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The Concepts of High Power CW Gasdynamic Lasers for Industrial Application

A brief discussion of different concepts of the existing CW gasdynamic CO₂ lasers is made from the viewpoint of the possibility of adopting them to technological operations requiring radiation beams of high average power. Three basic variants are distinguished:

1. CO₂ - N₂ GDL with thermal excitation and selective pumping in a stream mixing process; open cycle.
2. CO₂ - N₂ GDL, thermally excited by combustion and nonselectively pumped during supersonic expansion; open cycle.
3. CO₂ - CO - N₂ GDL with thermal excitation by combustion and selective pumping; open cycle.

The fourth concept - of a closed electric-discharge convection laser (EDCL) on CO₂ - N₂ - He mixtures is put forward as a possible proposition opposing the previous ones.

I. Introduction. Preliminary selection of gasdynamic laser types

I.1. Industrial applications of lasers

I.1.1. Attempts to apply lasers as new tools for some specific technological operations (e.g. melting, cutting, drilling or welding) are being observed lately. The conditions to be met by a laser facility in order to perform such operations are, obviously, not so rigorous as those demanded by the lasers designed for laboratory or communication purposes. The said conditions are restricted, roughly, to some demands concerning the external laser characteristics as e.g. the average emitted power, overall efficiency (with account taken of power consumed by supplying and auxiliary devices) and beam configuration. As to the beam shape, possible deviations can be corrected with the use of an appropriate optical system guiding the beam from the transmitting laser mirror to the worked material.

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On the other hand, usual demands posed generally on the production devices can be essential also for this application of lasers. These are:

- a) low costs of manufacturing and operation (inexpensive commercial gases used as a working medium),
- b) reliability and durability (stability of operation with regard to misadjustment of the optical resonator, insensibility to environmental conditions),
- c) possibly small dimensions and defectlessness,
- d) unification of elements of radiation producing devices.

I.1.2. The above presented requirements, both the specific requirements for lasers and the general ones, restrict the variety of the laser types which may be employed.

According to the review paper [1], carbon dioxide and neodymium (Nd : glass or Nd : YAG) lasers fit best these purposes. Many modifications of the both types have been thoroughly investigated. Now they have attained a sufficient reliability to be employed for production purposes. As to the CO₂ lasers, difficulties arise in processing smooth metal surfaces because of high reflectivity to the long-wave infrared radiation (for instance, the coefficient of reflectivity of aluminium surface amounts to 98 percent at carbon dioxide laser wavelength $\lambda = 10.6 \mu\text{m}$). Therefore, the preliminary stage of operation is performed with a low efficiency, till the processed surface is slightly melted. Better results can be obtained in processing surfaces with preliminarily lowered reflectivity. Processing with a radiation beam aided by an oxygen jet has been also employed; however, the use of oxygen may be disadvantageous for other reasons.

Gasdynamic lasers and high energy pulse lasers are powerful enough for processing metals without auxiliary means. Moreover, carbon dioxide lasers are useful for melting, cutting and drilling ceramic and organic materials. Their large advantage from the viewpoint of manufacturing applications is that gases they exploit and materials they are made of are inexpensive and available without difficulty, which results in low operational costs. At last, for gasdynamic lasers there is a possibility of cheap and efficient preparation of the working medium by combustion.

I.1.3. Main technical data of various types of lasers suitable for industrial purposes have been presented in Table I, after [1, 2]. Lasers are especially advantageous for operations requiring certain specific conditions to be fulfilled; these are for instance:

- necessity of restricting the area of heat dissipation within the material,
- necessity of avoiding the accumulation of electric charges on the processed element (material),
- necessity of processing materials in the atmosphere of a definite gas (predetermined mixture composition and pressure) or in vacuum or for processing materials difficult to work on by conventional methods.

The last two items show the possibility, at least theoretical, for lasers to compete with electron or sun furnaces. It is evident directly from Table 1 that if necessity of concentrating very large continuous power densities on a surface of processed material is postulated as a main requirement, gasdynamic lasers are presently the most promising proposition.

However their possible mobility is considerably limited because of large dimensions and weights of auxiliary devices.

It must be again pointed out that in lasers designed for manufacturing purposes typically optical features of the radiation beam (coherence, single mode or multimode work) are of minor importance; the beam shape (dimensions and transverse intensity distribution) is the only important optical parameter. For instance in a 60 kW laser device (see Table 1) the divergence of multimode radiation beam amounted to $\theta \approx 22''$.

Table 1

Type of a laser	Wavelength [μm]	Regime of operation	Typical power value [W]	Pulse repetition rate	Pulse duration	Remarks
Ruby	0.6943	long pulse	10 ⁵ (peak)	1 pulse	0.2 - 5 ms	small dimensions, compact, economical at low powers
Nd : glass	1.06	long pulse	10 ⁵ (peak)	1 pulse	0.5 - 10 ms	
Nd : YAG	1.06	continuous work	200	—	—	
CO ₂	10.6	continuous work	100 - 1000	—	—	very large, high power
CO ₂	10.6	repeated pulses	100	100 s ⁻¹	10 - 100 μs	big, economical
CO ₂	10.6	continuous work-gas-dynamic	60 000 maximum obtained power of CW lasers	—	—	economical, supply and auxiliary devices of large dimensions
Argon	0.4880 and 0.5145	repeated pulses	20 (peak)	200 s ⁻¹	50 μs	too low power for majority of applications

Some specific features of gasdynamic lasers are worth mentioning, allowing to attain the output radiation powers exceeding the above quoted value. As a gasdynamic laser a gas laser is meant in which population inversion in the working medium is obtained because of different rates of changing populations of specified energy levels of molecules during rapid expansion of the working gas. The flow direction is perpendicular to the optical resonator axis; it allows for an additional increase of the output power, approximately in proportion to the flow velocity of the optically active medium. This increase results from rapid removal of excess energy from the lasing region by a strong forced convection. In conventional lasers the slow rate of removing excess energy (by diffusion to walls) is the main limitation of the maximum output power available. The removal of waste energy by a strong convection is characteristic generally for all high-mass flow lasers (see e.g. [3]). On the basis of published data one can expect of typical gasdynamic lasers a rise of output power density per unit volume of the resonator cavity to be 10³ through 10⁶ times higher than with conventional lasers.

1.2. Gasdynamic lasers—discussion of published data

The available data on some gasdynamic lasers constructed till now have been listed below in a chronological sequence:

1. The CO_2 – N_2 or N_2O – N_2 gasdynamic laser constructed at United Aircraft Res. Lab., East Hartford, Connecticut by Bronfin, Boedeker and Cheyer [4]. The population inversion was accomplished by injecting CO_2 or N_2O into supersonic flow of N_2 –He mixture, with nitrogen thermally excited before expansion with the use of an arc heater heating it to the temperature of $T_0 = 1000 - 3000^\circ\text{K}$ at atmospheric pressure. The mixture of working gases was next passed through an optical cavity, embraced by mirrors with surfaces parallel to the stream direction, at a velocity of about 10^3 m/s (Mach number $Ma = 3.4$).

For the CO_2 – N_2 mixture output powers higher than 60 W have been obtained from the cavity of 6 cm^3 volume. The substitution of N_2O for carbon dioxide resulted in stimulated emission of radiation at wavelength $\lambda = 10.8\text{ }\mu\text{m}$ ($00^01 \rightarrow 1000$) transition in N_2O ; no quantitative data for power have been reported. Typical mole fractions were: N_2 – 0.4, CO_2 – 0.2 and He – 0.4. Static pressure within the resonator cavity was equal to 50 Tr. High mirror losses have been observed, causing absorption of the main part of generated radiation. For instance at $T = 2600^\circ\text{K}$ the measured values of radiation powers were: the transmitted power $P_t = 0.3\text{ W}$ (7 W), the absorbed power $P_a = 45\text{ W}$ (17 W). It is also worthy to mention that the efficiency of mixing CO_2 with N_2 performed by injecting the first component into the stream of the other one was high.

2. CO_2 – N_2 gasdynamic lasers of 6 kW and 60 kW output power built at Avco-Everett Res. Lab. under supervision of Gerry [5] (for the data see also popularized articles [2, 6, 7]). Their working principle was based upon supersonic expansion of a thermally excited mixture in a nozzle system, with population inversion in CO_2 obtained as a result of difference in relaxation rates of CO_2 (00^01) and CO_2 (10^00) vibrational levels.

The necessary increase of the lower laser level relaxation rate was achieved by adding water vapour. Exemplary data for the 6 kW laser were: gas mixture delivery 6.5 kg per second, $Ma = 4.0$, mole fractions: CO_2 – 0.08, CO – 0.002, N_2 – 0.91, H_2O – 0.008, energy conversion efficiency of the order of 1 percent. Similar device of larger delivery (14 kg per second) produced about 30 kW of output power at the single mode regime (with unstable optical resonator – see [5]) and about 60 kW at the multimode regime. The optical path length was equal to 0.3 m and gas velocity to about 1300 m/s. Both the devices were combustion driven with carbon oxide or cyanogen C_2N_2 (in the smaller device) serving as a fuel.

3. CO_2 gasdynamic laser built at Lebedev Institute of Physics, Moscow by Konyukhov, Prokhorov and others [8]. Here the population inversion was accomplished by expanding the mixture of CO_2 , N_2 and water vapour, laser action arising in an optical cavity furnished with flat-concave ($R = 2\text{ m}$) gold coated (98% reflectivity) mirror set, with the resonator length equal to 0.34 m and the transmitting mirror having a 1 mm diameter central hole. Experiments have shown indispensability of water vapour as a catalyst for the laser action to arise. The amount of H_2O needed was equal to 1–3% (with N_2 : CO_2 ratio equal to 43 : 7). The output power was of the order of several watts.

4. $\text{CO}_2 - \text{N}_2$ gasdynamic laser constructed at the Institute of Fluid-Flow Machines, Polish Academy of Sciences, Gdańsk [9, 10, 11, 12], working principle identical with that of [4]. Gas delivery: $\text{CO}_2 - 20 \text{ Nm}^3$ per hour, $\text{N}_2 - 48 \text{ Nm}^3/\text{h}$, $\text{Ar} - 6 \text{ Nm}^3/\text{h}$, static pressure in the lasing region equal to 13 Tr, Mach number $Ma=4.3$, optical path length 0.15 m.

During experiments with the use of gold coated steel mirrors for the optical cavity (mirror diameter 9 mm, a concave mirror of 1.7 m radius of curvature, a flat transmitting mirror with a central hole of 2 mm diameter) the output power of 35 W was measured. The stagnation temperature of nitrogen was equal to $T=1700^\circ\text{K}$.

5. There is some evidence [2, 6] of other gasdynamic lasers existing as well as of theoretical investigations on them being done, but little or no data are available. Also laser action in shock wave driven expansion channels has been reported (see [13, 14, 15]). Such devices are suitable for modelling the processes occurring in CW gasdynamic lasers.

6. A number of essential data concerning gasdynamic chemical lasers have been presented by Cool [16].

Chemically driven gasdynamic lasers or those of discontinuous flow do not introduce any new elements into the concept of CW gasdynamic laser as presented above (points 1 through 4). Novel ideas have been brought by the article of:

7. McKenzie [17] of NASA Ames Research Center who has analysed the possibility of generating coherent radiation in a high velocity flow of $\text{CO} - \text{N}_2 - \text{Ar}$ mixture. Population inversion is obtained in this laser in carbon monoxide, nitrogen playing the same part as in $\text{CO}_2 - \text{N}_2$ gasdynamic laser. Another possibility suggested in the McKenzie paper is to substitute nitrogen by carbon oxide in the $\text{CO}_2 - \text{N}_2$ laser. A reduction in the pumping efficiency (due to the fact that the disparities between $\text{CO}_2(00^0n)$ and $\text{CO}(v=n)$ vibrational energy levels are more marked than between $\text{CO}_2(00^0n)$ and $\text{N}_2(v=n)$) can be compensated here by increasing the mass flow of the working gas mixture which is easily producable by combustion of conventional fuels.

The idea of high mass flow of working medium across the optical cavity gave also way to the concept of high power CW lasers essentially different from the gasdynamic lasers. It is the concept of electric-discharge convection laser (EDCL).

Fluid-flow techniques are in these lasers used only for moving a gas in the channel; they can also play auxiliary part in establishing most appropriate discharge geometry. This is the situation entirely different than with gasdynamic lasers where fluid-flow techniques play essential part in creating population inversion of energy levels. For EDCL the electric discharge, existing in principle within an optical cavity, is the only means of obtaining such inversion of excited molecules population. Two distinct attainments have been reported in the field of CW EDCL. These are:

8. A closed cycle fluid-flow laser built by Tiffany, Targ and Foster [18] of Sylvania Electronic System with $\text{CO}_2 - \text{N}_2 - \text{H}$ mixture as a working fluid. The characteristic data of this laser are: optical path length equal to 1 m, flow velocity of the order of 30 m/s, partial pressures of components $p_{\text{CO}_2}=2 \text{ Tr}$, $p_{\text{He}}=6 \text{ Tr}$ and $p_{\text{N}_2}=12 \text{ Tr}$, and output power of the order of 1 kW. During experiments carried out at constant volume flow of helium, an increase in the volume flow of nitrogen or in the electric discharge power resulted in increasing the laser output power. Similar was the influence of the gas delivery being

enlarged up to the value of 120 m^3 per minute. The output power was insensitive to the changes in gas delivery when beyond the above value.

