Optical Aberrations in Gas Lenses

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ABSTRACT

Gas lenses work on the basis that aerodynamic media can be used to generate a graded refractive index distribution which can be used to focus a laser beam. An example is a spinning pipe gas lens (SPGL). It is a steel pipe whose walls are heated to a preselected temperature and then rotated along the axis to any desired speed to generate a cooler core of incoming air. A laser beam propagating through these lenses is focussed in space. However, experimental observation has shown that distortions are generated in the beam. We provide a computational fluid dynamics (CFD) model of the lens and experimental results of the Zernike aberrations measured using a Shack-Hartmann wavefront sensor which show that the aerodynamic medium in the lens have a deleterious effect on laser beam quality (M^2). The effect on the SPGL is that the beam deterioration increases with rotation speed and temperature though the worst M^2 measured at speed 20 Hz and temperature 155 ºC was ~3.5 which is fairly good.

Keywords: spinning pipe gas lens (SPGL), optical aberrations, beam quality factor

1. INTRODUCTION

Laser beam propagation in random media can be investigated by letting a laser beam propagating through media generated by gases. In this media, random aberrations are generated on the beam wavefront. By studying these aberrations, we can characterize this media measuring these aberrations with a Shack-Hartmann wavefront sensor. The device discussed in this paper is a spinning pipe gas lens which is an open-ended pipe. It is a focusing device which works by establishing a parabolic refractive index distribution in which the density along the cooler axis is relatively higher than that at the hotter margins which are against the heated pipe walls.

The measurements involved are of the beam quality factor, Zernike aberration coefficients and wavefront error. With the Shack-Hartmann sensor, these results are acquired for each frame for more convenient comparison. This means that the beam quality deterioration can be compared to the respective change in aberration coefficients and increment of the wavefront error.

The paper is divided into the following sections. The section that comes first is on how the SPGL works followed by its computational fluid dynamics model. Finally, the experimental results of the investigation of the aberrations generated by the lens as measured with a Shack-Hartmann wavefront sensor are presented. The last section is a conclusion to the paper.

2. THE SPINNING PIPE GAS LENS

The spinning pipe gas lens is a horizontal metal pipe which whose walls are heated to a suitably high temperature and rotated along its axis in the process forming a parabolic refractive index distribution. This profile leads to waveguiding if a laser beam is made to propagate along the axis and for a pipe of the right length, a focused beam behind the pipe can be acquired. It is for this reason this device is referred to as a spinning pipe gas lens (SPGL). Invented in 1975[1], it has been used as for focusing high power lasers[2,3] and as a telescope objective[4]. The aberrations generated by the SPGL were first characterised by a Shack-Hartmann sensor thereby quantifying its aberrations and its focusing capabilities[5-7].

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The SPGL functions on the fact that increasing the temperature of a gas increases its viscosity. As the wall temperature is increased, the viscosity of the gas in the temperature field of the wall goes up as well. As the pipe rotates, it drags with it the layer of air closest to it to co rotate with it which in turn drags the next layer and so on until a warm layer air of thickness of which depends on the temperature of the field. The greater the wall temperature, the thicker this layer is. The centripetal force exerted by the SPGL on gas results in a reactionary centrifugal force by the gas onto the wall. This drives this warm air out of the lips of the pipe since the ends of the pipe are open. This means, to replace the escaping warm air, cooler air form the environment is sucked along the axis making it cooler than the air near the wall. We can then see that the density along the wall is higher than the air in the margins. According to the Gladstone-Dale law, this means that for a SPGL, the refractive index is highest along the axis and experiences a graded decrease on approaching the wall, a density distribution conducive to focusing.

2.1 The computational fluid dynamics model

To fully understand how it operates, a computational fluid dynamics (CFD) model was prepared, based on the k-ε model[9,10], to help illustrate the flow dynamics to establish an understanding between the rotation speed, temperature and the optical changes in the beam. The cross-sectional density distribution of a heated but stationary gas lens is shown to have a density distribution in which a line of symmetry along the centre density which shows that it is affected by gravity as shown in Figure 1 (a). Rotation creates a rotationally symmetric distribution with maximum density at the centre (Figure 1 (b)). This shows that that rotation reduces distortions induced by gravity. From an optics point of view, this means that a laser beam propagating through a stationary pipe is dominated by y-tilt. Rotation reduces this tilt to a minimum and increases defocus until it becomes the dominant aberration.

