Efficiency of High-Power Laser Propulsion

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Abstract

In the twentieth century the development of shuttlecrafts with rocket engines was considered as one of the promising ways in space exploration. But at the same time, the first projects on vehicles with laser propulsion were proposed, in which high-power lasers were used to produce thrust. Now, the high-power laser propulsion systems are considered as one of the perspective and effective aerospace transport facilities. It is known that the laser propulsion is a part of more general concept of beamed energy propulsion. The characteristic property of laser propulsion is that the processes being responsible for the thrust production are "switched on" under the action of powerful laser radiation. In the paper, the power efficiency of laser propulsion as subject to the processes of the thrust production is considered.

1. INTRODUCTION

High-power laser propulsion (HPLP) is considered as one of the perspective directions in the development of effective transport systems [1-4]. It is shown the HPLP system will be economically sound with a great number of vehicles launched to near-earth orbit (more than 1000 launches per year) [4-6]. At that to launch a 100 kg vehicle in the orbits, a laser radiation power of 100 MW is required. The application capability of the HPLP will depend strongly on the total efficiency of the laser launch system.

At present, the HPLP includes the following main units: a) laser propulsion engine (LPE), operating by a specific mechanism of the laser propulsion production; b) laser with a telescopic transmitter system, and c) vehicle with the LPE and optical receiver system on board.

It is clear that the total efficiency of the HPLP system will depend on:

- development of efficient laser propulsion engines with high specific thrust characteristics, providing minimal consumption of propellant;
- development of high-power lasers with small (diffraction limited) divergence of laser beam;
- spatial high precision of laser power delivery to a vehicle through the Earth's atmosphere.

The researches on development of the high-power laser propulsion systems made in the twentieth century can be subdivided into three consequent steps.

In the 1970's (the 1-st step) the most part of the problems of laser propulsion production [5] were considered, including:

1. Mechanisms of laser propulsion with laser energy absorption, in particular, effective heating of propellant by laser radiation and conversion of the heat energy into thrust.
2. Conjugation of optical elements with the design components of a laser propulsion engine such as a nozzle and so on.
3. Optimization of thermal characteristics of propellant to achieve high absorption of laser power.

In the 1980's (the 2-nd step) the progress in a study of laser propulsion was achieved due to the progress in the development of high-power lasers, the techniques of compensation for laser beam distortions, caused by the Earth's atmosphere, and with the progress in development of large aperture transmitter telescopes. The authors of [6, 7] showed also the HPLP systems for launching of vehicles into the near-earth orbit would be potentially realizable with the relevant progress in the development of efficient laser propulsion engines.

During this period principal criteria for selection of propellants for laser propulsion based on the laser ablation effect were considered, namely: small depth of laser radiation absorption, easy ways of plasma ignition, optimal conditions for generation of laser detonation waves, and small losses of flow speed in exhaust jet. Polyoxymethylene (Delrin®) was proposed as the perspective propellant for laser propulsion [7, 8].

The most remarkable result obtained during the 1980's was the engineering design of the Lightcraft Technology Demonstrator which was developed and tested by using a 10 kW CO_2-laser [9].

In the 1990's (the 3-rd step) the application area of laser propulsion was extended up to the development of vehicles for space exploration. And the following projects were developed by NASA [7] as applied to the high-power laser systems during this period, namely:

- SELENE – Space Laser Energy – a general space laser power system;
- PAMELA – Phased Array Mirror, Extendable Large Aperture – a large adaptive telescope;
- NAOMI – National Advanced Optics Mission Initiative – development of the relevant experimental equipment in the USA.

It is important that the concept of Laser Orbital Transfer Vehicle (LOTV) was proposed by a few authors [8, 10, 11] in that period. LOTV is an orbital transport tug, which is assumed to be used for transposition of satellites from near-earth orbits to geostationary ones by lasers of a 10 MW class.

Thus, as is seen there are a lot of scientific studies of high-power laser propulsion systems which are carried out to the present time. The results of these studies allow summarizing and developing perspective ways of the laser propulsion production. In the paper we analyze only those results which concern to the processes affecting the efficiency of laser propulsion production. The results on the development of high-power lasers with low beam divergence and efficient delivery of the laser power to a vehicle with LPE through the Earth's atmosphere will be presented later on.

2. MECHANISMS OF LASER PROPULSION PRODUCTION AND ITS PRODUCTION EFFICIENCY

The principal laser propulsion mechanisms include: a) laser breakdown of gases and generation of blast waves (or shock waves), b) laser ablation of solid materials, c) laser detonation of energy materials, which causes liberation of internal energy of material under the action of laser pulse. The laser breakdown of gases seems also to be the most attractive for laser propulsion application in the atmosphere, when the air may be used as a propellant producing a thrust.

To define the efficiency of laser power utilization in laser propulsion, momentum coupling coefficient is used. The coefficient is determined as the ratio of thrust T to laser radiation power P, i.e. $C_m = T/P$ [5]. Propellant consumption in LPE is characterized by the specific impulse I_{sp}, which is equal to the ratio of thrust to propellant consumption per second, $\dot{m}$: $I_{sp} = T/\dot{m}\,g = v/g$, where v is the average exhaust velocity and g is the acceleration of gravity. The higher the specific impulse, the less the propellant consumption. These parameters allow us to determine the efficiency η of laser propulsion production [4] as follows:

$$\eta = C_m I_{sp} g/2 \, . \tag{1}$$

High-performance laser propulsion with $\eta \sim 80\%$ is considered as a perspective transport system for space inter-orbital missions with a specific impulse of 10^3 s and a thrust up to 10^2 N [11]. And the system could be used to launch vehicles with a mass up to 100 kg into a near-earth orbit. In this case, a thrust more than 1000 N and a specific impulse not less than 500 s has to be produced [12].

The physical and technical limits of the laser propulsion in terms of various mechanisms of laser radiation interaction with propellants are considered below. First of all, we pay an attention to the momentum coupling coefficient C_m that determines the laser power in use and, correspondingly, determines the state-of-the-art capabilities of high-power laser propulsion.

2.1 Laser breakdown of gases, laser air-breathing propulsion

The most complete study of the air-breathing mechanism of laser propulsion under a pulsed mode of laser operation is presented in [12, 13]. It is shown the laser propulsion is produced due to movement of generated shock waves in a jet nozzle of laser propulsion engine. Various nozzles, such as a cone, a paraboloid of revolution, a hemisphere, and a flat plate are examined in [13]. It is shown on the basis of these examinations that the process of the air-breathing propulsion production in the context of the local explosion theory is defined correctly (see figure 1). The dependence of the momentum coupling coefficient on propulsion nozzle geometry factors and laser pulse characteristics is a distinctive feature of the laser air-breathing propulsion.