9. A closed cycle flow laser designed by Hill of Air Force Weapons Lab., Albuquerque [19, 20]; with $\text{CO}_2 - \text{N}_2 - \text{He}$ mixture employed as a working medium, its delivery equal to 14 m^3 per second. Characteristic feature of the laser was that the electric discharge was positioned along the flow channel.

1.3. Basic types of the CO_2 gasdynamic lasers – introductory remarks

1.3.1. Three basic types of the gasdynamic lasers can be distinguished; each of them will be discussed in this work. These are:

Type I. $\text{CO}_2 - \text{N}_2$ gasdynamic laser with thermal excitation of nitrogen and selective pumping of carbon dioxide by collisions with excited N_2 molecules. The energy transfer takes places when streams of cold CO_2 are being mixed with streams of nitrogen with vibrational temperature „frozen” at high level. Two of the facilities mentioned in the foregoing chapter (items 1 and 4) were of this type [2, 4, 9]. The main advantage of the type is a large pumping efficiency. Only open cycle is possible; commercial gases of not very high degree of purity can be utilized.

Type II. $\text{CO}_2 - \text{N}_2$ gasdynamic laser with thermal excitation of a mixture, followed by supersonic expansion in a nozzle. Population inversion occurs as a result of different relaxation rates of vibrational levels 00^0_1 and 10^0_0 of carbon dioxide molecules. The facilities described above under 2 and 3 were of this type. The main advantage is an easy way of producing large quantities of working medium by combustion of fuels (e.g. carbon or hydrocarbons) in oxygen or air. The gasdynamic laser facility of 60 kW power which has been largest to date was of this type. Only open cycle is possible.

Type III. $\text{CO}_2 - \text{N}_2 - \text{CO}$ gasdynamic laser thermally excited by combustion, constituting an extrapolation of the concept formulated in [17] (see item 7). It combines advantages of the GDL of type I (selective pumping) and of type II (production of large amounts of working medium by combustion).

For the sake of comparison another type of a flow laser will be described, namely:

Type IV. Electric-discharge convection laser on $\text{CO}_2 - \text{N}_2 - \text{He}$ mixture (see Hill [19, 20], and Tiffany and others [18]). Its main advantages are: closed cycle, compactness of a construction.

II. Thermally excited $\text{CO}_2 - \text{N}_2$ fluid mixing gasdynamic laser

II.1. Schematic arrangement of the facility

Schematic arrangement of the facility is shown in Fig. II.1. Nitrogen and carbon dioxide are continuously delivered to separate plenum chambers to be subsequently expanded through two nozzle systems into a common channel; here conflow streams of the

both gases are mixed under constant pressure. Nitrogen fed at pressure p_{0p} from an external cylinder through a regenerative heat exchanger and an arc heater reaches the high temperature T_{0p} in the plenum chamber. After rapid expansion its pressure drops to the value p_m , translational temperature to the value T_{2p} , the velocity becomes equal to v_{2p} . At the same time a "freezing" of nitrogen vibrational temperature occurs because of the low relaxation rate of vibrationally excited $N_2(v)$ molecules, the vibrational temperature being conserved at a level approximately equal to the stagnation temperature T_{0p} . Correspondingly high is the population of excited molecules of nitrogen. Small amounts of argon (a few percent of nitrogen flow) can be added, if necessary, for protection of the arc heater cathode.

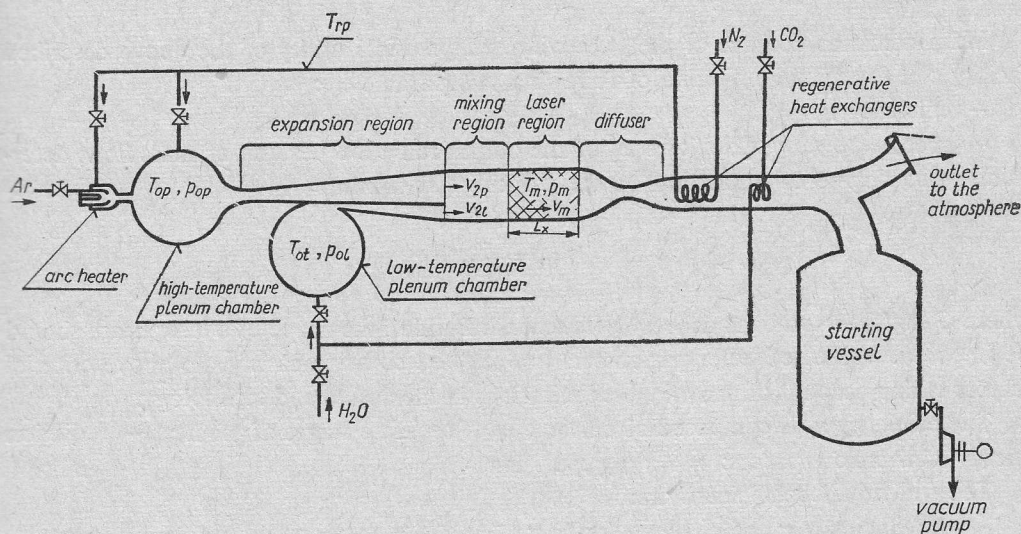


Fig. II.1. Schematic diagram of a thermally excited and selectively pumped $CO_2 - N_2$ gasdynamic laser

Carbon dioxide is delivered to the other plenum chamber through a heat exchanger. Its stagnation parameters are: temperature T_{0t} and pressure p_{0t} . After expansion the temperature drops to the value p_m and velocity raises to the value v_{2t} . The $CO_2 - N_2$ mixture formed in the course of constant pressure mixing is characterized by the following set of parameters: temperature T_m , pressure p_m and velocity v_m .

Initial parameters of CO_2 are chosen in such a way that immediately ahead of nozzle outlets the vibrational excitation of CO_2 molecules is negligible. Besides, the efficiency of the laser action is increased by adding small amount (about 5 - 15 Tr) of water vapour. This keeps the lower laser level $CO_2(10^0)$ population low whereas the upper laser level $CO_2(00^01)$ is populated by way of selective energy transfer between vibrationally excited $N_2(v)$ molecules and unexcited $CO_2(v)$ molecules. Population inversion obtained in this way between v_3 and v_1 groups of carbon dioxide vibrational energy levels enables the occurrence of a laser action between them, at wavelength $\lambda = 10.6 \mu m$.

The flow ahead to the lasing region is exposed to compression up to the pressure of $p_d = 1$ ata, making possible to let the used up gas mixture out to the atmosphere after passing it through regenerative heat exchangers. Variable diffuser throat as well as a

starting vessel are required for starting the facility, because the optimum value p_m of the pressure within the lasing region is much lower than 1 atm.

Thermal efficiency of the facility $\eta_c = P_c/P_a$ — where P_c and P_a are, respectively, output radiation power and the arc heater power — is being increased by applying the regenerative heat exchangers for preliminary heating of nitrogen and carbon dioxide. Further heat recovery — from exhaust gases and from water cooled walls of the arc heater and plenum chamber (in external receivers) — may be considered for larger devices.

II.2. Preliminary selection of parameter values

Main demands decisive of the effectivity and practical utility of the above described facility call for maximum value of following two parameters:

- efficiency η_c ,
- specific power g_c [kW/kg·s⁻¹] of the output radiation per unit of mass flow, determining the degree of utilization of the working gas mixture

$$g_c = \frac{P_c}{G},$$

where G [kg/s] — total gas delivery pers second. Besides, the shape of a laser beam should be imposed. Values of other parameters are selected so as to satisfy the above criterial factors taking account of unavoidable limitations in the design and technology.

The efficiency η_c is composed of efficiencies of separate stages of the heat — radiation energy conversion proces: $\eta_c = \eta_p \eta_w \eta_v \eta_k$.

The individual coefficients are:

- the efficiency η_p of nitrogen heating:

$$\eta_p = P_w/P_a,$$

where

$$P_w = 4.187 G_p (C_p|_{0}^{T_{0p}} T_{0p} - C_p|_{0}^{300} \cdot 300) \text{ [kW]}$$

is the net power consummed by nitrogen during heating to temperature T_{0p} ; η_p is determined with account taken of the losses for wall cooling as well as for a gain from heat recovery during the preliminary regenerative nitrogen heating ($C_p|_0^T$ [kcal/kg] — the average nitrogen specific heat).

— the efficiency η_w of nitrogen excitation P_w , determining the fraction of power P_{v0} which can be recovered from excited nitrogen — through coupling with CO₂ — in form of laser radiation emitted by carbon dioxide molecules:

$$\eta_w = P_{v0}/P_w,$$

where

$$P_{v0} = G_p \frac{h\nu}{m_{N_2}} \cdot \frac{\sum_{n=0}^{\infty} n N_{N_2(v=n)}}{\sum_{n=0}^{\infty} N_{N_2(v=n)}} \cong 400 \cdot \frac{\exp\left(-\frac{\theta_1}{T_{0p}}\right)}{1 - \exp\left(-\frac{\theta_1}{T_{0p}}\right)} G_p \text{ [kW]}$$

describes virtual (i.e. maximum available) radiation power in the high-temperature plenum chamber and is expressed in terms of radiation quanta $h\nu = 1.875 \cdot 10^{-20}$ J (for $\lambda = 10.6 \mu\text{m}$); N_2 molecule is regarded as a harmonic oscillator ($\theta_1 = 3350^\circ\text{K}$), $m_{\text{N}_2} = 0.4685 \cdot 10^{-25}$ kg

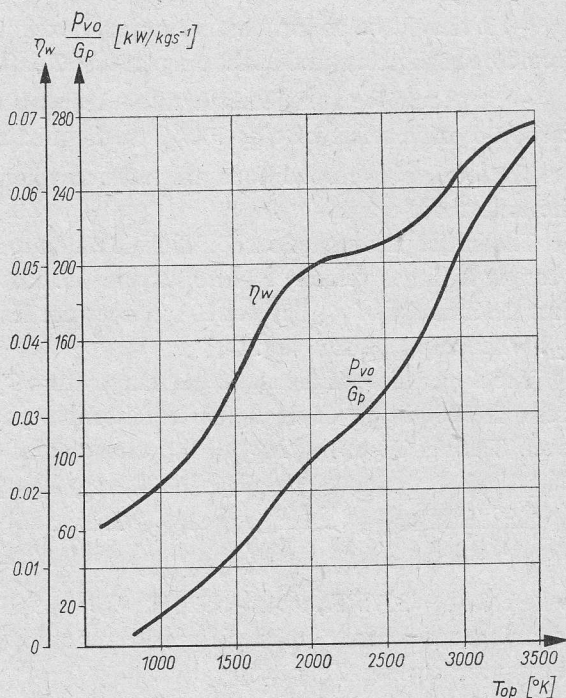


Fig. II.2. Approximate dependence of η_w and P_{v0}/G_p — parameters on the temperature in the high-temperature plenum chamber

is the mass of N_2 molecule, G_p [kg/s] denotes mass flow of nitrogen. The dependence of the ratio P_{v0}/G_p and efficiency η_w on stagnation temperature T_{0p} is shown on Fig. II.2.

— the efficiency η_v of the virtual power transport from the plenum to the lasing region:

$$\eta_v = P_v / P_{v0},$$

where P_v [kW] denotes the virtual power at the entrance to the laser region; account is taken in η_v of power losses caused by vibrational relaxation of N_2 (v) and CO_2 (v_3) excited molecules during expansion and mixing.

— quantum efficiency of the laser action:

$$\eta_k = P_c / P_v$$

describing the efficiency of changing P_v into P_c within the lasing region.

The following criterions of a selection of the parameter values may be established on the basis of the above presented considerations:

The temperature T_{0p} in the high-temperature plenum ought to be kept possibly high, because the higher the temperature the larger values of g_c and η_w . However, an optimum has been estimated (cf. Fig. II.2) at $(T_{0p})_{\text{opt}} \cong 2500^\circ\text{K}$ because of excessive heat losses to wall cooling at temperatures above this level which would, consequently, lead to decrease of the efficiency η_p .

Although the temperature T_{rp} should, obviously, be as close to T_{0p} as possible, it is kept for technological reasons at the level: $(T_{rp})_{\max} \cong 1300^\circ\text{K}$.

The initial value of the temperature of a lasing gas (T_{0l}) results from the following conditions:

- it should be as low that vibrational excitation of carbon dioxide after expansion would be negligible and that the temperature T_m after mixing be possibly low,
- it should be sufficiently high to keep up to 10 percent admixture of H_2O (with carbon dioxide referred to as 100%) in the mixture in gaseous state.

The both above conditions are satisfied when T_{0l} equals $(400\text{--}500)^\circ\text{K}$ depending on the amount of water.

The initial pressure of carbon dioxide ought to be as high as possible in order to obtain possibly high gas velocity v_{2l} after expansion. However, physical properties of CO_2 cause that the increase of p_{0l} beyond 10 ata does not lead to any significant increase of velocity v_{2l} . Whence $(p_{0l})_{\text{opt}} \cong 10$ ata.

