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MEASUREMENT OF VIBRATIONAL TEMPERATURES IN THE WORKING CHAMBER OF A TECHNOLOGICAL ELECTRIC-DISCHARGE CO2 LASER

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Results are given for the reconstruction, based on spectral distributions of the amplification factor of the active medium, of the progressive temperature and the upper laser level temperature in the working chamber of a 1.2-kW technological CO_2 laser. The obtained data on the temperature distribution in the zone of excitation of the medium enabled us to formulate requirements on organizing the process of laser energy removal and to assess the efficiency of the resonator devices used.

The current introduction of highly efficient laser technologies goes hand in hand with creating second-generation industrial technological lasers that are distinguished by compactness of the design, high quality of the radiation, and the use of microprocessor control systems [1]. In this case in the stage of introducing a technological laser system the need arises for a detailed preliminary investigation of its working regimes under laboratory conditions both with the aim of optimizing the operation of the laser device and for establishing the reasons affecting the energy and power characteristics of the technological laser.

One of the major factors that govern the operating efficiency of a technological laser as a whole is the characteristics of the working medium in the region of pumping and energy removal. We note that to optimize various laser systems knowledge of the spatial distribution of the progressive and vibrational temperatures, which govern the amplification factor of the laser-active medium in the working zone, is necessary since the functional characteristics of the basic laser assemblies, which include the systems of pumping and heat transfer, feed of components, forced circulation of the medium, energy removal, etc., govern ultimately the change in the characteristics of the laser-active medium [2].

One of the most widespread methods that enable us to diagnose molecular states of laser-active media is the method of reconstructing laser level temperatures on the basis of recorded spectral distributions of the amplification factor [3–5]. This procedure was also used in this present work to assess the efficiency of a second-generation technological CO_2 laser of 1.2-kW power.

Experiments were carried out on an MLT-1200 laser module, which was developed at the Institute of Flow Machines of the Polish Academy of Sciences [6] and was a kilowatt CO_2 laser (Fig. 1) with a closed circuit for pumping the working mixture and excitation of the medium by a self-maintained glow discharge. All the basic elements (the gas circuit, the heat exchanger, the optical resonator, and the electrode system) were mounted inside a vacuum chamber 1 m in diameter and 2 m long. The gas mixture, containing CO_2, N_2, and He in a 1:9:15 ratio and prepared directly in the laser working chamber, was pumped through the discharge gap using a centrifugal fan that ensured a flow rate $\simeq 70$ m/sec at a static pressure of 50 hPa. The working chamber was a channel 1 m in wide, 0.075 m in high, and 0.5 m long. To maintain the discharge, a regulated power supply of 56-kW power was used that ensured currents up to 15 A in the discharge gap at an electrode voltage of 3.75 kV. To produce the discharge, 80 polished sleeve anodes 0.007 m in diameter and 0.07 m long, oriented along the channel, were built into the bottom wall of the working channel, which was made of ceramics. A copper water-cooled sleeve cathode

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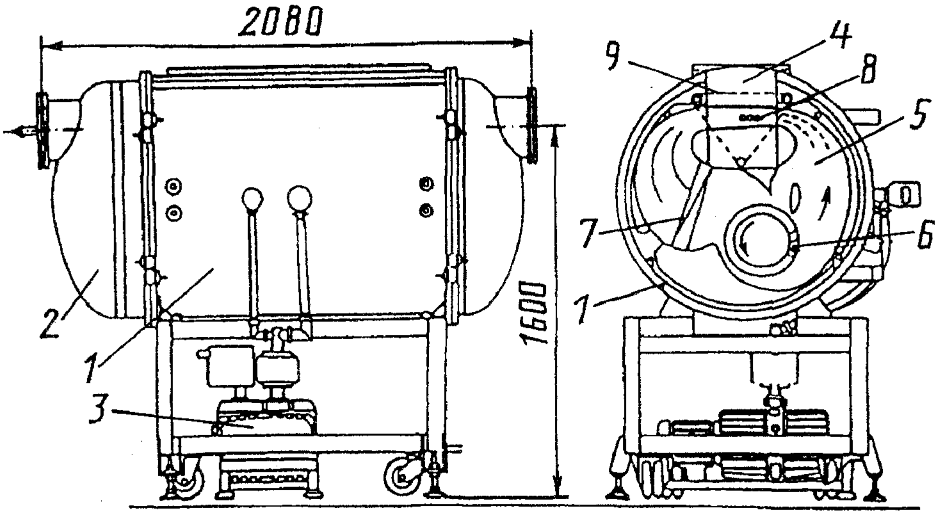


