SELECTING GAS DYNAMICS CHANNEL PARAMETERS FOR ELECTRICAL DISCHARGE FAST FLOWRATE LASERS

A. I. Ivanchenko, V. V. Krashennikov,
A. G. Ponomarenko, and A. A. Shepelenko

UDC 621.373.8:533.6.01

Using lasers with powers over 1 kW has become common in industry. Compactness and high efficiency are important requirements to take into account when designing lasers. Fast flowrate CO_2 lasers with independent discharges have wide application in industry, whose radiators are quite large because of the low density of the working gas. When considering the compactness and efficiency of these lasers, one must not ignore questions concerning the optimal correspondence of the characteristics for the pumping device (PD) of the gas and for the closed gas dynamics channel (CGDC) of the laser radiator. The PD must ensure circulation of the gas at a rate determined by the assigned power of the laser for the smallest size of the radiator and for small noise and vibration levels. The configuration and dimensions of the CGDC, the means of arranging its elements, the characteristics of the gas flow in the pumping zone, and the power of the active medium all determine the gas resistance of the closed channel and the loss of power at pump, which is 5 to 25% of the total power required in lasers with powers up to 10 kW [1, 2]. One may find information on the application of various PD in fast flowrate lasers [3-9], but there is no data on the characteristics of closed CGDC, which are determined by the PD parameters. There is currently an absence of literature dealing with the selection of optimal parameters for the electrical discharge, the gas flow, and the configuration of the flow section of the CGDC. We will take a comprehensive approach to determine the parameters for the gas flow in the pumping zone and the gas characteristics for the contour elements and the pumping device.

Possible values of gas velocity and pressure in electrical discharge systems are often determined according to data on the limiting energy characteristics of the discharge. As an example, we will consider possible values of the parameters for a flow in a laser with an unsectioned electrode system [10], whose limiting energy characteristics were determined as functions of the gas flow velocity in [11], using the additional generation data given in Fig. 1, where ε is the specific energy contribution, P and I are the generation power and the discharge flow (lines 1 and 2), which are given in relation to a meter of the length of the electrodes. The data in Fig. 1 corresponds to an electrode gap of 7.5 cm and a gas mixture of CO_2:N_2:He = 3.3:10:6.7 hPa. It is evident that the flow velocity at the input to the pumping zone must not be less than a certain threshold velocity for obtaining stable heating of the discharge. Using the limiting characteristics, a range for stable discharge states can be determined in pressure-velocity coordinates.

Values for the threshold velocity v^* as a function of gas pressure p for electrode gaps of 5.1 and 2.8 cm (lines 1 and 2, where the dashed sections indicate extrapolation). The range of values for the gas velocity and pressure that lies to the left of curves 1 and 2 corresponds to stable modes. Limiting values of the gas pressure (which are not shown in the plots) do not exceed 50-60 hPa. Because of the low pressures and velocities of the gas flow, the flow states in the laser channels correspond to low Reynolds numbers (Re = 10^2-10^4). Figures 1 and 2 give all the information that is necessary for determining the characteristics for the contour and the pumping device. It should be emphasized, however, that the discharge is inhomogeneous over the height of the channel, the energy contribution is nonuniform, and the local values of the gas velocity and temperature greatly differ from the average values. This leads to additional losses in the total pressure — an irreversible transformation of the kinetic energy of the flow into pressure — during gas flow in the channels of the pumping zone and of the diffusor. Using Figs. 1 and 2, one can determine the gas

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 3-8, November-December, 1986. Original article submitted October 22, 1985.