The upper limit of the static gas temperature T_m in the lasing region can be determined from the condition of negligible equilibrium population of the CO_2 (100) vibrational level. Taking $(N_{\text{CO}_2(100)}/N_{\text{CO}_2}) = 1\%$ one obtains from the formula:

$$\frac{N_{\text{CO}_2(100)}}{N_{\text{CO}_2}} = \exp\left(-\frac{\theta_{1000}}{T_m}\right) \left[1 - \exp\left(-\frac{\theta_{1000}}{T}\right)\right] \left[1 - \exp\left(-\frac{\theta_{0001}}{T}\right)\right] \left[1 - \exp\left(-\frac{\theta_{0100}}{T}\right)\right]^2$$

(where $\theta_{0001} = 3375^\circ\text{K}$, $\theta_{1000} = 1920^\circ\text{K}$, $\theta_{0100} = 960^\circ\text{K}$) the value $(T_m)_{\max} \cong 300^\circ\text{K}$. A more advantageous course of relaxation processes at low T_m – leading to higher η_k – is another reason for closing T_m possibly low.

The dependence of T_m on the temperatures after expansion, T_{2p} and T_{2l} , of pumping (N_2) and lasing ($\text{CO}_2 + \text{H}_2\text{O}$) gases is as follows:

$$T_m = \frac{G_p C_p^{(p)} T_{2p} + (G_l + G_d) C_p^{(l)} T_{2l}}{G_p C_p^{(p)} + (G_l + G_d) C_p^{(l)}},$$

where G_l [kg/s] – carbon dioxide mass flow, G_d [kg/s] – water mass flow, $C_p^{(l)}$ [kcal/kg] – specific heat C_p of $\text{CO}_2 + \text{H}_2\text{O}$ mixture, $C_p^{(p)}$ [kcal/kg] – specific heat C_p of nitrogen.

Low content of CO_2 in the mixture leads to predominant influence of T_{2p} on T_m . On the other hand there is $T_m < T_{2p}$ because of $T_{0l} \ll T_{0p}$. Hence from the above one obtains $T_{2p} \cong 350^\circ\text{K}$, whereas the ratio $T_{0p}/T_{2p} \cong 7.1$ leads to the pressure ratio:

$$p_m/p_{0p} = (T_{2p}/T_{0p})^{\frac{\kappa_p}{\kappa_p - 1}} \cong 10^{-3}.$$

Nitrogen velocity after expansion is equal to:

$$v_{2p} \cong \sqrt{\frac{2\kappa_p}{\kappa_p - 1} R_p (T_{0p} - T_{2p})} \cong 2150 \text{ m/s},$$

with the assumption of isentropic expansion and the following values of parameters $\kappa_p = 1.40$, $R_p = 297 \text{ [m}^2\text{s}^{-2}\text{deg}^{-1}\text{]}$.

The following premises ought to be considered when selecting the value of pressure p_m :

– p_m possibly high so as to have, for a required G , a possibly small channel. Besides, with higher p_m the compression of gas in the diffuser is facilitated and the channel leaks are reduced.

– p_m sufficiently low to assure that vibrational relaxation times for $N_2(v)$ and $CO_2(v_3)$ are longer than the time needed for CO_2-N_2 mixing process. On that condition a high value of efficiency η_v can be reached.

– p_m sufficiently low so as to have the value of p_{0p} (as given by the above formula) not too high to handle with.

A discussion of above contradicting requirements led to a preliminary selection of the following values: $p_m \cong 0.02$ ata, $p_{0p} \cong 20$ ata. Now the temperature T_{2l} and velocity v_{2l} can be estimated from the following formulas:

$$T_{2l} \cong T_{0l} (p_m/p_{0l})^{\frac{\kappa_l - 1}{\kappa_l}} \cong 100 \div 130^\circ \text{K},$$

$$\bar{U}_{2l} = \sqrt{\frac{2\kappa_l}{\kappa_l - 1} R_l (T_{0l} - T_{2l})} \cong 720 \div 800 \text{ m/s}.$$

Here isentropic expansion with over-cooling after reaching boundary $x=1$ was assumed for CO_2 and H_2O , κ_l was equal to 1.28, $R_l = 189 \text{ [m}^2\text{s}^{-2}\text{deg}^{-1}\text{]}$.

The gas mixture velocity v_m just ahead of the mixing region depends on v_{2l} , v_{2p} , G_p and

$$G_l : v_m = (G_p v_{2p} + G_l v_{2l}) / (G_p + G_l).$$

Taking above given average values and assuming that G_l/G_p equals to about 1/4 one obtains $v_m \cong 2000 \text{ m/s}$. This estimation can be used to establish preliminarily the length L_x of the lasing region in the direction of the working channel axis.

Preliminary values of the parameters:

$$\alpha_{lp} \cong G_l/G_p, \quad \alpha_{dl} = G_d/G_l$$

and required course of the laser action ought to be selected from the viewpoint of obtaining possibly high efficiency η_k . In the assumed approximation the maximum efficiency may equal to $(\eta_k)_{\max} = 1$. The following premises ought to be taken into account in this case:

1. Intensive pumping by vibrational energy transfer from excited nitrogen molecules $N_2(v)$ to unexcited carbon dioxide molecules $CO_2(0)$ is required to utilize all the excited N_2 molecules during their flow across the lasing region; for first excited states this reaction can be described by the equation:

$$\left(\frac{dN_{N_2(v=1)}}{dt} \right)_p = -k_{pl} N_{N_2(v=1)} N_{CO_2(0000)} + k_{lp} N_{N_2(v=0)} N_{CO_2(0001)}.$$

It is evident that the above postulate will be fulfilled if:

– the initial reaction time τ_{pl} for pumping is much shorter than time needed by a molecule to pass across the lasing region:

$$\tau_{pl} = 1/k_{pl} N_{CO_2(0000)} \ll \tau_v = L_x/v_m$$

where L_x [m] denotes the width of the lasing region,

— number density $N_{\text{CO}_2(00^0_1)}$ of excited carbon dioxide molecules is maintained at low level within the whole lasing region (which is important because coefficients k_{pl} and k_{lp} are nearly equal). Thus $N_{\text{CO}_2(00^0_1)} \ll N_{\text{CO}_2(00^0_0)}$.

2. The laser action (stimulated emission of radiation) has to be intensive enough to follow the pumping process:

$$\left(\frac{dN_{\text{CO}_2(00^0_1)}}{dt} \right)_l = (-B_{mn}f_m N_{\text{CO}_2(00^0_1)} + B_{nm}f_n N_{\text{CO}_2(10^0_0)}) N_f.$$

Here B_{mn} , B_{nm} , f_m , f_n and N_f are, respectively: the modified Einstein coefficients for stimulated emission and absorption, Maxwellian distribution functions over rotational degrees of freedom of CO_2 molecules excited to the lower and upper laser levels, and photon number density.

The following requirements ought to be fulfilled for the above postulate to be valid:

— the initial radiational depopulation time τ_l has to be smaller than τ_{pl} ; $\tau_l = 1/B_{mn}f_m N_f \ll \tau_{pl}$,

— because of $B_{mn}f_m \cong B_{nm}f_n$ the number density of molecules on the lower laser level should, within the entire lasing region, be kept much smaller than that of molecules on the upper laser level $N_{\text{CO}_2(00^0_1)}$; $N_{\text{CO}_2(10^0_0)} \ll N_{\text{CO}_2(00^0_1)}$.

3. Collisional relaxation of $\text{CO}_2(v_1)$ molecules ought to be intensive enough for inequality $N_{\text{CO}_2(10^0_0)} \ll N_{\text{CO}_2(00^0_1)}$ to be satisfied. As a first approximation, based on the fact of prevailing influence of water vapour on the relaxation process, there is (for $v_1=1$):

$$\left(\frac{dN_{\text{CO}_2(10^0_0)}}{dt} \right)_r \cong -k_{rd} N_{\text{CO}_2(10^0_0)} N_{\text{H}_2\text{O}},$$

whence the following requirement can be formulated:

$$\tau_{rn} = 1/k_{rd} N_{\text{H}_2\text{O}} \ll \tau_l,$$

where τ_{rn} denotes the relaxation time of the lower laser level $\text{CO}_2(10^0_0)$.

4. The influence of the collisional relaxation on depopulating of $\text{N}_2(v)$ and $\text{CO}_2(v_3)$ levels is to be much smaller than the influence of pumping or laser action. Water vapour is assumed to be the main agent causing relaxation; there is therefore, in the first approximation, (for the levels $\text{N}_2(v=1)$ and $\text{CO}_2(00^0_1)$):

$$\begin{aligned} \left(\frac{dN_{\text{N}_2(v=1)}}{dt} \right)_r &= -k_{md}^{(p)} N_{\text{N}_2(v=1)} N_{\text{H}_2\text{O}}, \\ \left(\frac{dN_{\text{CO}_2(00^0_1)}}{dt} \right)_r &= -k_{ml}^{(l)} N_{\text{CO}_2(00^0_1)} N_{\text{H}_2\text{O}}, \end{aligned}$$

whence

$$\tau_{rp} = 1/k_{md}^{(p)} N_{\text{H}_2\text{O}} \gg \tau_{pl},$$

$$\tau_{rm} = 1/k_{ml}^{(l)} N_{\text{H}_2\text{O}} \gg \tau_l.$$

All the inequalities concerning characteristic times combine into collective inequalities:

$$\tau_{rn} \ll \tau_l \ll \tau_{pl} \ll \tau_v \ll \tau_{rp}, \quad \tau_l \ll \tau_{rm}$$

which form a criterion for a proper selection of the parameter values.

It is easy to show that the ratios

$$\frac{\tau_{rm}}{\tau_{rn}} = \frac{k_{n0}}{k_{md}^{(l)}}; \quad \frac{\tau_{rp}}{\tau_{rn}} = \frac{k_{n0}}{k_{md}^{(p)}}$$

depend on temperature T_m only, whereas the ratio

$$\frac{\tau_{pl}}{\tau_{rn}} = \frac{k_{n0} N_{\text{H}_2\text{O}}}{k_{pl} N_{\text{CO}_2(0001)}} \cong \alpha_{dl} \frac{M_{\text{CO}_2} k_{n0}}{M_{\text{H}_2\text{O}} k_{pl}}$$

(where $M_{\text{H}_2\text{O}} = 18$ and $M_{\text{CO}_2} = 44$ are molecular weights) depends, in the first approximation, on T_m and α_{dl} exclusively. It is evident therefore that when the latter ratio can be changed by a proper alteration of the value α_{dl} , the former ones remain constant for constant T_m . Their dependence on temperature T_m is shown in Fig. II.3.

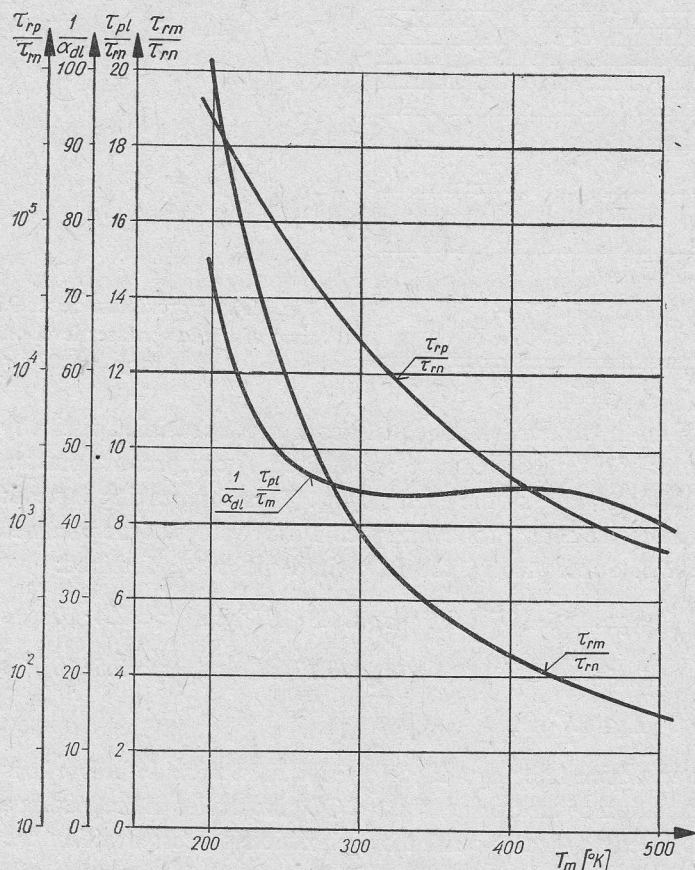


Fig. II.3. Approximate dependence of the ratio of relaxation and pumping times on temperature T_m

Fig. II.4 illustrates the dependence of relaxation time τ_{rn} on T_m , α_{ip} and α_{dl} (for the above assumed value of the pressure p_m). It is worth noticing that, within the frames of the approximation made, the relaxation time ratios are independent of α_{ip} , each time being proportional to α_{ip} .