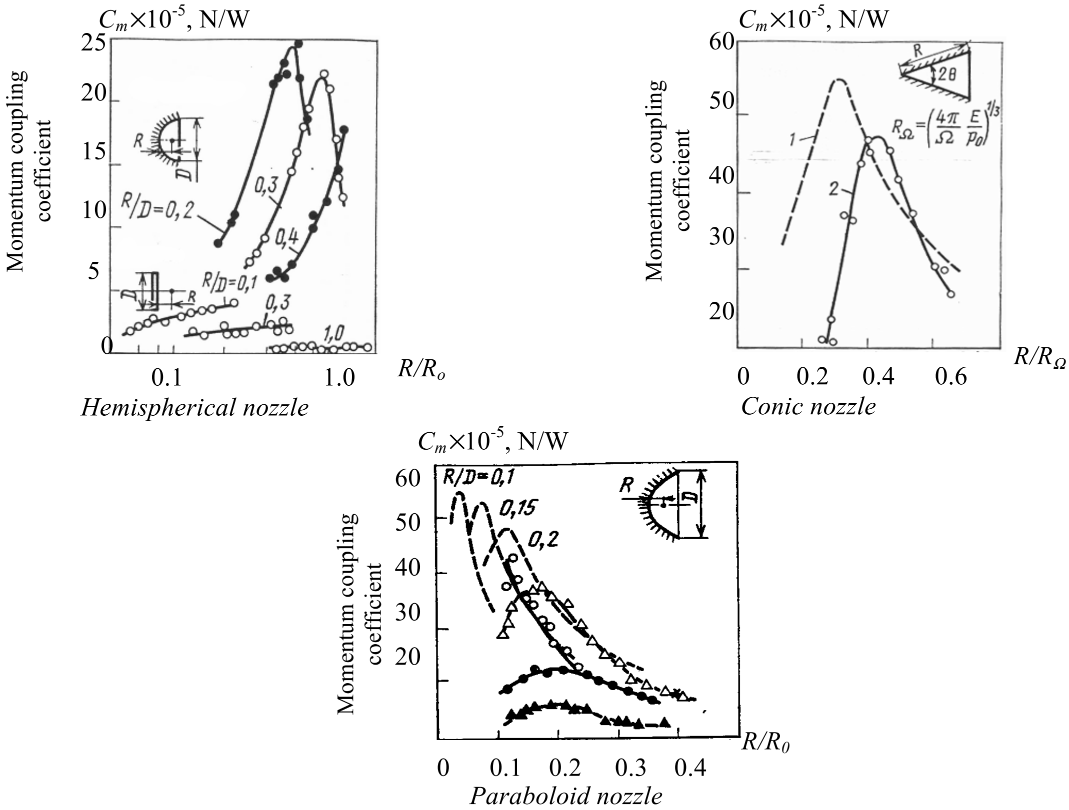


Figure 1. C_m dependences on dynamic parameters of "local explosion" R/R_0 and $R/_{R\Omega}$. Solid and dashed lines are theoretical estimations; marks are the experimental data [13].

Specifically, C_m is a function of complex parameter R/R_0, where R_0 is a "dynamic" radius of the local explosion theory; R and D are geometrical parameters related to the jet nozzle, where D is the diameter of nozzle exit section and R is the focus (for paraboloid and sphere nozzles) or the slant height of cone. In figure 1, Ω is the solid angle, at which the base of paraboloid is seen from the paraboloid focus point, p_0 is the initial gas pressure in the nozzle, E is the laser pulse energy as well as:

$$R_\Omega = \left(\frac{4\pi}{\Omega}\times\frac{E}{p_0}\right)^{1/3}; R_0 = \left(\frac{E}{p_0}\right)^{1/3}; \quad (R/R_0)_{\text{opt}} = 0.3\ [1 + (4R/D)^{-2}]^{-1}. \tag{2}$$

In accordance with the explosion theory, a nozzle exit section made in the form of a cone is equivalent to a spherical surface by the transferred recoil impulse (see figure 2 (a)) so that the recoil impulse I_{jnh} imparted to the paraboloid nozzle is determined as:

$$I_{jnh} = 2\pi(1+\cos\theta)R_1^2\, I^{(1)}(R_1). \tag{3}$$

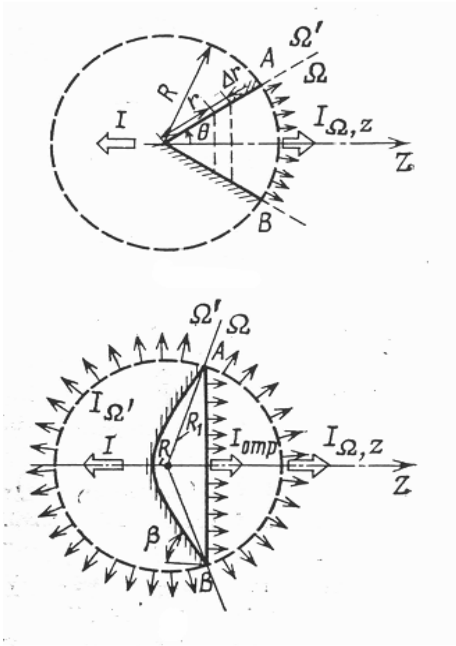
The symbols of the formulae are explained in figure 2; 2θ is a cone vertex angle, $\Omega=2\pi(1+\cos\theta)$, R_1 is a distance from focus point of paraboloid to the paraboloid exit, For a parabolic nozzle, it may be surmised that the laser breakdown ("local explosion") occurs in the paraboloid focus region. And the shock wave impulse is transformed by the paraboloid into gas flow along the paraboloid axis.

By the analogy with a cone nozzle, the following expression for the momentum coupling coefficient of paraboloid can be deduced, taking into account that the paraboloid length along its axis is equal to $L=D^2/16R$:

$$I/E = (4\pi/c_0)[(R_1/R_0)^2 - (R/R_0)^2]J^{(1)}(R_1/R_0),\ R_1 = R[1+(4R/D)^{-2}]. \tag{4}$$

Here $J^{(1)}(x)$ is the pressure impulse in the theory of a spherical local explosion, E is a laser pulse energy [13].

It follows from (4) that the recoil impulse for sufficiently long paraboloids (when $R/D \to 0$) tends to the same value as for a cone nozzle with $\theta \to 0$, i.e. a sufficiently long paraboloid is close to an equivalent long cone with respect to thrust production efficiency but does not exceed it.



Conical nozzle

Parabolic nozzle

Figure 2. Thrust model for calculation of the recoil impulse imparted to two types of jet nozzles [13].

In accordance with the local explosion theory, one can state that the momentum coupling coefficient of the laser air-breathing propulsion will not exceed 50×10^{-5} N/W under optimal nozzle parameters. For the example, maximal C_m can be obtained in a parabolic nozzle with $R/D = 0.15$ when the dynamic parameter $R/R_0 \sim 0.105$. Fluctuations of the conditions of laser propulsion production from the optimal conditions defined by the local explosion theory (such as non- instantaneity, non-locality of the explosion, and so on) will cause C_m to decrease.

