An Improved Thermal Gas Lens for Optical Beam Waveguides

By P. KAISER

(Manuscript received September 3, 1969)

The quality of thermal gas lenses can be significantly improved if the heated gas is exhausted radially. This type of exhaust is typically created in a counter-flow lens where opposing gas flows pass through two closely spaced lens sections and exhaust radially through a small gap between these sections. We found that the stability of the focusing behavior depends on a laminar flow transition region of sufficient length, a properly chosen width and shape of the exhaust gap, and on mechanical symmetry and smoothness.

We describe the guiding properties of a single lens as well as a beam waveguide consisting of up to eleven counter-flow lenses. Off-axis injections of the light beam with displacements amounting up to 45 percent of the lens radius resulted only in changes of the beam width (less than 23 percent for 11 lenses), whereas the gaussian profile was essentially maintained.

I. INTRODUCTION

Gravitational and spherical aberrations in thermal gas lenses are known to cause distortions of light beams with gaussian intensity distribution.[1–5] The eventual use of this lens in long distance optical communication links depends in part on our ability to improve its quality and to develop effective beam control devices which periodically free the distorted beam from higher order modes.[6]

By analyzing the severe aberrations of the thermal gas lens reported in an earlier paper in this journal,[4] we found that the axial exhaust of the heated gas was primarily responsible for the low quality of that lens. We demonstrate that a significant improvement of the focusing properties of the thermal gas lens can be achieved if the heated gas is exhausted in the radial direction.

II. CRITICAL APPRAISAL OF AN EARLIER THERMAL GAS LENS

The thermal gas lens used in a recent experiment[4] was highly aberrated and caused severe beam deformations already for small off-axis injections of a light beam into the lens guide. Attempts to decrease the predominantly gravitational aberrations by increasing the flow velocity resulted in instabilities of the focusing action. This was the apparent consequence of residual turbulent motion of a gas flow with nonuniform temperature distribution. We found that the occurrence of flow instabilities was attributable to its construction (see Fig. 1). Exponential inlet and exhaust regions connected the lens elements with a larger diameter spacing tube which served as heat sink for cooling purposes. At higher flow rates, the laminar flow transition tubes preceding the heated lens elements were too short (stable focusing action requires the gas flow to be fully developed and free from residual random motion when it enters the heated lens section). For that purpose the gas has to pass through a tubular transition region with the same inner diameter as the lens and whose minimum length L_t depends on this diameter and the Reynolds number R_e,[7]

$$L_t \geqq 0.04\, dR_e$$

$$R_e = \frac{\langle v \rangle_{av} \cdot d}{\nu}$$

d = lens diameter (=0.635 cm)
$\langle v \rangle_{av}$ = average gas velocity
ν = kinematic viscosity (0.15 cm^2/s for air).

For an air flow rate of 3 liters per minute and for a resulting R_e of 670, the minimum length is at least 27 lens diameters. However, this value is only approximate since the stratification of the flow depends on the particular type of injection used and the initial amount of eddies present. Furthermore, it depends on the degree of beam stability required.

Another reason that focusing fluctuations occurred was the presence of flow separation in the fast expanding exhaust region, which again resulted in a fluctuating temperature distribution. Because of its attractively simple design, we tried to retain the axial exhaust of the continuous flow system, and we attempted to improve its shortcomings. Through the selection of a longer transition tube, laminar flow can be obtained in the entrance region. However, in order to avoid flow separation, expansion of the diffuser behind the lens has to occur very gradually. Eventually the gas is not cooled back to its original temperature by mere heat exchange with an insulated diffuser wall and the diffuser would have to serve as a heat sink as well. During the cooling process the temperature profile becomes distorted. Thus, any cooling