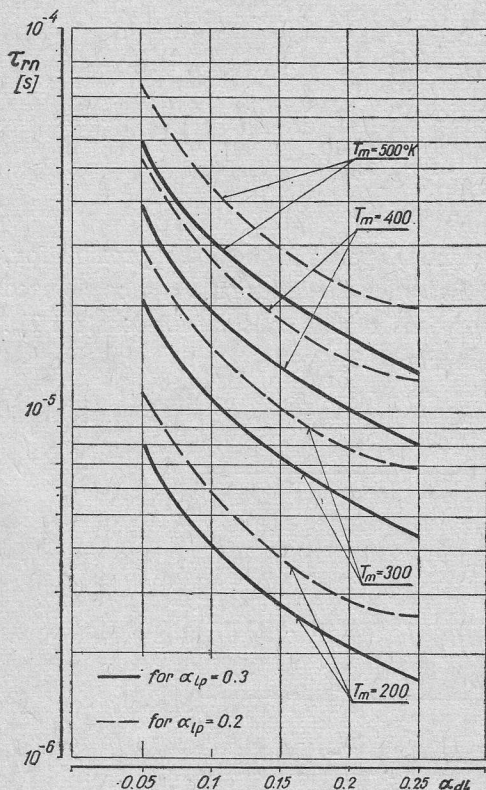


Fig. II.4. Approximate dependence of relaxation time of the lower laser level on the α_{ip} and T_m , for $p_m = 0.02$ atm

Now it is evident that the criterial inequalities cannot be satisfied distinctly i.e. differences of about one order of magnitude cannot be obtained. A compromise must be sought, aimed at reaching reasonable value of the efficiency η_k . Therefore, taking instead: $\tau_{rn} < \tau_l < \tau_{rm} \approx \tau_{pl} < \tau_v < \tau_{rp}$ one can select the following preliminary values of the parameters α_{ip} and α_{dl} : $\alpha_{ip} \approx 0.20$, $\alpha_{dl} \approx 0.18$. Subsequently, the following values are obtained:

$$\tau_{rn} \approx 0.85 \cdot 10^{-5} \text{ s}, \quad \tau_{pl} \approx 6.8 \cdot 10^{-5} \text{ s}, \quad \tau_l \approx 2.4 \cdot 10^{-5} \text{ s},$$

$$\tau_{rm} \approx 6.8 \cdot 10^{-5} \text{ s}, \quad \tau_{rp} \approx 0.17 \text{ s}, \quad \tau_v \approx 3.5 \cdot 10^{-4} \text{ s},$$

$$L_x \approx 0.7 \text{ m}.$$

Water vapour, which is being added to the carbon dioxide before it is expanded, accelerates the relaxation of the excited N_2 and CO_2 molecules in the mixing as well as lasing region. Vibrational energy losses caused by relaxation processes within the mixing region were not included into calculations; for that reason the proper value of L_x ought to be smaller than that given above.

Designing of the optimum nozzle systems is a typical task. Their construction — especially for the pumping gas must allow for a rapid expansion of the gas with friction losses in boundary layers and losses for separation of flow made as small as possible. Effective mixing of CO_2 and N_2 should take place ahead of the nozzle outlets. The attained efficiency η_v is the unique criterion of proper nozzle construction.

In order to establish approximate values of the main criterial parameters it was estimated that $\eta_v \cong 0.9$, $\eta_k \cong 0.7$. In addition, it was assumed that heat losses for cooling of walls are fully compensated by regenerative heating of nitrogen, so that $\eta_p \cong 1$.

On the basis of the above values it was calculated that:

$$\eta_c \cong 0.033, \quad g_c = \frac{Pv_0}{G_p} \cdot \frac{\eta_v \eta_k}{1 + \alpha_{ip}} \cong 73 \text{ kW/kg} \cdot \text{s}^{-1}.$$

III. Gasdynamic CO_2 — CO — N_2 fluid mixing laser excited by combustion

III.1. Schematic arrangement of the facility

Schematic diagram of the facility is shown in Fig. III.1. Use is made of combustion of graphite dust in oxygen enriched air as a source of thermal energy. Graphite dust, oxygen, air and small quantities of pure water are supplied continuously to the facility. A part of graphite dust is fed to an auxiliary combustion chamber KS2 to be burned

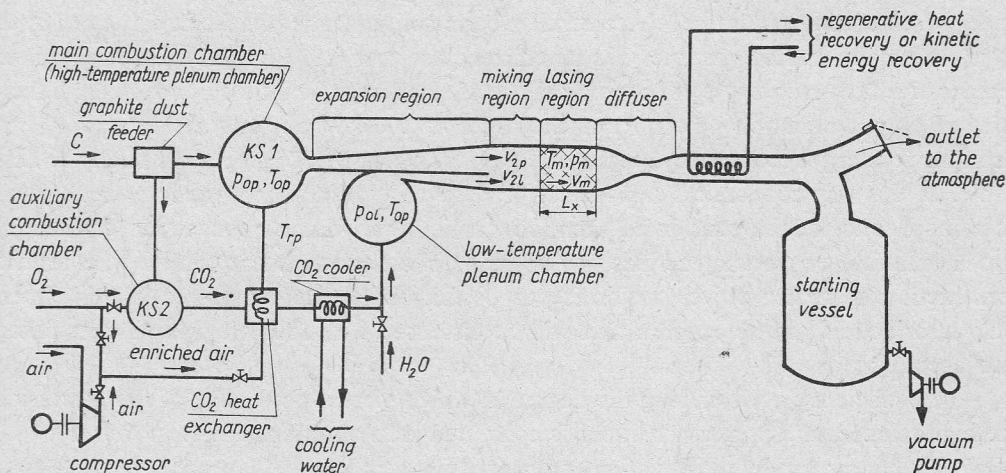


Fig. III.1. Schematic diagram of a selectively pumped CO_2 — CO — N_2 gasdynamic laser excited thermally by combustion

stoichiometrically in O_2 . The resulting carbon dioxide (together with small quantities of C and O_2) is led at pressure p_{01} , after cooling in a heat exchanger and cooler to a low temperature T_{01} , to a low-temperature plenum chamber. Here H_2O is added. Next, the CO_2 — H_2O mixture is expanded in a nozzle system to be mixed afterwards with a pumping gas in the mixing region. The rest of graphite dust is burned under pressure p_{0p} inside the main

combustion chamber KS1 in oxygen enriched air, preheated previously within the heat exchanger to temperature T_{rp} . Burning is conducted without sufficient oxygen, so that the combustion gases of temperature T_{op} contain mainly N_2 and CO , and only small quantities of CO_2 and O_2 . This mixture, after expanding to the mixing region, serves as the pumping medium. Next, after passing the lasing region, the gas is compressed in a diffuser up to a pressure of $p_d \cong 1$ ata. It is let out into the atmosphere after cooling in a regenerative heat exchanger. Auxiliary equipment to the facility consists of a compressor for compressing the air to the pressure above p_{op} , a graphite dust feeder, a starting vessel, a vacuum pump and a gear for the diffuser throat control. Proper combustion conditions are necessary to assure that the number density of solid particles in the working medium is small; the particle dimensions ought to be less than $0.1\lambda_c \cong 1 \mu m$ to prevent radiation scattering inside the lasing region.

The schematic arrangement of the facility has been designed in a way allowing to restrict the supply, besides air, to graphite dust and oxygen only. Another arrangement is possible namely where the facility is also supplied with CO_2 . In this way the auxiliary combustion chamber, the heat exchanger and the CO_2 cooler could be eliminated. Instead, the regenerative heating of CO_2 and air- O_2 mixture would be necessary. This requirement could be fulfilled by heat exchangers placed inside the outlet pipe of the diffuser (cf. Fig. IV.1).

III.2. Determination of criterial parameters

Parameters representing the criterions of efficiency and practical utility of the facility under consideration cannot be selected until a basic assignment of the facility is determined. Every thermally excited gas laser has its efficiency so low (see Fig. II.2) that a complete regenerative heat recovery is an economical necessity of large facilities. For very large facilities of output radiation power P_c of the order of 100 kW not only heat recovery but also kinetic energy recovery (by means of a gas turbine or MHD generator) might be desirable. In this way economical reasons can lead to a situation where the laser action will be a by-product of the considered thermodynamic cycle whereas conversion of thermal into mechanical or electric energies will be its main assignment. A question whether the construction of such a power station is purposeful will not be considered in this paper. Only laser action and its optimization will be discussed with following parameters taken into account:

- the efficiency η_l describing the degree in which virtual power P_{v_0} of the gas inside the high-temperature plenum chamber is converted into output radiation power P_c :
 $\eta_l = P_c / P_{v_0} = \eta_v \eta_k$; for definitions of η_v and η_k (see Chapter II),
- specific power per unit mass flow g_c [kW/kg $\cdot$ s $^{-1}$] (see Chapter II) characterizing the degree of utilization of the working gas,
- specific power g_g [kW/kg $\cdot$ s $^{-1}$] describing the radiation power output per unit mass flow of the graphite dust $g_g = P_c / G_g$, where G_g [kg/s] is the total dust delivery into combustion chambers KS1 and KS2.

The obvious demand that η_l , g_c and g_g be as large as possible may not always be feasible (for instance the increase of g_c can lead to a drop of g_g or η_l , etc.) and compromise solutions might be required.

The lay-out of the gasdynamic laser under discussion is similar to that presented in Chapter II with two alterations, namely:

– different pumping gas composition (N_2 –CO mixture with small quantities of CO_2 and O_2),

– different way of heating the pumping gas: by burning carbon.

For this reason optimum values of the laser parameters will differ but slightly from those obtained in Chapter II. The low-temperature plenum chamber is fed with carbon dioxide from a separate gas generator and not from an external vessels. It does not, however, influence any of the important laser parameters.

Physical similarity of CO and N_2 molecules justifies the assumption of similarity of the pumping of carbon dioxide by excited $N_2(v)$ or $CO(v)$ molecules. Scanty data [17, 21, 22] do not allow for detailed calculations; the results obtained ought to be understood as estimates not wholly justified. For rough calculations it was assumed that:

a) N_2 –CO mixture consists of molecules each of them capable of carrying the same quanta of vibrational energy; virtual power contained inside the high-temperature plenum chamber is given by the formula as given in Chapter II where G_p [kg/s] must be understood as a total delivery of N_2 and CO,

b) oxygen and carbon dioxide are understood as impurities accelerating vibrational relaxation of nitrogen and carbon monoxide, and decreasing in this way the efficiency η_v ,

c) collisional relaxation rates for collisions of the pumping gas molecules with molecules of additives are assumed to be equal to those for nitrogen,

d) pumping of the laser medium by vibrational energy transfer from the pumping gas is described by the following relations:

$$\left(\frac{dN_m^{(l)}}{dt}\right)_{\text{pump}} = k_{pl} N_m^{(p)} N_0^{(l)} - k_{lp} N_m^{(l)} N_0^{(p)},$$

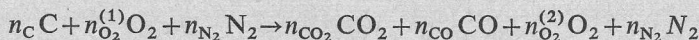
$$k_{pl} = \frac{N_{N_2} k_{pl}^{(N_2)} + N_{CO} k_{pl}^{(CO)}}{N_{N_2} + N_{CO}},$$

$$k_{lp} = \frac{N_{N_2} k_{lp}^{(N_2)} + N_{CO} k_{lp}^{(CO)}}{N_{N_2} + N_{CO}} \cong k_{pl},$$

where (cf. [21])

$$k_{pl}^{(CO)} \cong \frac{1}{4} k_{pl}^{(N_2)}, \quad k_{lp}^{(CO)} \cong \frac{1}{4} k_{lp}^{(N_2)}.$$

The combustion of pure carbon in a mixture of nitrogen and oxygen, in accordance with the reaction:



is described by the following relations:

$$p_{Op} = p_{CO_2} + p_{CO} + p_{N_2} + p_{O_2},$$

$$\frac{k_1 p_{CO_2}}{k_2 p_{CO}} = (p_{O_2})^C,$$

$$p_{0p} = (p_{\text{CO}_2} + p_{\text{CO}}) \left(1 + \frac{\alpha_{\text{C}}^{\text{O}_2}}{\alpha_{\text{N}_2}^{\text{O}_2}} \frac{M_{\text{C}}}{M_{\text{N}_2}} \right),$$

$$2p_{0p} \alpha_{\text{C}}^{\text{O}_2} \frac{M_{\text{C}}}{M_{\text{O}_2}} = (2p_{\text{CO}_2} + p_{\text{CO}} + 2p_{\text{O}_2}) \left(1 + \frac{\alpha_{\text{N}_2}^{\text{O}_2}}{\alpha_{\text{C}}^{\text{O}_2}} \frac{M_{\text{N}_2}}{M_{\text{C}}} \right),$$

$$p_{0p} = p_{\text{N}_2} \left(1 + \frac{\alpha_{\text{N}_2}^{\text{O}_2}}{\alpha_{\text{C}}^{\text{O}_2}} \frac{M_{\text{N}_2}}{M_{\text{C}}} \right),$$

$$\frac{p_{0p}}{1 + \frac{\alpha_{\text{C}}^{\text{O}_2}}{\alpha_{\text{N}_2}^{\text{O}_2}}} \left[\eta_s Q_s + \frac{\alpha_{\text{C}}^{\text{O}_2}}{\alpha_{\text{N}_2}^{\text{O}_2}} \frac{M_{\text{C}}}{M_{\text{N}_2}} c_p^{\text{N}_2} \Big|_0^{T_{rp}} T_{rp} + \alpha_{\text{C}}^{\text{O}_2} \frac{M_{\text{C}}}{M_{\text{N}_2}} c_p^{\text{O}_2} \Big|_0^{T_{rp}} T_{rp} \right] =$$

$$= (p_{\text{CO}_2} c_p^{\text{CO}_2} \Big|_0^{T_{0p}} + p_{\text{CO}} c_p^{\text{CO}} \Big|_0^{T_{0p}} + p_{\text{N}_2} c_p^{\text{N}_2} \Big|_0^{T_{0p}} + p_{\text{O}_2} c_p^{\text{O}_2} \Big|_0^{T_{0p}}) T_{0p},$$

where: $G_p = G_{\text{C}} + G_{\text{O}_2} + G_{\text{N}_2}$ is mass delivery of the pumping gas; $\alpha_{\text{C}}^{\text{O}_2} = G_{\text{O}_2}/G_{\text{C}}$, $\alpha_{\text{N}_2}^{\text{O}_2} = G_{\text{O}_2}/G_{\text{N}_2}$ are mass fractions of individual components at the inlet to KS1, p_i are partial pressures of components at the KS1 outlet, $c_p^i \Big|_0^T$ [kcal/kg $^{\circ}$] – average specific heat, Q_s [kcal/kg]

