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NONSTATIONARY RADIATION-GASDYNAMIC MODEL OF A LASER-PLASMA ACCELERATOR

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Based on the system of two-dimensional axisymmetrical continuity equations, Navier–Stokes and energy equations, and the equations of selective heat radiation transfer, a computational model is constructed and conditions of unsteady subsonic flows in a cylindrical channel of a power unit of the laser-plasma accelerator type are investigated. The governing parameters of the model are calculated, at which numerical solutions can be obtained to describe steady laminar gas flow in the neighborhood of the region of heat release, nonstationary oscillatory motions, and nonstationary vortex motion.

Introduction. A laser-plasma accelerator (LPA) is a power unit in which the energy of laser radiation is converted to the kinetic and thermal energy of a low-temperature plasma flow. Laser-plasma accelerators are subdivided into two groups: LPAs of continuous and pulsed-batch action.

The operation of a continuous-action LPA is based on the phenomenon of a laser combustion wave (LCW) [1] or a continuous optical discharge (COD) [2], respectively, of the subsonic motion of an absorption wave of laser radiation in a gas toward a laser beam and of the steady state of a low-temperature plasma in a focused laser beam (as a rule, of a c.w. CO_2 laser). The fundamental physical feature of these processes is that their implementation needs only a substantial prebreakdown power of the laser radiation that is absorbed in the previously generated plasma. Typical parameters of laser radiation and a COD plasma under laboratory conditions are as follows: c.w. CO_2-laser power 3–5 kW (at a wavelength of 10.6 μm), focal distances 10–20 cm of the optical system, dimensions 0.05–0.1 cm of the high-temperature region (with laser-radiation power, the dimensions of the hot region can also be increased), the working gas is air at atmospheric pressure, temperature inside the hot region 15,000–20,000 K. When the gas is blown through the high-temperature region, a plasma jet is formed, which allows such a unit to be defined as an LPA.

Operation of a pulsed-batch LPA is based on the phenomenon of gas breakdown by the focused laser radiation and the use of the kinetic energy of a shock wave running back from the place of breakdown.

We have analyzed some distinctive features of gas- and plasma-dynamic processes in continuous-action subsonic LPAs. The prime objective of the investigation of LPA parameters is the creation of accelerators possessing prescribed characteristics with the highest efficiency of conversion of the input energy to the kinetic and (or) thermal energy of a plasma jet. The main parameters determining their efficiency are the wavelength and power of laser radiation, the dimensions of the focusing region (the caustic cross dimension) and of the working chamber, the pressure and composition of the working medium, and the gas flow velocity at the LPA-chamber inlet. Numerous experimental and calculation-theoretical works have established that the steady state of the laser plasma in a gas flow is possible only with quite definite relationships between the parameters indicated [3]. Moreover, there is experimental evidence and some calculation results that testify to the fluctuations of gas-flow parameters initiated by a localized energy release in the subsonic flow [4]. The matter is not elucidated completely since both the statement of the experiments and the obtaining of reliable calculated data need special investigations, the component part of which is the present work.

As has already been mentioned, the the numerical study [4] of subsonic gas dynamics of the regions of intense local heat release placed in an unconfined flow has shown the fundamental possibility of the existence

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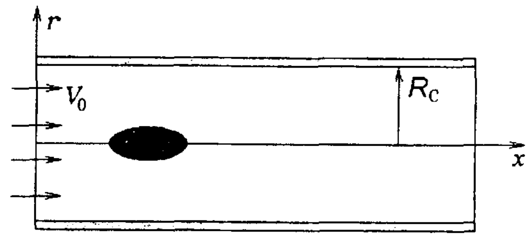

Fig. 1. Calculation scheme with the localized region of energy release.

of the modes of nonstationary oscillatory motion of gases behind the regions of heat release and the occurrence of eddy stationary and nonstationary structures. The phenomenon of spontaneous vortex formation near the energy-release regions, which is of interest from the viewpoint of fundamental gas dynamics, needs further investigations since only provisional calculated data have been obtained.

The phenomenon mentioned seems no less important from the applied viewpoint, too, since such a qualitative change in the flow structure as the transition from the steady to spontaneous unsteady mode and especially the occurrence of eddy structures can exert a strong influence on the LPA characteristics, in the working chambers of which the indicated process occurs. Unlike the regions of energy release in an unbounded channel, in the case of an LPA it is necessary to take into consideration the surfaces bounding the working region. Apparently, under the conditions of subsonic motion this can lead to a qualitative change in the results. Therefore, one of the prime objectives of the numerical analysis made in the present work is investigating the possibility of existence of different flow modes in a space with localized energy release that is bounded with walls. In order to exclude the influence of a possible natural COD oscillation in space [3], in the present work the region of energy release is assumed to be fixed in space and to have parameters which are rather similar to those implemented in the COD.