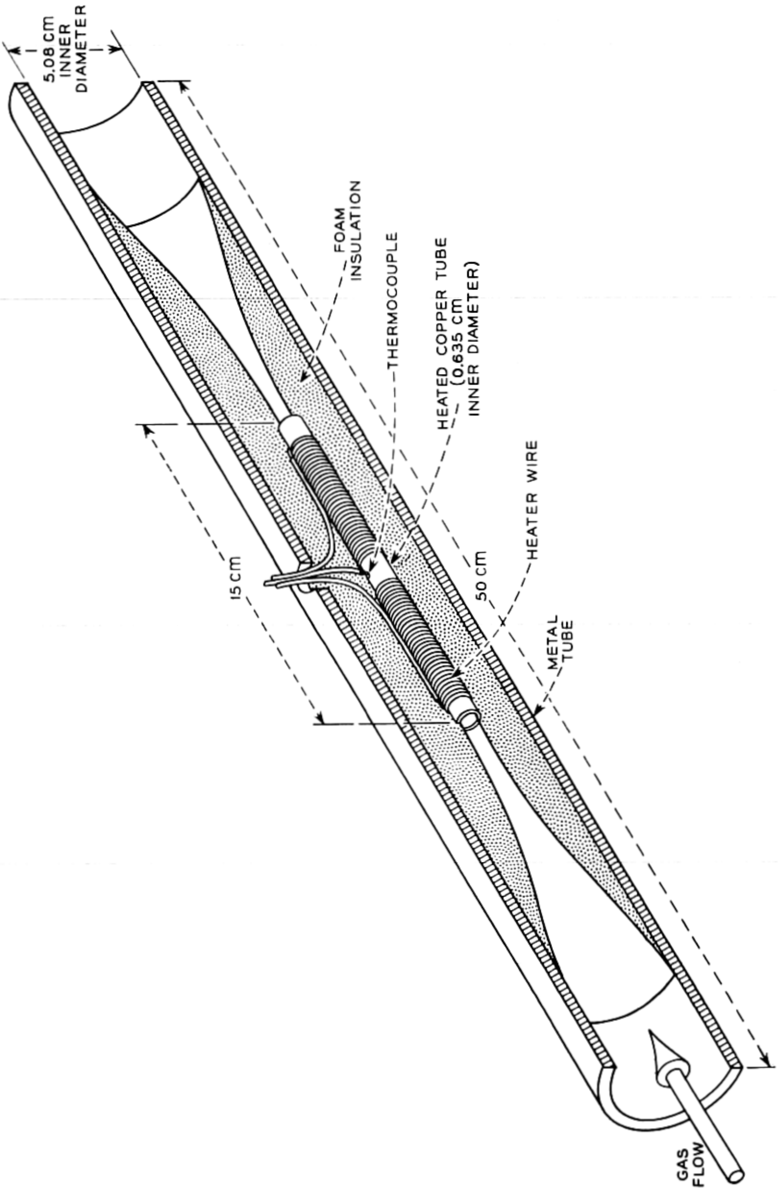

Fig. 1 — Thermal gas lens with axial exhaust.

of the heated gas in the path of the light beam appears to be associated with large aberrations. With our present knowledge, therefore, their practical usefulness seems to be rather limited.

We can avoid the lens deteriorations which are associated with an axial exhaust by exhausting the heated gas radially. This type of exhaust is suitably created through the confluence of two opposing flows in the counter-flow lens (CFL). This lens consists of two tubular lens sections which are separated by a small gap (Fig. 2). Laminar flows of cold gas enter the counter-flow lens from both sides and exhaust through the gap in the center via a free stagnation flow. The flow pattern and optical properties of the counter-flow lens are the subject of the following study.

The possibility of reducing the spherical aberrations of the thermal gas lens by using two such lenses with opposing flows back to back was originally suggested by Marcuse.[1] His theoretical analysis, however, neglected gravity forces as well as effects in the exhaust region. An experimental comparison between a counter-flow lens and a lens of identical length with unidirectional flow, whose radial exhaust at the end of the lens was created with a glass plate, revealed no discernible difference between their focusing qualities. The theoretically proven difference in their spherical aberrations is obviously small and becomes apparent only after the passage of many lenses. Nevertheless, it adds to the attractive features of the counter-flow lens. Berreman had already used the counter-flow principle in his "chimney lens", in which the flow velocity was determined by free convection.[8]

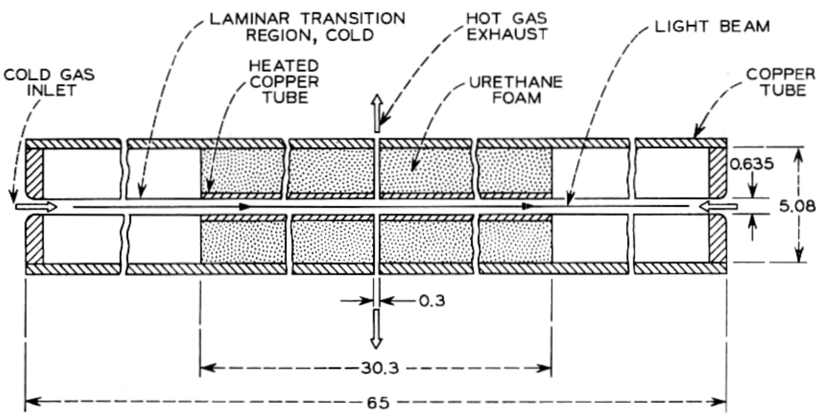

Fig. 2—Thermal counter-flow gas lens with radial exhaust. (All dimensions are in centimeters.)

