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SPECIFIC POWER OUTPUT OF A GASDYNAMIC CO_2 LASER WITH NOZZLES OF WEDGE AND CONTOURED GEOMETRIES

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UDC 621.375.826

The results of an investigation of the specific power output of gasdynamic CO_2 lasers with nozzles of different constructions are presented and the prospects for their use in technological equipment are discussed.

The results of theoretical and experimental research on gasdynamic CO_2 lasers (CO_2 GDL) obtained up to now and presented in a number of works [1-3] can in principle serve as a good foundation for the practical construction of test laser technological equipment (LTE) [4]. At the same time, in the creation of continuous LTE of this type a number of specific engineering problems arise, the solution of which determines the possibility of their technical realization to a considerable extent.

One of the most important problems in the creation of LTE is to provide a nozzle apparatus with a long continuous operating life. For the range of working temperatures of the gas mixture required in practice, $T_0 \approx 1600$-2000°K, the primary requirement evidently is the development and fabrication LTE nozzles with cooled constructions. The operation of a test technological GDL with a cooled nozzle apparatus is reported in [4], where it is shown that a technically simple and reliable system for efficient nozzle cooling can be realized only for sufficiently large-scale mononozzles at present. But a complex technical solution is required to implement a system for cooling a large number of small nozzles, which comprise the most promising GDL nozzle apparatus based on the recommendations of the physical research of [1, 2].

In the first stage of work on continuous LTE one can evidently recommend only the simplest constructions for the nozzle apparatus, consisting of large mononozzles with a simplified supersonic contour, of wedge profile, for example, which allow one to provide their efficient cooling and hence the capacity to operate for a long time. Such LTE make it possible even now to solve a number of the problems connected with the study of the peculiarities of the application of laser radiation in industry [5, 6]. Of course, the feasibility of such equipment depends primarily on how much one can reduce the losses of stored energy in nozzle apparatus of simplified construction as compared with the optimum nozzle arrays.

Institute of High Temperatures, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 3, pp. 364-369, March, 1985. Original article submitted January 3, 1984.

In the present paper we compare the values of the specific power output for GDL in which alternate use is made of large mononozzles having a wedge and a contoured supersonic part and a contoured nozzle array of small vanes.

The main experimental results were obtained on a steady wind tunnel [7, 8] with individual supply from tanks of high-pressure, technically pure gases, N_2, CO_2, and He, which were heated with a three-phase plasmatron and discharged into a preliminary evacuated vessel with a volume of $\sim$50 m^3.

The nozzle devices used — wedge and contoured mononozzles and a contoured nozzle array — were described in detail in [9]. The output cross section of the nozzle was joined to a working section with dimensions of 378 × 30 × 200 mm [4], in which a single-pass stable resonator was placed, the axis of which was separated by x_r = 100 mm from the cut of the nozzle apparatus. The resonator was formed by an opaque, concave, copper mirror (radius of curvature of the surface 10 m, mirror diameter 150 mm) and a plane output mirror of the same diameter with an assigned transmission coefficient. The optimum transmission coefficient for the output mirror, chosen on the basis of preliminary calculations made in [10] and experiments of [8], was provided by depositing dielectric interference coatings onto backings of germanium or potassium chloride. To relieve the output mirror from atmospheric pressure, the laser beam was extracted from the resonator through a monocrystalline NaCl plate 14 mm thick. The energy of the output radiation was measured by a calorimeter with a wiring diagram described in [8].

The parameters of the working mixture in the gasdynamic channel of the equipment were determined by a method presented in detail in [8], while the static pressures in the working section were measured in two cross sections, separated from the cut of the nozzle apparatus by x_1 = 50 mm and x_2 = 150 mm.

From the measured values of the stagnation pressures P_0 and static pressures P_1 and P_2 we calculated the Mach number M_i in the gas stream for the corresponding cross sections of the supersonic channel of the GDL. When the GDL channel is combined with a wedge mononozzle the quantities M_1 and M_2 change the most along the stream, $M_1 - M_2 \approx 0.3$, which is indirect evidence of the presence of gasdynamic nonuniformities in the stream. In the case of a profiled mononozzle the Mach numbers change insignificantly along the stream, which is connected with the better uniformity of the stream in the working section, while for the case of a nozzle array one can speak of constancy of the Mach numbers along the stream.

Shadow photographs of the supersonic streams behind mononozzles obtained in [9] show that the field of gas flow located behind the first compression shocks and behind their intersection node lies in the zone of the optical resonator. An estimate of the gasdynamic parameters behind the first compression shocks (the angle of inclination of a shock is $\sim$13°, allowing us to classify them as weak), made for a working mixture of 10 CO_2-45 N_2-45 He with stagnation parameters $P_0 \approx 1.8$ MPa and $T_0 \approx 1700$°K from the theory of an oblique compression shock [11] without allowance for heat exchange with the ambient medium or viscous effects, as well as without allowance for relaxation processes, shows that the gas temperature behind the shock increased by $\sim$11% while the pressure increased by $\sim$57%. A decrease in the stream velocity (and hence the Mach numbers) should be clearly observed in this case, which was confirmed by experimental measurements of the pressures P_i. Thus, for a wedge mononozzle the calculated Mach number at the cut is M = 5.9, while when shocks are present in the actual flow section M_1 = 5.7 behind the first shock and M_2 = 5.4 behind the second.

By virtue of the fact that the flow parameters and the experimental conditions — the diameters and radii of curvature of the resonator mirrors, the transmission coefficients of the output mirrors, the flow rate of the working mixture through the nozzle apparatus, etc. — were similar for the different compositions of the GDL channel, it is correct to compare all the experimental results on the specific power output W_i in one figure.

