversion of laser radiation energy into other forms of energy.

Once high-power lasers with sufficient efficiency of conversion of electricity into laser energy are developed, it may be advantageous to transmit the energy with a laser beam rather than over copper wires. Then a laser motor can be useful at the consumption point.

A laser motor can be used in principle to control mechanisms on artificial satellites and other flying objects, to which the energy is transmitted by laser beam. It can also be used under conditions when the delivery of electricity or of gasoline is difficult, such as

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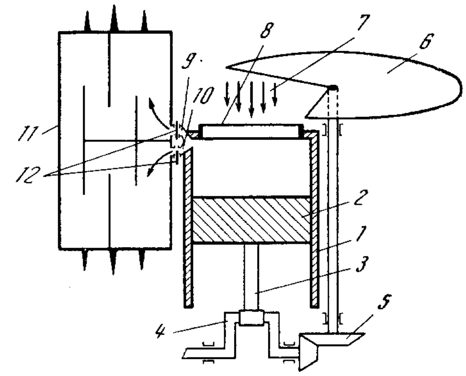

Fig. 1. Diagram of laser motor. 1) Cylinder; 2) piston; 3) piston rod; 4) crankshaft; 5) obturator drive; 6) obturator; 7) laser radiation; 8) transparent window; 9) intake pipe; 10) exhaust pipe; 11) heat exchanger; 12) intake and exhaust valves.

under mountainous conditions. A useful power on the order of 1 kW obtained at distances of several kilometers may be feasible even in the near future.

2. Arrangement of Piston Laser Engine

The basis of the PLE design can be an ordinary internal combustion engine whose operating cycle is effected not by burning fuel but by heating the working gas with a laser beam. The working gas is a mixture of the filler gas and of a gas that resonantly absorbs the laser radiation. It is convenient to use as the filler gas a monatomic inert gas (for example, argon [4]). The choice of the absorber gas is determined by the wavelength of the laser radiation. In the case of a CO_2 laser, a convenient absorbing component of the mixture is SF_6 [2, 4]. The percentage content of the mixture is determined by the requirement that the mean free path of the photon be commensurate with the dimension of the "combustion" chamber. In the laser motors we constructed, the thermodynamic properties of the working mixture are determined by the filler gas, since the content of the SF_6 does not exceed 1-2%. Since no chemical reactions take place in the laser motor, the working gas operates in it in a closed cycle and the exhaust is into a heat exchanger, from which the cooled mixture is again drawn into the cylinder (Fig. 1). The laser beam enters the cylinder through a window made of a substance that is transparent to the laser radiation. In the case of a pulsed laser, a special system must be provided to synchronize the position of the laser-motor piston with the laser pulse [2]. The laser motors we produced are driven by a cw laser. In our system an obturator is placed on the motor shaft and admits the laser beam into the cylinder at the required time.

3. Indicator Diagrams of PLE Driven by a cw Laser

In contrast to gasoline engines, as well as laser engines driven by pulsed lasers, the form of the indicator diagram of the laser engine driven by a cw laser can be altered by changing the manner in which the laser energy enters the cylinder. This makes it possible to obtain an optimal indicator diagram, depending on which of the engine parameters (e.g., power, efficiency, torque, specific power) is of decisive importance. Naturally, the choice of the optimal indicator diagram depends on many factors that are difficult to calculate or even estimate quantitatively, such as losses to friction, thermal losses in the entire cycle, imperfect compression, etc. In modern "gasoline" motor design, these factors are estimated on the basis of the very extensive experience of earlier designs. There is no such experience for laser motors, so we must start with consideration of an idealized case and only then estimate qualitatively the allowances for losses.

It is convenient to start out with an adiabatic indicator diagram. This diagram has the largest efficiency of all other diagrams for engines with the same degree of compression.* Its efficiency depends only on the degree of compression ε and on the adiabatic exponent γ:

$$\eta_i = 1 - 1/\varepsilon^{\gamma-1}. \tag{2.1}$$

Let us compare the efficiency of an ideal adiabatic cycle for a laser and gasoline engine. In the gasoline engine the working gas is air and $\gamma \simeq 1.4$, while the compression ratio does not exceed 8-9 in practice, since it is limited by the detonation. Therefore, at $\varepsilon = 8$ the indicator efficiency is $\eta_i = 1-8^{-0.4} = 0.56$. In a laser engine $\gamma = 5/3$ (monatomic working gas) and the compression ratio is not limited by detonation. At $\varepsilon = 8$ we have $\eta_i = 1-8^{-0.67} = 0.75$, and at $\varepsilon = 11$ we have $\eta_i = 0.80$.