III. FLOW CHARACTERISTICS OF THE COUNTER-FLOW LENS

The counter-flow lens used in our experiments consisted of two identical lens halves which were mounted independently (see Figs. 2 and 7). Air was injected into the lens from both sides via 5.08 cm diameter porous tubes (2.54 cm long). These were followed by 0.635 cm diameter flow transition tubes and copper tubes of identical diameter. The assembly was surrounded by a 5.08 cm diameter copper tube for mechanical rigidity. The use of porous tubes allowed us to reduce the length of the transition tubes and still achieve laminar flow. Their omission caused unstable focusing and forced us to increase the length of the transition tubes beyond that indicated in Fig. 2. We concluded at this point that we can shorten the transition length by laminar injection of the gas through porous tubes having identical diameters as the transition tube and lens. This assumption proved to be true in later experiments.

In a typical mode of operation, the counter-flow lens is closed on both sides with glass windows in order to prevent leakage of the gas. In a simplified mode of operation, we can omit the windows if we suck air from the surrounding atmosphere into the lens by means of a vacuum pump connected to the exhaust gap. Aside from its simplicity, the latter method allows us to determine the focusing characteristics of the counter-flow lens more accurately and without the interference of end windows. Note that the length of the transition tubes in this case had to be increased to more than twice the length indicated in Fig. 2 in order to avoid beam fluctuations.

A properly chosen width and shape of the exhaust gap proved to be important for avoiding flow instabilities. When the gap was either too small or too large, we observed fluctuations of the focused beam, particularly for slightly misaligned lens halves and asymmetric flows. We observed most stable focusing when the width of the gap assumed approximately the same value as the lens radius. In this case, the radial exhaust area amounted to twice the cross-sectional area of one lens. As might be imagined, the flaring of the inner diameter near the exhaust gap was also noticed to have some influence on the beam stability. Tubes having inner diameters rounded off and with a radius whose value corresponded to that of the wall thickness (1.6 mm) proved to be inferior to a sharp-edged exhaust. But we believe that some rounding of the edges helps to avoid flow instabilities in that region. Similarly, lack of smoothness of the end faces of both lens halves in the exhaust gap was also found to be conducive to instabilities.

As a result of this study, we recognize that flow instabilities pose a major problem in the operation of the counter-flow lens. This is particularly true when we remember a fact well known in the field of fluid amplification: depending on the boundary conditions, the flow in a rapidly expanding channel can assume several flow patterns. Thus, slight perturbations of the flow or the boundary conditions can cause it to change, for example, from an axially symmetric pattern to an asymmetric pattern, or to oscillate between two asymmetric patterns. Therefore, it seems to be advisable to introduce deliberately a certain asymmetry into the exhaust gap. Its specific character must be left to future investigation, but it is desirable that it does not adversely affect the lens quality.

In studying the instabilities, we limited ourselves to low frequent beam fluctuations detectable by visual observation and by an ordinary x-y recorder.

IV. OPTICAL CHARACTERISTICS OF THE COUNTER-FLOW LENS

The counter-flow lens is put into operation by establishing the proper gas flow rate and heating the lens elements to a temperature which yields the desired focal length. The temperature difference between wall and inlet air (at room temperature) was limited to approximately 100°C because the foam insulation (Nopcofoam H402N) could not tolerate higher temperatures.

Coaxial alignment of the counter-flow lens with a slightly diverging gaussian light beam was accomplished with the aid of a photoelectric probe containing a pinhole. The radius of the unfocused beam at the center of the lens was 0.66 mm. Supported by theoretical analysis, we assumed the center of the counter-flow lens to be the location of the principal plane.[1] We measured the profile of the focused beam at an arbitrary distance of approximately 4 meters from the lens with the aid of an automatic recording system, consisting of a motor-driven photosensor with a pinhole, movable in two perpendicular directions, an amplifier, and an x-y recorder.

The focal length was determined by a substitution method: The half power width of the focused beam was compared with that of a set of glass lenses with known focal lengths. These were placed into the beam instead of the counter-flow lens, yielding a calibration curve beamwidth versus focal length. The focal length f as function of the temperature difference ΔT between wall and inlet air for different flow rates F (with $F/2$ flowing in either lens half) is shown in Fig. 3.

