FOCUSING PROPERTIES OF A FLAME

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The ability of a gas burner flame to focus light rays is considered. It is shown experimentally that a flame can serve as a short focus cylindrical lens.

Theoretical studies of aerothermo-optical light guides have demonstrated their applicability as optical connection lines [1]. Thermogas lenses have received wide use in experimental light guides. These lenses have focusing distances of the order of tens or hundreds of m. In some cases it is desirable to employ lenses with a much shorter focus. Extremely small focus distances are provided by high temperature gradients. Such a condition occurs in the combustion of a gas flowing out of a cylindrical tube — upon passage through the combustion surface the temperature changes rapidly. Available experimental data [2] indicate that there exists within a flame a region upon passage through which a light beam directed perpendicular to the flame axis will be deflected toward the center. Such deflection is produced by the decrease in the index of refraction occurring upon increase in distance from the flame center. These significant gradients in refractive index, especially on the flame front, create a situation where light rays undergo a deflection which would be difficult to obtain with conventional thermogas lenses.

The possibility of focusing with a flame may be determined as follows. Let the flame be cylindrically symmetrical, $n = n(r)$ (n, index of refraction; r, distance of point considered from flame axis). This fact has good experimental support and is a consequence of small vertical temperature gradients. Using the geometrical optics approximation, we will calculate the deflection of a light beam upon its passage through such a flame. The angle of deflection will be assumed small ($\tan\varphi \approx \varphi$) so that we have ([3], p. 207)

$$\varphi = \frac{2}{n_0}\int_y^\infty \frac{\partial n}{\partial r}\frac{y}{\sqrt{r^2-y^2}}\,dr, \tag{1}$$

where n_0 is the index of refraction of the medium surrounding the flame; y is the distance from the origin to the straight line along which the light beam propagates in absence of flame (the axis of the cylindrical coordinate system coincides with the axis of symmetry of the flame).

For the function n(r) we will take the simplest function which satisfies the most general physical requirements, namely: let $n(r) - n_0$ tend to zero as $r \to \infty$, decrease upon approach to the flame front (in this region the temperature is at a maximum and the index of refraction, a minimum), and tend to zero at the center of the flame ($r = 0$) (for $r = 0$ the gas velocity and also its distance from the front are maximum, and so the temperature is close to that of the medium). To satisfy these requirements we may choose the function

$$n_0 - n(r) = Ar^2e^{-\alpha r^2}, \tag{2}$$

where A is a constant determined by the combustion conditions, pressure, temperature, mixture composition; α is a constant determined by the size of the channel supplying the gas mixture.

In the above derivation we have not considered the effect on the index of refraction of the varying concentrations of gases which participate in and are formed by the combustion process, since this effect is significantly smaller than that of temperature ([4], p. 201). Substituting Eq. (2) in Eq. (1) and

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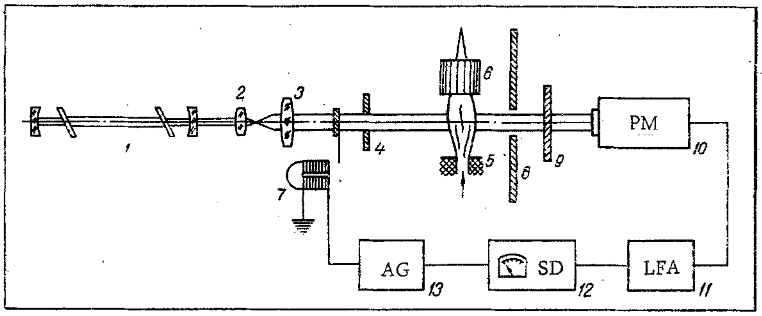

Fig. 1. Block diagram of apparatus for studying focus properties of gas flame: 1) laser; 2, 3) lenses; 4) diaphragm; 5) burner; 6) stabilizing ring; 7) shutter; 8) light shield screen; 9) light filter (or photographic film); 10) photomultiplier; 11) low-frequency amplifier; 12) synchronous detector; 13) audio generator.

calculating the integral, we obtain

$$\varphi = \frac{A}{n_0}\sqrt{\frac{\pi}{\alpha}}\,(1-2\alpha y^2)\,y e^{-\alpha y^2}. \tag{3}$$