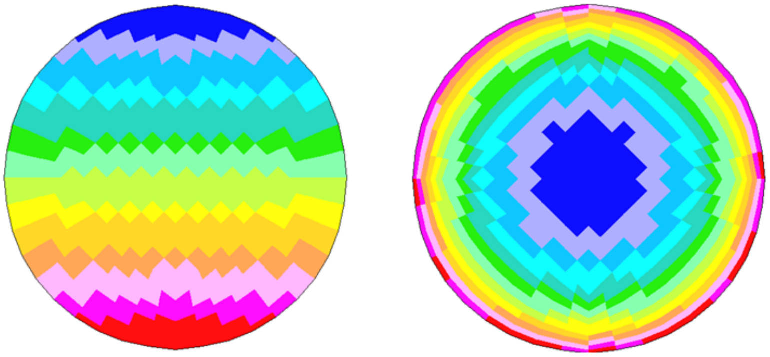

(a) (b)

Figure 1. Cross–sectional density profiles of an SPGL showing: (a) the initial state after heating, and (b) the rotating steady–state near the end face of the pipe, with high density centre (red) and low density edges (blue).

Density distribution data was acquired form the CFD model and used to prepare the graph in Figure 2. It shows the density along the plane which passes through the axis. The graph also shows cross-sections across various planes indicated by the pointers. It shows that the density distribution is indeed parabolic. However, as one gets to the wall, the distribution becomes uniform. This means the distribution becomes fourth order which means that it is a fourth order density distribution with a small fourth order coefficient. What we also observe that the distribution is also not the same longitudinally.

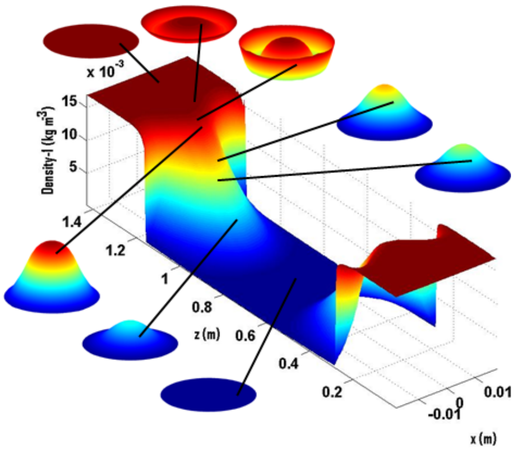


Figure 2. The density distribution of the spinning pipe gas lens calculated from CFD

Looking at the cross-sections confirms that the radial density distribution is not second order but is more likely fourth order which can be approximated by the equation:

$$\rho(r,z) = \beta(z)r^4 + \gamma(z)r^2 + \alpha(z) \tag{1}$$

where β, γ and α are terms which depend on the longitudinal distance, *z*. The fourth order variation means that the phase has a quartic term which means that the other aberration of importance is spherical aberration. The model shows that a small beam, would have only defocus but as the beam size is increased, spherical aberration is increased as the margins of the beam encroach the boundary layer which means the effect of the wall increased. The model shows that the gradient is maximum just inside the pipe from both ends. It is at these two points that β and γ are maximum and where focusing takes place as well.

2.2 Experimental Results

The experiment was carried out to verify this. An expanded HeNe laser beam steered by flat mirrors, is made to propagate through a heated steel pipe of length 1.43 m and inner radius if 1.83 cm. A Shack-Hartmann wavefront sensor was placed just behind the lens and used to measure the beam's quality and aberrations for rotation speeds up to about 17 Hz for the temperatures 351, 373, 400 and 422 K . The schematic for this set up is shown in Figure 3 (a) with the laboratory set up in Figure 3 (b). The spinning pipe gas lens is shown with the Shack-Hartmann wavefront sensor on the extreme left, a cathode ray oscilloscope to measure speed rotation in the forefront and a pair of thermocouples to measure wall temperature to the centre left. The first result in Figure 3 conforms that the SPGL can focus a laser beam. The first image is a graph showing the graph relating rotation speed with focal length at the selected wall temperatures. It confirms that increasing either rotation speed or temperature reduces focal lens. The image beside is a beam spot of a focused laser beam at the focal plane of a lens at wall temperature of 422 K at a rotation speed of 17 Hz.

