EXPERIMENTAL INVESTIGATION OF A CIRCULATING GAS LENS

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The temperature distribution in the focusing tube of a circulating gas lens, with and without a glass filler, is measured and analyzed. The focusing properties of this type of gas lens are evaluated.

During experimental investigations of the thermal mechanisms of certain types of thermal gas lenses, asymmetry was observed of the temperature profiles in them [1, 2]. The cause of this effect is warping of the flow lines inside the lens under the action of the gravitational field. A theoretical analysis of the temperature distributions [3] and optical properties [4] of a circulating gas lens showed that under the action of gravitational forces the thermal and optical axes of the lens are displaced below their geometrical axis. For the purpose of verifying the theoretical propositions, the temperature profiles in the focusing tube of the circulating gas lens were measured and its focusing properties were investigated.

The arrangement for measuring the temperature profiles in the focusing tube of the lens is shown in Fig. 1. The circulating lens was mounted on a support – a "platform" – in such a way that its focusing tube was arranged horizontally. The "platform" was moveable by means of micrometer screws in two mutually perpendicular directions, perpendicular to the axis of the focusing tube. As the lens is symmetrical relative to its central arm, it was sufficient to study only one half of it.

The temperature was measured with a thermocouple with spaced electrodes secured in special holders, which permitted the thermocouple to be pulled into a string. The thermocouple holders and the "platform" with the lens were moved along rails. The diameter of the thermocouple junction did not exceed 5 mm.

The temperature was measured by moving the lens relative to the stationary thermocouple in three directions with an accuracy of 0.1 mm in the vertical and horizontal sections and 1 mm along the axis.

The temperature profiles were measured inside the focusing tubes of two types of lenses. One type of lens was made of metal tubes and the temperature of the focusing tube was maintained constant. The other type of lens was made from glass tubing, the outside surface of which was metallized at specified positions so that only the temperature of the outer surface of the glass focusing tube was found to be constant. Theoretical analysis [3] of the temperature distributions showed that in these cases they should be different from one another.

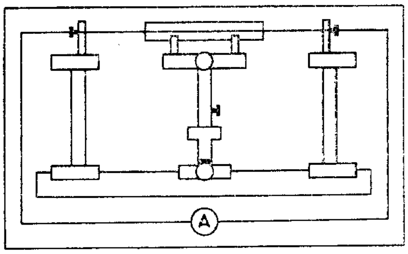

Fig. 1. Arrangement for measuring the temperature profiles in the focusing tube of the lens.

In Fig. 2 the solid lines are the experimental temperature relations for lenses of one or other type in the horizontal (a) and vertical (b) sections of the focusing tubes. The distance, z cm, of the section being studied from the inlet section of the cold gas into the tube serves as a parameter in both cases.

For plotting the horizontal temperature profile of the glass lens, the measurements were carried out in sections every 1 cm apart starting from $z = 0$ (Fig. 2, IIa). In the other cases (Fig. 2,

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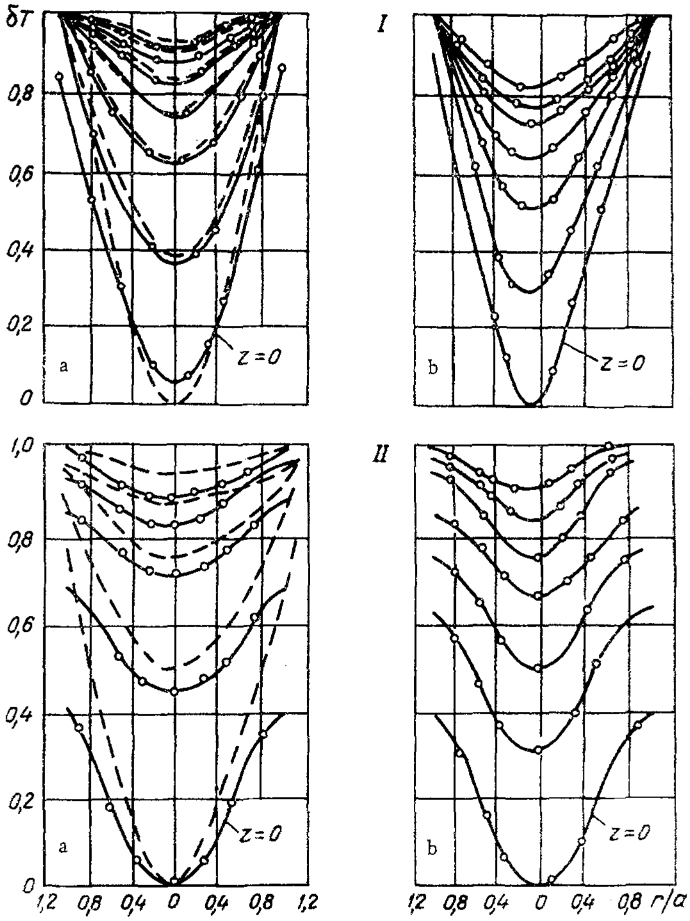

Fig. 2. Temperature distribution in the focusing tube of the metal circulating gas lens (I) and in the glass circulating gas lens (II): a) horizontal section; b) vertical section.