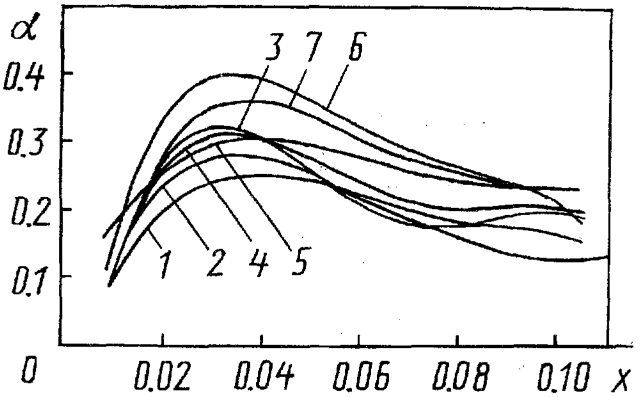
Fig. 1. Schematic diagram of a module technological CO_2 laser: 1) frame; 2) end caps; 3) vacuum pump; 4) working chamber; 5) gas channel; 6) fan; 7) heat exchanger; 8) resonator; 9) resonator holder.

0.01 m in diameter, offset by 0.005 m from the start of the anodes, was located at a height of 0.031 m from the anodes perpendicularly to the flow. The total width of the discharge gap was 0.96 m. To remove the energy, in a series of experiments use was made of a stable multitransmission resonator formed by two fully reflecting plane silicon mirrors and one semitransparent spherical ZnSe mirror with a curvature radius $R = 10$ m. The resonator was mounted inside the vacuum chamber and was thermally stabilized. Operation of all laser systems was automated and controlled by a MERA-60 minicomputer.

Diagnostic measurements of the MLT-1200 active medium were carried out in laser module operation in the amplifier regime using a probing laser that was rapidly tunable over the lasing spectrum [7]. Amplifying characteristics of the working medium of the technological laser were determined on eight P16-P28 lines of the 00^01-10^00 CO_2 band on the channel axis at a height of 0.013 m from the surface of the anodes in various cross sections of the discharge chamber. In connection with the fact that during operation of the technological laser in the regime without renewal of the working mixture we observed a constant increase in the progressive temperature of the medium at the inlet to the discharge chamber all measurements were performed at the same initial temperature of the medium in front of the working chamber $T_0 = 290-300$ K. The amplification factor was measured by a double-arm scheme by comparing intensities in the working and reference beams. Noncooled RADEC R-005-2 Cd and Hg/Te detectors, onto the sensitive area of which probing laser radiation was focused, were used as IR detectors. Detector signals were recorded and processed on a digital oscillograph.

As spectral measurements of α showed, the distribution of this parameter along the discharge chamber length is nonuniform, and the value of α attains its maximum at distances of $\simeq 0.03$ m from the cathode and then drops smoothly along the channel length. As an illustration, Fig. 2 gives distributions of α from the cathode edge downstream for various diagnostic lines. It is pertinent to note that α for different transitions of the 00^01-10^00 band differ quite insignificantly, which may, in particular, lead to retuning of the generated radiation frequency using a nonselective resonator.