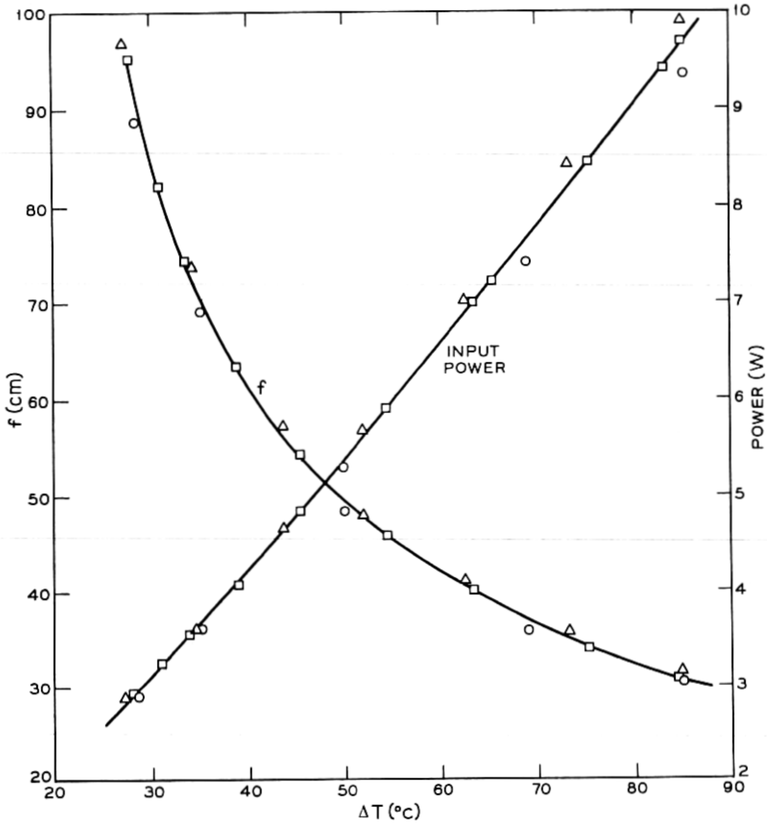

Fig. 3 — Focal length and power consumption of the counter-flow lens as function of the temperature rise for different air flow rates, F. (○ — 5.25 L/min; □ — 5.75 L/min; △ — 6.25 L/min.)

We selected the respective flow rates because we found them to be associated with smallest aberrations as we will see below. We notice that at above values the focal length is essentially independent of the flow rate and depends mainly on the temperature rise. Theoretical analysis[9] has shown that also without the consideration of free convection effects, minimized focal length distortions coincide with flow rates for which the focal length assumes minimum values.

The power consumption P of the counter-flow lens increases as function of the flow rate as shown in Fig. 3. For a focal length of 0.40 m, the required input power was 7.08 W ($F = 6.0L$/min, $\Delta T = 61.8$°C).

The same temperature difference without gas flow requires an input power of 2.48 W. The difference of 4.60 W is thus necessary to heat the gas. The theoretical value for the heat transferred to the gas at above ΔT is given by[10]

$$P_{th} = \pi k L \, \Delta T \frac{v_o}{V} \left[1 - 0.820 \exp \left(-7.316 \frac{V}{v_o} \right) \right]$$

with

k = thermal conductivity of gas
L = length of one heated lens element
v_o = maximum gas velocity

$$V = \frac{kL}{a^2 \rho \, c_p}$$

a = lens radius
ρ = gas density
c_p = specific heat at constant pressure

and is calculated to be $4.65W$ ($k = 6.28 \cdot 10^{-5}$ calories/cm second degree, $L = 15$ cm, $\Delta T = 61.8$°C, $v_o = 318$ cm/s, $a = 0.3175$ cm, $\rho = 1.21 \cdot 10^{-3}$ gram/cm^3, $c_p = 0.240$ calories/gram degree).

Making use of the fact that the temperature profile of the gas flow is still maintained for some distance behind the heated tube, we could reduce the power consumption of the thermal gas lens by substituting the latter portion of the heated tubes with insulating tubes.

As mentioned before, for the given geometry, we observed minimized lens aberrations at flow rates near 6 liters per minute. We determined these optimum flow rates in the following way: a gaussian beam was injected into the lens with increasing parallel displacements. Since the focal length in the aberrated gas lens changes with the radius, we used the resulting changes of the beam width as a measure of distortion. Normalized changes of the width as function of off-axis injections for different flow rates are presented in Fig. 4. At flow rates below approximately 6 liters per minute we found pronounced asymmetry for vertically displaced beams due to gravity. At flow rates beyond 6 liter per minute this asymmetry gradually disappeared, but similar symmetric changes of both the vertical and horizontal beam width for growing off-sets indicated the increasing presence of spherical aberrations. Near 6 liters per minute we recorded smallest changes of the width, but still noted a vertical asymmetry.

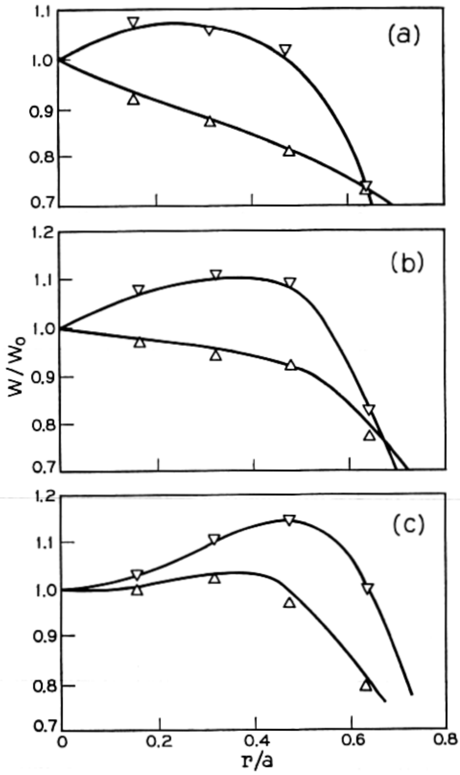

Fig. 4 — Relative change of beam width as function of off-axis injections for beams injected above (△) and below (▽) the optical axis ($f = 0.40$ m, $\Delta T = 62°C$, w_o = on-axis beam width, a = lens radius). (a) $F = 5.5$ L/min; (b) $F = 6.0$ L/min; (c) $F = 6.5$ L/min.