The adiabatic cycle presumes "instantaneous" energy input at the upper dead center (UDC), whereas when a motor is driven by a cw laser the energy enters during an appreciable fraction of the cycle. Let us examine the indicator diagram and estimate the efficiency for this case (Fig. 2a). On segment 1-2 we have adiabatic compression, at point 2 the obturator opens and the gas receives energy from the laser, point 3 is the UDC, at the point 4 the obturator closes and the energy supply stops, adiabatic expansion takes place from 4 to 5, and in sections 5-1 the gas gives up heat to the cooler (since rapid cooling of the working gas is practically impossible, what actually takes place is replacement of the hot gas with cold gas, while the hot gas is relatively slowly cooled in the heat exchanger).

For proper choice of the optimal instants when the obturator opens and closes, and also for a calculation of the efficiency of the entire cycle, it is convenient to introduce the concept of "local" efficiency of the indicator diagram. The "local" efficiency determines what part of the thermal energy obtained by the gas at a given point of the indicator diagram will go over into mechanical energy. It is easy to show that to calculate the "local" efficiency at an arbitrary point φ of the indicator diagram it is necessary to draw an infinitely narrow adiabatic cycle through the point φ. The efficiency of this cycle determined by Eq. (2.1), in which the compression ratio is $\varepsilon_\varphi = V_1/V_\varphi$, will be the "local" efficiency η_φ:

$$\eta_\varphi = 1 - 1/\varepsilon_\varphi^{\gamma-1}. \tag{2.2}$$

Since the "local" efficiency η_φ is determined by the volume V_φ, it is symmetrical about the UDC. The dependence of η_φ on the angle of the crankshaft φ is shown in Fig. 2b. It was obtained under the assumption that the volume V_φ is given by

$$V_\varphi = \frac{V_h}{\varepsilon - 1} + \frac{V_h}{2}(1 - \cos\varphi), \tag{2.3}$$

where V_h is the working volume of the cylinder, and the angle φ is measured from the UDC. From the presented plot of η_φ it follows that it is advantageous to use a large obturator opening angle α. Therefore, a sufficiently high efficiency (referred not to the energy entering the cylinder but to the total energy radiated by the laser) can be obtained only when several cylinders are used and receive the laser radiation in succession.

It is convenient to calculate the indicator efficiency of the laser motor by expressing all the quantities as functions of the angle φ. Then the work of the indicator cycle is given by

$$A_i = \frac{1}{\omega}\int_0^{2\pi} \eta_\varphi u\,d\varphi = \frac{1}{\omega}\int_0^{2\pi}\left\{1 - \left(\frac{\varepsilon+1}{2\varepsilon}\right)^{\gamma-1}\left[1 - \frac{\varepsilon-1}{\varepsilon+1}\cos\varphi\right]^{\gamma-1}\right\} u\,d\varphi, \tag{2.4}$$

where u is the laser radiation power absorbed by the working gas. For a laser motor fed from a cw laser, u = const when the obturator is open and u = 0 in the remaining time. Therefore, the indicator efficiency of a laser motor depends on the angles φ_2 and φ_4 at which the obturator opens and closes, respectively:

$$\eta_i = A_i \Big/ \frac{1}{\omega}\int_0^{2\pi} u\,d\varphi = 1 - \left(\frac{\varepsilon+1}{2\varepsilon}\right)^{\gamma-1}\frac{1}{\alpha}\int_{\varphi_2}^{\varphi_4}\left[1 - \frac{\varepsilon-1}{\varepsilon+1}\cos\varphi\right]^{\gamma-1} d\varphi, \tag{2.5}$$

where α is the obturator opening angle.

*We are not considering diagrams with heat regeneration.