On the basis of the obtained spectral distributions of the amplification factor the progressive T and the vibrational temperature of the upper laser level T_3 were reconstructed. The reconstruction procedure was implemented under the assumption that the lower laser level temperature T_{12} is close to the progressive temperature of the medium, which appears quite justified on the basis of data of [8]. The sought values of the temperature were found by simultaneously minimizing over two parameters, namely, T and T_3, the squares of the disrepancies between α values measured experimentally on different lines and their theoretical dependences [5]. We note that the spectral distribution of the amplification factor of the working medium was recorded during one measurement



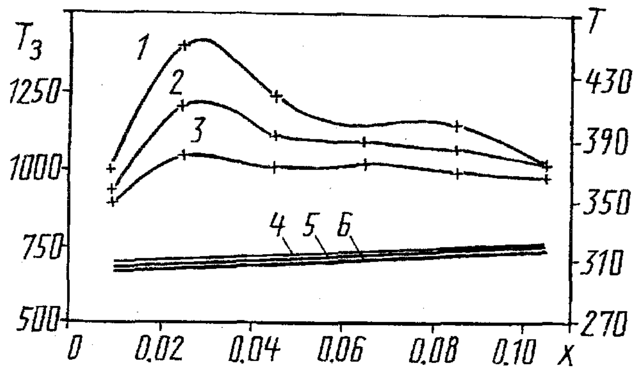


Fig. 2. Distribution of the amplification factor of the active medium downstream for different vibrational-rotational transitions of the 00^01-10^00 band: 1) P28; 2) P26; 3) P24; 4) P22; 5) P20; 6) P18; 7) P16; $P = 40$ hPa; $I = 8$A. α, m^{-1}; x, m.

Fig. 3. Distribution of temperatures in the working zone of the technological laser at different pumping currents: 1, 4) 10 A; 2, 5) 8 A; 3, 6) 6 A; 1, 2, 3) T_3; 4, 5, 6) T; $P = 40$ hPa. T_3, T, K.

in ~300 μsec. In connection with the fact that a contribution to the value of the amplification factor measured on a line of the 10^00-00^01 basic band can be made on account of the effects of spectral line overlap, by both the "hot" transitions of the 11^10-01^11 band and the 10^01-00^02 band, in the present work, to correctly calculate α in reconstructing the temperatures, we took into account the possibility that the wings of 50 nearby vibrational-rotational transitions of the above bands overlap the basic line [9].

According to the analysis of [5], with the contraint $T_3 < 4T$ the relative error in determining the progressive temperature does not exceed half the value of the relative error in measuring α, and for the temperature T_3 it is $0.1\Delta\alpha/\alpha$. Thus, for a relative error in determining the amplification factor $\Delta\alpha/\alpha$ not exceeding 14%, the maximum error in reconstructing T and T_3 will be no more than 7 and 1.4%, respectively.

To improve the accuracy of the reconstructed parameters, T and T_3 were averaged over 3–5 spectral distributions $\alpha(j)$, and the influence of fluctuations of the flow parameters of the active medium on the reconstructed characteristics was thereby decreased. Results of processing the distributions $\alpha(j)$ are given in Figs. 3 and 4, which show the distributions of the reconstructed temperatures T and T_3 along the discharge chamber length for various working pressures and pumping currents. As is evident from the above dependences, the progressive temperature of the medium in the discharge zone increases insignificantly over the entire range of working channel pressures and pumping currents: the maximum increase in T, corresponding to a pressure of 53 hPa, did not exceed 30 K at the pumping currents $I = 6-10$ A, which indicates both small relaxation losses in the medium and an efficient system for cooling the electrodes. Here the increase in the progressive temperature depends weakly on the value of the discharge current (see Fig. 3). At the same time a distinct increase in T in the discharge zone was recorded only when the working medium pressure was increased (Fig. 4).

As concerns the distribution of the asymmetric mode temperature T_3 downstream in the pumping zone, as the data in Figs. 3 and 4 indicate, the value of T_3 and its spatial change are governed by the excitation conditions and depend on both the pumping currents and the medium pressure.