Similar results for C_m were obtained by other authors later on. In particular, $C_m \sim (20\text{-}30)\times10^{5}$ N/W in a parabolic nozzle at the use of an E-beam sustained CO_2-laser with a 40 µs pulse duration in [14]. At that, the maximum of $C_m = 30\times10^{-5}$ N/W is achieved by lengthening of a nozzle with a cylindrical attachment with a diameter equal to the nozzle exit section. Application of the cylindrical attachment for the parabolic nozzle increases C_m by 20-30%, on the average, depending on the attachment length and R/R_0 parameter.

To make clear the pattern of the laser propulsion production under the pulse mode of laser operation, a system of gas-dynamic models is used in [15], including various models of interaction of laser pulse with gases, namely: (A) - perfect gas model; (B) - equilibrium plasma model; (C) - nonequilibrium plasma model.

Figure 3 (a, b) demonstrates the time variation of thrust impulse in a paraboloid nozzle. Figure 3 (a) corresponds to the thrust calculated by the pressure distribution over the paraboloid walls, Figure 3 (b) corresponds to the thrust calculated by the exhaust jet stream. Curves in the figures are denoted as 1 that is the impulse calculated at $\gamma = 1.4$, $E = 0.0025$ J; 2 is the impulse calculated at $\gamma = 1.1$, $E = 0.00983$ J; 3 is the impulse for equilibrium plasma at $E = 0.012$ J; and 4 is the impulse for equilibrium plasma at $E = 0.0025$ J.

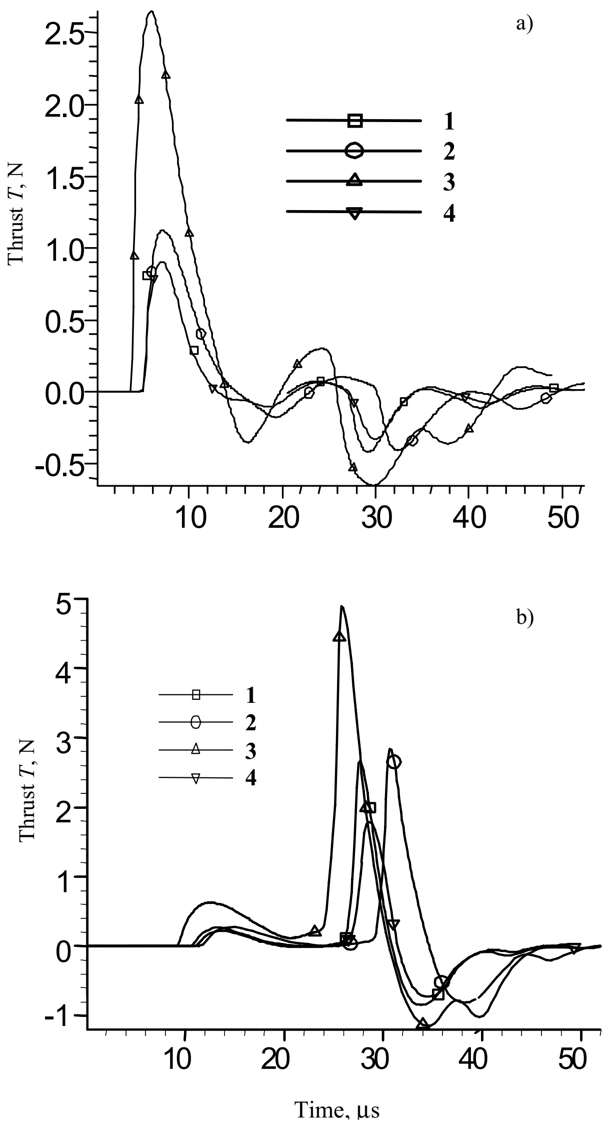


Figure 3. Temporal variation of thrust impulse calculated by using different gas plasma models [15].

As is seen from figure 3 (a), the thrust impulse originates at that moment of time when the shock wave initiated by a laser breakdown of gas comes to a paraboloid wall. Time dependence of the pressure impulse on the wall has a nonmonotonic character. It may be negative in value and is related to coming of rarefaction waves onto the paraboloid inner surface and ambient gas pressuring onto outer surface of the paraboloid. It follows from figure 3 (b) that the initiation of exhaust jet is registered later than the pressure impulse start and the jet appears only then when the shock wave outcomes the nozzle.

At repetitively pulsed mode of laser operation, the effects of nozzle geometric on production of laser propulsion are studied in [16, 17] by using high power CO_2 lasers. It is shown the produced thrust can be sufficiently increased by using a special cylindrical attachment on a jet nozzle.

But, the production efficiency of the laser air-breathing propulsion depends strongly on the efficiency of laser pulse energy absorption by ignited gas plasma and generation of blast waves in gaseous propellant. Under all modes of the laser pulse and propellant interaction (breakdown, laser power absorption, laser explosion or combustion), these processes take place over a limited time and in a bounded volume, varying with time.

To determine the efficiency of laser energy input into laser breakdown plasma, we made special experiments on the interaction of the CO_2- and Nd-laser pulses and gaseous media [18]. A distinct technique that enables us to estimate the efficiency of energy input into the plasma was developed. At that, the “explosion” energy and plasma volume were measured simultaneously. Dimensions of the plasma volume were estimated from recordings of lateral intensity distribution of a probing beam formed out of the original laser beam. The bounds of the volume were determined from the shadow picture recorded in the plane of a matrix photodetector.

The estimations of efficiency of the laser energy input into the laser breakdown plasma are based on the local explosion theory [13]. It is assumed that shock wave propagating from the breakdown region carries the information about the laser energy absorbed in the plasma volume. To enter the shock wave delay time against the plasma ignition point of time, a pressure sensor was used. The time of the laser plasma ignition was recorded with a photodiode operating in the visible range of light spectrum. Both signals (from the pressure sensor and photodiode) were digitally processed and entered into a computer. The experimental procedure allowed estimating the efficiency of laser energy conversion into heat energy of gas (conversion factor).

Results obtained after processing the experimental data showed that the conversion factor α does not depend on the laser pulse energy and remains at a level of 35% with changes of the pulse energy over the range E = 20-100 J under the atmospheric gas pressure. This was correct both for nitrogen and air. In pure nitrogen, α decreases smoothly as the nitrogen pressure decreases less than 0.3 atm (see figure 4).

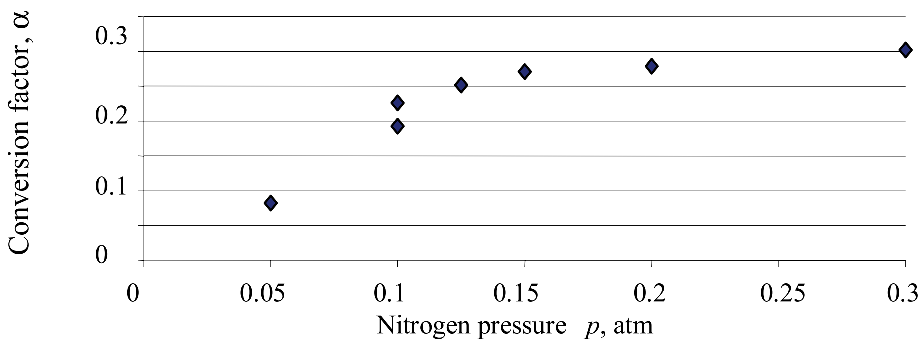


Figure 4. Dependence of the conversion factor a on gas pressure by the interaction of Nd-laser pulse with nitrogen.

