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Propagation of a cw Laser Beam Through a Moving Stagnation Zone

M. C. Fowler* and D. C. Smith†
United Technologies Research Center, East Hartford, Conn.

This paper reports the results of an experimental study of the thermal blooming which occurs in a stagnation zone, a region of the propagation path in which there is no net flow of the medium transverse to the laser axis. A stagnation zone results from the cancellation of the relative motion between the laser beam and the air path by a wind and beam slew, and motion of the zone occurs when the latter accelerates. This study considered both stationary and moving stagnation zones and found that their thermal blooming properties can be characterized by a simple expression involving a single parameter whose value is determined by beam and medium properties and encounter kinematics.

Nomenclature

a = laser beam radius at which intensity is e^{-1} of its value on axis
C_p = specific heat of medium
F = ratio of beam radius at beginning of range to radius at target for the undistorted beam
f = focal length of thin lens created by absorption of laser energy by medium
I_r = ratio of maximum intensity of bloomed beam to that of undistorted beam
ℓ = length of medium
N_L = stagnation zone thermal blooming parameter
P = laser power
R' = distance from stagnation zone center to beam focal spot
t = elapsed time
x_0 = speed of cell base
x_ℓ = speed of cell top
y = position of stagnation zone center
z = propagation distance in the medium
α = medium absorption per centimeter
δz = thickness of thin lens
μ_T = temperature coefficient of refractive index of medium
ρ = medium density
ω = laser beam slew rate

Introduction

THE propagation of cw laser energy from its source to the target through the atmosphere is hindered by thermal blooming which results when atmospheric constituents absorb a fraction of the beam energy, heating the atmosphere, and giving rise to density gradients which refract and spread the beam, thereby reducing its intensity on the target.[1] Mechanisms which serve to reduce these gradients also reduce the severity of the thermal blooming problem, and the presence of a wind transverse to the beam axis is known to alleviate thermal blooming.[1] The wind may be a background one, being constant in magnitude over the range from laser to target, or be generated by the slewing motion of the beam as the laser tracks a moving target. Slew generated wind is directed opposite to the slew direction and is zero in magnitude at the laser, increasing linearly along the range until the target is reached. In some situations, the background wind and the slewing motion can be in the same direction with the net wind being zero at some point along the range, giving rise to a stagnation zone in which the density gradients causing thermal blooming can grow unabated by convective heat transfer of wind and slew. In addition, because of temporal variations in both the laser-target distance and slew rate, a stagnation zone moves axially from one point to another within the range. The effect of such moving stagnation zones on laser beam propagation is the subject of this study.

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*Experimental Physicist, Experimental Optics.
†Manager, Experimental Optics.

Apparatus

Apparatus Kinematics

The apparatus is shown schematically in Fig. 1. The absorption cell is mounted vertically on a plate which is moved normal to the cell axis by an electric motor at speed $\dot{x}_0$. The top of the cell is free to rotate about the pivot point at its base and is coupled to a second electric motor which is fixed to the plate on which the cell is mounted. The speed of the second motor is controlled by a rheostat which can be coupled to the base plate such that the motor speed varies linearly with the base plate position. Thus, the top of the cell can be driven at a time varying speed $\dot{x}_\ell + \ddot{x}_\ell t$ opposite in direction to $\dot{x}_0$. Since motion in the positive direction is considered to be from left to right in Fig. 1, the position y at which the net motion of the cell is zero is given in terms of the cell length, by

$$y = \ell(-\dot{x}_0/\dot{x}_\ell)(1+\ddot{x}_\ell t/\dot{x}_\ell)^{-1} \tag{1}$$

Laser Optical Train

The laser used in this study was a water-cooled CO_2 electric discharge laser, apertured intracavity to ensure oscillation in the TEM_{00} mode. This beam was passed through a telescope which focused it onto the gold-doped germanium detector equipped as shown in Fig. 1 with a 200 μm pinhole. The beam was directed onto the detector by a mirror oscillating about an axis normal to the cell motion. The knife edge shutter used to turn on the laser beam and begin the experiment was located at the focal spot in the telescope to ensure that beam turn-on occurred quickly on the time scale of the experiment. The radius of the Gaussian beam profile, defined as the displacement from beam center at which the intensity is e^{-1} of its value on center, was measured at the telescope using an apertured power meter and at the detector by examination of the scanned intensity profile with the cell evacuated, and this information was used to calculate the beam radius as a function of displacement from the detector.

