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INVESTIGATION OF THE DEFOCUSING PROPERTIES OF A VORTICAL GAS FLOW

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Results are presented of measurements of the focal length of a gas lens formed in a swirling gas flow as well as during combustion of a glow discharge therein. An analytic dependence is obtained to estimate the focal length.

1. At this time several papers [1-3] devoted to the creation of the active medium of a CO_2 laser on the basis of a glow discharge in a swirling (vortical) gas flow have been published. Under the action of centrifugal forces and heat liberation of the discharge in such a flow, the gas density in the central domain turns out to be less than at the circumference. The optical radiation of such a flow in the gas passing along the axis of rotation acts similarly to a scattering lens. The optical strength of this lens must be known for a correct selection of the laser resonator parameters. Moreover, such an apparatus is of independent interest as a gas lens, for instance, to control the radiation of powerful lasers. It is proposed to use a swirling gas flow as a scattering lens in [4]. However, at this time there are neither theoretical nor experimental work in which the optical force of a gas lens of this kind was investigated.

Results are presented in this paper of experiments to measure the optical force of a vortical gas lens and to study its dependence on the vortex flow parameters and the power liberated in the gas by an electrical glow discharge. Theoretical relationships permitting estimation of the parameters of the gas lens that occurs are also represented.

2. Estimates of the focal length of a lenslike gas medium in a self-vacuumizing vortex tube (SVT) without a discharge can be carried out on the basis of the theory proposed in [5]. The dependence of the gas density on the radius in the vortex tube has the following form in a one-dimensional adiabatic flow approximation [5]

$$\rho=\rho_1\left(a+b\left(\frac{r}{R}\right)^2\right)^{\frac{1}{\gamma-1}}, \qquad (1)$$

where

$$a=\left(\frac{1}{\pi}\right)^{\frac{\gamma-1}{\gamma}};\ b=\frac{\gamma-1}{2r_2^4}M^2;$$

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$$r_2^2 = \frac{(\gamma - 1) M^2}{1 - \left(\frac{1}{\pi}\right)^{\frac{\gamma-1}{\gamma}} + \frac{\gamma - 1}{2} M^2}$$

is the radius of vortex separation. Neglecting total pressure losses in the nozzle, π is determined from the expression

$$\pi = \frac{\pi^*}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}},$$

where π^* is the ratio between the total pressure P^* at the SVT entrance and the static pressure on the axis P_{ax}.

Expanding (1) in a power series in the radius and keeping just the quadratic term, we obtain

$$\rho(r) = \rho_0 \left(1 + \frac{1}{\gamma - 1} \frac{b}{a} \left(\frac{r}{R}\right)^2\right),$$

where $\rho_0 = \rho(0)$.

Hence, taking account of the dependence of the refractive index on the density $n = 1 + (n_0 - 1)\, \rho/\rho_0$, we will have

$$n(r) = n_0 \left(1 + \frac{1}{\gamma - 1} \frac{b}{a} (n_0 - 1) \left(\frac{r}{R}\right)^2\right).$$

We here obtain for the focal length of the gas lens of extent L the following expression [6]

$$F = -R \sqrt{\frac{(\gamma - 1) a}{2b (n_0 - 1)}}\, \mathrm{sh}^{-1} \left(\sqrt{\frac{2b (n_0 - 1)}{(\gamma - 1) a}} \frac{L}{R}\right).$$

Expanding the hyperbolic sine in a series and keeping only the linear term, by taking account of the dependence of the gas density at the axis on the pressure and temperature, we obtain

$$F = -\frac{760 (\gamma - 1) a^2}{(2 + (\gamma - 1) M^2)(n_1 - 1) b} \frac{R^2}{LP_{ax}}. \quad (2)$$

The values of the focal length obtained from (2) are a quantity from −100 to −10 m for the SVT dimensions utilized in our experiments and the values of the gas flow velocities that are characteristic for vortex tubes [5].

3. The diagram of the experiment is represented in Fig. 1. The SVT 1 consisting of a 15 mm diameter and 230 mm long cylindrical flow-through part, an input nozzle apparatus in the form of two nozzles with critical section area comprising 0.1 the cross-sectional area of the cylindrical flow-through part, and an output slot diffusor. The SVT diffusor was connected to the vacuum pump 2 of 20 liter/sec productivity. The pressure at the SVT entrance P^* was measured by a vacuum gauge and regulated during the experiments between 20 and 120 mm Hg by using the throttle 3. The pressure on the vortex tube axis was altered by regulating the entrance pressure. The parameter π^* could be changed by introducing hydraulic drag in the evacuation mainline. Two cylindrical electrodes connected to the supply source 4 between which the glow discharge was ignited were mounted along the SVT axis. The flow-through part of the SVT near the nozzle apparatus was connected through the cylindrical electrode of 9 mm inner diameter to a small cavity of the fastening component of a window transparent to radiation. The pressure in this cavity was measured by a gas-discharge vacuum gauge VDG-1 and taken equal to P_{ax}. The difference between the total and static pressures is negligibly small in this case since the gas flow rate near the axis is small. Radiation from the He–Ne laser 5 passed through the chopper 6, the collimator 7, the iris 8 and was divided by the plate 9 into sounding and reference beams. The sounding beam was incident on the iris 10 of 50 μm dimensions mounted near the focus of the spherical mirror 11 after a double pass through the SVT and was recorded by the PD-1 photodiode. The reference beam was recorded by the PD-2 photodiode. The filter 12 equilibrated the reference and sounding beam intensities. The difference signal from the two photodetectors was recorded by the synchronized detection method by using the amplifier U2-8.