The method of off-axis injection permits us to probe exactly the different portions of the counter-flow lens with their aberrations. A somewhat faster, but less detailed method of determining the optimum flow rate is to focus a comparatively large beam which fills a major portion of the lens's cross section. The distorting influence of the lens aberrations is thus magnified. The beam radius chosen for that purpose was 1.10 mm. The temperature at selected flow rates was adjusted so as to result in a focal length of 40 cm, measured as a constant half power width of the horizontal profile. As a measure of distortion, we used the change of the intensity profile at the 1/10 power point, whereby the profile obtained with a high quality glass lens served as reference (Fig. 5). In case of the asymmetrically focused vertical profile, we considered

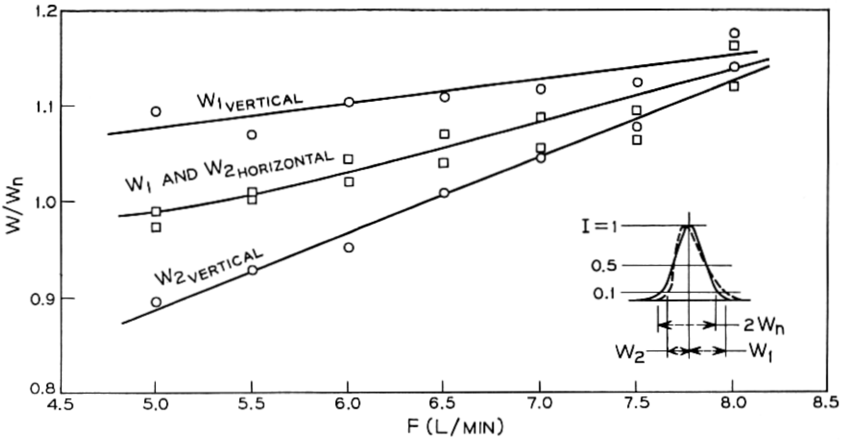

Fig. 5 — Distortion of an oversized beam as function of the flow rate (f = 0.40 m). —— reference beam; — — — — deformed beam; normalized at $I = 1$ and $I = 0.5$ with reference beam.

the changes of the upper and lower half width—counted from the position of the maximum intensity—as a measure of the gravitational aberrations. The approximate symmetric increases for horizontal and vertical profiles at higher flow rates are due to spherical aberrations. As with the method before, the optimum flow rate is again seen to lie somewhere between 5.5 and 6 L/min, where horizontal beam width changes are smallest. Temperature differences and the power consumption at the different flow rates are shown in Fig. 6.

The flow rates associated with minimized total aberrations still have noticeable gravity aberrations which have to be compensated for. For a coaxial alignment of the two lens halves and for the flow rates and temperatures of interest, the difference between the mechanical and optical axes was approximately 0.20 mm. This compares favorably with the 0.5 mm measured with an earlier gas lens with axial exhaust.[4]

If we align the counter-flow lens on its optical axis, the focal length and power consumption are slightly different from those shown in Fig. 3. Note that the optical axis itself depends on the flow rate and the temperature difference.

V. A BEAM WAVEGUIDE COMPOSED OF COUNTER-FLOW LENSES

For the purpose of examining further the flow pattern and the optical properties, we constructed a beam waveguide consisting of up to eleven counter-flow lenses. We supported the lenses in a U-channel in the same fashion as described earlier.[4] The air was supplied by a 2-inch pipe which ran parallel to the guide and had taps with valves as needed (Fig. 7).

The fundamental mode of the beam waveguide was generated in a laser cavity which consisted of a curved ($R = 0.80$ m) mirror and a plane mirror, and a 17-cm-long He-Ne discharge tube with a 2-mm bore. The ideal beam radius at the center of each lens amounted to 0.382 mm.