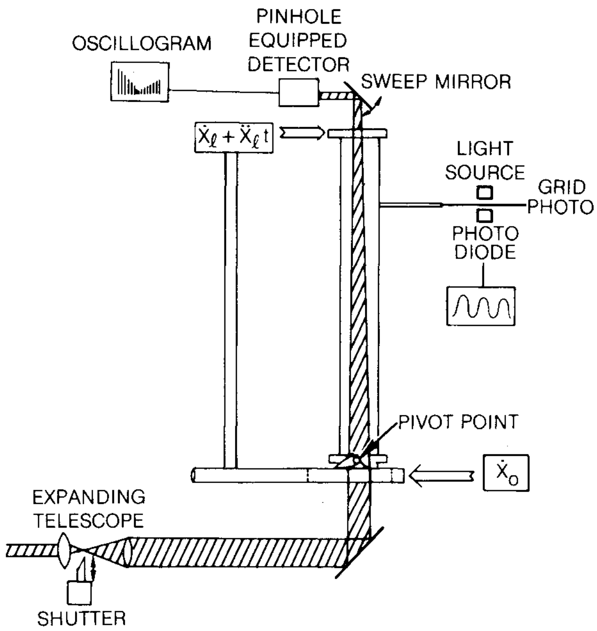

Fig. 1 Apparatus for stagnation zone experiments.

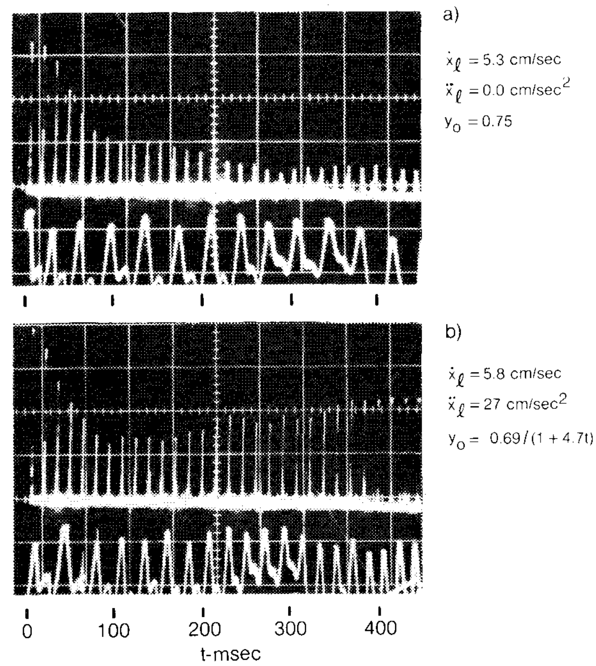

Fig. 2 Measured laser beam intensity propagated through a stagnation zone.

An important quantity in these experiments is the degree of focus, the ratio of the beam radius at the cell entrance window to its value at the exit window. By changing the telescope configuration, the value of F was varied between 4.8 and 1.2.

A second quantity of importance is the product $\alpha\ell$. To vary this, two different gas mixtures were employed. For values up to 0.2, a mixture of N_2 and propylene was used while for a value of 0.45, pure CO_2 was used. For either mixture, the total gas pressure was 10 atm absolute to minimize the role of conduction in determining the thermal blooming properties in the experiment.[2]

Data Characteristics

In a stationary medium, the effect of thermal blooming is to spread the laser power symmetrically about the beam axis, but putting the medium in motion causes the spreading to be symmetric only about the plane passing through the beam axis and parallel to the medium velocity, with the maximum intensity in this plane not always coinciding with the unperturbed beam axis.[1] Since the quantity of interest in the present study was the behavior of this maximum intensity, the data records consisted of sweeping the beam across the detector aperture in the plane described above at a frequency of 166 Hz and observing the variation of the maximum intensity in this plane with $\dot{x}_0$, $\dot{x}_\ell$, and $\ddot{x}_\ell$ for various combinations of F, $\alpha\ell$, and P.