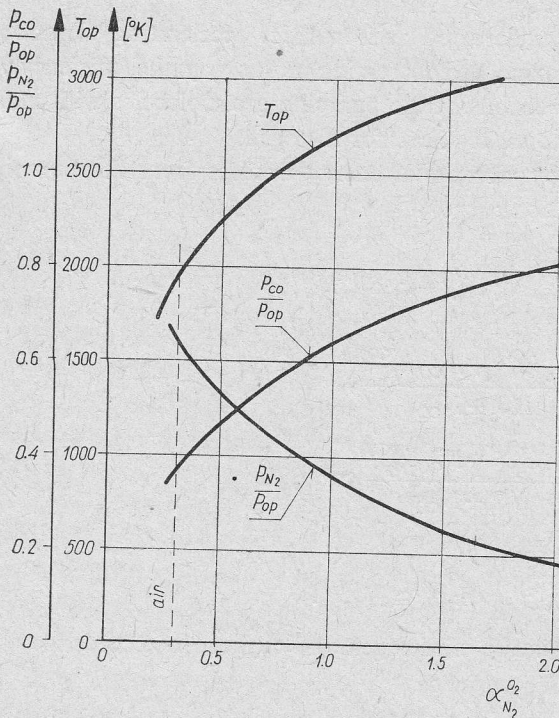


Fig. III.2. Approximate dependence of temperature T_{0p} and volume fractions of CO and N₂ in the pumping gas on the composition of oxidizer ($T_{rp} = 1300^{\circ}$, $Q_{sp} = 7840$ kcal/kg, $\eta_s = 0.95$, $\alpha_{\text{C}}^{\text{O}_2} = 1.33$)

– calorific value of the coal used, η_s – combustion efficiency (including losses for incomplete burning and wall cooling); $M_{\text{CO}_2} = 44$, $M_{\text{CO}} = 28$, $M_{\text{O}_2} = 32$, $M_{\text{N}_2} = 28$ molecular weights.

The requirements concerning combustion in the main combustion chamber KS1 are as follows:

a) small percentage (less than a few percent) of CO₂ and O₂ in combustion gases,

- b) possibly large content of N_2 ,
- c) possibly high burning temperature T_{0p} (its value ought to be limited by technological reasons only),
- d) graphite dust consumption possibly small.

The postulates a) and b) are brought about as a result of a tendency for obtaining large efficiency η_l , the postulate c) is related to critical parameter g_c whereas the postulate d) leads to large specific power g_g .

A set of combustion equations can be solved accurately only by means of numerical methods. However it is useful to make preliminary calculations based on a simplified, idealized model of combustion where (in accord with a)) the combustion gases contain nitrogen and carbon monoxide only, i.e. $p_{CO_2} \cong p_{O_2} \cong 0$.

This model is valid only under the condition that $\alpha_c^{O_2} = G_{O_2}/G_c \cong 1.33$ and that temperature T_{0p} is not very high. The results of calculations based on the idealized model mentioned above are shown in Fig. III.2. The following data were assumed for the calculations: $Q_s = 7840$ [kcal/kg], $\eta_s = 0.95$, $T_{rp} = 1300^\circ K$.

III.3. Preliminary selection of parameter values

Molecular and gasdynamic processes occurring in the presently considered variant of a gasdynamic laser and those discussed before (see Chapter II) are, in principle, the same. For that reason a preliminary selection of parameter values can be executed on the basis of considerations presented in section II.2. The only material difference is in the values of the coefficients k_{pl} and k_{lp} which, in consequence, influences the rate of the laser action and a choice of optimum contents of H_2O in the lasing gas.

Following are preliminary estimates of the optimum parameter values:

$$\begin{aligned} T_{0p} &\cong 2500^\circ K, & T_{rp} &\cong 1300^\circ K, & T_m &\cong 300^\circ K, & T_{0l} &\cong 400^\circ K, \\ p_{0p} &\cong 20 \text{ ata}, & p_{0l} &\cong 10 \text{ ata}, & p_m &\cong 0.02 \text{ ata}, \\ v_m &\cong 2000 \text{ m/s}. \end{aligned}$$

From Fig. III.2 there is, for the assumed value of T_{0p}

$$\alpha_{N_2}^{O_2} \cong 0.75, \quad p_{N_2}/p_{0p} \cong 0.43, \quad p_{CO}/p_{0p} \cong 0.57,$$

whence:

$$k_{pl} \cong k_{pl}^{(N_2)} \left(\frac{p_{N_2}}{p_{0p}} + \frac{1}{4} \frac{p_{CO}}{p_{0p}} \right) \cong 0.57 k_{pl}^{(N_2)}$$

which means that the pumping process runs at a rate equal only to about half of that characteristic of the gasdynamic laser with pure nitrogen serving as the pumping medium. In order to keep the ratios of relaxation times (see Chapter II) without change, the value of α_{dl} parameter ought to be decreased correspondingly to the decrease of α_{lp} .

Taking $\alpha_{ip} \cong 0.20$, $\alpha_{dl} \cong 0.10$ one obtains:

$$\begin{aligned}\tau_{rn} &\cong 1.49 \cdot 10^{-5} \text{ s}, & \tau_{pl} &\cong 11.9 \cdot 10^{-5} \text{ s}, & \tau_i &\cong 4.2 \cdot 10^{-5} \text{ s}, \\ \tau_{rm} &\cong 11.9 \cdot 10^{-5} \text{ s}, & \tau_{rp} &\cong 0.3 \text{ s}, & \tau_v &\cong 6.1 \cdot 10^{-4} \text{ s}, \\ L_x &\cong 1.2 \text{ m}.\end{aligned}$$

If preliminary estimates of the values of η_k and η_v efficiencies are taken after Chapter II, the specific power per unit mass flow is equal to $g_c \cong 73 \text{ kW/kg} \cdot \text{s}^{-1}$ which is a value identical with that given in Chapter II. The ratio of carbon deliveries to both of the combustion chambers can be calculated from a formula

$$\frac{(G_C)_{ks2}}{(G_C)_{ks1}} = \frac{\alpha_{ip}(1 + \alpha_C^{O_2} + \alpha_{CO}^{O_2}/\alpha_{N_2}^{O_2})}{1 + M_{O_2}/M_C}$$

where $M_C = 12.0$ is atomic weight of carbon. The degree of graphite dust utilization is given by:

$$g_g = g_c \frac{(1 + \alpha_{ip})(1 + \alpha_C^{O_2} + \alpha_{CO}^{O_2}/\alpha_{N_2}^{O_2})}{1 + (G_C)_{ks2}/(G_C)_{ks1}} \cong 293 \text{ kW/kg} \cdot \text{s}^{-1}.$$

IV. Gasdynamic CO_2 – N_2 laser with mixture expansion and thermal excitation by combustion

IV.1. Arrangement of the facility

Schematic diagram of the facility is shown in Fig. IV.1. The facility is of a design similar to that presented in the previous chapter, with some simplifications. The differences are of two kinds:

- a) in design: lack of the low-temperature plenum chamber and nozzle system for expanding the lasing gas, water feeder installed instead,
- b) in course of combustion: a possibly pure mixture of $\text{N}_2 + \text{CO}_2$ (in place of $\text{N}_2 + \text{CO}$ mixture) should be obtained at the combustion chamber outlet; it can be shown that air is an oxidizer good enough for this purpose so that the oxygen enrichment is not indispensable in that facility.

The process of pumping the lasing medium before it reaches the lasing region is executed in a different way than in the variants of gasdynamic laser discussed in Chapters II and III. The pumping gas (N_2) and the lasing gas (CO_2) form a mixture, which is expanded from a high-temperature plenum chamber through a nozzle into a laser channel. Conditions inside the chamber – which, simultaneously, is a combustion chamber fed with graphite dust and air – are characterized by the pressure p_{op} and temperature T_{op} . Ahead of the nozzle outlet small amount of water is added to the mixture. Gasdynamic parameters of the gas in the lasing region are: pressure p_m , temperature T_m and velocity v_m .

Populations of energy levels of nitrogen and carbon dioxide molecules before expansion result from the equilibrium (Boltzmann) distribution for the temperature T_{op} . Thus for CO_2 , in particular, the v_2 group of levels is more numerous than the v_3 group. During the expansion, the rates of relaxation processes are different for each type of CO_2 molecules vibrations. The relaxation of the v_2 and v_1 groups is rapid, their temperature following

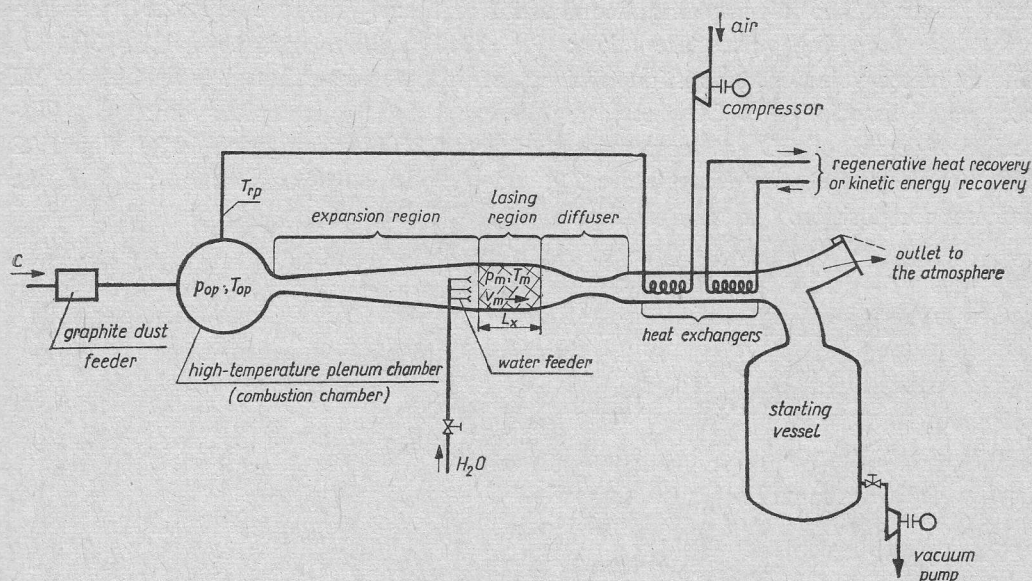


Fig. IV.1. Schematic diagram of a CO_2 – N_2 gasdynamic laser with mixture expansion and thermal excitation by combustion of C

rather closely the translational temperature of the gas. The CO_2 (v_3) and N_2 (v) groups, coupled together by the near-resonance process of vibrational energy transfer CO_2 (v_3) $\leftrightarrow$ N_2 (v), relax slowly, their vibrational temperature keeping approximately to the value of high-temperature plenum chamber T_{0p} . In that way the population inversion of CO_2 (00^01) and CO_2 (10^00) vibrationally excited states arises at a certain point along the flow of working medium. The lasing region is located behind this point. Here the excess of population of the v_3 group (continuously supplemented by energy exchange with the v group) over the v_1 group will be converted into energy of radiation ($\lambda = 10.6 \mu\text{m}$). The lasing region terminates at the point where vibrational temperatures of the v and v_3 groups approach the translational temperature of the gas. Water is added to the working gas in order to increase relaxation rates of CO_2 (v_2) and CO_2 (v_1) vibrationally excited states; the water feeder outlet is placed directly before the lasing region. Influence of H_2O molecules on the laser action is identical with that discussed in Chapters II and III.

IV.2. Preliminary selection of parameter values

The considerations of section III.2 concerning criterial parameters are valid for the gasdynamic laser variant under discussion. The formulas concerning carbon combustion in the high-temperature chamber as well as the formulas allowing for a preliminary estimation of water contents in a gas flow $\alpha_{dl} = G_{\text{H}_2\text{O}}/G_{\text{CO}_2}$, the lasing region length and characteristic time τ_l of radiational deactivation by stimulated emission, are valid too.