Formulation of the Problem. A calculation scheme of the problem is shown in Fig. 1. In the axisymmetrical cylindrical channel at a distance x_p from the inlet section is located the center of a hot region with the fixed law of heat release:

$$Q(x, r) = \frac{Q_0}{\pi R_0^2} \exp\left[-\left(\frac{r}{b_r}\right)^m - \left(\frac{x - x_p}{b_x}\right)^m \right]. \tag{1}$$

At the inlet of the calculation region the following parameters of an undisturbed gas flow are prescribed: velocity $\mathbf{V}_0 = (u = V_0,\ \dot{v} = 0)$ and temperature T_0. As a working gas, free air is chosen which is considered to be viscous, heat-conducting, emitting and absorbing thermal radiant energy.

The computational model consists of the following two-dimensional continuity equations, Navier–Stokes and energy equations, and equations of selective heat radiation transfer

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{V}) = 0, \tag{2}$$

$$\frac{\partial \rho u}{\partial t} + \operatorname{div}(\rho u \mathbf{V}) = -\frac{\partial p}{\partial x} - \frac{2}{3}\frac{\partial}{\partial x}(\mu \operatorname{div} \mathbf{V}) + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right] + 2\frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x} \right), \tag{3}$$

$$\frac{\partial \rho v}{\partial t} + \operatorname{div}(\rho v \mathbf{V}) = -\frac{\partial p}{\partial r} - \frac{2}{3}\frac{\partial}{\partial r}(\mu \operatorname{div} \mathbf{V}) +$$

$$+ \frac{\partial}{\partial x}\left[\mu \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right] + 2\frac{\partial}{\partial r}\left(\mu \frac{\partial v}{\partial r} \right) + 2\mu \frac{\partial}{\partial r}\left(\frac{v}{r} \right), \tag{4}$$

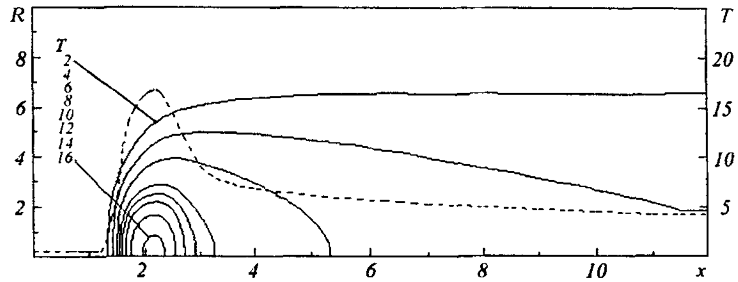

Fig. 2. Temperature distribution at V_0 = 6 m/sec and Q_0 = 5000 W/cm: the solid curves are the isotherms (from 2000 to 16,000 K with a step of 2000 K); the dashed curve shows the axial temperature distribution (the scale is to the right of the figure). R, mm; x, cm; T, kK.

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{V} \operatorname{grad} T = \operatorname{div} (\lambda \operatorname{grad} T) - Q_R + Q , \quad (5)$$

$$Q_R = \sum_{g=1}^{N_g} \kappa_g (U_{b,g} - U_g) \Delta\omega_g , \quad (6)$$

$$\operatorname{div} \left(\frac{1}{3\kappa_g} \operatorname{grad} U_g \right) = - \kappa_g (U_{b,g} - U_g) , \quad g = 1, 2, \dots , N_g . \quad (7)$$

It is assumed that local thermodynamic equilibrium holds. The gas composition is assumed to be in chemical equilibrium at each point of the calculation region at the prescribed temperature and pressure. Because of the small gas velocities the energy equation does not include terms describing the heat release due to gas compressibility.

The computational model employs the real temperature dependences of thermophysical, transport, and optical properties of the hot air in tabulated form (density, heat capacity at constant pressure, dynamic viscosity factor, thermal conductivity, group coefficient of absorption).

Use is made of the following boundary conditions ($f = \{u, v, T, U_g\}$)

$$\text{at } x = 0 : \mathbf{V} = (u = V_0 , v = 0) , \quad T = T_0 , \quad U_g = U_{b,g} (T_0) ;$$

$$\text{at } x = L \ (x \to \infty) : \ \frac{\partial f}{\partial x} = 0 \ \text{ or } \ \frac{\partial^2 f}{\partial x^2} = 0 \quad (8)$$

$$\text{at } r = 0 : \ \frac{\partial f}{\partial r} = 0 , \quad v = 0 ;$$

$$\text{at } r = R_c : \ u = v = 0 , \quad T = T_0 , \quad U_g = U_{b,g} (T_0) .$$

The system of equations (2)-(7) with boundary conditions (8) was numerically integrated by the method of nonstationary dynamic variables [5] aimed at calculating subsonic unsteady flows in the vicinity of regions with an arbitrary density drop.