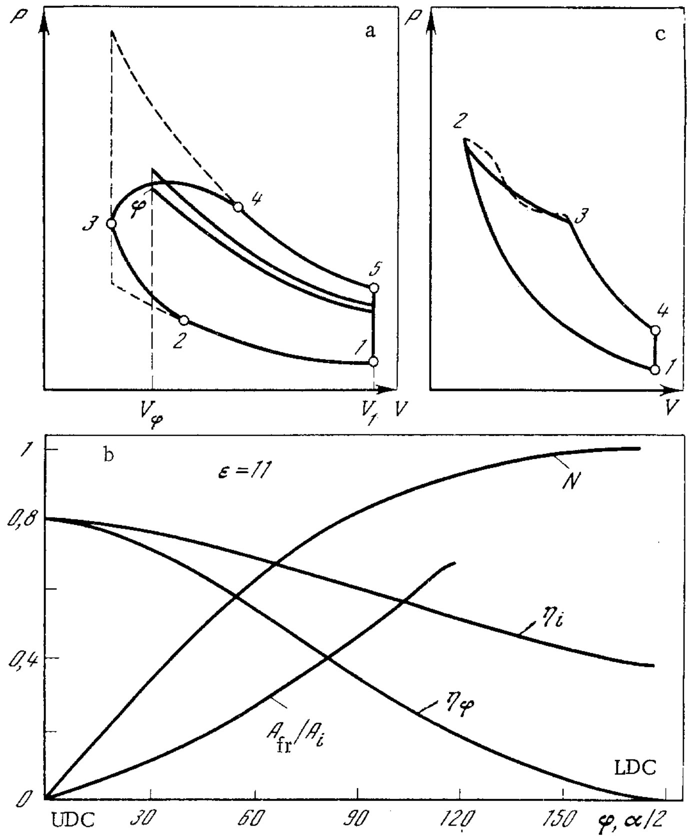

Fig. 2. Indicator diagrams of PLE (a, c) and plots of the relations between the PLE parameters (b). b) The abscissas represent the angle φ for the η_φ curve and the angle $\alpha/2$ for the remaining curves.

It follows from (2.5) that in an idealized cycle, the optimal is obturator opening symmetrical about the UDC, and the indicator efficiency decreases with increasing opening angle α. From the plot shown in Fig. 2b for the case of obturator opening symmetrical about the UDC it is seen that at $\varepsilon = 11$ and $\gamma = 5/3$ we have $\eta_i = 80$, 70 and 53% at $\alpha/2 = 0$, 60 and 120°, respectively.

Now we take into account the losses that are always present in a real engine. The total loss to friction makes the effective shaft power always less than the indicator power, so that the indicator efficiency η_i is always larger than the effective efficiency η_e, and it is the latter which characterizes the output parameters of the engine. Allowance for friction in the case of a laser motor is all the more necessary because the optimal efficiency of the idealized cycle corresponds to a minimum opening of the obturator at the UDC. In the presence of friction, the maximum η_e will correspond to a finite obturator opening angle α. The calculations performed have shown that the optimal will be the opening angle α at which the following equality is satisfied

$$1 - \frac{\eta_{\alpha/2}}{\eta_{i\alpha}} = \frac{A_{fr}}{A_i}, \tag{2.6}$$

where A_{fr} is the work consumed in friction, and A_i is the indicator work of the cycle.

The A_{fr}/A_i curve shown in Fig. 2b determines the optimal obturator opening angle $\alpha/2$ given the friction loss. The optimal obturator opening angle $\alpha/2$ with respect to efficiency is 35 and 97° at 10 and 50% friction loss, respectively.

The heat loss at the cylinder walls, and also the imperfect compression, cause deviations from the idealized indicator diagram. The heat losses are larger the stronger the working gas is heated and the longer its high temperature is maintained; therefore heating the gas to the UDC is accompanied by larger heat loss than heating at a point of the working cycle that is symmetrical about the UDC. This difference increases with increasing distance from the UDC. As a result, the optimal setting of the obturator is not symmetrical with respect to UDC, as would follow from the idealized indicator diagram, but a setting with delay, which is larger the smaller the number of engine revolutions.

We note here that in the case of a single-cylinder cw laser engine, an essential characteristic of the output parameters of the motor becomes its efficiency not with respect to the laser-radiation energy entering the cylinder, but with respect to the total laser radiation. The maximum of this efficiency is reached under the same conditions as the maximum of the motor power. Since the local efficiency of the idealized indicator diagram is always positive, the maximum power N for the idealized cycle is reached without any obturator at all (see Fig. 2b). In a real engine, heating of the gas on a certain section past the lower dead center will only interfere with the operation of the motor. Therefore, in real cycles the use of an obturator is always advantageous.

One other deviation of a real motor from the idealized one is connected with the limit on the temperature of the working mixture. For example, SF_6 becomes chemically unstable at temperatures exceeding 1400°K [9]. This limitation most strongly affects engines driven by pulsed lasers. In cw laser engines the maximum cycle temperature (at the same useful work) is much lower. It can be further decreased by changing the form of the cycle and expanding the gas along the isotherm. The optimal diagram for this case is shown in Fig. 2c, where 1-2 is an adiabat, 2-3 an isotherm, and 3-4 an adiabat. At a correctly chosen constant laser power, the sinusoidally varying piston velocity and the gas cooling associated with the expansion cause the real diagram to cross the isotherm twice between points 2 and 3. We note also that in this case it may be convenient to use not a monatomic but a diatomic filler gas (e.g., nitrogen), since it has a higher energy at the same temperature and the rotational energy stored in it in section 3-4 of the cycle is partially converted into translational energy.

4. Experiment

In the present study we performed a new experiment with PLE. We constructed a PLE with a 2.5-cm^3 working volume, analogous to that described in [4]. The motor was modified somewhat to allow for the higher supply power. The ribbed surface of the input-window frame was increased. The axis of the motor cylinder was vertical, and the laser radiation was fed from above. This was done to be able to prevent oil from dropping (by gravity) on the input window, for this would damage the window at high radiation density. The working surface of the heat exchanger was increased and exceeded 1000 cm^{-2}. The input windows were germanium with nonreflecting surfaces and NaCl. The NaCl windows do not require anti-reflection treatment, and NaCl itself is more resistant to an intense power flux. NaCl, however, is easily damaged if the surface is contaminated.