The first lens was aligned coaxially with the beam at a distance of one lens spacing from the curved mirror. Near the laser, the lens was closed with a flat, antireflection coated window. On the opposite side (behind feed 2; see Fig. 7) the lens was temporarily closed with a glass window for the purpose of establishing air flows in both lens halves. The lenses were then aligned on their optical axes. The temperatures were adjusted such as to produce the same width of the focused beam as that of the original beam after the target was moved farther away from the laser cavity the equivalent of one lens spacing. By doing this for all lenses, we guaranteed periodicity of the guided beam despite variations existing between their mechanical and optical properties. Thereafter the first half of the second lens was connected with feed 2. We used a flexible coupling between the lenses in order to avoid mechanical feedback. After we removed the alignment-probe, we increased the gas flow into the second feed to 6 liters per minute. Since the temperature of the thermal gas lens is sensitive to changes of the flow rate, and since the

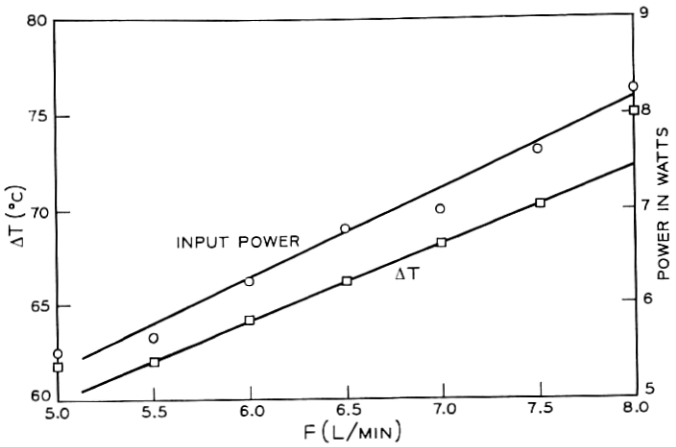

Fig. 6 — Temperature differences and power consumption as function of the gas flow rate for a constant focal length of 0.40 m.

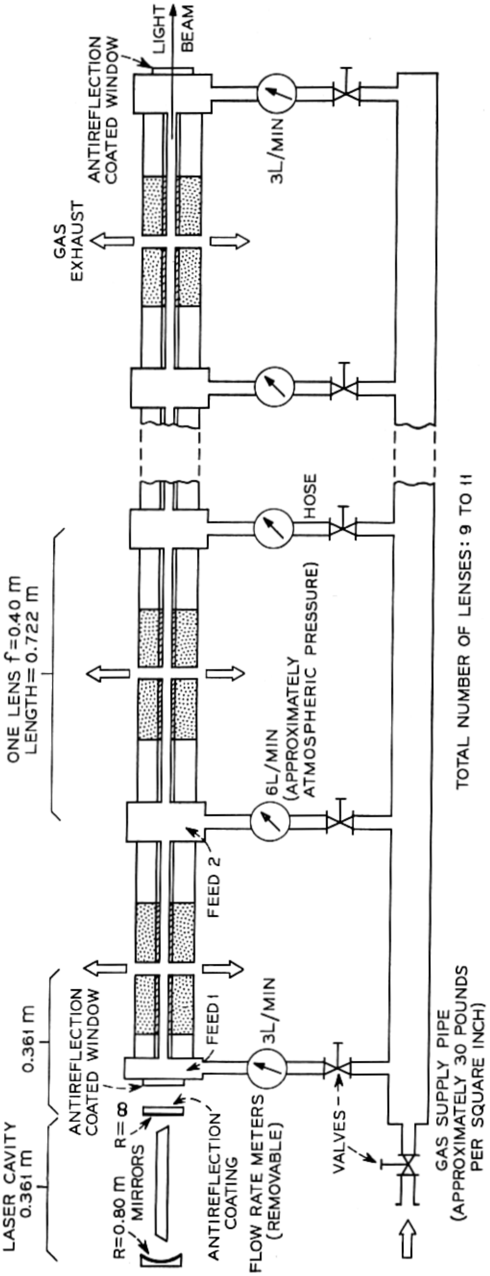

Fig. 7 — Beam waveguide composed of counter-flow lenses.

temperature of the first lens did not change appreciably after the flow into feed 2 was increased, we had an indication for the symmetric subdivision of the total flow into both directions. Subsequently, the second half of the second lens was aligned and the lens put into operation as before. All other lenses were aligned analogously.

The vertical and horizontal power profiles of the on-axis beam after passing eleven lenses, together with profiles of beams which were injected into the guide with increasing parallel displacements are shown in Fig. 8. For beam displacements amounting up to approximately 45 percent of the lens radius (relative off-axis injection: 0.45), the gaussian profile was maintained and only changes of the beam width took place. One notes that the changes of the beam width for vertical and horizontal off-sets are comparable.

Due to the different phase relationships existing between the fundamental and higher order modes at successive lenses, we obtain a more accurate picture of the higher order mode content by comparing the beam profiles after the ninth, tenth, and eleventh lenses of the guide (Fig. 9). After nine lenses, the beam width first decreased for growing offsets, went through a minimum around 0.3, and approached again its original width near 0.45. Then it rapidly increased, and the profile deteriorated for larger offsets. As could be expected from the phase progression of the second order mode, which is mainly responsible for beam width changes, a similar dependence was observed after eleven lenses. Here, the maximum changes of the beam width were in the order of 10 percent for relative offsets smaller than approximately 0.45. Largest changes of the beam width for up to 11 lenses occurred for 10 lenses and were in the order of 23 percent for relative off-axis injections up to 0.45.