Results of Numerical Modeling. We have set the following initial data: R_0 = 1 cm; L = 12 cm; coordinate of the center of the energy-release region x_p = 2 cm; b_x = 0.5 cm; b_r = 0.2 cm; m = 2; Q_0 = 5000–10,000 W/cm.

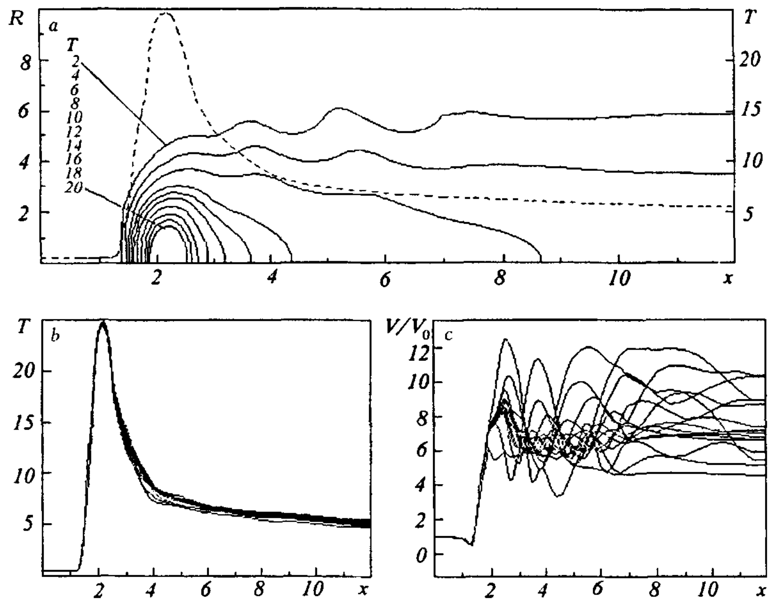

Fig. 3. a) Instantaneous temperature distribution at some fixed instant at V_0 = 20 m/sec and Q_0 = 10,000 W/cm (the solid curves are the isotherms from 2000 to 20,000 K with a step of 2000 K; the dashed curve shows the axial temperature distribution, the scale is to the right of the figure); b) distribution of temperature and c) velocity over the axis of symmetry at successive instants with a step of 1 msec.

Figure 2 shows results of the calculations of a temperature field in the working LPA chamber at V_0 = 6 m/sec and Q_0 = 5000 W/cm. We obtain the steady-state solution at which the distributions of all the gas-dynamic parameters do not change with time. As is seen, the temperature in a plasma jet at the LPA outlet exceeds 4000 K; the radial dimensions of the hot-temperature core of the jet are ~0.2 cm. The plasma jet velocity in the outlet section of the channel attains ~40 m/sec.

At V_0 = 12 m/sec, the calculations have revealed the nonstationary process of fluctuations of the plasma flow velocity behind the region of energy release and of insignificant temperature fluctuations. In this case, the temperature in the plasma jet at the channel outlet attains 5000 K and its velocity makes up 70 m/sec. The amplitude of longitudinal-velocity fluctuations over the axis of symmetry is several meters per second.

A more pronounced oscillatory mode of the flow is obtained with increase in the power of energy release up to Q_0 = 10,000 W/cm and the flow velocity at the inlet up to V_0 = 20 m/sec (Fig. 3). Figure 3a shows the instantaneous configuration of the temperature field. The wavy temperature distribution in a relatively cold part of the jet reflects only some phase of the process of gas-flow oscillations. A complete picture of the oscillations is observed with a successive analysis of the resulting unsteady solution which for the present calculation version can be observed as long as is wished, periodically repeating the same configurations. Some idea of this is given by Fig. 3b and c, in which the axial distributions of the temperature and of the longitudinal velocity component are shown in succession with a time step of 1 msec. In this case, the amplitude of fluctuations of the longitudinal velocity component at the channel outlet is ~40 m/sec at a mean velocity of ~120 m/sec. It is interesting that the amplitude of temperature fluctuations still remains not so great (within ~500 K against 6000–7000 K).