When fed from a cw CO_2 laser of 25-W power, the obturator was opened 30° ahead of the UDC and was closed at 90°. This opening angle corresponded approximately to the optimal efficiency, since the loss to friction in this regime was more than 50% of the indicator power of the motor. At this supply power, the motor was capable of operating for a long time (within 1 h). The maximum motor speed was 1000 rpm.

Experiments were performed in which this motor was fed by a single-mode CO_2 cw laser of 1-kW power. Several mirrors and lenses were placed between the exit window of the laser and the input window of the motor, to change the beam direction and to match the output and input apertures. As a result, the power reaching the motor was on the order of 700 W at the beam diameter of ≈ 8 mm. At high laser power, the relative friction loss decreases, and the indicator diagram at a higher rotary speed of the motor approaches the idealized one. Therefore, the optimum operation of a motor fed by a 1-kW laser took place at a total obturator opening angle α equal to 90°, practically symmetrical about the UDC. This operating regime of the motor (working volume 2.5 cm^3 and 700-W power at the obturator) can be called forced, since this radiation power is close to the limit that the motor can withstand. In this regime, the motor reached 3600 rpm at no load. No direct measurement of the shaft power was made, but it was indirectly estimated to exceed 15 W.

The motor was turned on repeatedly for a time of ≈ 2 min each. No noticeable damage to the germanium window was observed. It appears that the endurance of the window was due to the intense cooling of the germanium by the working gas drawn from the heat exchanger.

Rapid damage of germanium took place when the diameter of the laser beam was decreased to 4 mm. Damage to the NaCl motor windows was observed in our experiments. This could be due either to traces of oil falling on the inner surface of the window or to the low mechanical strength of NaCl windows. When the motor was worked in the forced regime, noticeable erosion of the surface of the bottom of the piston took place. This was apparently caused by local heating of the working gas at the piston surface absorbing the laser radiation to a temperature higher than the chemical stability of the SF_6 and by oxidation of the metal by the products of its decomposition.

We have constructed and tested a piston laser engine with a 45-cm^3 working cylinder volume. It was constructed from parts of a moped D-6 motor, which is a two-cycle gasoline motor with slide valve in the inlet channel. The presence of the valve decreases the power needed to produce rarefaction in the crankcase during the intake process, an important factor for a laser motor, since lasing motors have at present much smaller torques than gasoline engines. To decrease the friction loss, the parts were given a preliminary finish. The volume of the heat exchanger was 50 liters. The obturator mounted on the engine shaft had a diameter of 400 mm. The NaCl input window, 15 mm thick, had a diameter 40 mm. In view of the low mechanical strength of the window, the compression ratio did not exceed 5. The working gas was argon with SF_6 added. The space between the cylinder walls and the input window was made in the form of a maze, to decrease the flow of oil from the cylinder walls to the input window. The motor was tested with the aforementioned 1-kW laser, whose beam was broadened to a 3-cm diameter. A number of test starts have shown that the motor can operate. The speed reached 200-250 rpm at no load.

The experiments yielded data which are now used as a basis to optimize the engine parameters.

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LITERATURE CITED

1. A. I. Barchukov, F. V. Bunkin, V. I. Konov, and A. M. Prokhorov, Pis'ma Zh. Eksp. Teor. Fiz., 23, 237 (1976).
2. M. Garbuny and M. J. Pechersky, Appl. Opt., 15, 1141-1157 (1976).
3. Sci. Digest, 80, No. 5, 90 (1976).
4. L. I. Gudzenko, S. D. Kaitmazov, and E. I. Shklovskii, Pis'ma Zh. Tekh. Fiz., 3, 1125-1127 (1977).
5. A. I. Barchukov, L. I. Gudzenko, S. D. Kaitmazov, and E. I. Shklovskii, in: Ninth All-Union Conf. on Coherent and Nonlinear Optics, Abstracts, Moscow (1978), Part 1, p. 15.
6. L. I. Gudzenko, I. S. Slesarev, and S. I. Yakovlenko, Zh. Tekh. Fiz., 16, 9 (1975).
7. L. I. Gudzenko and S. I. Yakovlenko, Plasma Lasers [in Russian], Atomizdat (1978), pp. 217-238.
8. B. F. Gordiets, L. I. Gudzenko, and V. Ya. Panchenko, Pis'ma Zh. Eksp. Teor. Fiz., 26, 3 (1977).
9. A. A. Opalovskii and E. U. Lobkov, Usp. Khim., 44, 193 (1975).