Figure 2 presents the data records of two experimental runs. Each record consists of two traces. The top trace in each case is the detector output as a function of time. This output appears as a series of spikes, each of which represents a sweep of the beam across the detector face as described above. The bottom trace represents the output of a GE H13B1 Photon Coupled Interrupter Module, essentially a compact light source and detector, which measures the amount of light at a fixed point through the photograph of a grid of alternating zones of high and low opacity. This grid, as indicated in Fig. 1, is fixed to a point displaced 74 cm from the cell pivot so that x is determined by noting the elapsed time between two maxima in the bottom trace and combining this with the known distance, 0.055 cm, between opacity minima on the film and the knowledge of the position of the film relative to the cell pivot. In Fig. 2a $\ddot{x}_\ell$ is observed to be zero and $\dot{x}_\ell$ has a value of 5.4 cm/s. In contrast, Fig. 2b indicates a value of 5.7 cm/s for $\dot{x}_\ell$ and 27 cm/s^2 for $\ddot{x}_\ell$. For both experiments $\dot{x}_0$ has a value of -4.0 cm/s so that Fig. 2a represents thermal blooming in a stationary stagnation zone situated at 75 cm above the entrance window, and in Fig. 2b the stagnation zone, situated initially 69 cm above the entrance, moves toward the entrance window, reaching a point only 24 cm from the window as given in Eq. (1). It is seen that the laser intensity for these two runs shows a different temporal development, becoming constant at a relatively low value in Fig. 2a but passing through a minimum and increasing markedly in Fig. 2b. The reasons for this temporal development will be discussed in the following section.

Analytical Model

When a medium of length δz positioned at z' along the range absorbs energy from a laser beam of Gaussian intensity distribution, the absorbed energy per unit volume of medium and resulting density decrease exhibits a maximum on the beam axis with the result that the optical path through the medium exhibits a minimum on the axis and increases, to a first approximation, as the square of the displacement from the axis. The medium can then be envisioned as having become a thin lens whose focal length is given by[3]:

$$f = \pi\rho C_p a(z')^4/(\mu_T \alpha P t \delta z) \tag{2}$$

The unperturbed laser beam, propagating along z, has radius a_0 at its origin and converges to a focus at a distance R' beyond z'. The effect of the lens of focal length f is to move the focal point from R' to R_e whose magnitude is given by the thin lens law:

$$R_e = R'f/(R'+f) \tag{3}$$

and thereby to increase the beam radius at a point z_f between z' and R' given by (assuming geometric optics):

$$a'(z_f) = \frac{a_0 R'(R_e + z' - z_f)}{R_e(R'+z')} \tag{4}$$

The quantity of interest is the time behavior of the beam intensity $I(z_f,t)$ at z_f. The temporal variation in $I_r(z_f,t)$, the ratio $I(z_f,t)/I(z_f,0)$, is given by:

$$I_r(z_f,t) = \left(1 - \frac{a(z')(z_f - z')}{f a(z_f)}\right)^{-2} \tag{5}$$

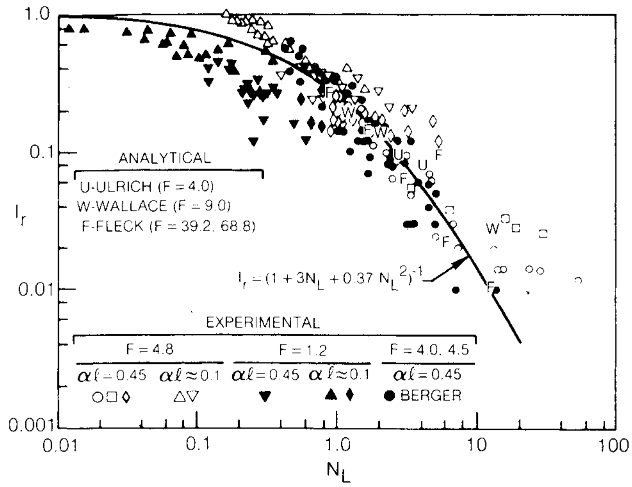

Fig. 3 Stationary stagnation zone results: I_r vs N_L.