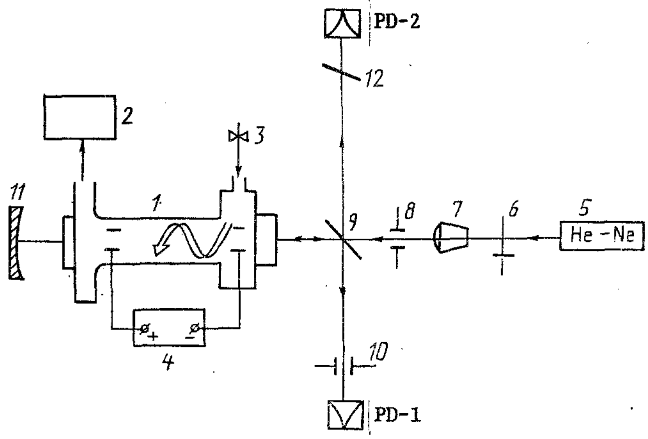

Fig. 1. Diagram of the experimental set up.

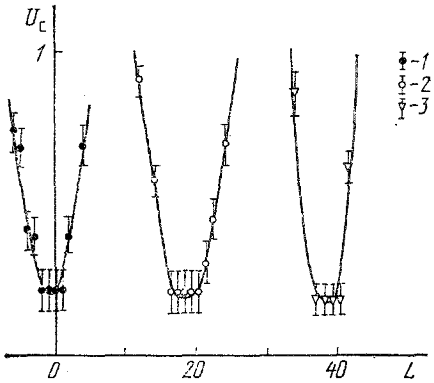

Fig. 2. Dependence of the amplitude of the difference signal from the photodetectors PD-1 and PD-2 on the position of the iris 10 along the sounding beam axis for different P_{ax} pressures: 1) no flow or lens; 2) P_{ax} = 22 mm Hg; 3) 31. U_c, rel. units; L, mm.

The dependence of the amplitude of the signal being recorded on the position of the iris 10 along the sounding beam axis is shown in Fig. 2 for different pressures on the SVT axis. A ~2% change in the intensity here corresponded to the complete changes in the magnitudes of the signal represented in the figure. As is seen from Fig. 2, the method permitted determination of the location of the focus with ±1 mm accuracy when using the magnitude of the focal length of the mirror 11, which was 0.8 m. Let us note that the influence of radiation scattering on the turbulent inhomogeneities of the gas resulted in a negligibly small reduction in the sounding beam intensity.

The shift in the location of the focal point of the optical system consisting of the SVT and the mirror 11 caused by the gas flow from its location in the absence of the gas flow in the SVT was measured in the experiments. The focal length of the gas lens being formed in the SVT was determined from this data. For instance, a ~6 mm shift in the focal point corresponded to a −100 m focal length of the lens. The method described permitted measuring the focal length with a ±15% error.

4. Values of the focal length obtained for the scattering lens formed in the SVT without a discharge are shown by points in Fig. 3 as a function of the pressure P_{ax} on the axis. The quantity π^* is a parameter. As the pressure on the axis increases, the focal length of the gas lens diminishes. Thus variation of P_{ax} between 6 and 26 mm Hg for $\pi^* = 4.1 \pm 0.1$ resulted in a diminution of the focal length from −120 to −13.5 m. As is seen from the figure, an increase in π^* permitted diminution of the focal length. As π^* changes between 2.9 and 4.1 for a constant pressure on the axis, the focal length diminishes approximately two times.