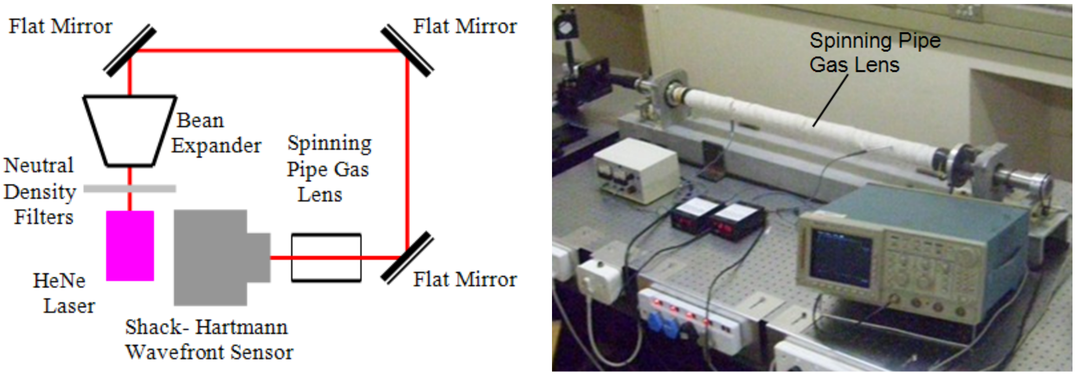
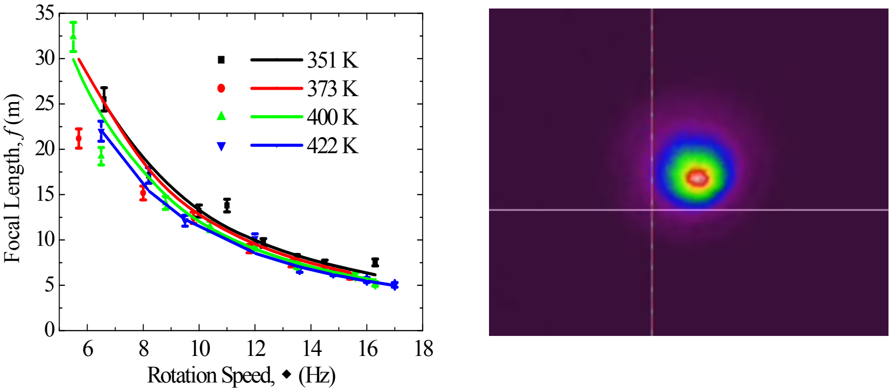


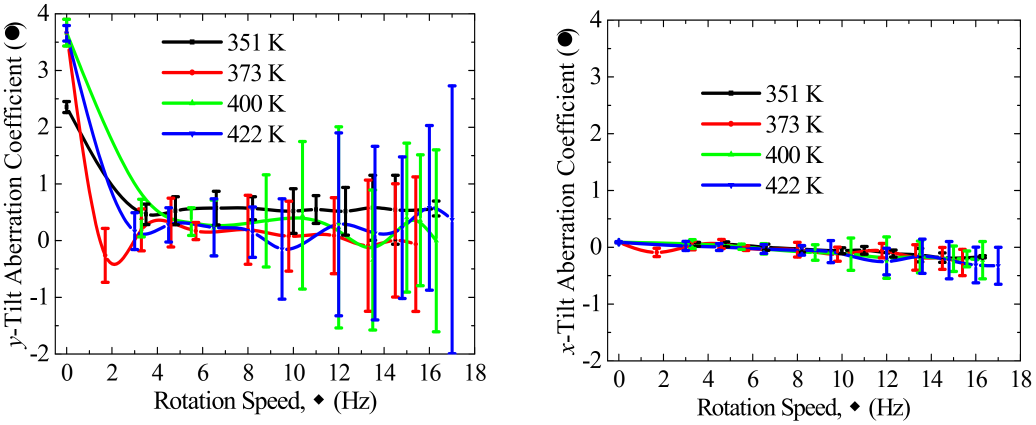
Figure 3. The experimental set up in the form of a schematic (a) and in the laboratory.



(a) (b)

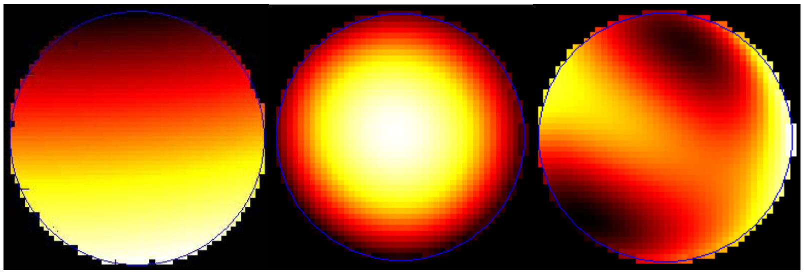
Figure 4. (a) The focal length of the SPGL as calculated from the optical wavefront and confirmed by inspection, and (b) the intensity distribution during rotation ($T = 422$ K).

The next result confirms the fact that rotation removes distortions which are caused by gravity by the way in which by the way in which *y*-tilt which is induced by gravity is reduced to a bare minimum (Figure 4 (a)). On the other hand *x*-tilt remains almost invariant and very small at about 0 λ. (Figure 4 (b)).