0021-8944/86/2706-0791$12.50

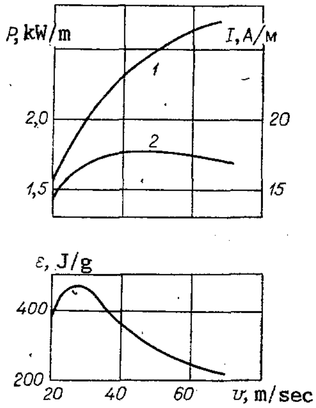

Fig. 1

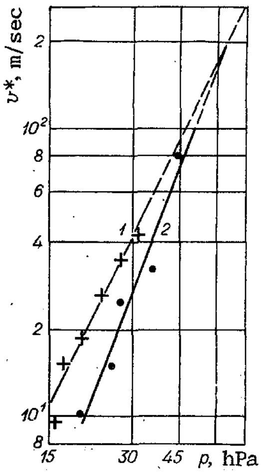

Fig. 2

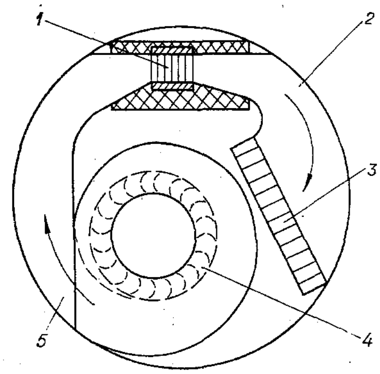

Fig. 3

pressure and velocity at the input to the pumping zone, but they will be limited by the characteristics of the CGDC and PD.

We will consider the characteristics of the CGDC and PD as functions of the velocity of the gas flow and of the specific energy contribution. A schematic of the CGDC is illustrated in Fig. 3, where 1 is the pumping zone, 2 is the diffusor, 3 is the thermal exchange, 4 is the PD, and 5 is the channel connecting the PD with the pumping zone. The characteristics of the CGDC can be put in the form $\Delta p = \zeta\rho v^2/2$, where Δp is the pressure loss in the CGDC, ζ is the resistance coefficient of the CGDC, and ρ and v are the gas density and velocity at the input to the pumping zone. The resistance coefficient of the CDC is a sum of the resistance coefficients of its individual sections related to the velocity v. The basic sources of pressure loss in the CGDC are the following: the pumping zone, the thermal exchanger, the diffusor, the elements for equalizing the velocity profile before the pumping zone, and the organization of the closed cycle (the rotation, etc.). To determine the pressure loss in the CGDC, we will ignore a change in the temperature at the channels connecting the pumping zone with the PD and with the thermal exchanger and the thermal exchanger with the PD.

We will estimate the pressure losses in the pumping zone that are due to a change in the temperature of the gas, where it is assumed that all of the electrical energy contributed to the gas flow is transformed into thermal energy. Losses due to friction will be ignored, which is permissible if the length of the channel in the direction of the flow is comparable with the size of the electrode gap. In the channel with the thermal feed, the pressure losses are determined by the relation [12]

$$\Delta p_1 \approx (T_1/T - 1)\rho v^2/2,$$

where T and T_1 are the temperatures of the gas at the input and output of the pumping zone, respectively. Assuming that $T_1 \approx T + \varepsilon/c_p$ (c_p is the specific heat of the working gas), the expression for the resistance coefficient of the channel during pumping has the form $\zeta_1 \approx \varepsilon/(c_p T)$.

For estimating the pressure loss at the thermal exchanger, we will use the relation between the power adsorbed by the thermal exchanger and the losses due to friction [13]

$$\Delta p_2 \approx \rho_2 v_2^2 (T_1 - T_0)/t.$$

Here, T_0 is the temperature of the gas at the output of the thermal exchanger; ρ_2 and v_2 are the gas density and velocity in the channels of the thermal exchanger; t is the average thermal pressure between the gas and the walls of the thermal exchanger. It is evident that for a decrease in Δp_2, one must increase the area of the cross section of the thermal exchanger. However, the pressure losses due to expansion of the flow in the diffusor connecting the pumping zone and the thermal exchanger increase. Hence, losses at the thermal exchanger must be considered in their relation to losses in the diffusor. Pressure losses due to expansion of the gas flow in the diffusor can be estimated with the following equation [14]

$$\Delta p_3 = \varphi (1 - 1/n)^2 \rho_1 v_1^2/2,$$

where φ is a coefficient (when $\varphi = 1$, it is called the Board equation); n is the degree of expansion in the diffusor (the ratio of the wide to narrow areas of the channel); ρ_1 and v_1 are the gas density and velocity in the narrow section of the diffusor. For small Reynolds numbers ($Re < 2 \cdot 10^5$), one can find no data for making accurate calculations of φ [14]. To decrease the size of the laser, one should use short diffusors with large-angle openings (greater than 40°) or staggered diffusors. For these diffusors, as was shown in [14], calculations of the pressure losses with the Board equation agree well with experimental results. Therefore, we will assume that $\varphi = 1$. Under real conditions, the quantity φ can be much greater than unity due to the nonuniformity of the velocity at the input to the diffusor [15]. Pressure losses in a diffusor with resistance at the output can be considered a sum of the loss due to isolated diffusors and the resistance [15], and the expression for the resistance coefficient for the diffusor-thermal-exchanger system has the form