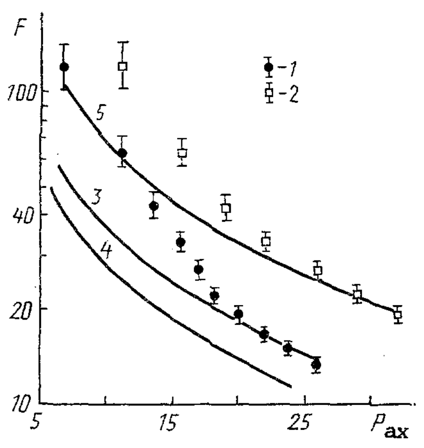

Fig. 3

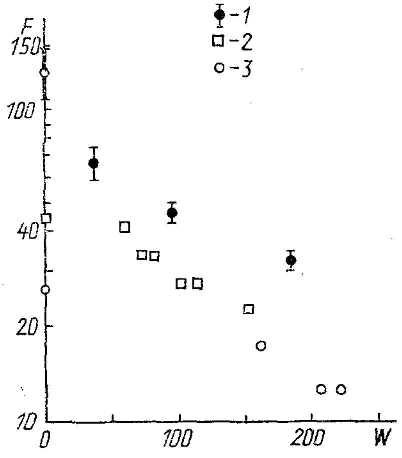

Fig. 4

Fig. 3. Dependences of the focal length of a defocusing lens in the SVT on the pressure P_{ax}. Experiment: 1) $\pi^* = 4.1$; 2) $\pi^* = 2.9$. Computation by (2) for $\gamma = 1.4$; 3) $\pi^* = 4.1$, M = 0.97; 4) 4.1 and 0.79; 1) 2.9 and 0.89. F, m; P_{ax}, mm Hg.

Fig. 4. Dependence of the lens focal length on the electrical power embedded in the positive column of a glow discharge: 1) P_{ax} = 20 mm Hg; 2) 24; 3) 33. F, m; W, W.

Computational dependences determined by the expression (2) are represented by the solid curves in Fig. 3. It is seen that the computation agrees qualitatively with the results of experiment. The existing quantitative discrepancies are apparently due to the simplified nature of the model utilized. The most substantial disadvantage of the model is the assumption of adiabaticity of the flow. In principle, this contradicts the existence of the vortex effect itself that consists in reduction of the gas stagnation temperature in the near-axis domain. It is more correct to use the representation of the process in the vortex tube as polytropic [7]. In this case the adiabatic index γ in (2) must be replaced by the polytropic index. However, as computations showed, the influence of the value of γ on the result is not large and does not result in substantial improvement in the agreement between theory and experiment. The selection of the value of the Mach number M has a stronger effect on the computation results. Curves 3 and 4 are constructed for the values M = 0.97 and 0.79, respectively, that are typical for vortex tubes. The values of M for curves 3 and 5, selected from the condition of best conformity between computation and experiment, correspond approximately to the Mach number dependence on π^* for one-dimensional adiabatic flow [5].

Therefore, the gas density distribution found within the framework of the one-dimensional adiabatic flow model examined in [5] permits estimation of the focal length of the gas lens in the SVT. To obtain better quantitative correspondence, a more complex flow model must be utilized that takes account of damping of the velocity and the jet nature of the flow [8].

5. The influence of a glow discharge on the focal length of the gas lens was also studied in the experiments. Experimental dependences of the focal length on the electrical power embedded in the positive column of a discharge are shown in Fig. 4. The cathode potential drop for a discharge in air and a copper cathode was here taken equal to 370 V [9]. As is seen from the figure, the heat liberation of the glow discharge diminishes the lens focal length. This affords a possibility of regulating the gas lens focal length by changing the discharge current. A change in the energy contribution from 0 to 200 W for pressures P_{ax} between 20 and 33 mm Hg results in a 3-4 times diminution in the focal length.

In these experiments π^* varied between 1.5 and 2.5. Analysis showed that the observed influence of the energy contribution due to the glow discharge on the focal length can be explained when using the approximation of an isotherm vortex and a parabolic temperature distribution near the tube axis. However, the solution is not obtained successfully in explicit form in this case and only a numerical computation is possible.

6. Therefore, magnitudes of the focal length of a scattering lens formed in the swirling gas flow in a SVT were determined experimentally in this paper and varied between −120 and −13 m in the experiments, depending on the flow parameters.

A method of measuring the focal length of long-focus lenses, whose accuracy was no worse than 15% for focal lengths of ~100 m was proposed and utilized. Since the method permits information to be obtained about the gas density distribution in the SVT it can be considered as an instrument for the investigation of swirling flows.

An analytic dependence is proposed that permits estimation of the magnitude of the focal length of a vortical gas lens.

It is shown that the action of a glow discharge burning along the SVT axis on the flow results in a substantial diminution of the focal length of the vortical gas lens.

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NOTATION

R is the radius of the cylindrical part of the SVT; L is the SVT length; r is the running radius; ρ_0 is the gas density on the flow axis; ρ_1 is the gas density on the circumference of the flow; ρ is the running density; P^* is the total pressure at the SVT entrance; P_{ax} is the static pressure on the SVT axis; $\pi^* = P^*/P_{ax}$; γ is the adiabatic index; n_0 is the refractive index for the density ρ_0; n_i is the refractive index of air under normal conditions; and M is the Mach number at the circumference of the flow.

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