These experiments reveal the fact that the energy conversion factor for the CO_2-laser pulse at the atmospheric pressure of nitrogen remains sensibly constant (at a level of 20%) over a wide range of the pulse energy variation. Under the gas pressure of 0.1 atm, the conversion factor is less by 20-25% as compared with a obtained under the atmospheric nitrogen pressure.

Moreover, the experiments made in [18] showed that efficiency of the laser energy input into a gas did not depend on the kind of gas (nitrogen, air) and did not change with injection of water aerosol into the gaseous medium. Actual efficiency of the laser energy input into air or nitrogen and its mixtures with water aerosol do not exceed 20% for the CO_2-laser pulse and 30% for the Nd-laser pulse. At that, the specific energy input into the Nd-laser-ignited plasma makes up 300-500 J/cm^3 over the gas pressure range 0.3 - 1 atm and decreases twice as the pressure decreases to 0.1 atm.

To interpret the obtained experimental data, a model of multi-ionized gas plasma was used [19]. The model confirms the fact that α does not depend on the kind of gas and it is completely determined by the plasma temperature and initial gas pressure if the laser radiation intensity I ~10^{12} W/cm^2. In this case, the interaction between laser radiation and plasma is determined only by the mechanisms of multiphoton ionization and inverse Bremsstrahlung absorption.

Since the available efficiency of laser energy input into gas plasma is evidently low, it is not worthy to use gaseous propellants only to get high efficient laser propulsion. To increase the efficiency of the laser energy conversion into heat energy of a propellant, the temperature and density of ignited plasma have to be increased significantly. This is possible if the laser breakdown of evaporated propellant near surface of solid materials is achieved. This effect is closely coupled with laser ablation phenomena.

2.2. Laser ablation propulsion

Laser propulsion based on the effect of laser ablation of solid materials occupies a special part in the development of laser propulsion engines. The laser ablation propulsion includes three fundamental processes:

- direct laser ablation of solid propellant when the propulsion is produced due to the pressure of evaporated material (evaporation mechanism of propulsion production) [20];
- combined ablation when auxiliary shock wave arising with the laser breakdown of evaporated material near its surface is used to produce thrust [21];
- laser ablation in structured materials [22].

The most complete review of publications on the laser ablation propulsion is given in papers [23, 24]. Here we consider only such properties of this type of laser propulsion which determine its application efficiency.

2.2.1. Direct laser ablation

It is experimentally shown that the momentum coupling coefficient C_m of laser propulsion under the direct laser ablation depends on the grade of solid material and laser pulse characteristics. At that, C_m increases with the laser radiation intensity and reaches its maximum when the laser pulse intensity reaches the laser breakdown threshold of material vapors [12]. There are different estimates of maximal C_m in the laser ablation propulsion theory. According to [12], the upper limit of C_m for the specified material is achieved if the laser pulse is rather long ~ 1 ms and it weakly depends on the laser radiation wavelength:

$$C_{m\,max} = A_2 / a \times (\gamma T_b / m_i) \tag{5}$$

Here A_2 is the absorption coefficient of laser power by solid material during its evaporation, a is the specific heat of evaporation, J/g, γ is the effective adiabatic index of evaporated material, T_b is material boiling point, and m_i is the mass of atoms or molecules of evaporated material. As it is resulted from the formula given above, to get the maximal C_m, it is necessary to choose a material with the maximal ratio $\gamma T_b / a^2 m_i$, and to provide the maximal absorption of laser power by the material. Estimations of C_m made by the given formula coincide with the experimental data on C_m closely, for example: $C_{m\,max} = 6 \times 10^{-5}$ N/W for aluminum and $C_{m\,max} = 10 \times 10^{-5}$ N/W for cooper.

But, ignition of plasma close to surface of a solid target by a laser pulse when the laser radiation intensity exceeds the laser-breakdown threshold causes C_m to decrease [23]. In this case [25], the following self-similar approximation for the momentum coupling coefficient is performed with good accuracy if the laser radiation intensity exceeds the breakdown threshold of evaporated material:

$$C_m = b(I\lambda\tau^{1/2})^n \tag{6}$$

Here I is the radiation intensity, W/cm^2, λ is the radiation wavelength, cm, τ is the pulse duration, s, b and n are empirical parameters; b = 5.6 for aluminum alloys, for example, b = 6.5 for C-H materials, and n = - 0.300 for both materials. The ratio (6) is regular over the wide range of the laser pulse intensity variations from 3 MW/cm^2 to 70 TW/cm^2, the pulse duration from 500 ps to 1.5 ms, and the radiation wavelength from 0.248 μm to 10.6 μm. It is significant that the formula enables us to generalize the examination of different types of lasers for laser propulsion but at some restrictions given below. C_m obtained experimentally under the direct laser ablation for some metals and nature materials are presented in Table 1, for example. As is seen, maximal C_m amounts to a few dynes/W only. Here F is the laser energy fluence.

2.2.2. Combined laser ablation propulsion

One of the possible ways of increasing C_m is producing of additional thrust by shock waves, generated at laser breakdown of evaporated materials close to the solid surface. At that, the laser plasma extension is accompanied by the shock waves so that the gas pressure in plasma increases up to 10^3-10^6 atm, and the plasma temperature makes up tens and hundreds electron-Volts. In a vacuum, the effect results in increase of C_m by 1-2 orders as compared with the direct laser ablation. Besides, the long lifetime of the shock wave maintains the pressure impulse on the solid surface 2-3 times longer than the laser pulse duration is.

Table 1. Experimental C_m under direct ablation of different materials [21].

Material	C_m 10^{-5} N/W	λ, μm	F J/cm^2	Pulse duration, ns
Aluminum 2024	4.08	1.06	3.53	25 ns
Carbon Phenolic	2.91	1.06	19.8	50, 25 ns
PMMA (polymethylmethacrylate,)	1.07 10	1.06 10.6	21.4 20	63, 65 ns 20 40 !s
Ice	2.93	1.06	20.9	47, 24 ns
Limestone	1.4	1.06	24.2	51 22 ns

Theoretically, C_m of combined laser ablation propulsion can be estimated by the following formula [24]:

$$C_m = (10)^{5/3}\chi(\rho\times10^9/I)^{1/3} , \quad (7)$$

where $\chi = ((\gamma + 1)/2\gamma)^{2\gamma/(\gamma-1)}$, ρ is the density of surrounding gas. As seen from the formula, C_m is determined by the gas medium properties and laser radiation intensity and does not depend on the kind of solid material and radiation wavelength.