$$\zeta_2' \approx (1 - 1/n)^2 + \zeta_T/(n^2k^2).$$

Here, k is the coefficient for the cross section of the thermal exchanger (the ratio of the area of the cross section of the thermal exchanger to the area of the output cross section of the diffusor); ζ_T is the resistance coefficient of the thermal exchanger. According to [13, 16], $\zeta_T \approx A\mu c_p(T_1 - T_0)/Nu\lambda t)$, where A is a coefficient that accounts for the form of the channel and for the cooling efficiency; μ is the coefficient of dynamic viscosity; Nu is the Nusselt criterion; and λ is the coefficient of thermal conductivity of the working gas.

Values of ζ_2' as a function of n are given in Fig. 4 that were calculated with the mixture $CO_2:N_2 = 1:3$, $T_1 - T_0 = 200$°K, $\zeta_T = 13.6$, $k = 0.75$. The minimum value of $\zeta_2'(\approx 1)$ is obtained when $n = \zeta_T/k^2 + 1$, but it is evident that already for n = 8-10, $\zeta_2' \approx 1$. It then follows that an increase in the ratio of the area of the thermal exchanger to the area of the channel cross section in the pumping zone is more than 8-10 and does not allow a substantial gain in reducing the pressure loss due to cooling of the working gas. Hence, the minimum value of the total resistance coefficient of the diffusor with the thermal exchanger can be taken as equal to unity. Recalculating the parameters of the gas flow at the input to the pumping zone, we find that $\zeta_2 \approx 1 + \varepsilon/(c_pT)$.

We will estimate the pressure losses in the CGDC due to the organization of the closed cycle and to the need to obtain a uniform velocity field before the pumping zone. A compression channel section and grids are typically used for equalizing the velocity profile. According to [15], the resistance coefficient of the grid must be equal to 2-3, and, then, in combination with the diffusor beyond the PD, the resistance coefficient of the section with the equalizing elements leading to the cross section of the channel at the output of the PD will be approximately 0.7. Using the data in [16] on the optimal configuration of the channel, the resistance coefficient for the compression sections can have a minimum value of 0.1 and rotational values of 0.1-0.2. With sufficiently large transmission cross sections for the rotational sections (the input area to the PD must in this case be equal to or greater than the area of the channel cross section in the pumping zone), the total minimum resistance coefficient for the flow-formation sections is related to the parameters of the flow before the pumping zone, $\zeta_3 \approx 1$.

Summing the resistance coefficients for individual elements of the contour, we find that $\zeta_{min} \approx 2(1 + \varepsilon(c_pT))$.

For a high flow rate laser, the maximum value of the specific energy contribution is limited by the temperature of the gas at about 600°K ($T_1 \approx 2T$), where one already observes significant thermal isolation of the lower laser levels, $\varepsilon_{max} \approx c_pT$. Hence, $\zeta_{min} \approx 4$.

In the closed cycle, the working state of the PD corresponds to $p - p_0 = \zeta\rho v^2/2$, where p and p_0 are the gas pressures at the output and input to the DP, respectively. The operation of the PD is characterized by the value of the pressure coefficient $\pi_K = p/p_0$. The values of π_K as a function of the gas flow parameters in the pumping zone can be written as

$$\pi_K = 1 + \frac{3v^2}{2a^2}\zeta$$

(a is the thermal velocity of the molecules).

Knowing the value of π_K, one can estimate the gas temperature at the output of the PD from the conditions of adiabatic gas compression

$$T = T_0\pi_K^{(c_p - c_V)/c_p}$$

(T_0 is the temperature at the input to the PD).