Equation (5) predicts that I_r will monotonically approach zero with the elapse of time as f approaches zero. In practice, for a stagnation zone located at z' this is not the case, for convection due to the background and slew generated wind results in clean-out of the medium, first at points farthest from z' and then progressively closer such that the lens can be thought to shrink with time while the density decrease within it continues to increase, and the focal length as a result becomes constant in value after an initial transient. The length of this transient is on the order of a_0/wz_f, where w is the angular velocity of the medium about the stagnation zone and also is the slew rate of the target about the laser.[4] Setting z_f equal to ℓ, the quantity $t\delta z$ in Eq. (2) is therefore replaced by $a_0\ell/\dot{x}_\ell(t)$ where the possibility that $\dot{x}_\ell$ be time dependent is noted implicitly, and Eq. (5) becomes:

$$I_r(z_f,t) = (1+N_L)^{-2} \tag{6}$$

where

$$N_L = \frac{-\mu_T \alpha P \ell^2 F^4 \dot{x}_\ell(t)\,(\dot{x}_\ell(t)+\dot{x}_0)\,e^{-\alpha\ell(-\dot{x}_0/\dot{x}_\ell(t))}}{\pi\rho C_p a_0^3\,(F\dot{x}_\ell(t)+(F-1)\dot{x}_0)^3} \tag{7}$$

and the factor $e^{-\alpha y}$ has been included to account for the attenuation of the laser beam power in the path preceding z'.

Equations (6) and (7) provide in simple form a prediction for the behavior of I_r in stagnation zone experiments after the elapse of the noted transient. When $\ddot{x}_\ell$ is zero, the stagnation zone is stationary, and I_r is expected to assume a constant value consistent with the behavior shown in Fig. 2a. In contrast, when $\ddot{x}_\ell$ is positive so that the stagnation zone moves toward the laser, analysis of N_L (Ref. 4) reveals that in the present experiments I_r is expected to increase as the stagnation zone moves, a behavior consistent with the results shown in Fig. 2b. The quantitative use of N_L in predicting stagnation zone experiments is the subject of the next section.

Experimental Results

Stationary Stagnation Zones

As indicated in Fig. 2a, the value of $I_r(t)$ for a beam propagating through a stationary stagnation zone experiences a transient decay before assuming a constant value whose magnitude is determined by the properties of the medium, the beam and the kinematics determining the zone position in the range. Data was taken for stationary stagnation zones over a range of values for F and $\alpha\ell$ and the post transient value of I_r obtained in these measurements is plotted in Fig. 3 as a function of N_L along with data taken by Berger[5,6] and analytical results obtained by Ulrich et al. as presented by Berger[5] and Fleck.[7] Also shown is the analytical expression

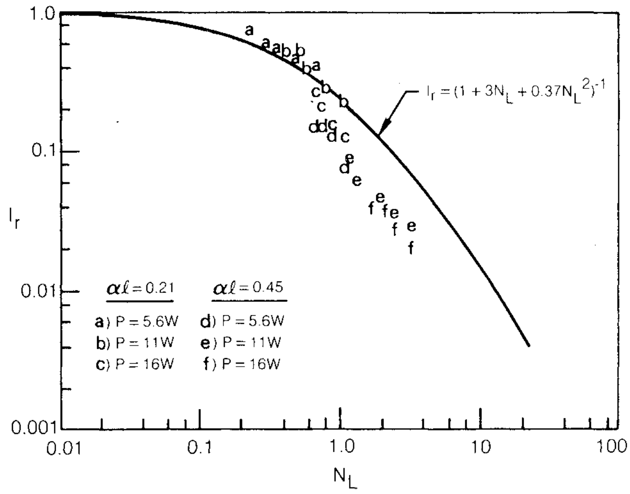

Fig. 4 Moving stagnation zone results. I_r vs N_L: for $\alpha\ell = 0.21$: a) $P = 5.6$ W, b) $P = 11$ W, c) $P = 16$ W. For $\alpha\ell = 0.45$: d) $P = 5.6$ W, e) $P = 11$ W, f) $P = 16$ W.