An idealized model of combustion will be assumed for preliminary calculations; namely, in accord with the postulate b) of the section IV.1 it will be assumed that carbon dioxide

and nitrogen are the only products of combustion so that: $p_{\text{CO}} \cong p_{\text{O}_2} \cong 0$, $\alpha_{\text{C}}^{\text{O}_2} \cong 2.67$. Furthermore, the following values are taken: $Q_{sp} = 7840$ kcal/kg, $\eta_{sp} \cong 0.80$, $T_{rp} \cong 1300^\circ\text{K}$. The estimated value of combustion efficiency η_{sp} is lower than that given in Chapter III because of dissociation of CO_2 increasing the losses due to incomplete combustion (dissociation degree of CO_2 at temperatures of about 2500°K can reach 10%). Fig. IV.2 shows the dependence of temperature T_{0p} and composition of combustion gases on the oxidizer composition.

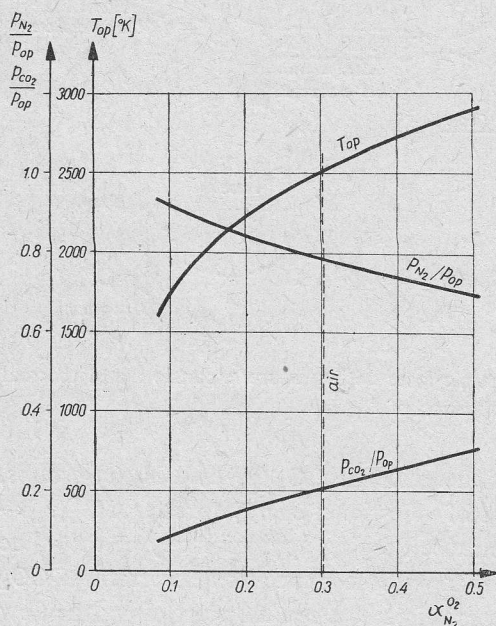


Fig. IV.2. Approximate dependence of temperature T_{0p} and (volume) content of CO_2 and N_2 in the working fluid on the composition of oxidizer ($T_{rp} = 1300^\circ\text{K}$, $\alpha_{\text{C}}^{\text{O}_2} = 2.67$, $\eta_s = 0.80$, $Q_{sp} = 7840$ kcal/kg — heat of combustion of C)

Air has been taken as the optimum oxidizer for this variant of the gasdynamic laser. Therefore, the following preliminary set of optimum values of parameters was assumed:

$$\begin{aligned} T_{0p} &\cong 2.500^\circ\text{K}, & T_{rp} &\cong 1300^\circ\text{K}, & T_m &\cong 300^\circ\text{K}, \\ p_{0p} &\cong 20 \text{ ata}, & p_m &\cong 0.02 \text{ ata}, & v_m &\cong 2000 \text{ m/s}, \\ \alpha_{\text{N}_2}^{\text{O}_2} &= 0.303, & \alpha_{lp} &= \alpha_{\text{N}_2}^{\text{CO}_2} = \frac{M_{\text{CO}_2}}{M_{\text{C}}} \frac{\alpha_{\text{N}_2}^{\text{O}_2}}{\alpha_{\text{C}}^{\text{O}_2}} \cong 0.416, \\ \alpha_{dl} &= \frac{G_{\text{H}_2\text{O}}}{G_{\text{CO}_2}} \cong 0.18. \end{aligned}$$

Making use of the above data one can obtain from Fig. II.4, the following characteristic values:

$$\begin{aligned} \tau_{rm} &\cong 0.41 \cdot 10^{-5} \text{ s}, & \tau_{pl} &\cong 3.3 \cdot 10^{-5} \text{ s}, & \tau_l &\cong 1.2 \cdot 10^{-5} \text{ s}, \\ \tau_{rm} &\cong 3.3 \cdot 10^{-5} \text{ s}, & \tau_{rp} &\cong 0.08 \text{ s}, & \tau_v &\cong 1.7 \cdot 10^{-4} \text{ s}, \\ L_x &\cong 0.34 \text{ m}. \end{aligned}$$

Nonselective pumping of carbon dioxide causes that the efficiency η_v of virtual power transport from the plenum chamber into the lasing region is worse than that estimated in Chapter II, referring to selective pumping. However, this value cannot be simply assessed and numerical calculations of the working gas expansion are necessary to obtain an estimate.

An estimate of virtual power value P_{v0} can be obtained under assumption that CO_2 present inside the plenum chamber does not carry any useful vibrational energy and is only a ballast. A corresponding dependence $P_{v0}/G_p = f(T_{0p})$ is shown in Fig. IV.2. One can obtain, in conclusion, in accord with above presented numerical data $g_c = 74\eta_v$ [kW/kg s^{-1}], $g_g = g_c (1 + \alpha_{lp}) (1 + \alpha_c^{O_2} + \alpha_c^{O_2}/\alpha_{N_2}^{O_2}) \cong 1215\eta_v$ [kW/kg $\cdot \text{s}^{-1}$]. It seems probable that $\eta_v \cong 0.5$.

A relatively large value of the coefficient α_{lp} is worth noticing. As a result, the precisely calculated optimum value for the $\alpha_{N_2}^{O_2}$ coefficient may be less than the estimated one, for a drop of T_{0p} caused by the drop of $\alpha_{N_2}^{O_2}$ can be more than compensated by an increase of η_v ; the values of g_c and g_g will be correspondingly larger. However, change of the oxidizer composition (i.e. — enriching the air with oxygen) may not prove useful in view of the necessity of much more complicated installations.

IV.3. Carbon monoxide as a fuel

Carbon dioxide-nitrogen mixture at temperature of about 2500°K can be obtained as a result of burning carbon monoxide in a nitrogen-oxygen mixture. For the idealized combustion model, as determined previously, and under additional assumptions that: $H_{sp} \cong 67$ kcal/kg, $\eta_{sp} \cong 0.8$, $T_{r(N_2+O_2)} \cong 1300^\circ\text{K}$; $T_{r(w)} \cong 300^\circ\text{K}$ (where H_{sp} — total enthalpy

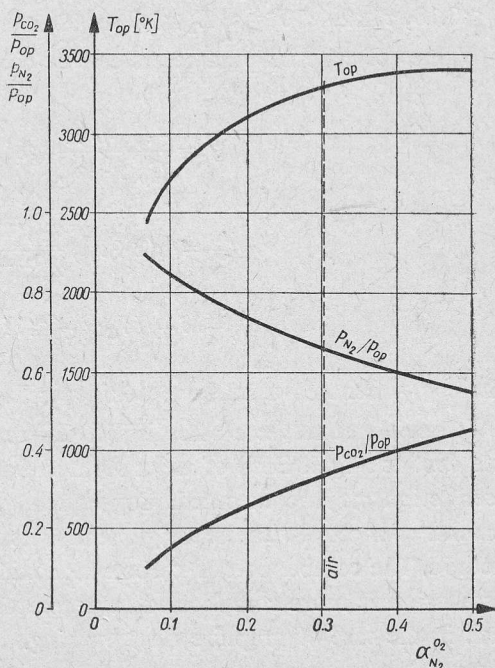


Fig. IV.3. Adiabatic combustion temperature T_{0p} and (volume) content of CO_2 and N_2 in the working fluid vs. composition of oxidizer ($T_{rp} = 1300^\circ\text{K}$, $\alpha_c^{O_2} = 2.67$, $\eta_s = 0.80$, $H_{sp} = 67$ kcal/kmol — heat of CO combustion)

of CO combustion), a dependence of temperature T_{0p} and combustion gases composition on the oxidizer composition has been calculated. The results are presented in Fig. IV.3. The T_{0p} function ought to be understood as a theoretical one because carbon monoxide is practically incombustible at temperatures of about 4000°K (because of nearly complete dissociation of carbon dioxide at this temperatures). An analysis of Fig. IV.3. leads to the following conclusions:

a) the value $T_{0p}=2500^\circ\text{K}$ can be obtained for any value of $\alpha_{\text{N}_2}^{\text{O}_2}$ within the range of $0.1 \div 0.5$ by way of a proper decreasing (in relation to assumed value $T_r \cong 1300^\circ\text{K}$) the temperature of regenerative oxidizer heating,

b) air cannot be used as oxidizer because of too large contents of CO_2 in resulting combustion products,

c) the optimum oxidizer composition is characterized by the value $\alpha_{\text{N}_2}^{\text{O}_2} \cong 1$; the corresponding index of combustion gas content being $\alpha_{ip} \cong 0.2$. The value $T_{0p} \cong 2500^\circ\text{K}$ can be obtained at parameter values as given above.

In conclusion, the following set of optimal values of characteristic parameters for the considered variant of gasdynamic laser is obtained:

$$T_{0p} \cong 2500^\circ\text{K}, \quad T_{r(\text{N}_2 + \text{O}_2)} \cong 1300^\circ\text{K}, \quad T_{r(\text{CO})} \cong 300^\circ\text{K},$$

$$p_{0p} \cong 20 \text{ ata}, \quad p_m \cong 0.02 \text{ ata}, \quad v_m \cong 2000 \text{ m/s},$$

$$\alpha_{\text{N}_2}^{(\text{O}_2)\text{utl}} \cong 0.115, \quad \alpha_{\text{CO}}^{(\text{O}_2)\text{utl}} \cong 0.572, \quad \alpha_{ip} \cong \left[1 + \alpha_{\text{N}_2}^{(\text{O}_2)\text{utl}}\right] \frac{\alpha_{\text{N}_2}^{\text{O}_2}}{\alpha_{\text{CO}}^{\text{O}_2}} \cong 0.2$$

for which corresponding relaxation times are identical with those calculated in Chapter II: $\alpha_{il} \cong 0.18$, $\tau_l \cong 2.4 \cdot 10^{-5} \text{ s}$, $L_x \cong 0.7 \text{ m}$.

Values of criterial parameters can be calculated according to the following formulas:

$$g_c = \frac{P_{v0}}{G_p} \frac{\eta_v \eta_k}{1 + \alpha_{ip}} \cong 81 \eta_v [\text{kW/kg} \cdot \text{s}^{-1}],$$

$$g_{\text{CO}} = g_c (1 + \alpha_{ip}) \frac{\alpha_{\text{CO}}^{(\text{O}_2)\text{utl}}}{\alpha_{\text{N}_2}^{(\text{O}_2)\text{utl}}} \cong 474 \eta_v [\text{kW/kg} \cdot \text{s}^{-1}],$$

$$g_g = M_{\text{CO}}/M_C \cdot g_{\text{CO}} \cong 1100 \eta_v [\text{kW/kg} \cdot \text{s}^{-1}],$$

where g_{CO} denotes a carbon dioxide utilization parameter $g_{\text{CO}} = P_c/G_{\text{CO}}$.

It is evident that there is no distinct difference in using either carbon monoxide or graphite dust as a fuel. Each of them secures that the same course of processes leading to the laser action may be executed. Consequently, the technological reasons or other requirements connected with the assignment or usage will decide about a choice of the particular method. The combustion of carbon monoxide is simpler to cope with, but the required installation is more complicated (a generator of carbon monoxide, a vessel for nitrogen) than in the case of graphite dust burning.

V. Transverse flow $\text{CO}_2\text{--N}_2\text{--He}$ electric-discharge convection laser (closed cycle)

V.1. Introduction

The gasdynamic laser concepts discussed above can be regarded as promising if sources of continuous coherent radiation of large and very large powers (of the order of hundreds of kilowatts and more) are considered. However, their low total efficiency (of about 1%) entails serious problems of economical disposing of vast powers not utilized in the radiation generation process. In that instance the design of the gasdynamic laser proper becomes a problem of secondary importance accompanying, in a way, a more general problem of constructing a suitable power station of possibly high efficiency.

In this connection searching for more economical solutions of the problem of continuous radiation generation, whenever possible, seems purposeful. The lasers pumped in an electric discharge with high velocity flow of a lasing medium in the direction transverse to the optical cavity axis seem to be one of the possibilities [19, 20, 23]. About ten times higher total efficiency (of the order of 10%) is their advantage over the gasdynamic lasers. However, the power range of these lasers is not extending so far as that of the gasdynamic lasers, because of limited power range of continuously excited electric discharge. In practice the electric-discharge convection lasers (EDCL) may appear more promising than the gasdynamic ones within the range of output radiation powers from 1 to $10 \div 50$ kilowatts.

V.2. The concept of EDCL facility

The execution of the working medium flow through the lasing region cancels the principal limitation imposed on the laser power, because even very large quantities of waste energy, not used up in the energy conversion process, (e.g. electric energy to light) can be removed by convection if only a proper flow velocity of the working medium is applied. It can be shown that the ratio of power densities (per unit volume of a laser cavity) for lasers with transverse flow and conventional ones is given by

$$\frac{(p_c)_{\text{flow}}}{(p_c)_{\text{conv}}} \cong \frac{D}{\lambda_g} Ma,$$

where D — width of the laser region, λ_g — average free path of molecules, Ma — Mach number. As evident, there are in principle two ways of increasing a laser power: by increasing the pressure and by increasing the flow velocity.

The concepts of high velocity flow lasers have been considered in the previous chapters from the viewpoint of the possibility of pumping a laser with the use of fluid flow techniques only. The concept of thermal excitation comes out at that as an obvious proposition. However, only open cycle facilities are feasible, the closed cycle being either impossible (for a GDL with selective pumping) or impractical.