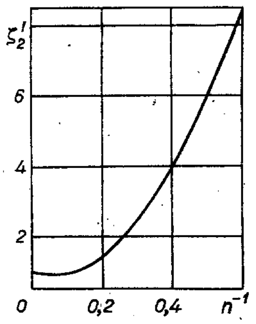

Fig. 4

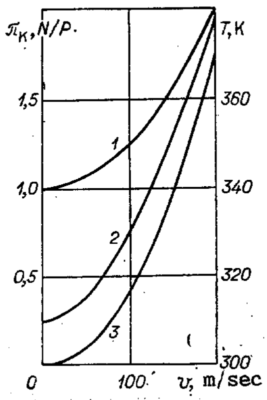

Fig. 5

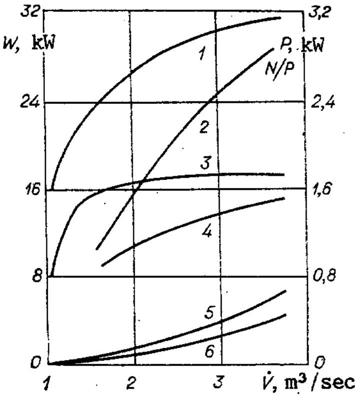

Fig. 6

We will consider the power loss in the pump as a function of the generation power and of the parameters ε and v. The generation power is related to the flow parameters by the relation [17] $P = \eta\varepsilon G$, where η is the electro-optical efficiency, typical values of which are 0.15-0.25 for CO_2 lasers; G is the mass flow rate of the gas through the pumping zone. The power at the pump can be expressed by the relation $N = \zeta G v^2/2$. Then, the expression for the power at the pump, which is related to the generation power, has the form

$$\frac{N}{P} = \zeta \frac{v^2}{2\eta\varepsilon},$$

and we have the following for the unavoidable power expenditures at the pump in a contour with minimal losses

$$\frac{N_{\min}}{P} \approx \left(1 + \frac{\varepsilon}{c_p T_0}\right) \frac{v^2}{\eta\varepsilon} \approx \frac{2v^2}{\eta c_p T}.$$

The specific power of the pump N/P characterizes the efficiency of using the PD and the quality of the CGDC.

Lines 1-3 in Fig. 5 represent the dependences of π_K, T, and N/P on the velocity v for fixed value of η and ε, ζ = 4 and $c_p/c_V = 1.4$. It is evident that when v < 70 m/sec, the quantity π_K does not exceed 1.15, and the temperature in the PD increases to a level no greater than 10°K. The PD is conditionally classified in terms of π_K, where the smaller the value of π_K, the fewer are the requirements imposed on the flow section, while the range $\pi_K < 1.15$ pertains to the ventilators [18]. For flow velocities greater than 70 m/sec, π_K, T, and N/P increase greatly. Increasing T requires one to add another thermal exchange after the PD, which in turn increases π_K and N/P. Hence, the use of electrical discharge devices for pumping where v > 70 m/sec imposes more requirements on the profile-forming flow section of the PD and the CGDC. As one can see, there are significant limitations in selecting v that are related to the technological design of the PD and the CGDC, whose operation determines the reliability of the laser and the efficiency of using pump technology.

In real systems, the size of the laser is decreased only at the expense of increasing the total pressure loss, and, therefore, one employs pump technology with the largest value of π_K, expending additional power in the pumping of the gas.

Measurements are given in Fig. 6 for the dependences on the flow rate of the gas through the pumping zone; lines 2, 4 — the generation power P; 1, 3 — the power contributed to the discharge W; 5, 6 — the ratio of the power expended on the pumping of the gas to the generation power N/P. The power due to pumping of the gas is determined by direct measurements of the power at the electric drive of the ventilator, from which preliminary losses due to friction and in the mechanical sections of the ventilator and losses in the drive are calculated. The results are given for two lasers consisting of identical CGDC elements in addition to pumping channel cross sections (the cross section of the pumping channel of one of the lasers is 1.7 times greater than that of the other). Lines 1, 2, and 6 pertain to a laser with a pumping channel cross section that is increased by using two identical electrode systems [10] that are located in parallel flows of gas and are connected by the same resonator. The generation power and the power expenditure due to the pumping of the gas are best determined with two excitation systems rather than one. The gain in generation power is related to the higher energy contribution that is possible in a laser with two electrode systems. However, the relation for the cross-sectional dimensions of the CGDC elements is less than optimal, n = 3, where n = 6 for a single-electrode system. Therefore, the gain in N/P is related only to an increase in the generation power, it can be much greater if the relation between the contour elements is more optimal. The maximum power expenditures due to pumping are 4% of the power contributed to the discharge.