But an application of the combined laser ablation propulsion has a number of essential restrictions. Compression and energy release in the shock wave front result in heating of the material vapors in the ablation regions so that the laser radiation does not penetrate the solid surface. The total heating of the material results in a damage of the solid material. For example, the depth of material damage as a consequence of the heat effect may significantly exceed the depth of material evaporation and melting during the laser pulse if the laser pulses intensity exceeds 10^{11}-10^{12} W/cm^2.

2.2.3. Confined laser ablation in multilayer structured targets

Confined laser ablation is the process of interaction of laser radiation with matter when the region of interaction is spatially bounded [21-24]. The confinement is achieved by using multilayer (structured) materials. Application of multilayer materials results in increasing of C_m as compared with the direct ablation at the same radiation intensity. It is just the method that enables to get the unprecedented values of $C_m \sim 5\times10^{-3}$ N/W [21] and higher, obtained with a Nd-laser. The increase in effectiveness of the thrust impulse production in this case is called like a "cannon-ball" effect [22].

General principle design of multilayer solid targets is as follows. A substrate of ablator material (sometimes with an absorption layer) is in adhesion contact with the coating which is transparent at the laser radiation wavelength in use. Under the action of laser radiation upon the target, the radiation passes through the transparent coating and penetrates into the substrate, being absorbed at a depth of a skin-layer. When the radiation intensity threshold is exceeded, the material evaporates through the clearance between the substrate and coating, which serves as a shield and prevents from the steam discharging. When the radiation intensity exceeds the laser breakdown threshold, the plasma is generated in the clearance. This process is accompanied by generation of two shock waves, which advance in the substrate as well as the coating.

From the law of conservation of momentum flux for the two shock waves propagating in opposite directions $(\rho_1U_1^2 = \rho_2U_2^2)$, it follows that the ratio of kinetic energy fluxes is determined by the ratio of densities of the coating ρ_1 and substrate ρ_2 materials only, i.e. $W_1/W_2=(\rho_2/\rho_1)^{1/2}$. Besides, the pressure impulse in its duration exceeds the laser pulse duration several times as in a case of the combined mechanism of laser ablation. At that, C_m weakly depends on the substrate material.

The effect of solid coating material on C_m is most completely investigated in [26] where theoretical consideration and experimental measurement of the maximal pressure impulses transmitted to the structured target for a Nd-laser, a pulse duration of 40 ns, and intensity ~ 0.74×10^9 W/cm^2 are demonstrated. Following materials are considered as coating, namely: plexiglass (Perspex), silicone caoutchouc, к9 glass, quartz glass, and lead glass. The aviation aluminum alloy 2024T62 is used as a substrate, on which the coatings are deposited. To increase the laser power absorption between the substrate and coating, an additional absorbing layer of black is deposited too.

In Tables 2 and 3 the values of acoustical impedance Z_1 of coating materials under investigation (column 2), the pressure impulse duration (column 3), the vapor pressure experimentally measured P_{max} (column 4), the calculated pressure P_{max} (column 5), the pressure impulses experimentally measured I_m (column 6), and C_m calculated from the experimental data are given. Acoustical impedance for aluminum is $Z_1 = 1.4 \times 10^6$ g/cm × s.

Table 2. The pressure behind shock wave and C_m in multiplayer targets with intermediate black absorbing layer [26].

Coating material	I_0 $\times 10^9$ W/cm^2	Z_1, g/cm×s	Pressure impulse duration, ns	P_{max} calcul. $\times 10^8$ Pa	P_{max} exper. $\times 10^8$ Pa	I_m exper. Pa×s	C_m $\times 10^{-5}$ N/W
Perspex	0.74	0.32	53	11.0	11.3	58.8	19.9
Silicone caoutchouc	0.74	0.47	54	12.9	13.8	72.9	24.6
κ9 glass	0.68	1.14	160	17.6	15.9	265.6	97.6
Quartz glass	0.76	1.31	131	18.3	17.2	217.5	71.5
Lead glass	0.90	1.54	126	19.2	22.8	240.2	66.7

Table 3. The pressure behind shock wave and C_m in multiplayer targets without intermediate black absorbing layer [26].

Coating material	I_0, $\times 10^9$ W/cm^2	Z_1, g/cm×s	Pressure impulse duration, ns	P_{max} calcul. $\times 10^8$ Pa	P_{max} exper. $\times 10^8$ Pa	I_m exper. Pa×s	C_m $\times 10^{-5}$ N/W
Perspex	0.84	0.32	75	3.8	4.3	28.5	8.4
Silicone caoutchouc	0.80	0.47	62	6.1	6.4	37.8	11.8
κ9 glass	0.72	1.14	99	15.9	15.9	133.7	46.4
Quartz glass	0.72	1.31	81	13.9	13.9	112.6	39.1
Lead glass	0.75	1.54	89	13.8	14.2	122.8	40.9

As is seen from Table 2, the calculated maximal pressure and experimentally measured pressure are in good agreement with each other. Application of a transparent coating with high impedance provides higher values of P_{max}. The pressure impulse duration and C_m increase with the impedance increase also, although the relations are not linear. The coating thickness affects greatly the value of C_m.

The problems of the radiation resistance of coating as well as application of this type of laser ablation propulsion under the repetitively pulsed mode of laser operation call for additional consideration. If the coating is not damaged during the laser operation period, the same propellant may be used under the repetitively pulsed mode. In the case of the coating damage, it is necessary to provide the laser spot replacement on the ablator surface.

For that, the liquid films as propellants can be used, especially water [22]. Water comes from a reservoir between two plates through the holes of small diameter onto the ablator surface, and it is retained on the surface due to the surface tension force. The hole diameter R is calculated so that time t of the water film restoration on the surface is to be less than $1/f$, where f is the pulse-repetition rate; $t = (\rho R^3/3\sigma)^{1/2}$, where σ is the surface tension.

Thus, we can draw a preliminary conclusion that the most promising way to get high C_m at a level of several hundreds dynes/W is the application of multiplayer targets. Ablation in the multiplayer targets combines such advantages as availability of maximal values of C_m at medium radiation power, operation in vacuum, and also advantages of the combined ablation and detonation wave, namely, long duration of the recoil momentum, which exceeds the laser pulse duration 2-3 times. But this technique of laser propulsion has a disadvantage of principle, namely, the specific impulse of exhaust jet makes up only several tens of seconds, which results in high consumption of propellant.

2.3. Laser detonation propulsion with propellants of CHO-chemical composition

In our opinion [27], significant increase in laser propulsion efficiency can be attained with using energetic propellants of CHO-chemical composition, in which laser pulse initiates chemical reactions with noticeable chemical energy release.

As an example, it is shown in [14] that the use of such polymer as Delrin® increases maximal C_m twice as compared with momentum coupling coefficient obtained in LPE with an ordinary parabolic nozzle in air-breathing mode of laser propulsion. But the momentum coupling coefficient was less than in pure air with the presence of Delrin® when nitrogen was used as a working gas.

