NOTATION

v_x, v_y, v_z, flow velocity components; r, z, radial and axial coordinates; p, pressure; ρ, medium density; ν, kinematic viscosity; L, cylinder length; h, fluid layer thickness; ω, angular cylinder rotation velocity; Re, Reynolds number; u_0, v_0, azimuthal and radial velocity components of a medium in a flow core; δ_0, δ_1, boundary layer thicknesses on fixed and rotating cylinder ends; a, b, parameters for the velocity profiles in boundary layers; A, dimensionless parameter; ψ, stream function ($v_z = \partial\psi/\partial x$, $v_x = -\partial\psi/\partial z$).

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THE SPATIAL SCALES OF HETEROGENEITIES IN THE DIRECT-CURRENT DISCHARGE STREAM

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The results of a calculational-experimental investigation of spatial scale heterogeneities in a gas stream with direct-current discharge are presented. The numerical modeling was made within the framework of the Navier-Stokes equations with a distributed source of input energy density in a gas. The experimental study was conducted by the Talbot-interferometry method. The Shtrel number was used as the criterion of the optical homogeneity of the stream.

The creation of efficient technological electrical discharge lasers [1] is to a considerable extent connected with provision of high homogeneity of the active medium in the region where the output radiation is formed. The presence of interconnected processes during the realization in the stream of an independent glow discharge makes the modeling of the flow region in the gas discharge chamber (GDC) more complex, proving the necessity of studying and obtaining data about the stream structure [2]. The results of a calculational-experimental study of the stream region in a direct-current discharge GDC are presented. At the same time, the main attention is given to studying the structure of spacial scale heterogeneities in a gas flow and to their influence on the optical quality of the active medium.

The energy put into a self-sustaining glow discharge is divided mainly between translational and oscillatory degrees of freedom of molecules. When $E/N < (1\text{-}2)\cdot 10^{-12}$ $W\cdot m^2$, up to 80% of the discharge energy [3] may be put into the oscillatory degrees of freedom of molecules. The rest of the energy goes into the translational degrees, causing quick warm-up of the gas and, thus, changing its gas dynamic parameters. This is also proved by the results of a numerical study [4]. At the same time, a low gas velocity and density (in GDC length $Re \sim 9000$) lead to the growth of boundary layers on side wall-electrodes, the thickness of which increases quickly along the stream under the conditions of volume energy input. A variation of gas dynamic stream parameters induces the development of refraction index gradients and a corresponding distortion of the medium's optical homogeneity.

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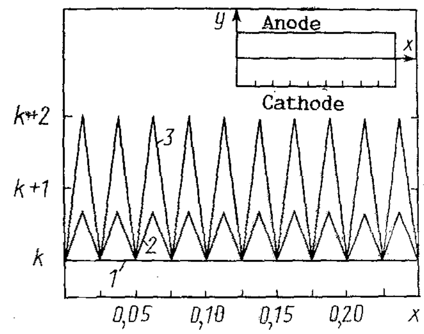

Fig. 1. The gas energy-input density function (k – base ten logarithm of heat evolution; x – GDC length along the stream); 1 – background heat generation level; 2 – the heating level when y = 0.005 m; 3 – the same when y = 0 m. x, m.

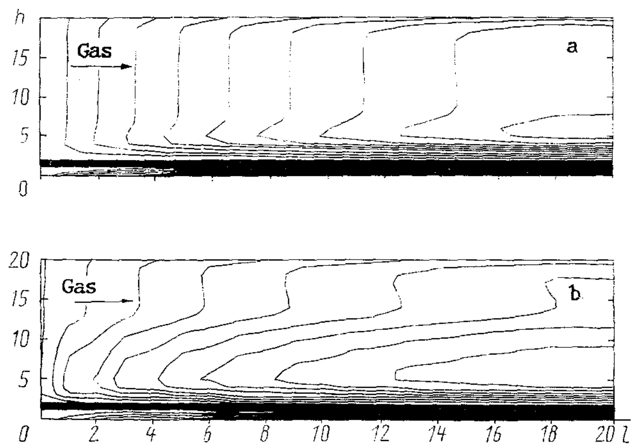

Fig. 2. Isolines of gas density in GDC: (a) continuous; (b) sectional cathode. h, mm; *l*, cm.