The main conditions of the series of experiments under discussion are: G = const = 0.5 kg/sec, $P_0 \approx 1.2$-1.9 MPa, $T_0 \approx 1400$-2000°K, composition of the working mixture 10 CO_2-45 N_2-45 He, transparency of the output mirror $\sim(18\mp2)$%, reflection coefficient of the opaque mirror $\sim$98%. The values of W_i were determined by the method of [10] for the experimental conditions; a special subprogram was introduced into the calculation program allowing for the experimentally observed structure of the oblique compression shocks in the resonator space. The angles of inclination of the shocks were estimated from Töpler pictures of preliminary cold blow throughs [9]. It was assumed that as the gas passes through a compression shock with a thickness of several mean free paths there is a change in the parameters of

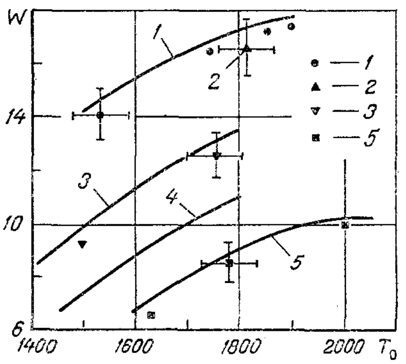

Fig. 1. Calculated curves and experimental values of the specific power output W (J/g) as functions of the stagnation temperature T_0 (°K) for combinations of the CO_2 GDL channel with different nozzle apparatus: 1) profiled nozzle array; 2) profiled mononozzle; 3) wedge mononozzle; 4) wedge mononozzle without allowance for compression shocks; 5) simplified nozzle array.

state, while the internal degrees of freedom are "frozen in," i.e., they relax far more slowly than the translational degrees of freedom. Relaxation processes beyond the shock lead to a change in the adiabatic index γ, which was taken into account in the numerical calculations.

The specific power output and the length of the transitional channel for combining the GDL channel with a contoured nozzle array were optimized earlier [8, 10] for conditions analogous to those given above (curve and points 1). In the experimental data for a contoured mononozzle (point 2) at $T_0 \simeq 1800$°K a specific power output $W_2 \simeq (17 \mp 2)$ J/g was obtained, while for a wedge mononozzle (curve and points 3) $W_3 \simeq (13 \mp 2)$ J/g. Thus, it was shown that contouring the profile of the supersonic part of a large GDL nozzle results in a noticeable but still not very large increase in the specific power output in comparison with a wedge mononozzle. It is appropriate to note that a calculation made from the model of [10] without allowance for the structure of the compression shocks in the resonator space predicted a value of $W_4 \simeq 11$ J/g under the experimental conditions. After allowance for the change in the parameters of the gas stream in the oblique compression shock in the calculated model, the calculated value of the specific power output grew by about 1.2 times compared with the experimentally obtained value W_3. This very unexpected positive influence of a compression shock in the resonator space on the specific power output has not been noted earlier in the literature, so far as we know.

The explanation for this phenomenon, after it was discovered experimentally and verified by the appropriate calculations, seems trivial. For the working parameters chosen in these tests, as the calculation and measurements showed, the following changes in the inversion medium occur as the gas passes through a compression shock: The gas temperature T grows from ~270°K to ~350°K (for $T_0 = 2000$°K), the static pressure P increases by more than 2 times, and the amplification ratio k_0 before the shock is about equal to k_0' after the shock: $k_0 = 1.1k_0'$ [12]. With the relatively small dimensions of the resonator cavity (a length of 378 mm across the stream) and mirror size (150 mm) used in the experiment, all these changes lead to a considerable increase in the intensity of laser radiation in the resonator, which significantly increases the efficiency of conversion of vibrational energy into laser radiation, decreases the loss of excited N^*_2 molecules, and ultimately increases the efficiency of the resonator. A comparison of the results of a measurement of the specific power output with a contoured mononozzle (W_2) and the results obtained in a GDL with a contoured nozzle array (W_1) [8, 10], with close working parameters of the flow, shows that these values are fully comparable to within the measurement errors ($W_1 \simeq W_2$) and in satisfactory agreement with the calculations.

In Fig. 1 we also present calculated data and experimental results on an investigation of the specific power output when the GDL channel is combined with a nozzle array built by a simplified technique (curve and points 5). The supersonic contour of the vanes of such an array is laid out along a radius. It is seen that such simplification of the technique of building the accelration part of the vanes with a simultaneous decrease in the length of the transitional channel resulted in a significant decrease in the specific power output to $W_5 \simeq 9$ J/g.

The experimental results obtained show that the use of large mononozzles, including a wedge mononozzle, to create the active inversion medium of GDL enables one to obtain a very high level of specific power output, which, considering the extremely simple technique of building such a nozzle apparatus and a number of obvious operating advantages (such as the attractive possibility of achieving a reliable system for nozzle cooling in this case), allows us to recommend it as one of the possible variants of the construction of the nozzle apparatus for continuout LTE.

NOTATION

P_0 and T_0, stagnation pressure and temperature of the gas in the forechamber, Pa and °K, respectively; G, total flow rate of the mixture, kg/sec; x_i, distance along the stream from the cut of the nozzle apparatus, mm; M, dimensionless Mach number; P_i, static pressure, Pa; T_i, static temperature, °K; W, specific power output, the ratio of the generation power to the total flow rate of the mixture, J/g; γ, adiabatic index of the working mixture; k_0 and k_0', amplification ratios for a weak signal before and after passage through the compression shock, m^{-1}.

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