At the working pressure $P = 39$ hPa the vibrational temperature T_3 attains a maximum at a distance of $\simeq 0.03$ m from the cathode over the entire pumping current range and then drops to a "plateau" level at $x = 0.075$ m (see Fig. 3). A further drop in T_3 is observed beyond the zone in which the discharge exists, i.e., after $x = 0.075$ m. The maximum value of T_3 and the value of T_3 in the "plateau" zone increase as the pumping current increases.

The similarity of the spatial distributions of T at different pumping currents I indicates above all an insignificant change in the efficiency of the working medium pumping as the discharge current is increased to 10

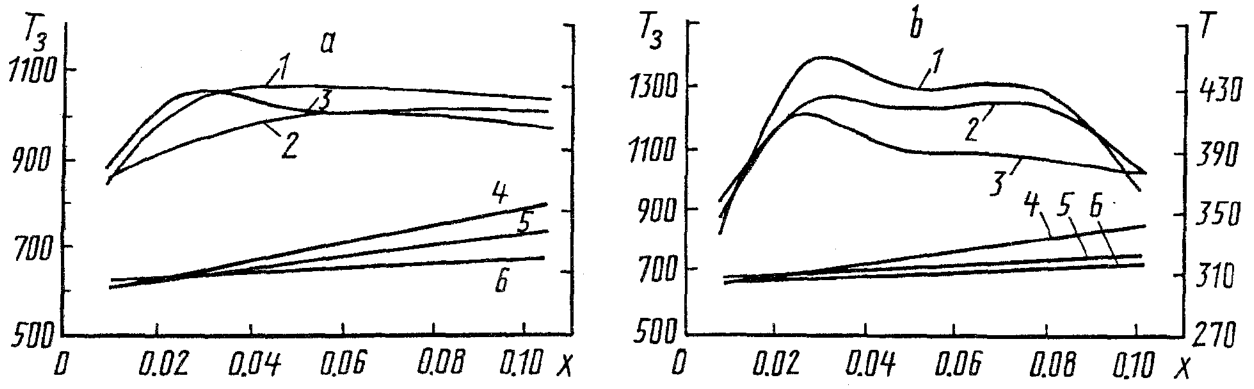


Fig. 4. Distribution of temperatures in the working zone of the technological laser at different pressures and pumping currents: a) $I = 6$; b) 8 A; 1, 4) 53 hPa; 2, 5) 46; 3, 6) 40 hPa; 1, 2, 3) T_3; 4, 5, 6) T.

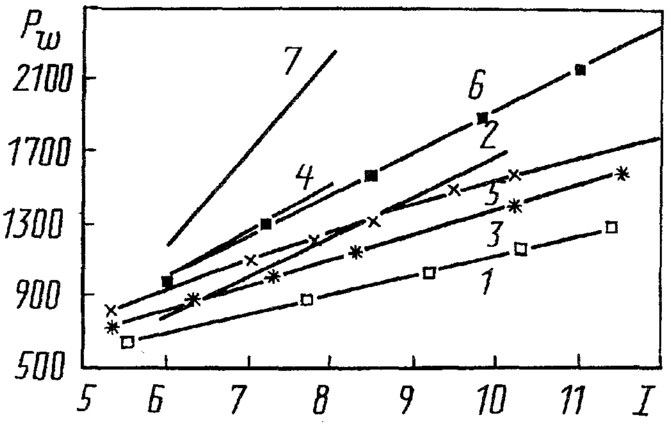


Fig. 5. Power characteristics of the technological laser at different pumping currents and working pressures: 1, 2) 40 hPa; 3, 4) 46 hPa; 5, 6, 7) 53 hPa; 1, 3, 5) three-transmission resonator; 6) four-transmission resonator; 2, 4, 7) limiting estimates of the power obtained on the basis of values of T_3 and T. P_w, W; I, A.