Ia, b and 2, IIb) the temperature was measured in sections 0.5 cm apart, starting from z = 0. The curves are plotted in the relative units:

$$\frac{T_{\text{т}} - T_0}{T_{\text{м}} - T_0} = \delta T\left(\frac{r}{a}\right),$$

where T_T is the measured value of the temperature at a given point, which permitted shape distortion due to change of conditions of the surrounding medium to be eliminated. Both lenses were heated to a temperature of $T_M - T_0 = 30.0° \pm 0.5°$.

In the first place, from visual analysis of the curves obtained, the behavior at the wall is worthy of note. If, in the case of the metal lens, all the temperature curves at the wall converge on one point, which confirms the constancy of the focusing tube temperature, then in the presence of the glass filler the wall temperature in each section of the tube has its own value obviously determined by the temperature distribution in the glass sheath. This circumstance is confirmed theoretically in [3]. The shape of the curves in both cases is similar and in the horizontal sections the curves appear symmetrical relative to the geometrical axis of the tube, but in the vertical sections their asymmetry can be seen clearly, appearing as a displacement of the temperature minimum in the lower half-plane of the section being studied.

For the purpose of obtaining more precise data concerning the nature of the measured profiles, the curves were approximated by power series of the type

$$\delta T\left(\frac{r}{a}\right) = 1 - b_0\left[1 + \sum_{n=1}^{N} b_n \left(\frac{r}{a}\right)^n\right],$$

TABLE 1. Coefficients of Power Series for Horizontal Temperature Profiles

z, cm	b_0 with glass	b_0 without glass	b_2 with glass	b_2 without glass	b_4 with glass	b_4 without glass
0	0	0	—0,7110	—1,4329	0,0338	0,7197
0,5	—	0,3434	—	—0,9480	—	0,2288
1,0	0,4510	0,5783	—0,7522	—1,2038	0,0270	0,2438
1,5	—	0,7048	—	—1,3932	—	0,3483
2,0	0,7165	0,7952	—0,8516	—1,3255	0,0346	0,1255
2,5	—	0,8554	—	—1,2148	—	—0,4741
3,0	0,8711	0,8795	—1,3280	—1,2400	0,0496	—0,6400
4,0	0,8995	—	—1,2695	—	0,0239	—

TABLE 2. Coefficients of Power Series for Vertical Temperature Profiles

z, cm	b_0 with glass	b_0 without glass	b_1 with glass	b_1 without glass	b_2 with glass	b_2 without glass
0	0	0	—0,1073	—0,2233	—0,5975	—1,1156
0,5	0,2952	0,2988	—0,1106	—0,3370	—0,6555	—0,7922
1,0	0,4729	0,4939	—0,1109	—0,1832	—0,7229	—0,9760
1,5	0,6235	0,6402	—0,0684	—0,3037	—0,7680	—0,9503
2,0	0,7349	0,7561	—0,0599	—0,4022	—0,8301	—0,9622
2,5	0,8072	0,7927	—0,0080	—0,3640	—0,9004	—0,9834
3,0	0,8735	0,8476	0	—0,3205	—1,0265	—0,7920

z, cm	b_3 with glass	b_3 without glass	b_4 with glass	b_4 without glass	b_5 without glass	b_6 without glass
0	—0,0675	0,4661	0,0245	—0,2598	—0,2428	0,4160
0,5	0,1176	0,3865	0,0261	—0,7147	—0,0495	0,5069
1,0	0,1921	—0,1766	0,0117	0,2014	0,3598	—0,2253
1,5	0,0815	0,0723	0	0,0225	0,2314	—0,0722
2,0	0,0116	+0,0111	—0,1080	—0,1089	0,3911	0,0711
2,5	0,0032	0,0047	—0,1486	—0,0832	0,3413	0,0667
3,0	0	0,0025	—0,2749	—0,1602	0,2958	—0,0478