Hence, we have analyzed the effect that the geometric characteristics of the fundamental elements of the gas dynamic contour of a laser and the parameters of the gas flow in the pumping zone have on the characteristics of the pump system in a high flow rate laser with a closed-cycle gas flow. Ranges on the states of a laser with an independent electric discharge have been given, which allows one to select the parameters of the gas flow before the pumping zone and the dimensions of the electrode configuration for laser design. Expressions were obtained for determining the unavoidable power loss due to pumping. Minimal power expenditures due to pumping for every kilowatt of generation can be obtained for maximal energy contributions, which are limited by the heating of the gas to a limiting temperature (~600°K), where the pumping efficiency and the efficiency of the laser decrease. At these energy contributions $\varepsilon/c_pT \approx 1$ and $\zeta \approx 4$.

It was shown that when designing a contour with optimal dimensions (with respect to minimal power expenditure due to pumping), a PD such as a ventilator can be used to achieve a flow rate of up to 70 m/sec; where one attains a power of ~3 kW for every meter along the active length of the laser. A further increase in the laser power an be achieved by increasing the cross section of the active medium through the use of two or more discharges in parallel gas flows.

LITERATURE CITED

1. G. A. Abil'siitov, A. V. Artamonov, et al., "Steady-state, high-technology CO_2 laser with a power of 10 kW," Kvantovaya Elektron., 7, No. 11 (1980).
2. V. V. Elov, V. A. Kuklin, et al., "Research on an active medium for a high flow rate laser with a closed cycle," Kvantovaya Elektron., 9, No. 8 (1982).
3. R. I. Soloukhin, E. I. Vyazovich, et al., "Use of a diametric ventilator in a flow laser with a closed gas circulation system," Inzh.-Fiz. Zh., No. 1 (1979).
4. N. A. Generalov, V. I. Zimakov, et al., "Using an aviation compressor in lasers with closed cycles," Dokl. Akad. Nauk SSSR, 221, No. 2 (1975).
5. P. I. Belomestnov, A. I. Ivanchenko, et al., "Electrical discharge continuous-action CO_2 laser with a closed cycle," in: Gas Lasers [in Russian], Nauka, Novosibirsk (1977).
6. A. I. Ivanchenko, V. V. Krashennikov, et al., "A CO_2 laser of average power," in: All-Union Conference on the Application of Lasers in Machine Construction Technology [in Russian], Nauka, Moscow (1982).
7. G. A. Abil'siitov, V. S. Golybev, and F. V. Lebedev, "Problems in designing production process lasers with powers of 1-10 kW," Izv. Akad. Nauk SSSR, Ser. Fiz., 47, No. 8 (1983).
8. H. J. J. Sequin, J. Dow, and V. A. Seguin, "Simple and economic compressors for large-volume gas transport laser systems," Rev. Sci. Instrum., 54, No. 10 (1983).
9. G. A. Abil'siitov, E. P. Velikhov, et al., Powerful Gas Discharge CO_2 Lasers and Their Application in Technology [in Russian], Nauka, Moscow (1984).
10. A. I. Ivanchenko, V. V. Krasheninnikov, and A. A. Shepelenko, "A high flow rate CO_2 laser with unsectioned electrodes," in: All-Union Conference on the Application of Lasers in the Production Process of Machine Construction [in Russian], Nauka, Moscow (1982).
11. A. I. Ivanchenko, A. G. Ponomarenko, and A. A. Shepelenko, "Limiting characteristic of the independent discharge of a CO_2 laser with a closed cycle," in: All-Union Conference on the Application of Lasers in Machine Construction Technology [in Russian], Nauka, Moscow (1982).
12. N. N. Abramovich, Applied Gas Dynamics [in Russian], Nauka, Moscow (1969).
13. É. R. Ekkert and R. M. Dreik, Theory of Thermal and Mass Exchange [in Russian], Gosenergoizdat, Moscow—Leningrad (1961).
14. M. E. Deich and A. E. Zaryankin, Gas Dynamics of Diffusors and of Exhaust Nozzles for Turbine Machines [in Russian], Energiya, Moscow (1970).
15. I. E. Idel'chik, "Impact losses in a flow with a nonuniform velocity distribution. Equalizing effect of resistance beyond a diffusor," Proc. N. Ye. Zhukovskii Central Institute of Aerohydrodynamics (TsAGI), No. 662 (1948).
16. I. E. Idel'chik, Handbook on Hydraulic Resistance [in Russian], State Scientific and Technical and Publishing House of Power-Engineering Literature (GEI), Moscow (1960).