To find out the effect of energy characteristics of the CHO-materials upon the production efficiency of laser propulsion, we studied [27] a number of polymeric and polycrystalline materials of CHO compositions with negative oxygen balance, for which basic thermal parameters were specified, including specific heat of combustion, detonation and delayed burning of detonation products.

To consider the interaction of laser radiation with energetic materials, a physical-chemical model of detonation process of the CHO-materials initiated by a laser pulse is applied. It is known [28] the laser radiation induces evaporation and thermal decomposition of the CHO-materials. This is pyrolysis, which starts at a temperature of 500-700° C in the absence of air oxygen. In the air the reaction of high-temperature oxidation (combustion) of the pyrolysis products occurs according to the following reductive scheme:

$$C_aH_bO_c + O_2 \rightarrow CO_2 + H_2O + Q, \tag{8}$$

where Q is the specific heat of combustion, that is released during two successive chemical reactions, namely, detonation and delayed burning of detonation products: $Q = Q_{det} + NQ_{db}$; N is the coefficient of after-burning of detonation products, and $C_aH_bO_c$ is a general chemical formula of the CHO materials.

The first of the reactions is the detonation initiated by a laser pulse. The detonation means propagation of chemical oxidation of combustible components in a volume with the velocity exceeding an acoustic speed. At that, detonation energy Q_{det} is released in accordance with the reaction:

$$C_aH_bO_c \rightarrow CO_2 + H_2O + H_2 + C + Q_{det}. \tag{9}$$

To calculate Q_{det}, we use the uniform system of the detonation products being formed for all types of explosive materials on the basis of the thermodynamics principles in [29]. Applying it to the CHO materials, we have the following chemical chain of the detonation products: CO_2-H_2O-O_2-H_2. According to the accepted assumption, CO_2, H_2O, may be the detonation products but not CO. Moreover, production of CO_2 prevails over H_2O.

The second reaction is the delayed burning of the incompletely oxidated detonation products in oxygen of the air, at which the delayed burning energy Q_{db} is released. This type of chemical reaction is realized, for example, in an air-breathing jet engine with the carbon-to-hydrogen fuel:

$$C + H_2 + O_2 \rightarrow CO_2 + H_2O + Q_{db}. \tag{10}$$

Taking into account the accepted assumptions, the heat of the detonation and delayed burning reactions may be calculated by the Hess law:

$$Q_{det} = -(\Delta H_{pr} - \Delta H^{o}_{f\,298}); \tag{11}$$

$$Q_{db} = -\Delta H_{pr}, \tag{12}$$

where ΔH_{pr} is the formation enthalpy of the reaction products; $\Delta H^{o}_{f\,298}$ is the formation enthalpy of the material.

The energy balance of vapors of CHO-materials and combustion of its components in oxygen of the air, which corresponds to standard conditions of laboratory experiments at laser ablation of the materials, can be expressed in the following form:

$$\left(M+m\right)\frac{v^{2}}{2}=\beta\left[\alpha E+mQ\right] , \tag{13}$$

where m is the mass of the evaporated material, M is the air mass in a volume of the laser propulsion nozzle, v is the average exhaust velocity, α is the coefficient of laser energy conversion into heat energy of propellant, β is the coefficient of conversion of propellant heat energy into exhaust flow kinetic energy.

Then in accordance with the general definition of the momentum coupling coefficient C_m, we have:

$$C_{m\,1}=J/E=Mv/E=\sqrt{2M\beta\alpha\,/\,E} , \tag{14}$$

$$C_{m\,2}=J/E=(M+m)v/E=\sqrt{2(M+m)\beta[\alpha E+mQ]\,/\,E^{2}} , \tag{15}$$

where $C_{m\,1}$ is the momentum coupling coefficient of laser air-breathing propulsion under atmospheric conditions, $C_{m\,2}$ is the momentum coupling coefficient with the CHO-materials as auxiliary propellant. And the relative increase κ (efficient factor) of the momentum coupling coefficient can be defined in the case of the use of laser detonation as:

$$K=C_{m\,2}/C_{m\,1}=\sqrt{\left(1+m\,/\,M\right)\left(1+mQ\,/\,\alpha E\right)} \cdot \tag{16}$$

To analyze the thrust impulse production in LPE with CHO-chemical solid propellants, we can use the parameter of specific ablation energy $Q^* = E/m$ [24] in addition. If we input the parameter into the formula for κ coefficient (16), we consequently have:

$$K=C_{m\,2}/C_{m\,1}=\sqrt{\left(1+m\,/\,M\right)\left(1+Q\,/\,\alpha Q^{*}\right)} \cdot \tag{17}$$

The efficient factor κ enables us to estimate the effect of plasma-chemical processes at laser breakdown of CHO-chemical materials upon the production efficiency of thrust as compared with the similar laser air-breathing propulsion in laboratory conditions.

Polyoxymethylene (Delrin®) $[-CH_2-]_n$, polyvinylchloride $[-CH_2CHCl-]_n$ polystyrene $[-C_8H_8-]_n$, and polycarbonate $[-C_{16}H_{14}O_3-]_n$ are studied in [27] as polymeric propellants. The polyvinylchloride was chosen because it demonstrated high effective thrust production in [28]. The first two polymers belong to the linear aliphatic ones, the thermal decomposition of which (break of chain) occurs at a moderate temperature (~ 200º C). These polymers have high chemical activity and belong to the low-temperature constructional materials [29]. The following two polymers have the benzene rings in their composition. They absorb the laser power and redistribute it over the benzene ring links increasing the decomposition temperature of the polymer (up to ~ 350º C). Polymers with an aromatic main chain (polycarbonate, epoxy resins) belong to the second generation of high-temperature constructional materials with low chemical activity.

Preliminary thermodynamic calculations of combustion reactions make possible to choose several polycrystalline materials in the large group of CHO-composition, which possess the following properties: high dispersibility, relative chemical stability under standard conditions, non-hydroscopic property and non-toxicity. In the experiments [27], the following polycrystalline were used as propellants: metaldehyde C_2H_4O, carbamoyl hydrazine CH_5N_3O, oxybenzoic acid $C_7H_6O_3$, and dihydroxybenzene $C_6H_6O_2$. All the four substances are colorless crystals with moderate fusion temperature, and are used in pharmaceutical and food industries.

To define the efficient factor K, the comparative coefficients N of the delayed burning of the CHO-materials products of combustion in oxygen of the air are calculated. This procedure is performed with the use of the results of the conducted experiments and calculated detonation heat and heat of delayed burning of detonation products of polymers under investigation.