A, which makes possible the operation of the technological laser at elevated values of the pumping current. At the same time we note that the nonuniformity of the spatial distribution of T_3 indicates a nonuniform distribution of the discharge current density along the length of the sectioned anode, the further optimization of whose design will perhaps enable us to improve the spatial characteristics of the discharge and gain a more uniform inversion of the laser-active medium in the working zone the gasdynamic channel.

The spatial distribution of T_3 can also be changed by correspondingly choosing the working current and the medium pressure. As is evident from Fig. 4a, at low pumping currents and elevated pressures realization of uniform distributions of T_3 is possible in the discharge zone. At the same time visual observations of the discharge in this regime show the presence of both time instability and transverse nonuniformities in the glow discharge zone. We note that it is impossible to establish these effects by the methods of the diagnostics used owing to the recording of the amplifying characteristics of the medium of the averaged over the probing laser beam. Increasing the discharge current with a simultaneous increase in the working pressure (Fig. 4b) enables us to realize spatial distributions of T_3 similar to those in Fig. 4a.

Thus, in operation of a technological laser device at moderately low pressures ($\simeq$ 3.9–4.6 HPa) and average values of the pumping current ($\simeq$ 8–10 A) it is possible to create a uniform inversion zone extended over the flow, which assumes the use of highly efficient multitransmission resonator systems to remove the laser energy. For a distribution of T_3 that is characterized by an initial "burst," which is realized at elevated pressures of the working medium and large currents in the discharge gap, the energy can be removed efficiently by using resonators localized in the zone with the highest inversion characteristics.

On the basis of the values of the temperatures T and T_3 reconstructed from the spectral distributions $\alpha(j)$ by the procedure of [10] we assessed the maximum lasing power of the technological laser for various operating regimes. We assumed the use of a 100%-efficient resonator. The value of the energy removed in the form of laser radiation was assessed as the difference of the energies of the upper and lower laser levels with the corresponding temperatures T_3 and T with allowance made for the laser efficiency and particle density in the medium. A comparison of the obtained assessments of P_w with data for resonators of different types obtained experimentally is shown in Fig. 5. Comparing the maximum and realized values of P_w enables us to assess the efficiency of the resonator device used. Thus, for a three-transmission resonator with a mirror diameter $\simeq 0.02$ m for the pumping currents $I = 8$ A and $P = 40$ hPa a power level of $\simeq 900$ W (Fig. 5, curve 1) was attained at an assessed value of the maximum power for this regime of $\simeq 1300$ W (Fig. 5, curve 2). Taking into account that the resonator covers about 67% of the total volume of the inversion medium, the value of the maximum possible radiation power assessed from the amount of vibrational energy contained in the medium is $\simeq 900$ W. This is in good agreement with the experimental value of P_w, which in turn indicates high efficiency for the resonator used.

Therefore, the investigations of temperatures carried out in the working chamber of a powerful technological laser showed the high efficiency of the employed method of diagnostics, which enabled us not only to reconstruct the vibrational temperature of the upper laser level and the progressive temperature of the medium in the discharge zone but also to optimize the process of energy removal on the basis of the data obtained. Good agreement of the estimates for the maximum radiation power obtained on the basis of T and T_3 with experimentally recorded values if P_w confirmed the justification of making the assumption of close temperatures T and T_{12}, which enables us to use simplified methods of diagnostics in the future without additional radiation probing of CO_2-laser-active media in the 00^02-10^01 and 01^11-11^10 bands, which involves certain experimental difficulties.

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NOTATION

R, radius of spherical mirror curvature; T_0, initial temperature of the medium in front of the working chamber, K; α, $\alpha(j)$, amplification factor of laser radiation, m^{-1}; j, rotational quantum number; T, progressive temperature, K; T_3, vibrational temperature of the upper laser level, K; T_{12}, vibrational temperature of the lower laser level, K; I, pumping current, A; P, pressure, hPa; P_w, lasing power, W.

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