17. G. A. Abil'siitov, E. P. Velikhov, et al., "Schematics and methods of pumping for powerful production process CO_2 lasers (collection)," Kvantovaya Elektron., 8, No. 12 (1981).
18. V. M. Cherkasskii, T. M. Romanova, and R. A. Kaul', Pumps, Ventilators, and Compressor [in Russian], Gosenergoizdat, Moscow–Leningrad (1962).

INFLUENCE OF RADIATION INTENSITY AND PARAMETERS OF THE MEDIUM ON THE DEPTH OF COOLING AND THE CHANGE IN THE INDEX OF REFRACTION DURING THE ADSORPTION OF RADIATION WITH λ = 9.2-10.6 μm BY WATER VAPOR

A. A. Sorokin and A. M. Starik

UDC 539.196+546.214

The possibility of cooling molecular gases by laser radiation has recently attracted the interest of many investigators [1-5]. A decrease in the temperature of the medium in the channel of an actuating laser beam leads to the formation of a thermal converging lens and, as a consequence, to self-focusing of the laser beam [5]. One of the gases absorbing the radiation of a CO_2 laser with a wavelength λ = 9.2-10.6 μm most intensely is water vapor. It was assumed earlier that the adsorption of the energy of radiation with λ = 9.2-10.6 μm by water vapor leads to heating of the medium in the beam channel and the formation of a diverging thermal lens [2]. The possibility of cooling of a medium containing water vapor upon the action of a radiation pulse with λ = 9.2-10.6 μm and a duration less than the time of V–T relaxation of deformation vibrations of H_2O molecules was demonstrated only recently [6]. Here the cooling mechanism is analogous to the mechanism of cooling of a gas of diatomic molecules upon resonance absorption of radiation in the P branch of a vibrational–rotational transition discussed earlier [7].

In the present paper, on the basis of analytic relations obtained, we analyze the influence of the intensity of the actuating radiation and the parameters of the medium containing water vapor on the depth of cooling and the change in the index of refraction during the absorption of radiation of a CO_2 laser in vibrational–rotational transitions of H_2O molecules.

It is well known that the radiation of a CO_2 laser with a wavelength λ = 9.2-10.6 μm is absorbed, depending on its frequency, by water vapor both in the purely rotational band of the vibrational ground state and in vibrational–rotational transitions of the deformation mode ($0 \to \nu_2$) [8]. In the present work we consider only those radiation frequencies of a CO_2 laser which are absorbed in the $0 \to \nu_2$ band of the H_2O molecule for a medium consisting of the gases H_2O, O_2, and N_2. We recall that cooling of the gas in this case is possible only under the action of radiation with a frequency in resonance with the frequency of a line of a vibrational–rotational transition for which the rotational energies of the upper ($E_{j''}$) and lower ($E_{j'}$) levels satisfy the inequality $E_{j''} < E_{j'}$ [6].

As usual, we assume that the width of the line of the radiation acting on the medium is considerably less than the width of the spectral absorption line. We shall carry out the analysis for $\tau_I \gg \max(\tau_{R-T}, \tau_{V-V})$, where τ_I, τ_{R-T}, and τ_{V-V} are the characteristic times of induced transitions and of rotational–translational (R–T) and intramodal vibrational–vibrational (V–V) exchanges, respectively. In this case the distribution of H_2O molecules over the rotational levels can be taken as a Boltzmann distribution with a translational temperature T, while the change in the state of the medium over times $t < \tau_T$, τ_c (τ_T and τ_c are the heat-conduction and convection times) under the action of radiation with λ = 9.2-10.6 μm can be described by the system of equations [6]

$$\frac{d\varepsilon_1}{dt} = \frac{p}{kT}[L_{31}W_{31} - L_{12}W_{12}]; \quad (1)$$

$$\frac{d\varepsilon_2}{dt} = \frac{p}{kT}\left[\frac{k_\nu I\mu^2}{\rho^2 N_A^2 \gamma_1 h\nu_I} + 2L_{12}W_{12} + 2L_{32}W_{32} - L_{24}W_{24}\gamma_2 - (\varepsilon_2 - \varepsilon_{20})W_{20}\right]; \quad (2)$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 9-16, November-December, 1986. Original article submitted November 4, 1985.

 0021-8944/86/2706-0796$12.50