The numerical and experimental modeling was carried out for the characteristic conditions of pumped electric discharge lasers with the excitation of active molecules in a direct-current discharge. The gas-dynamic parameters at the inlet into the GDC had the following values: V_{in} = 30 m/sec, P_{in} = 5000 Pa, and T_{in} = 300 K. The working gas was air whose flow rate through the chamber cross section was set at the level of 0.03 kg/sec. The experimental apparatus described in [5] was a rectangular cross section channel with the length along and across the stream equal to 0.25 m. The upper and the lower walls of the channel were made of electrode plates between which a self-sustaining glow discharge was initiated. The cathode plate consisted of a set of cathode elements. The neighboring rows of edge-electrode cathode elements in the stream direction were separated by 0.025 m. The 0.3 m spacing between the electrodes and gasdynamic stream parameters at the inlet of the GDC made it possible to regulate the input energy density up to 6 MW/m^3 without a discharge contraction.

The numerical modeling was carried out on the basis of the steady-state two-dimensional Navier-Stokes equations for a gas in oscillatory-equilibrium with a distributed source component of heat release per unit volume into translational degrees of freedom in the energy equation and with isothermal boundary conditions at the electrodes. The equations were solved as finite-difference equations in vortex–current function variables according to the method of [6]. The approximation of the derivatives was directed up stream [7], followed by a solution of the system of algebraic equations using the Gauss-Zeidel method of consecutive displacements. The calculations proved that, under the conditions present at the GDC inlet, a laminar flow is realized (there's no turbulence); that has made solving the gasdynamic equations more simple. The highest complexity while modeling was connected with determining the heat source distribution function. There's a great number of zones in the discharge column, which differ both in their molecular-kinetic processes and in their heat evolution rates [8]. In this case, the

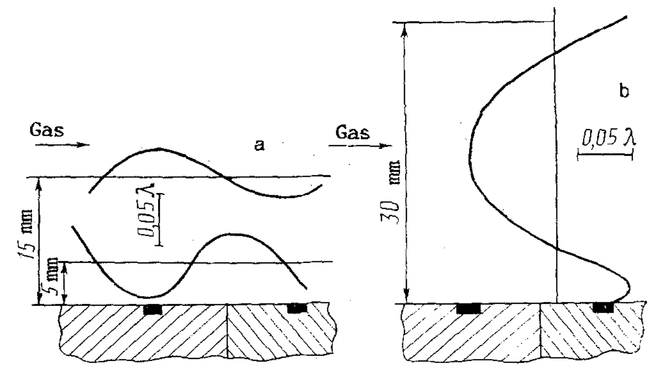

Fig. 3. Wave front cross sections according to the results of processing Talbot-interferograms; (a) in longitudinal direction; (b) in transverse direction.

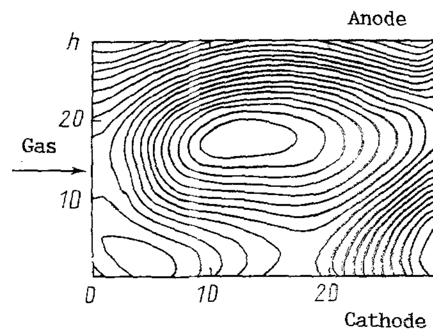

Fig. 4. Wave front phase isolines according to the results of inferogram processing. h, *l*, mm.

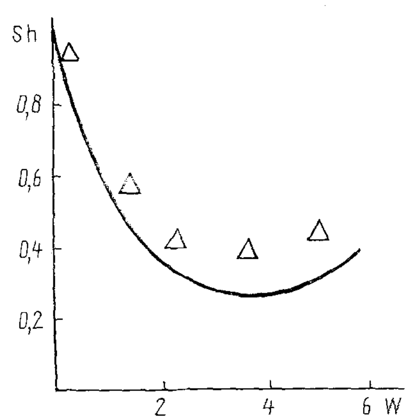

Fig. 5. Sh dependence on the input-energy power density into a discharge; curve – gas-dynamic calculation; points – according to the inferogram processing results. W, MW/m³.

heat source distribution function included two components which defined the regions of background and near-cathode heat evolution. According to [8], the near-cathode potential drop is characterized by a much larger (by approximately two orders) heat release rate in comparison with background heat evolution rate, which made it possible to assign an approximate function for the gas input energy density distribution in the form shown in Fig. 1.

Our calculations allowed us to construct a gas density distribution inside the region of GDC for a continuous and a sectional cathode. In Fig. 2 the isolines of density in GDC are shown. The calculations have shown that there are developed boundary layers, whose thickness grows quickly down stream, and an undertorbed core region in the stream. In a boundary layer, under the conditions of spatial energy input, profiles of gasdynamic parameters are realized which are characterized by the existence of extrem a: a maximum for temperature and velocity and a minimum for density. Besides, the sectioning of the cathode leads to the formation in a boundary layer not only of transverse density inhomogeneities but also of longitudinal periodic perturbations near the cathode plate with the dispersion in their values which is comparable with near-wall distortions in the transverse direction. Thus, these scales must together influence the optical stream quality in GDC. At the same time, an almost linear decrease of the density down stream forms, accompanied by the appearance of an optical wedge-type distortion which, as is well-known, does not degrade the radiation directionality.