Radical changes in the gas flow structure are observed upon further increasing the velocity V_0 (Fig. 4). At Q_0 = 10,000 W/cm and V_0 = 22 m/sec there occurs the transition from the oscillatory mode of the flow behind the region of energy release to the oscillatory mode of flow with a periodically occurring return vortex when counterflows periodically appear behind the energy-release region. Despite the considerable changes in the gasdynamic structure, in particular, immediately behind the region of heat release, the temperature distribu-

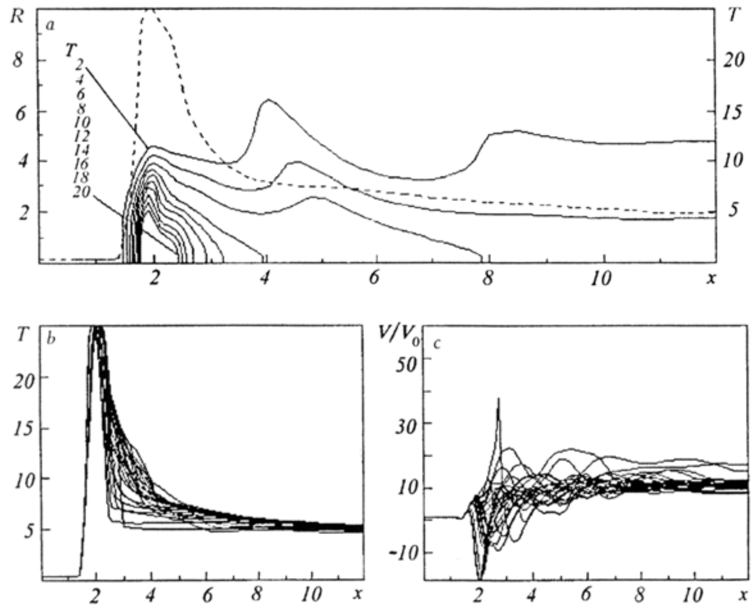

Fig. 4. The same as in Fig. 3 but at V_0 = 22 m/sec and Q_0 = 10,000 W/cm.

tions at the center of the hot region and in the plasma jet at the outlet of the calculated region undergo insignificant changes as compared to the previous version. The velocity at the outlet of the calculation region also bears practically no imprint of the change of flow modes.

Proceeding from the calculated data obtained, we can suggest a method of experimental determination of the existence of eddy motion inside the COD. Behind the region of heat release in the eddy flow there are clearly seen oscillations of the temperature field, which is caused by the fact that in the phase of return flow a substantially colder gas enters the region of energy release, leading to an abrupt temperature decrease. The temperature fluctuations mentioned must cause a periodic change in the emissive power, which can be found experimentally. In the absence of the eddy motion, temperature fluctuations are practically not noticed and, consequently, the emissive power also changes insignificantly with time.

Conclusion. In the present work, the regularities of flow past the regions of intense heat release in a cylindrical channel of a laser-plasma accelerator have been studied numerically.

In the numerical experiments, the following modes of gas flow in the region of local heat release have been obtained: laminar steady flow; laminar unsteady (oscillatory) motion; unsteady (oscillatory) motion with periodic occurrence of eddy structures.

A method of experimental detection of natural oscillations of a gas flow in a high-temperature region is discussed.

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NOTATION

x and r, axial and radial variables; ρ, c_p, and T, density, specific heat capacity at the constant pressure, and temperature; u and v, axial and radial components of the velocity **V**; t, time; p, pressure; μ and λ, dynamic viscosity factor and thermal conductivity; $\Delta\omega_g$, spectral range corresponding to the gth spectral group; κ_g, U_g and $U_{b.g}$, group coefficient of absorption and volume density of the radiant energy of the medium and the blackbody determined by averaging the corresponding spectral characteristics in $\Delta\omega_g$; N_g, number of spectral groups; Q_R and Q, volume power of energy release related to selective heat radiation transfer and prescribed power of energy release; Q_0, power of energy release per unit length; m, even factor of the slope of the energy-release front; $R_0 = b_r$, radius of the energy-release region; b_x, extent of the energy-release region along the x-axis; R_c and L, radius and length of the cylindrical channel.

REFERENCES

1. V. F. Bunkin, V. I. Konov, A. M. Prokhorov, et al., *Pis'ma Zh. Éksp. Teor. Fiz.*, **9**, 609-612 (1969).
2. Yu. P. Raizer, *Physics of a Gas Discharge* [in Russian], Moscow (1987).
3. S. T. Surzhikov and A. A. Chentsov, *Fiz. Plasmy*, **22**, No. 11, 1054-1061 (1996).
4. A. P. Budnik and S. T. Surzhikov, *Unsteady Subsonic Flows of an Emitting Gas. Flow Past the Region of Energy Release in a Free Space*, Preprint No. 2727 of the "FEI" State Scientific Center [in Russian], Obninsk (1998).
5. S. T. Surzhikov, *Mat. Model.*, **7**, No. 6, 3-31 (1995).