In Fig. 10 we show relative changes of the beam width for a sequence of 10 gas lenses, and also for a single lens with axial exhaust for comparison (see Fig. 1 and Ref. 4).

VI. CONCLUSIONS

The focusing properties of a thermal gas lens with radial exhaust were shown to be distinctly superior to those of a lens with axial exhaust. Laminar flow transition tubes of sufficient length and a properly chosen width and shape of the exhaust gap resulted in a flow pattern with stable focusing action. It also permitted us to increase the gas flow rate to a value at which the combined gravitational and spherical

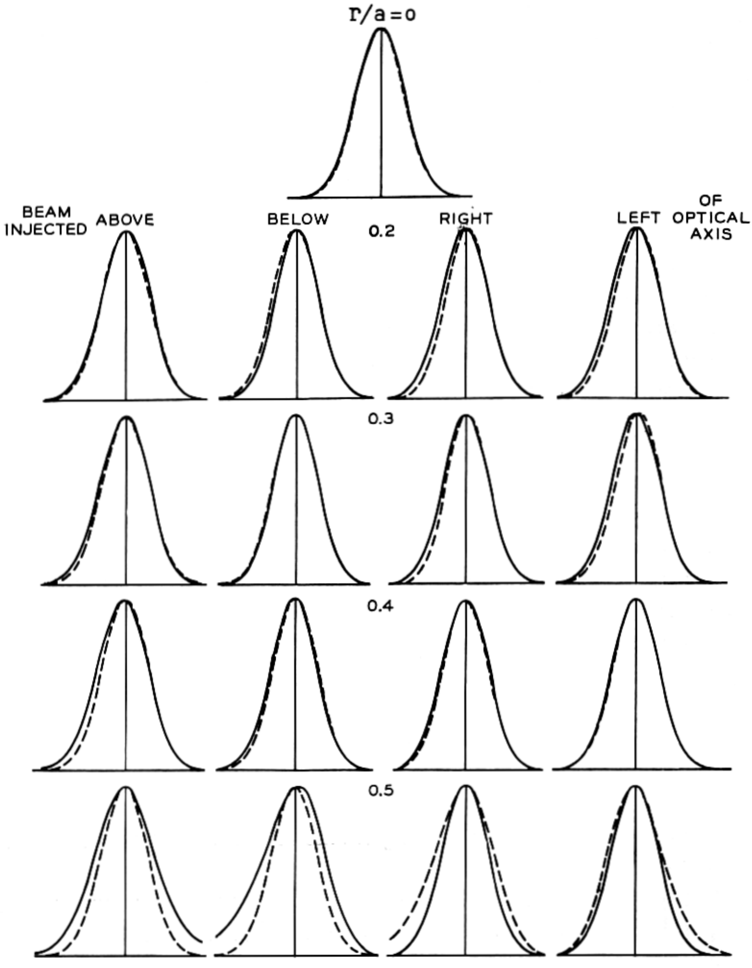

Fig. 8 — Vertical (——) and horizontal (— — — —) power profiles of beams injected off-axis into a beam waveguide composed of 11 counter-flow lenses (f = 0.40 m, distance/focal length = 1.8).

aberrations were minimized. For a total length of the heated lens section of 30 cm (Fig. 2), the optimum flow rate was near 6 liters per minute (diameter of the lens: 0.635 cm). At this flow rate an input power of 7 watts was required to maintain a temperature difference of 62°C between the inlet air and the wall, resulting in a focal length of 0.40 m. An input power of 2.5 watts was required to establish the same wall temperature without gas flow.

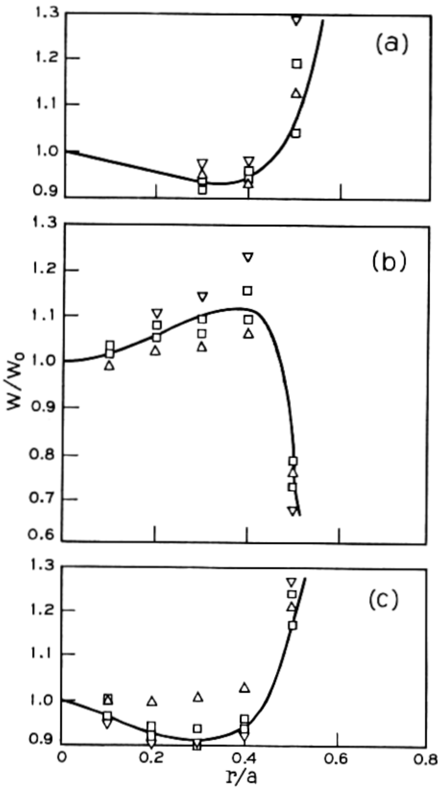

Fig. 9 — Relative change of beam width as function of off-axis injection into a guide composed of (a) 9, (b) 10, and (c) 11 counter-flow lenses ($f = 0.40$ m, $D/f = 1.8$, w_o = on-axis width, a = lens radius). Beam injected above (△), below (▽), and right and left (□) of optical axis.