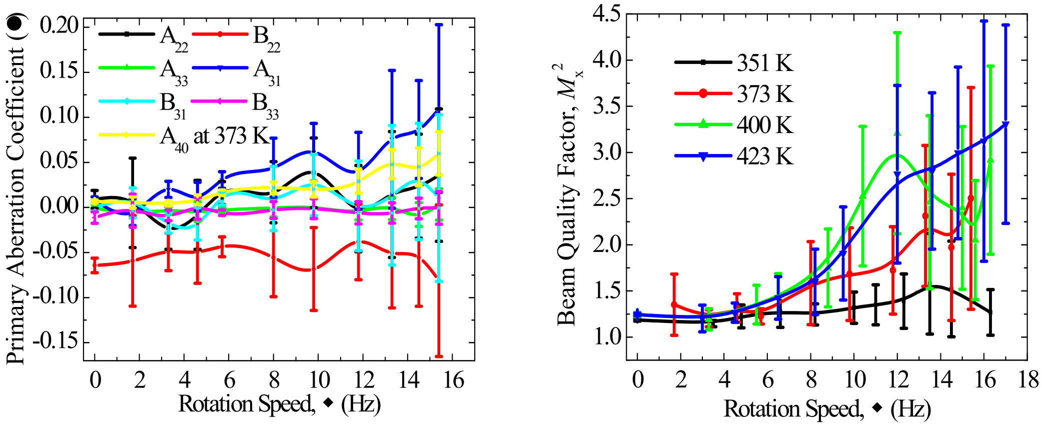
(a) (b)

Figure 5. (a) *y*–tilt and (b) *x*–tilt generated by a spinning pipe gas lens at selected wall temperatures and rotation speeds.



(a) (b) (c)

Figure 6. The phase distribution of the laser beam with: (a) no rotation but heated to 422 K, showing tilt; (b) after rotating the SPGL at 17 Hz, showing significant curvature on the wavefront; and (c) same conditions as in (b) but with defocus and tilt removed, revealing the higher order aberrations.



(a) (b)

Figure 7. (a) Higher order aberrations introduced by the SPGL; (b) increase in M_x^2 with rotation speed and temperature as a direct result of the aberrations in (a).

Study of other aberrations shows that these increase in size as rotation speeds and/or temperature is increased (Figure 7 (a)) thereby increasing the beam quality factor, M^2 (Figure 7 (b)). These are the aberrations responsible for deterioration of beam quality.

3. CONCLUSION

We have discussed the SPGL which uses gas which is heated indirectly heated. The spinning pipe gas lens has been with us for a while. It has a fairly long focal length (minimum ~5m) that can be varied but has the distinct advantage that it produces focused beams of good quality (maximum of 3.5). Beyond this paper the door is now open for better design of these lenses leading to even shorter focal lengths and better beam qualities and possible application.

REFERENCES

[1] Born, M. and Wolf, E. 1999 [Principles of Optics: Electromagnetic theory of propagation, interference and diffraction of light 7th Ed] Cambridge University Press, Cambridge 517-553 (1998).

[2] Mahajan, V. N., [Optical Imaging and Aberrations, Part I: Ray Geometrical Optics] SPIE Press (1998).

[3] Martynenko, O. G., "Aerothemooptics" International J. of Heat and Mass Transfer. 18, 793–796 (1975).

[4] Michaelis M. M., Notcutt M., and Cunningham P. F., "Drilling by a Gas Lens Focused Laser", Opt. Comm. 59, 369–374 (1986).

[5] Michaelis M. M., Kuppen M., Forbes A., Viranna N., and Lisi N., "Progress with gas lenses", Laser and Particle Beams 14, 473–485 (1996).

[6] Michaelis M. M., Dempers C. A., Kosch A. M., Prause A., Notcutt M., Cunningham P. F, and Waltham J., "Gas lens telescopy". Nature 353, 547-548 (1991).

[7] Mafusire, C., Forbes, A., Michaelis, M. M., and Snedden, G "Characterization of a spinning pipe gas lens using a Shack-Hartmann wavefront sensor", Laser Beam Shaping VIII, Ed. F. Dickey, Proc. SPIE., **6663** 6663H (2007).

[8] Mafusire, C., Forbes, A., Michaelis, M. M., and Snedden, G "Optical aberrations in a spinning pipe gas lens", Opt. Exp., 16 (13) 9850-9856 (2008).

[9] Mafusire, C., Forbes, A., Michaelis, M. M., and Snedden, G "Spinning pipe gas lens revisited", SA. J. Sc., 104.

[10] Davison, L., "An Introduction to Turbulence Models", Chalmers University of Technology. Downloaded online on 29-01-2010 from: www.tfd.chalmers.se/~lada/postscript_files/kompendium_turb.pdf

[11] Blazek, J., [Computational Fluid Dynamics - Principles and Applications] Ch 7 Elvesier, Oxford (2001).