The focusing properties of the flame are explained by the presence at small y of a linear segment $\varphi \approx (A/n_0)\sqrt{(\pi/\alpha)}y$, which corresponds to collection of rays with various y values into a single point on the light-beam axis. The distance from the flame center to the focus point f is then determined by the formula

$$f = \frac{n_0}{A}\sqrt{\frac{\alpha}{\pi}}\,. \tag{4}$$

A system was constructed for experimental verification of the above principles and is depicted schematically in Fig. 1. The light beam from laser 1 passes through two lenses 2, 3, which expand the beam to 4 mm. This expanded parallel beam intersects the flame of a mixture of natural gas and air at its base. The flame front is formed as a result of flow of the natural gas–air mixture from the burner orifice. The flame diameter in the region where the laser beam passes is 10 mm. At some distance from the flame is a photographic plate 9, protected from stray light by shield 8. With the aid of the photographic plate intensity distribution over the beam section was recorded.

Evaluation of the attenuation of the beam caused by passage through the burner flame was done with an apparatus using variable light beams. In this case an electromagnetic vibrator 7 was installed in the light path, with winding powered by audio generator 13. The light was thus modulated at a frequency of 80 Hz. In place of photographic plate 9, a red filter was installed to pass the laser beam and attenuate the natural light from the flame. The varying light signal falling upon the photomultiplier tube is converted to an ac voltage which is then amplified by a low-frequency amplifier. Detector 12 performs synchronous detection. The reference voltage is taken from the output of the audio generator feeding the shutter. The detected signal is measured by voltmeter 13.

Figure 2 shows photographs of the laser beam cross section (λ = 6328 Å) with flame off and on. Flame height was 15 cm. The air–gas ratio was chosen such that the flame had a laminar character at its base with blue radiation to a height of 2-3 cm from the base. Above this zone the flame was of a bright-yellow color. The focus point was located at a distance of 3 m from the flame. Measurements showed that light lost by absorption did not exceed 3%.

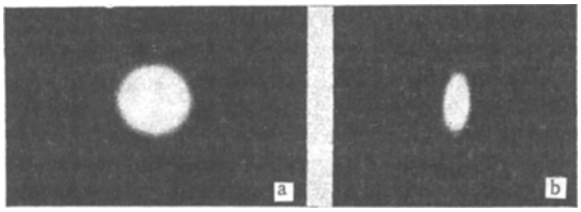

Fig. 2. Photographs of laser beam section: a) without flame; b) with flame.

To calculate the focus distance and determine which zone possessed the focusing properties (the zone in which $\varphi \sim y$), it is necessary to experimentally study the character of light-beam deflection upon passage through various parts of the flame. Figure 3 shows the results of measuring angle of deflection φ as a function of transverse flame displacement y. The solid line of Fig. 3 is the curve

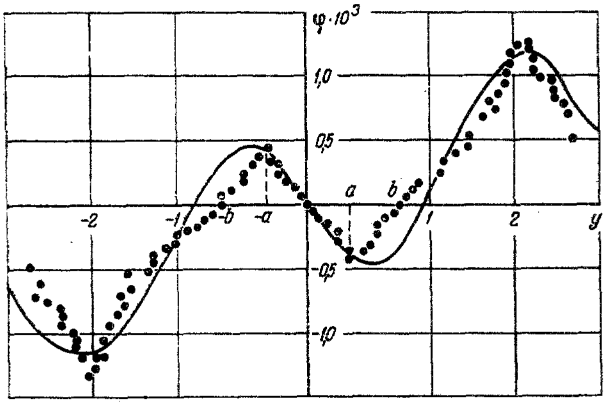

Fig. 3. Angle of laser beam deflection φ versus transverse displacement of flame y. Solid curve, Eq. (3); points, experiment. φ, rad; y, mm.

corresponding to Eq. (3) with constants A and α selected using two experimental points. Measurements were performed with an IAB-451 shadow apparatus using the needle-at-the-focus method [3]. It is evident from the figure that rays passing through the portion of the flame within the y interval from $-a$ to a are focused at one point. The flame segments with $y > b$, $y < -b$ have defocusing properties, while the segments $(-b, -a)$ and (a, b) show strong aberrations.

The above results permit the conclusion that for a light beam whose dimensions do not exceed the internal zone $(-a, a)$ limited by a surface close to the combustion surface, a burner flame can be used as a converging cylindrical lens, while Eq. (3) may be used to determine the focus zone and focus distance of the lens.

LITERATURE CITED

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