The guiding properties of a beam waveguide consisting of up to eleven counter-flow lenses were found (focal length 40 cm, lens spacing to focal length ratio 1.8): off-axis injections of the light beam with displacements amounting up to 45 percent of the lens radius resulted only in changes of the beam width (less than 23 percent for up to 11 lenses), whereas the gaussian profile was essentially maintained. In comparison, a beam passing through thermal gas lenses with axial exhaust was completely distorted when injected with similar displacements.

Thus, the counter-flow lens was proven to be a gas lens of superior quality which warrants its use in a lens guide encompassing a larger number of these lenses. In view of this, several improvements and further studies are presently under way which we will report on at a later date.

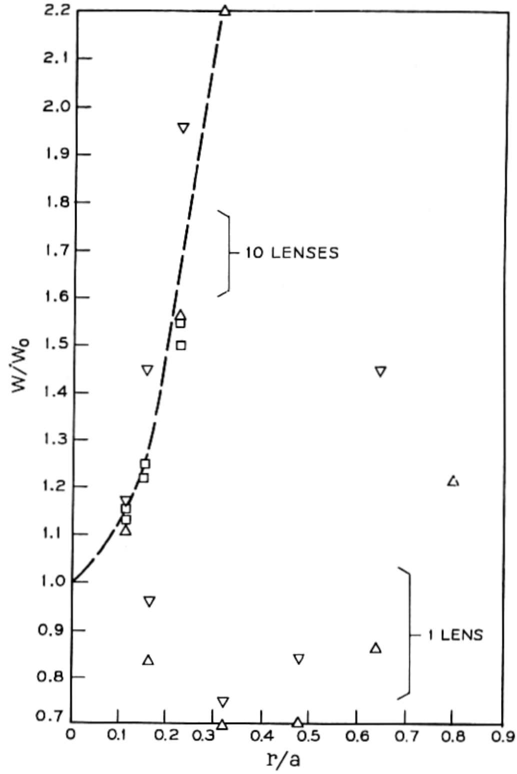

Fig. 10 —Relative increase of beam width for a beam injected off-axis into gas lenses with axial exhaust ($f \cong 0.50$ m, $F = 1.5L$/min, $\Delta T \cong 110°C$). Beam injected above (Δ), below (∇), and right and left ($\Box$) of optical axis.

VII. ACKNOWLEDGMENTS

I gratefully acknowledge the valuable comments and recommendations by E. A. J. Marcatili. I appreciate the assistance of M. D. Divino, who helped in carrying out the experiments. A discussion with I. Pelech helped to clarify some aspects of free stagnation flow.

REFERENCES

1. Marcuse, D., "Deformation of Fields Propagating Through Gas Lenses," B.S.T.J., *45*, No. 8 (October 1966), pp. 1345–1368.
2. Marcatili, E. A. J., "Off-Axis Wave-Optics Transmission in a Lens-like Medium with Aberration," B.S.T.J., *46*, No. 1 (January 1967), pp. 149–166.
3. Gloge, D., "Deformation of Gas Lenses by Gravity," B.S.T.J., *46*, No. 2 (February 1967), pp. 357–365.

4. Kaiser, P., "Measured Beam Deformations in a Guide Made of Tubular Gas Lenses," B.S.T.J., *47,* No. 2 (February 1968), pp. 179–194.
5. Steier, W. H., "Optical Shuttle Pulse Measurements of Gas Lenses," Appl. Opt., *7,* No. 11 (November 1968), pp. 2295–2300.
6. Marcatili, E. A. J., "Effect of Redirectors, Refocusers, and Mode Filters on Light Transmission Through Aberrated and Misaligned Lenses," B.S.T.J., *46,* No. 8 (October 1967), pp. 1733–1752.
7. Schlichting, H., *Boundary Layer Theory,* New York: McGraw-Hill, 1960, p. 171.
8. Berreman, D. W., "Convective Gas Light Guides or Lens Trains for Optical Beam Transmission," J. Opt. Soc. Amer., *55,* No. 3 (March 1965), pp. 239–247.
9. Marcuse, D., "Theory of a Thermal Gradient Gas Lens," IEEE Trans. Microwave Theory and Techniques, *MTT-13,* No. 6 (November 1965), pp. 734–739.
10. Marcuse, D. and Miller, S. E., "Analysis of a Tubular Gas Lens," B.S.T.J., *43,* No. 4 (July 1964), pp. 1759–1782.