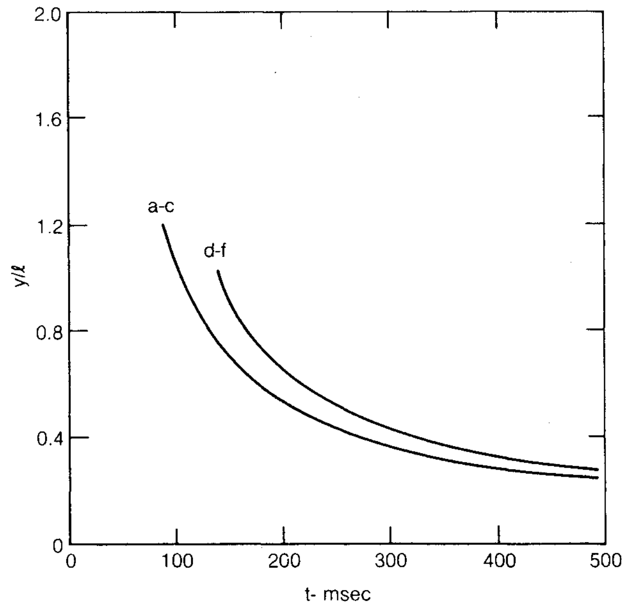

Fig. 5 Stagnation zone kinematics for the experimental results in Fig. 4. y/ℓ vs T. The letters refer to the correspondingly labeled results shown in Fig. 5.

$(1+3N_L+0.37N_L^2)^{-1}$, which is seen to correlate well with the data for I_r between .01 and 1 and N_L between .01 and 10. Although this expression for I_r is not identical with Eq. (7), N_L is seen to be useful in predicting the value of I_r in stationary stagnation zone experiments to within about a factor of two.

Moving Stagnation Zones

It is of interest to see whether N_L is useful in predicting I_r for moving stagnation zones. This was done experimentally by giving $\dot{x}_\ell(t)$ in Eq. (7) the explicit form $\dot{x}_\ell + \ddot{x}_\ell t$. Experiments were carried out for a range of P and $\alpha\ell$ values with the result that N_L was varied by more than an order of magnitude, and the measured I_r value varied over nearly two orders of magnitude. The value of I_r as a function of N_L is shown in Fig. 4 for the moving stagnation zone experiments. The kinematics of y/ℓ in these experiments is shown in Fig. 5 which reveals that the time variation of y/ℓ was essentially the same throughout this set of experiments. The analytical expression for I_r involving N_L, derived from the stationary zone experiments, is also shown in Fig. 4 for comparison with the moving zone results. Although the moving zone results do not lie directly on the analytical curve over the entire range of N_L values covered in the experiments, their departure from this curve is no worse than that of the stationary zone data from which the curve was derived. As a result, we draw the conclusion that, for the encounter kinematics considered in the measurement, I_r, having reached a value corresponding to the steady state value associated with N_L, will change in accordance with the sensitivity of I_r to the time varying value of N_L. It is important to emphasize that I_r is determined by N_L only after a steady state condition is reached. For example, Fig. 5 shows that for times prior to 100 ms, y/ℓ exceeds unity, and there is no stagnation zone in the laser beam. In this case, I_r is given quite accurately by Gebhardt and Smith's thermal blooming parameter N.[1] The data shown in Fig. 4 were all taken at times past 250 ms, leaving a time interval of 150 ms in which the stagnation zone expression for I_r overestimated, by as much as an order of magnitude, the severity of thermal blooming. This interval was seen in the data to be independent of the medium's responsivity, which is proportional to αP, and this fact indicates that the time required to set up the steady state is established by the kinematics of the cell as expressed by setting $t\delta z$ equal to $a_0\ell/\dot{x}_\ell(t)$.

Summary

In this study measurements have been made of the reduction in peak on-target intensity due to thermal blooming in stagnation zones. Measurements were carried out for both stationary and moving stagnation zones. It was found that the stationary zone data was expressible in terms of a single thermal blooming parameter, N_L. The measurements with moving zones indicated that the measured intensity tends to track the stationary zone value as given in terms of N_L with the observed temporal dependence in the intensity being determined by the temporal dependence of N_L.

Acknowledgments

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