such that only the even terms of the expansion were taken into account for the horizontal distributions. Table 1 shows the calculated values of the coefficients for temperature distributions in the horizontal sections and Table 2 similarly shows the coefficients for distributions in the vertical sections. In Fig. 2I and II the corresponding calculated points are denoted by circles. It can be seen that the horizontal distributions in both cases are described sufficiently well by two terms of the series (b_2 and b_4). In order to describe the vertical profiles, N = 4 was found to be adequate in the case of the glass lens and only N = 6 in the case of the metal lens. By comparing the values of the coefficients obtained, it can be concluded that the values of the coefficients b_0 which are similar in magnitude in both cases confirm the identical nature of the heating of the gas stream on the axis of the tube, i.e., the equivalence of the gas stream velocities. This would be expected, as the velocity of the gas stream in the tube is determined by the heating of the tube [4] – by the quantities $(T_M - T_0)$, which differed slightly from one another for the types of lenses studied. In this connection, the difference between the coefficients b_2 to b_6 is noteworthy, which in the case of the metal lens are found to be greater in magnitude for one and the same section and change (except b_2) more sharply with movement from section to section. The asymmetry of the vertical profiles in the metal lens is found to be stronger than in the glass lens. This is explained by the fact that the difference between the maximum (at the wall) and minimum (on the axis) temperatures in each section, which determine the change of temperature through the section, is found to be greater in the case of the metal lens. The coefficients b_2 increase more rapidly in the glass lens but their value in each section, with the exception of the final section, proves to be greater in the metal lens. Consequently, for lenses of identical length the focusing effect of the metal lens will be greater but the distortion of the focused light beam in the lens also will be greater.

It should be noted that, as a rule, all the coefficients defining the aberrations increase toward the center of the focusing section and then decrease. This also is understandable as, at the ends of the focusing tube, the gas temperature is more uniform over the cross section than in its central part, as a result of which distortion of the temperature profiles in these regions of the tube should be less. The theoretical

TABLE 3. Dependence of Focal Lengths on the Temperature and Intensity of Heating of the Lens

No. of lens	ΔT, °C	P, W	F_M	
			geometrical optics	with caustics
1	10,2	1,12	16,7	7,5
	14,7	1,72	11,8	6,5
	19,8	2,48	8,2	6,3
	25,7	3,37	5,7	5,4
	32,9	4,40	4,1	4,1
2	16,8	1,27	19,1	6,0
	23,7	1,71	5,4	5,6
	33,0	2,24	4,3	5,0
3	16,5	1,92	10,6	6,8
	24,4	2,84	5,3	5,3
	30,9	3,6	4,1	4,2
4	19,0	2,36	11,1	6,7
	28,8	3,46	5,5	5,1
	33,9	4,12	4,1	4,2

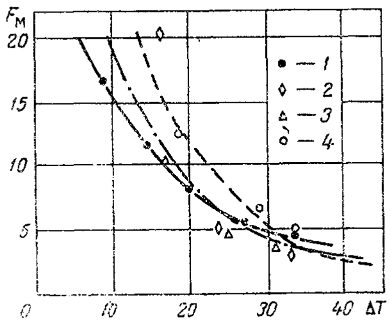

Fig. 3. Dependence of focal length of a circulating gas lens on the temperature (F_M; ΔT, °C): 1) according to data from [1]; 2) [2]; 3) [3]; 4) [4].

formulas found in [3] for describing the temperature distributions are extremely complex in form and, as shown, require the use of a computer for the numerical processing. An attempt was made therefore to construct the temperature profiles by simplified theoretical formulas of the type

$$\delta T = 1 - \exp\left(-\beta \frac{z}{a}\right) \frac{a}{r} M_{\frac{\beta_0^2 + K\beta_0}{4\sqrt{K\beta_0}},\, 0}\left[\sqrt{K\beta_0}\left(\frac{r}{a}\right)^2\right],$$

where the values of β_0 are determined by approximate formulas and for metal and glass are equal to 0.393 and 0.327 respectively.

The curves obtained in these cases are shown in Fig. 2 by dashed lines. It can be seen that the shape of the curves in both cases proves to be close to the shape of the experimental curves. In the case of the metal lens, the agreement between experiment and calculation by the simplified theoretical formula is found to be good. In the case of the glass lens, the simplified formula is found to be inadequate for describing the temperature distribution in the gas medium of the lens focusing tube and, in order to construct the theoretical temperature profiles, it is necessary to use a more accurate formula.