Figure 5 demonstrates the experimental results for C_m as a function of κ ~ [(1 + 2.5(Q_{det}/Q^* +

$NQ_{db}/Q^*)]^{1/2}$ for polymeric propellants (Diagram 1) over the range $1.75 \le \kappa \le 3.12$ under atmospheric conditions without regard to the presence of oxygen in the polymer composition. Diagram 2 corresponds to the dependence of C_m upon κ for polycrystalline propellants, the values of which for polyoxymethylene ($N = 1$), metaldehyde and carbamoyl hydrazine ($N > 1$) are proportional over the range $3.08 \le \kappa \le 5.96$. Values of C_m vs κ for dihydroxybenzene and oxybenzoic acid ($N < 1$) have a large spread and do not correspond to the dependence C_m on K.

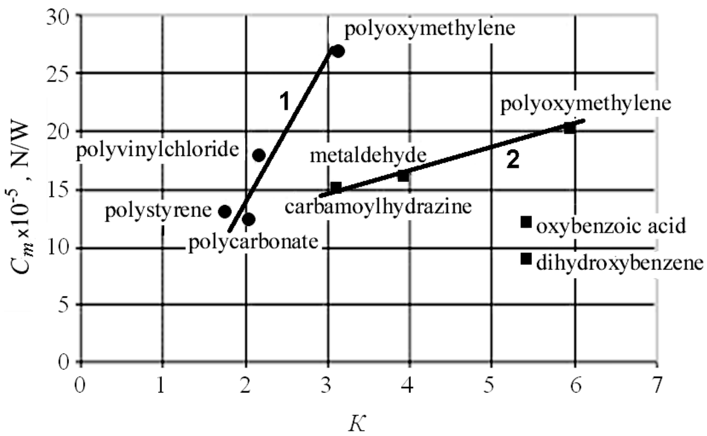


Figure 5. C_m vs κ for polymeric (1) and polycrystalline (2) CHO-type propellants.

The experiments showed that the delayed burning of detonation products of the evaporated CHO-materials under laser detonation in oxygen of the air is similar for all of the materials. And this reaction is the oxidation of liberated atomic carbon and gaseous hydrogen with formation of carbon dioxide and water molecules. At that, the delayed burning takes place sequentially to the detonation reaction and is limited by the bounded content of oxygen in the atmosphere air.

Analysis of the experimental data on laser propulsion with the polymeric materials used in the form of a plane target shows that the maximal $C_m = 27 \times 10^{-5}$ N/W relates to the oxygen-containing linear polymer polyoxymethylene with high detonation component in the momentum coupling coefficient (see Table 4). The polymer has a pronounced region of the CO_2 radiation absorption by the C-O-C stretching vibrations.

Table 4. Results of calculation of delayed burning coefficients *N*, κ and experimental data on C_m for polymeric propellants

Polimer	Q_{det}, kJ/kg	Q_{db}, kJ/kg	m_{av} $\times 10^{-6}$, kg	E_{av}, J	Q_{det}/Q^*	Q_{db}/Q^*	κ	N	$C_{m\,max}$ $\times 10^{-5}$, N/W
Polycarbonate**	661	29115	2.83	66.56	0.03	1.24	2.04	2.23	12.5
Polystyrene	0	40954	1.25	62.48	0	0.82	1.75	3.37	13
Polyvinylchloride	0	17857	4.11	50.64	0	1.45	2.15	1.90	18
Polyoxymethylene	2692	14615	12.33	61.01	0.54	2.95	3.12	1	27

** - calculation of $\Delta H^o_{f\,298}$ for polycarbonate is made with the use of a Franklin method [30], av means an averaged value.

Polycarbonate as another oxygen-containing polymer with a linear aromatic chain showed low $C_m = 12.5 \times 10^{-5}$ N/W because of weak absorption of IR- radiation by the deformation oscillations of C-H link. Such linear polymers as polystyrene and polyvinylchloride do not demonstrate high C_m also because of lack of detonation component in the combustion process, and main contribution into the momentum coupling coefficient is made by the processes of laser breakdown of the polymer vapors and delayed burning of their components in oxygen of the air. In addition, the deformation oscillations of C-H and C-Cl links result in insignificant absorption of the CO_2 laser power.

As is seen also from Table 5, the detonation component of the liberated energy is maximal for polyoxymethylene at the interaction of the laser radiation with the polycrystalline materials. It exceeds 10 times the detonation components of metaldehyde and carbamoylhydrazine and exceeds hundreds times the detonation components of oxybenzoic acid and dihydroxybenzene.

Table 5. Comparative coefficients of delayed burning *N*, efficiency factor *K*, and experimental data on C_m for polycrystalline materials

Substance	Q_{det}, kJ/kg	Q_{db}, kJ/kg	N	Q^*, kJ/kg	Q_{det}/Q^*	κ	κ_{av}	$C_m\times10^{-5}$, N/W
Polyoxymethylene	2692	14614	1	1200	2.24	6.09	5.96	20
- » -	- » -	- » -	- » -	1314	2.05	5.82		20.5
Metaldehyde	698.9	24391	2.04	3925	0.18	4.09	3.93	15
- » -	- » -	- » -	- » -	4733	0.15	3.77		16
Carbamoyl hydrazine	397.6	10685	3.86	2750	0.14	3.33	3.08	15.5
- » -	- » -	- » -	- » -	3971	0.10	2.82		15
Oxybenzoic acid	32.7	20937	0.71	974	0.03	6.26	5.42	10
- » -	- » -	- » -	- » -	1867	0.02	4.58		14
Dihydroxybenzene	277.6	24475	0.74	1425	0.19	5.77	5.42	7.2
- » -	- » -	- » -	- » -	1860	0.15	5.07		10.6

From the performed experiments, it may be deduced the delayed burning of detonation products of propellants under investigation does not significantly influence the momentum coupling coefficient. In the case of the use of polycrystallines, the losses that is spaying at the instant of laser breakdown of the materials out of the plasma region are possible. As a result, the noticeable part of the polycrystalline and free carbon (detonation product) do not burn down completely.

The results of the experimental investigations of the CHO-materials show the efficient factor K can be applied to select the polymer propellants for laser propulsion. For example, moderate κ is achieved for polymers with high Q^* (5000 -50000 kJ/kg), which agree well with the sufficiently high experimental values of C_m. In the case of the polycrystalline materials the values of Q^* are significantly lower (1200-4000 kJ/kg noticeable increase κ (two times for polyoxymethylene). But C_m for polycrystalline propellants is nevertheless 2.5 times less than the forecasting increase. At that, for both polymeric and polycrystalline propellants their own proportional dependence of C_m upon κ (for $N \geq 1$) is observed.

In spite of the simplicity of the proposed model of laser radiation interaction with the CHO -materials, it shows that the problem of choice of the optimal CHO-propellants lays in the correct definition of the specific ablation energy Q^*. Determination of this parameter calls for making special experiments.