Abandoning the idea of thermal excitation, one can consider the possibility of a closed cycle. Again the excitation by means of electric discharge seems, at least, the easiest to

be brought into being. Main advantage of the closed cycle facility comes from a very low gas consumption, which allows employing high purity gases in arbitrary compositions without limitations imposed by economical aspects. An efficient cooler is necessary, as well as a suitable pump for maintaining circulation. Severe demands concerning leakages have to be satisfied to prevent contamination of the working medium by impurities. However, a certain degree of contamination is unavoidable (since, for instance, a part of impurities is being freed within the closed installation) and a continuous replacement of a part of the gas is necessary.

The only practical method of gas excitation is, seemingly, the glow discharge. Thermal excitation with necessary deep expansion and — consequently — high compression of the pump is not promising. Besides, the efficiency of the laser facility with electric excitation is relatively high ($\eta_c \cong 10\%$).

V.3. Schematic arrangement of an EDCL

Schematic drawing of an electric-discharge convection laser is shown in Fig. V.1. The facility consists of:

- a working channel with a lasing region covering an electric (glow) discharge region,
- a heat exchanger (cooler) for removing excess energy from the moving gas,
- a pump maintaining circulation of the gas in the closed cycle facility.

The first of the lasers of this kind has been built by Tiffany *et al.* [18]; its short characteristic is as follows: $\text{CO}_2\text{—N}_2\text{—He}$ mixture as the working medium, output radiation power of about 1 kW, total efficiency of about 7%, length of the optical cavity equal to 1 m, pressure in the lasing region $p_m = 18$ Tr, working medium velocity $v_m = 30$ m/s. It is worth noticing that the large output of the device is obtained at relatively low p_m and v_m .

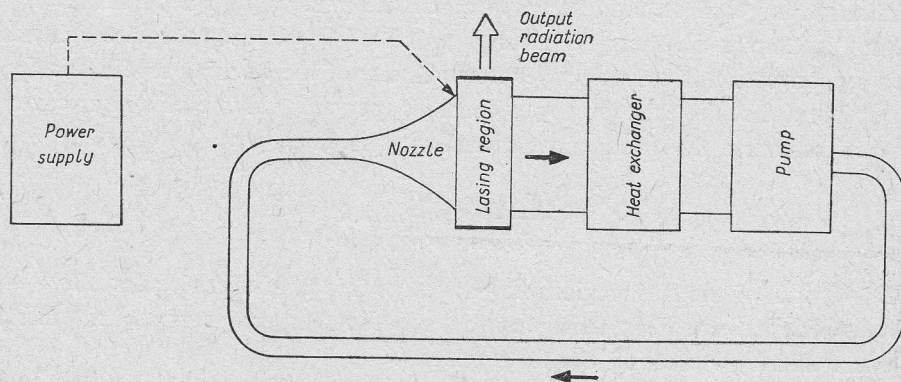
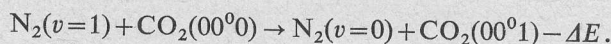


Fig. V.1. Schematic diagram of a transverse flow closed cycle electric-discharge convection laser (after [18])

In the laser under consideration the lasing medium is being pumped directly into the lasing region. The processes leading to the creation of population inversion have not been entirely explained. However, the opinion prevails that for the mixture of carbon dioxide-nitrogen flowing through the discharge region the basic pumping mechanism is as

follows: nitrogen molecules are excited directly by collisions with electrons, whereas direct excitation of CO_2 molecules is of secondary importance. Antisymmetric vibrations of CO_2 (the upper laser level) are excited through vibrational energy transfer by way of near-resonance reactions of the type:



The efficiency of N_2 - excitation in the discharge is increased by a considerably large amount of helium added to the mixture. Besides, helium facilitates the laser action because of its influence on the lower laser level relaxation rate.

The geometry of the discharge region (which simultaneously plays the part of a lasing region) of a large output electric-discharge convection laser with transverse flow entails a separate difficult problem. It is required that the spreading of the discharge within the entire volume available be homogeneous. Besides, possibly large discharge power densities per unit volume are desirable.

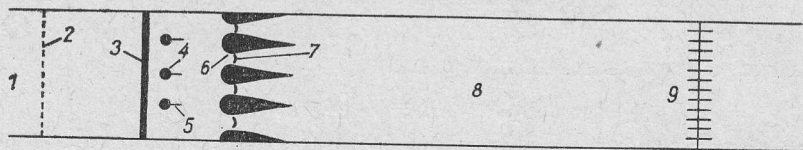


Fig. V.2. System producing homogeneous glow discharge with the use of fluid-flow techniques (after [20])

1 - upstream stagnation region, 2 - laminar flow screen, 3, 4 - vortex generators, 5 - anodes, 6 - nozzle array, 7 - shock wave, 8 - discharge channel, 9 - cathode structure

Several methods of solving the first problem for discharges at pressures exceeding several tens Torr are known. The most promising is the method utilising fluid flow techniques put forward by Hill [19, 20]. "Freezing" of a discharge in a nonstationary state can be obtained in a high velocity flow. Gradients of pressure of the electron gas and ion gas act the part of additional electric fields. When the equivalent field intensity for electrons is very small, the equivalent field acting on ions can be very large (e.g. for $\nabla P_{\text{ion}} = 15 \text{ Tr/m}$ and $n_e = n_i = 5 \cdot 10^{16} \text{ m}^{-3}$, $E_{\text{eg}i} \cong 250 \text{ kV/m}$). It is evident, then, that because of quasineutrality of the discharge plasma, fluid flow techniques are liable to control the discharge geometry simply by influencing mechanically the spatial distribution of ions. Schematic arrangement of elements used for obtaining homogeneous discharge distribution within the laser channel is shown in Fig. V.2. The discharge was generated in the direction of flow between a set of pin anodes (each having its individual load resistor) and a set of cathodes placed downstream. The discharge homogeneity was achieved by a combined use of vortex generators set in front of the anodes and nozzle system.

It has been shown experimentally that maximum discharge power (below the value at which instability develops) was a linear function of mass flow, its value equal to about 600 kW per 1 kg/s. This limit value was independent of gas composition changes as well as of pressure and flow velocity. Worth noticing is that pressure changes caused only field intensity changes whereas maximum current density remained constant and was equal to about $j_s = 20 \text{ mA/cm}^2$).

A very important parameter is the time constant characterizing homogeneous discharge lifetime. It has been established that for the discharge lengths larger than $l_c = \tau_c \cdot v_m$ electro-thermal instabilities always develop, downstream of the coordinate $x = l_c$. In the Hill's experiments [19, 20] τ_c was equal to about 2 ms. Two other parts are of great importance for the EDCL facility. These are the cooler and the pump. Nevertheless, their design is a typical engineering problem and therefore it will not be considered here.

V.4. Selection of parameter values

The working gas mixture ought to consist of three components: carbon dioxide, nitrogen and helium and the content of each is to be determined. This can be done on the basis of data concerning conventional lasers. As a rule the content of CO_2 is 2 - 3 times smaller than that of N_2 , whereas the content of He can reach even 80 percent of the whole volume. However, studies on the optimum composition of the working mixture for the convection laser under consideration are still to be performed.

Gas delivery can be determined on the basis of the output radiation power P_c required. Total discharge power is estimated first, namely

$$P_w = P_c / \eta_c = UI \text{ [kW]},$$

where η_c can be assumed as equal to about 5 - 10%; U and I are the discharge voltage and current. Next the required gas delivery is determined $G^* = P_w / \rho_{el}$ [kg/s], where ρ_{el} [kW/kg·s⁻¹] is a specific input power per unit mass flow (in [20] was equal to 600 kW/kg s⁻¹). The specific output power per unit mass flow $g_c = P_c / G_c^*$ can be estimated on the basis of data taken from [19, 20]

$$g_c = P_c / G_c^* = \eta_c \rho_{el} \cong 20 \div 50 \text{ kW/kg} \cdot \text{s}^{-1}.$$

Since the device works in a closed cycle, the last quantity is not as important as it is for gasdynamic lasers.

The gas temperature T_g ought to be possibly low, because an equilibrium population of the lower laser level and the CO_2 (01¹0) level rises rapidly with increasing T_g . It has been shown [24] that for $T_g \geq 800^\circ\text{K}$ population inversion between vibrational energy levels of carbon dioxide cannot be obtained.

Gas temperature at the lasing region inlet T_p should be close to the room temperature because more complicated cooling systems (like for instance coolers with liquid nitrogen), are to be avoided.

Heat dissipated in the gas during its passing across the discharge region causes the gas temperature to rise. If convection is the only considered way of heat removal (which is true at high flow velocities), then the total temperature rise is equal to

$$\Delta T_g = T_{g \text{ out}} - T_{g0} = P_t / 4.18 G^* C_p [^\circ\text{K}],$$

where $P_t = P_w - P_c$ denotes waste power and:

$$C_p = (C_p)_{\text{He}} \cdot d_{\text{He}} x_{\text{He}} + (C_p)_{\text{N}_2} \cdot d_{\text{N}_2} x_{\text{N}_2} + (C_p)_{\text{CO}_2} \cdot d_{\text{CO}_2} x_{\text{CO}_2} [\text{kcal/kg} \cdot ^\circ],$$

x_i - mole fractions,

$$(C_p)_{\text{He}} = 1.250 \text{ kcal/kg} \cdot ^\circ, \quad (C_p)_{\text{N}_2} = 0.249 \text{ kcal/kg} \cdot ^\circ, \quad (C_p)_{\text{CO}_2} = 0.202 \text{ kcal/kg} \cdot ^\circ,$$

$$d_{\text{He}} = 0.1785 \text{ kg/m}^3, \quad d_{\text{N}_2} = 1.25 \text{ kg/m}^3, \quad d_{\text{CO}_2} = 1.977 \text{ kg/m}^3.$$

Eventually

$$\rho_{el} = \frac{P_w}{G^*} = \frac{4.18 C_p \Delta T_g}{1 - \eta_c},$$

where the latter formula can be used for estimating the maximum specific input power ρ_{el} . For instance: with $T_0 = 300^\circ\text{K}$, $(T_g)_{\max} = 800^\circ\text{K}$, $\eta_c = 0.1$, $x_{\text{He}} = 0.8$, $x_{\text{N}_2} = 0.16$, $x_{\text{CO}_2} = 0.04$ one obtains

$$(\rho_{el})_{\max} \cong \frac{4.18 C_p (\Delta T_g)_{\max}}{1 - \eta_c} = 567 [\text{kW/kg} \cdot \text{s}^{-1}].$$

It is worth noticing that the experimentally obtained value of ρ_{el} [20] is close to above calculated.

The actual value of $T_{g\text{out}}$ will be lower than that calculated from the formulas for section V.3, if the flow velocity is too high for thermodynamic equilibrium to be established within the length of the lasing region.

In selecting the values of velocity v and pressure p of the gas flowing across the lasing region the premises listed below may be taken into account; however, the optimum choice is not so unique as in the case of temperature:

- p and v possibly high to reduce the dimensions of the facility;
- p and v sufficiently low to secure the glow discharge stability within the flow, electrodes arrangement and the lasing region geometry being decisive for $p_{\max}$ and $v_{\max}$ values;
- v sufficiently low to keep the pressure rise in the pump Δp within economically reasonable limits; estimates show that a velocity a little below the sound velocity is an optimum for output radiation powers of the order of several kilowatts;
- p sufficiently high to assure (for a given flow velocity v and lasing region width L_x) a time of particles flight across the lasing region, $\tau_v = L_x/v$, much longer than the characteristic times: τ_{pl} — for vibrational energy transfer from CO_2 to N_2 , and τ_n — for the lower laser region CO_2 (10^0) relaxation; the above times being equal to [20]:

$$p_{\text{CO}_2} \tau_{pl} = \frac{10^{-7}}{8.6 T^{-3/2} \exp\left(-\frac{26}{T}\right)} [\text{s} \cdot \text{Tr}],$$

$$p_{\text{tot}} \tau_n = \frac{2}{2.6 \cdot 10^{-6} T^{-10/3} x_{\text{CO}_2} + 7.3 \cdot 10^{-3} T^2 x_{\text{N}_2} + 22 T x_{\text{He}}} [\text{s} \cdot \text{Tr}]$$

(where x_i — mole fractions).

As an example, the values of τ_{pl} and τ_n have been calculated for the CO_2 — N_2 — He mixture with components ratio equal to 1 : 2 : 7, at the temperature of 500°K . The obtained values are:

$$p_{\text{CO}_2} \tau_{pl} = 0.137 \cdot 10^{-3} [\text{s} \cdot \text{Tr}],$$

$$p_{\text{tot}} \tau_n = 0.24 \cdot 10^{-3} [\text{s} \cdot \text{Tr}]$$

and for $p_{\text{total}} = 100 \text{ Tr}$.

$$\tau_{pl} = 13.7 \mu\text{s}, \quad \tau_n = 2.4 \mu\text{s}.$$

Here $\tau_n < 0.2 \tau_{pl}$.

One can take as a best estimate for the laser of several kW output the value of p of the order of hundreds Torr. However, the final choice of p and v values ought to be confirmed experimentally.