For the experimental study of the optical gas medium quality in the GDC channel under the self-sustained glow discharge conditions, the Talbot-interferometry was used [9]; it has a number of advantages such as the possibility of obtaining qualitative information about local angles of wave front inclination along two coordinates and also an acceptable spatial resolution under good vibration stability of the optical scheme. It must be noted that the discreteness of the information representation in Talbot-interferograms made it possible to automate interferogram processing with a subsequent wave front restoration with 0.001 m step in the investigated region, whose size was 0.03×0.03 m. The optical scheme allowed as to detect the part of the stream in the region of GDC between rows 6 and 7 of the knife-cathode elements. In Fig. 3 the wave front cross sections obtained as a result of Talbot-interferogram processing are shown. There are periodical distortions of the phase of the probe radiation near the cathode at the distance of about 0.005 m, the period of which corresponds to the distance between the neighboring knife-electrodes. There is also a periodic phase modulation at a cross section 0.015 m from the cathode plate but with a smaller amplitude. The perturbations in the longitudinal direction (Fig. 3a) are shifted in relation to each other by half a period, which may be explained by their drift due to the incident flow. The transverse wave front cross section (Fig. 3b) has a characteristic form determined by a considerable gas heating in the boundary layer region and by a great heat outflow to the cooled cathode wall. In Fig. 4 the wave front phase isolines obtained from Talbot-interferogram processing in a bored aperture are shown.

A calculation of far-zone radiation diffraction was made to determine the influence of heterogeneities in the investigated medium on optical quality. The wave fronts were fixed according to the results of a gasdynamic calculation and a physical experiment, whereas the values of the phase were increased by 4 times on the assumption of a proportional perturbation accumulation, which corresponds to the medium length along the ray of 1 m. The Shtrel number (Sh) [10] was used as a total criterion of the stream optical characteristic. Undoubtedly, a determination of the optical medium quality dependence on the energy input power into a discharge is of interest. Calculations and experiments have shown that perturbations in a moving gas are minimal (Sh = 1) in the absence of a discharge. When there is an energy supply, a rather sharp degradation of the optical stream homogeneity takes place due to a near-electrode boundary-layer increase and the formation of longitudinal periodic perturbations. The dependence of Sh on the energy input power density into a discharge is shown in Fig. 5. The solid line corresponds to the wave front radiation diffraction obtained by a gasdynamic calculation in GDC and the points denote the Sh values according to the results of interferogram processing. Clearly, the figure shows that the results of numerical modeling agree satisfactorily with the experimental data on evaluating the total heterogeneity level in the investigated medium. A small increase of Sh when the energy inputs are greater then 4 MW/m^3 is apparently connected with a considerable heating and, as a result, with a lowering of optical gas density in the discharge zone. Gasdynamic calculations have also shown that, when the energy input power is increased, a certain heterogeneity smoothing takes place due to a decrease of the overall gas density level.

As a result of our study, we have shown a satisfactory agreement between experimental and calculated data on the levels of heterogeneities in the studied medium in the GDC channel. For energy inputs greater than 2 MW/m^3, an abrupt degradation of the optical quality takes place, so that Sh decreases to 0.5. The most important role is played by the gasdynamic heterogeneities caused by near-electrode boundary layers and by longitudinal periodic density perturbations found numerically and confirmed experimentally. The main cause of all this is connected with the arrangement of knife-electrodes in cathode elements in rows oriented across the stream, near which regions of enhanced heat evolution in the gas are formed. Our calculations showed a considerable increase in the heterogeneity level along the stream, which proves the necessity of optimizing the location of the optical axis for an output-radiation producing system along the GDC length down stream. It is desirable to orient knife-cathode elements with respect to the radiation outlet direction in order to eliminate a longitudinal periodic heterogeneity scale in such a way that the overall average of heterogeneities along the light wave propagation path is the same as was implemented for the nozzle apparatus in [11]. An analogous effect may be achieved when using multipass resonators, where one of the radiation passes in the active medium is oriented at a certain angle relative to the direction of cathode element rows. Our calculations indicate that Sh may increase approximately by 30% as compared with the traditional placement of cathode elements for a corresponding orientation of the rows of cathode elements.

NOTATION

E/N, ratio of electric field intensity to the gas particle concentration; Re, Reynolds number; V_{in}, P_{in}, T_{in}, velocity, pressure, and temperature, respectively, at the GDC inlet; Sh, Shtrel number – maximum of intensity of radiation in the Fraunhofer zone; λ, radiation wavelength ($10.6 \cdot 10^{-6}$ m).

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