In order to estimate the focusing properties of a circulating gas lens, the energy distribution in the transverse section of the light beam passing through the lens was investigated. Measurements were carried out for four lenses of one type, subjected to different thermal conditions at different distances from the lens aperture. The focusing effect of the lens was estimated in practice by the convergence of the light beam in the region beyond the lens with a known diameter of the parallel beam incident on the lens. The diameter of the convergent beam was determined by the measured curves and then the focal length of the lens was calculated from the geometrical plots. The focal length of the lens was found from the geometrical plots (the focus of the lens is represented by a point on the axis) and also by allowing for the caustics (the focus was assumed to be located in the throat of the caustic).

Table 3 shows the values of the focal length, calculated from the experimental data, for the two cases mentioned and in Fig. 2 II the curve constructed for the geometric case for one of the lenses (No. 1) is shown by the solid line. The experimental values of the focal lengths for the two lenses are shown by points in this same figure.

It can be concluded from Table 3 that the focal lengths calculated by the two methods coincide very well at relatively small values (less than 6 m). With increase of focal length (decrease of temperature of heating) the difference in their values, determined by one or other method, increases as the effect of the diameter of the throat of the caustic becomes significant.

Together with the experimental values of the temperature differentials $\Delta T = T_M - T_0$, the table shows the magnitudes of the power expended on heating the lenses. It should be noted that during the experiment no special measures whatsoever were taken for thermally shielding the lenses. This, in particular, explains the spread of the focal lengths obtained for the various lenses (Fig. 3). Therefore, an averaged experimental curve was plotted for the relation between the focal length of the gas lens and the temperature (chained line in Fig. 3).

As shown in [4] the focal length F of the circulating gas lens can be calculated by the formula

$$F=\frac{8\nu l\lambda}{3ca^2c_p g h_0 \rho_0^2}\cdot\frac{1+\dfrac{\Delta T}{T_0}}{\left(\dfrac{\Delta T}{T_0}\right)^2},$$

obtained as a result of theoretical analysis of the lens. The results of the calculation by this formula are shown in Fig. 3 by the dashed line. It can be seen that the curve coincides with the averaged experimental curve. The slight difference in the curves is explained by the dissipation of energy which is not taken into account by the theory, but this difference decreases with increase of temperature, i.e., with decrease of the extent of the effect of external conditions on the functioning of the lens.

As would be expected, the focal length of the lens decreases with increase of the temperature of heating. In this case, it should be noted that for lenses with large focal lengths – which are of the greatest practical interest – the energy expenditure will be of the order of 1W per lens.

From the point of view of the optical properties of the lens, asymmetry of the temperature distribution in the first place should affect the difference in the values of the focal lengths of the lens measured in the horizontal and vertical planes. Measurement of the shape of the energy distributions, therefore, was carried out both in the vertical and horizontal cross sections of the beam. The procedure used in the experiment did not permit any difference whatsoever to be detected in the shape of the curves and in the value of the focal lengths. This confirms the weak effect of gravitational forces on the optical properties of an individual circulating gas lens.

Thus, the experimental investigation of the temperature profiles in the focusing tube of a circulating gas lens confirmed the symmetry of the temperature distribution in the horizontal cross section and the asymmetry in the vertical cross section. Asymmetry is manifested more strongly in the metal lens than in the glass lens. The effect of asymmetry on the optical properties of an individual lens is insignificant. But if a circulating gas lens is considered in a light-guide system, then from the point of view of the magnitude of the distortions introduced into the shape of the optical beam, it is preferable to use a lens with a glass filler.

NOTATION

T_0	is the absolute gas temperature at entrance to lens focusing tube;
T_M	is the absolute temperature of metal surface of focusing tube;
a	is the internal radius of focusing tube;
r, z	are the radial and longitudinal coordinates of the cylindrical system of coordinates;
g	is the acceleration due to gravity;
$K = gh_0a^3c_p(\rho_1-\rho_2)/4\nu l\lambda$;	
ρ_0, λ, c_p, ν	are the density, thermal conductivity, specific heat at constant pressure, and kinematic coefficient of viscosity of the gas at temperature T_0, respectively;
l, h_0	are the length of focusing section and "height" of lens;
ρ_1, ρ_2	are the density of gas in cross sections z = 0 and z = 1 respectively;
c	is the constant of the Clausius–Mosotti equation.

LITERATURE CITED

1. W. H. Steier, IEEE Trans., MTT-13, No. 6 (1965).
2. Y. Suematsu, K. Iga, and S. Ito, IEEE Trans., MTT-14, No. 12 (1966).
3. F. É. Hertzenstein, Inzh. Fiz. Zh., 17, No. 1 (1969).
4. F. É. Hertzenstein and A. Z. Fradin, Proceedings of the Communications Training Institutes, No. 41 (1968).