The configuration of the discharge region elements is the most significant factor, decisive for this region's dimensions as well as for the values of current density j_s [A/cm²] and electric field intensity E_s [V/cm]. The most efficient configuration of elements has been proposed by Hill [20] (see Fig. V.2); it seems reasonable to follow his idea when designing the discharge region. Therefore, for the discharge region length L_x the requirement $L_x \leq \tau_e v$ (where $\tau_e \approx 1-10$ ms — see section V.2) must be satisfied; the current number density is estimated to amount to $j_s = 20$ mA/cm² independently of p and v values [20]; electric field intensity (which is a linear function of pressure p) can be determined from the values of p_{1np} , j_s and L_x . In this way only rough estimates may be obtained. It must be emphasized that experimental investigations are indispensable before making final decisions about the design of the facility.

The discharge region, being simultaneously the lasing region, forms the most vital part of the electric-discharge convection laser facility. In the construction of the facility working in a closed cycle two additional components must be taken into account, namely a cooler and a pump for working gas circulation (see Fig. V.1).

As for the cooler, its design is a typical task. Its parameters can be selected uniquely, assuring — for a given set of p , G^* , T_0 and T_{out} a drop of the gas temperature equal to.

A laser facility of several kW output is not big enough to justify using a diffuser (at the lasing region output) for partial gas compression. In this case the entire required pressure rise Δp ought to be performed by a proper pump. The compression can be estimated as follows:

$$\Delta p = p_0 - p, \quad \frac{p}{p_0} = 1 - \frac{\kappa - 1}{2\kappa} \frac{v^2}{RT_0},$$

where κ (isentropic exponent) and R (gas constant) refer to the assumed composition of the working gas:

$$R = R_{He} d_{He} x_{He} + R_{N_2} d_{N_2} x_{N_2} + R_{CO_2} d_{CO_2} x_{CO_2} [\text{m}^2/\text{s}^2 \cdot 1^\circ],$$

$$\kappa = 1 + \frac{R}{\frac{R_{He} d_{He} x_{He}}{\kappa_{He} - 1} + \frac{R_{N_2} d_{N_2} x_{N_2}}{\kappa_{N_2} - 1} + \frac{R_{CO_2} d_{CO_2} x_{CO_2}}{\kappa_{CO_2} - 1}},$$

$$R_{He} = 2080 \text{ m}^2/\text{s}^2 \cdot 1^\circ, \quad R_{N_2} = 297 \text{ m}^2/\text{s}^2 \cdot 1^\circ, \quad R_{CO_2} = 194 \text{ m}^2/\text{s}^2 \cdot 1^\circ$$

$$\kappa_{He} = 1.66, \quad \kappa_{N_2} = 1.40, \quad \kappa_{CO_2} = 1.30.$$

VI. Concluding remarks

It seems purposeful to summarize the results of calculations and discussions given in the foregoing chapters, in order to assess the validity of conclusions concerning practical usefulness of individual modifications of the large output laser facilities in question.

The first concept (see Chapter II) has been based upon a most idealized model of a thermally excited gasdynamic laser; therefore basic estimates and calculation results can be recognized as correct. Thermal excitation and non-equilibrium expansion of pure nitrogen are not difficult to calculate, selective pumping of CO_2 by vibrationally excited N_2 is also well understood as well as the influence of H_2O on collisional deactivation of $\text{CO}_2(v)$ and $\text{N}_2(v)$ may be calculated. Only the process of mixing the streams of pumping and lasing gases cannot be fully described in terms of mathematical analysis, this, however, may be regarded as a matter of secondary importance.

On the contrary, the second concept (cf. Chapter III) is not so clear because the course of the process of carbon dioxide pumping by vibrational energy transfer from excited CO molecules is not known as well as it is for $\text{CO}_2 - \text{N}_2$ collisions. Since literature data are scarce and partially contradicting, the formulas describing them must be regarded as rough estimates, requiring additional experimental substantiation.

For the third concept (Chapter IV) the degree to which the analysis and estimates of course of processes is trustworthy is the same as for the first concept. However, the parameter η_v which appears in concluding formulas cannot be evaluated without detailed numerical calculations. Thus the discussion on the third concept lacks numerical values of main parameters, which is its obvious deficiency.

The concept of electric-discharge convection laser is the one where little theoretical calculations can be made. On the other hand, plenty of experimental data are available, and the feasibility of such a laser seems entirely proved.

The usefulness of the above discussed four variants of high power laser facilities ought to be evaluated from various viewpoints. The following conclusions come as a result:

1. The first and fourth variants are more advantageous than the others within the output power range $P_c \approx 1 \div 10$ kW. For higher powers ($P_c \geq 100$ kW) the two combustion driven laser facilities are more suitable.

2. The overall efficiency η_c and compactness of the fourth (EDCL) variant are better than those of the first one. However, its efficiency depends much more than that of the first one on the design correctness and proper working conditions. In general, the EDCL facility is more demanding and difficult in design than the fluid mixing GDL.

On the other hand, a very high (theoretical) efficiency of the latter can be achieved (much beyond that of EDCL) if a high degree of regenerative heat recovery is employed. It is doubtful, however, if such a mode of operation is economically justified for output radiation powers not exceeding 10 kW.

3. The third variant would be better than the second one if only $\eta_v \geq 0.25$; moreover, its design is simpler. Regenerative heat recovery (or gas stream kinetic energy recovery) is understood as necessary for each of the high power laser facilities discussed above if $P_c > 10$ kW. A comparison of calculated values of criterial parameters:

– for EDCL facility:

$$g_c \approx (20 \div 50) \text{ kW/kg} \cdot \text{s}^{-1}, \quad \eta_c \approx (5 \div 10) \%,$$

– for fluid mixing GDL facility:

$$g_c \approx 73 \text{ kW/kg} \cdot \text{s}^{-1}, \quad \eta_c \approx 3.3 \%,$$

— for combustion driven GDL facility:

$$g_c \cong 73 \text{ kW/kg} \cdot \text{s}^{-1}, \quad g_g \cong 293 \text{ kW/kg} \cdot \text{s}^{-1}$$

shows that for the first and second variants specific power per unit mass flow of the working gas is larger, but simultaneously their overall efficiency (without regenerative heat recovery) is lower. However some uncertainty is introduced because the results for EDCL were taken from experimental data [19, 20] whereas the other ones come from theoretical calculations without experimental proof. As for experimental data, those concerning the largest GDL facility built up to now (of 60 kW output) [5], with design similar to that of the third variant, are not as good as above presented theoretical ones. Namely:

$$g_c \cong 4.3 \text{ kW/kg} \cdot \text{s}^{-1}, \quad \eta_c \cong 1\%.$$

In the authors' opinion this is not the upper limit of parameters attainable. This limit for future design should rather be outlined on the basis of the theoretical data presented above.

References

- [1] J. F. Ready, *Mech. Engin.*, Sept. 1970.
- [2] The wraps torne off continuous high-power lasers, *Physics Today*, July 1970.
- [3] G. Moeller, J. D. Rigden, *Appl. Phys. Letters*, **7**, 10, (1965) 274.
- [4] B. R. Bronfin, L. R. Boedeker, J. P. Cheyer, *Appl. Phys. Letters*, **16**, 5, (1970).
- [5] E. T. Gerry, *IEEE Spectrum*, **7**, 11, (1970) 51.
- [6] J. L. Emmett, *Physics Today*, (1971).
- [7] New laser gives 6 kW, *Microwaves*, July 1970.
- [8] V. K. Koniuchov, I. V. Matrosov, A. M. Prokhorov, D. T. Shalunov, N. N. Shirokhov, *Pisma v ZETF*, **12**, (1970).
- [9] M. Brunné, G. Małaczyński, J. Milewski, J. Stańco, A. Zieliński, *Biuletyn IMP PAN*, nr 11/689/71, (1971).
- [10] M. Brunné, G. Małaczyński, J. Milewski, J. Stańco, T. Machowski, Z. Puzewicz, Z. Trzęsowski, *REK-IV*, Poznań 6-9, IV, 1970, EK-36, (1970).
- [11] J. Milewski, M. Brunné, J. Stańco, A. Zieliński, M. Irczuk, J. Kuśmierek, *REK-V*, Poznań, 24-27, IV, 1972, EK-1, (1972).
- [12] J. Milewski, M. Brunné, J. Stańco, A. Zieliński, M. Irczuk, J. Kuśmierek, *Bull. Acad. Polonaise des Sc.*, S. T. No. 4, (1972).
- [13] D. M. Kuehn, D. J. Ronson, *Appl. Phys. Letters*, **16**, 1, (1970).
- [14] A. P. Drinov, A. S. Diakov, E. M. Kudriavtzev, N. N. Sobolev, *Pisma v ZETF*, **11**, (1970).
- [15] V. A. Batakov, F. B. Bunkin, A. M. Prokhorov, V. B. Fiedorov, *Doklady AN SSSR*, **191**, 6, (1971).
- [16] T. A. Cool, J. A. Shirley, R. R. Stephens, *Appl. Phys. Letters*, **17**, 7, (1970).
- [17] R. L. McKenzie, *Appl. Phys. Letters*, **17**, 10, (1970).
- [18] W. B. Tiffany, R. Targ, Foster, *Laser Focus*, 9, (1969) 48.
- [19] A. E. Hill, *Appl. Phys. Letters*, **16**, 11, (1970).
- [20] A. E. Hill, *Appl. Phys. Letters*, **18**, 5, (1971).
- [21] R. L. Taylor, S. Bitterman, *Rev. Modern Phys.*, **41**, 1, (1969).
- [22] C. Wittig, J. C. Hassler, P. D. Coleman, *IEEE J. Quantum El.*, QE-6, (1970).
- [23] T. Kan, J. A. Stregack, W. S. Watt, *Appl. Phys. Letters*, **20**, 3, (1972).
- [24] M. C. Fowler, *Appl. Phys. Letters*, **18**, 5, (1971).

Koncepcje laserów gazodynamicznych o działaniu ciągłym dla zastosowań przemysłowych

Streszczenie

Omawia się zwięźle różne koncepcje istniejących laserów gazodynamicznych CO_2 o działaniu ciągłym, biorąc pod uwagę możliwość zastosowania ich w operacjach technologicznych wymagających dużej wartości mocy wiązki promieniowania. Wyróżnia się trzy podstawowe warianty tych laserów:

1. $\text{CO}_2 - \text{N}_2$ CW-GDL o wzbudzeniu termicznym i pompowaniu selektywnym w procesie mieszania strug; obieg otwarty.
2. $\text{CO}_2 - \text{N}_2$ CW-GDL o wzbudzeniu termicznym w procesie spalania i pompowaniu nieselektywnym podczas ekspansji mieszaniny; obieg otwarty.
3. $\text{CO}_2 - \text{CO} - \text{N}_2$ CW-GDL o wzbudzeniu termicznym i selektywnym pompowaniu; obieg otwarty.

Czwarta koncepcja — wzbudzanego wyładowaniem lasera $\text{CO}_2 - \text{N}_2 - \text{He}$ z przepływem poprzecznym jest sformułowana jako konkurencyjna w stosunku do wymienionych wyżej laserów gazodynamicznych.

Die Konzeption der gasdynamischen Laser mit Dauerbetrieb für Industriezwecke

Zusammenfassung

Es wird kurz über verschiedene Konzeptionen existierender gasdynamischer CO_2 -Laser mit Dauerbetrieb berichtet. Dabei wird auf ihre Anwendungsmöglichkeit in technologischen Operationen, die einen großen Leistungswert des Lichtstrahlbündels voraussetzen eingegangen.

Drei grundsätzliche Varianten dieser Laser werden erfaßt:

1. Der $\text{CO}_2 - \text{N}_2$ - Laser mit thermischer Erregung und selektivem Pumpen im Mischvorgang des Gasstrahls; Offener Zyklus.
2. Der $\text{CO}_2 - \text{Ne}$ - Laser mit thermischer Erregung im Verbrennungsprozeß mit nichtselektivem Pumpen während der Gemischekspansion; Offener Zyklus.
3. Der $\text{CO}_2 - \text{CO} - \text{N}_2$ - Laser mit thermischer Erregung und selektivem Pumpen; Offener Zyklus.

Eine vierte Konzeption, des durch Entladung erregten $\text{CO}_2 - \text{N}_2 - \text{He}$ - Laser mit Querströmung wurde als konkurrierend für die in 1 - 3 besprochenen Laser formuliert.

Идеи газодинамических лазеров непрерывного действия для промышленного применения

Резюме

Кратко обсуждаются различные идеи существующих газодинамических лазеров CO_2 непрерывного действия, с учетом возможности их применения в технологических операциях, требующих значительной величины мощности пучка излучения. Различаются три основных варианта этих лазеров:

1. $\text{CO}_2 - \text{N}_2$ — газодинамический лазер непрерывного действия с термическим возбуждением и селективной накачкой в процессе смешивания струй; открытый контур,
2. $\text{CO}_2 - \text{N}_2$ — газодинамический лазер непрерывного действия с термическим возбуждением в процессе сгорания и с неселективной накачкой во время расширения смеси; открытый контур.
3. $\text{CO}_2 - \text{CO} - \text{N}_2$ — газодинамический лазер непрерывного действия с термическим возбуждением и селективной накачкой; открытый контур.

Четвертая идея возбуждаемого разрядкой лазера $\text{CO}_2 - \text{N}_2 - \text{He}$ с поперечным течением считается конкурирующей по отношению к вышеперечисленным газодинамическим лазерам.