3. EFFICIENCY OF LASER PROPULSION ENGINES UNDER SPACE CONDITIONS

Now let us consider more general problems related to the LPE efficiency. As is known that the efficiency η of a jet engine using chemical fuel is determined as the relation of engine jet stream power P_{pc} to heat power P_Q, liberated in a combustion chamber of the engine:

$$\eta = \frac{P_{pc}}{P_Q} = \frac{g^2}{2} \cdot \frac{I_{sp}^2}{Q} = \frac{g}{2} \cdot \frac{I_{sp}}{C_T} , \quad (18)$$

where Q is the specific heat of the fuel combustion; $C_T = P_Q/T$ is the thrust coefficient.

The efficiency of the laser propulsion engine η_{LPE} may be determined for space conditions as the ratio of kinetic power of exhaust stream to laser radiation power [4]:

$$\eta_{LPE} = \frac{\dot{m}v^2}{2P} = \frac{T \cdot I_{sp} \cdot g}{2P} . \quad (19)$$

Taking into account that the momentum coupling coefficient C_m is the most frequently used parameter that characterizes the efficiency of conversion of laser radiation into thrust, the expression is as follows:

$$\eta_{LPE} = \frac{C_m I_{sp} \cdot g}{2} . \quad (20)$$

From the general definition, the efficiency of LPE may be characterized by the following processes:

- efficiency of conversion of laser power into heat (internal) energy of the propellant α, that can vary noticeably depending on the laser radiation characteristics and chemical composition of the propellant;
- efficiency of conversion of the heat energy into kinetic energy of exhaust jet β, which depends on the nozzle parameters and environment (pressure, temperature, etc.).

In this case we have the following definition of the efficiency of LPE [4]:

$$\eta_{LPE} = \frac{1}{2} C_m < v > = \alpha \beta \Phi . \quad (21)$$

Here $<v>$ is the average flow velocity in the jet, Φ is the ratio of square of the average velocity to mean square of the jet flow velocity:

$$\Phi = <v>^2/<v^2>. \quad (22)$$

Values $\alpha = 0{,}4$ and $\Phi \sim 1$ are close to the reality. As for β, its value usually varies over the range of 0,5-1. Then without great error we have:

$$\eta_{LPE} = \alpha\beta . \quad (23)$$

Taking into account the accepted assumptions, we have: $0.2 \leq \eta_{LPE} \leq 0.4$.

The efficiencies of various types of jet engines, calculated by the general formula, are given in Table 6.

The introduced efficiency of laser propulsion is a rough one if the processes of additional energy release have to be taken into account, for example, due to interaction of laser pulse CHO-materials. Therefore, we propose to determine the efficiency of LPE as the relation of power of exhaust gas stream to total power of heat sources in a combustion chamber by the analogy with the jet engines, i.e.:

$$\eta_{LPE} = \frac{\beta(\alpha P + \dot{m}Q)}{P + \dot{m}Q} . \quad (24)$$

Table 6.Thrust characteristics of chemical and laser propulsion engines

Propulsion engine	C_T , W/N	I_{sp}, s	η
IUS (International Upper Stage) – solid-propellant rocket engine	1.45×10^3	200	0.69
Centaur Upper Stage	2.04×10^3	300	0.74
Rocket engine with hydrogen-oxygen fuel	4.03×10^3	500	0.62
Rocket engine with fluid hydrazine	3.85×10^3	200	0.26
LPE with C_m = 50×10^{-5} N/W	2×10^3	160	0.4
LPE with C_m = 10×10^{-5} N/W	10^4	800	0.4

After simple transformations we have:

$$\eta_{LPE} = \frac{\beta(\alpha E + mQ)}{E + mQ} \text{ or } \eta_{LPE} = \frac{\beta(\alpha + mQ/E)}{1 + mQ/E} . \tag{25}$$

For comparison η_{LPE} with Delrin and polymethyl methacrylate, calculated for space conditions and studied in various experiments, are listed in Table 7.

Table 7. Efficiency η_{LPE} for the investigated CHO-materials (λ = 10.6mm, α = 0.4; β = 0.9).

Substance	Δm, ×10^{-6}, kg	E, J	mQ_{det}, J	mQ_{det}/E	η_{LPE} space conditions
Delrin® [14]	15.0	250.0	40.5	0.16	0.44
Delrin® [27]	12.33	61.0	33.19	0.54	0.55
Delrin® [27]	8.0	57.1	21.60	0.38	0.51
PMMA [17]	37.80	90.0	18.51	0.21	0.45
PMMA [17]	40.30	130.0	19.73	0.15	0.43

As is seen from the table, the CHO-propellant for laser propulsion engine operating in space conditions has to have the detonation energy higher than the polyoxymethylene detonation energy (Q_{det} = 2690 kJ/kg) to achieve high efficiency of the propulsion production (more than 55%). This will require specific study on the propellant composition, and it should be mentioned that the propellant has to be safe in use.

4. CONCLUSIONS

Up-to-date investigations on the laser propulsion show the noticeable progress in the development of laser propulsion techniques. By now, a number of mechanisms of the laser propulsion production are studied.

For the laser air-breathing propulsion, the dependence of efficiency of thrust production on the nozzle design parameters and laser pulse characteristics is the principal character. In this case, the thrust characteristics can be described in approximation of the local explosion theory sufficiently well. It is theoretically and experimentally shown that maximal C_m is limited by a value of $C_m = 5 \times 10^{-4}$ N/W that is determined by the peculiarities of the propulsion production with the impulse (explosive) bulk input of the laser pulse energy into gas propellants.

For the laser ablation propulsion, the most promising way of getting extra high C_m of several hundreds dynes/W is provided by using multiplayer targets. Confined laser ablation in the multiplayer targets combines such advantages as availability of maximal values of C_m at medium radiation power, operation in a vacuum, and also advantages of the combined ablation and detonation wave, namely, long duration of the recoil momentum, which exceeds the laser pulse duration 2-3 times. But, this technique of laser propulsion has a disadvantage of principle, namely, the specific impulse of exhaust jet makes up only several tens of seconds, which results in high consumption of propellant.

The laser detonation propulsion with CHO-polymers as propellants is the most promising technique of getting high efficient thrust. This type of laser propulsion provide higher values of momentum coupling coefficient owing to the additional chemical energy released in evaporated materials under laser pulse. This energy is liberated as a result of exothermic reactions of oxidation of the polymer vapors by oxygen in high-temperature plasma. Moreover, the use of the CHO-chemical polymers allows getting general efficiency of the laser propulsion higher than 40%.

Development of LPE with the maximal specific characteristics of propulsion assumes the engine efficiency at a level of 70-80%. These characteristics of LPE should allow saving significantly the laser power required for realization of flights of vehicles with LPE and saving the propellant consumption in the flight. Choices of the propellant composition and engine design are the principle problems in the development of prospective high-power laser propulsion systems.

And finally, A. Prokhorov quite cautiously wrote in his paper written in 1976 [12] about the prospects of the laser propulsion application: "The possibilities of application of aircrafts with LPE will depend, first of all, on the laser propulsion efficiency with the use of high-power lasers". We hope that the experience accumulated by now in the study of laser propulsion of various types enable developing of advanced laser propulsion engines and creating the high-power laser propulsion systems in the nearest future.

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