Measurement of temperature and temperature profile of an axisymmetric gaseous flames using Lau phase interferometer with linear gratings

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Abstract

In this paper we have investigated the utility of Lau phase interferometer with linear gratings and white light source to measure temperature and temperature profile of an axisymmetric flame. The temperature measured using Lau phase interferometer is in good agreement with the temperature measured with thermocouple and datalogger. Details of theoretical analysis and experimental investigation are presented.

Keywords: Refractive index; Temperature profile; Lau phase interferometer

1. Introduction

Several methods have been suggested for measurement of temperature and temperature profile of the gaseous flame. Some methods are contact type and some are non-contact type. The non-contact type methods do not interfere with the field of the flame and thus they do not cause any disturbance while the temperature is being recorded. Among the non-contact type, optical methods such as holographic interferometry [1–3], moiré deflectometry [4,5], schlieren photography [6], laser speckle photography [7,8], speckle shearing interferometry [9,10] and Talbot interferometry [11–15] have been analysed and used. Holographic interferometry
requires high mechanical stability and the data obtained have to be numerically differentiated, which add to the errors in measurement. Laser speckle photography is relatively less sensitive to vibration and also does not require a prior information regarding the temperature profile. When one uses the moiré deflectometry and a Talbot interferometer with linear grating, the fringe position correction is not required but a prior information regarding the temperature profile direction is necessary for the measurement of temperature distribution. Chandra Shakher and Anil Kumar Nirala [16] have reviewed most of the laser based optical techniques for the measurement of refractive index and temperature profile of a gaseous flame. All these techniques require spatially coherent illumination.

Several authors have investigated the Lau effect in detail. Bartlet and Jahns [17] demonstrated the formation of Lau phase interferometric fringes when the phase object was placed on finite distance between the two linear gratings. Patorski [18] treated the Lau effect as the incoherent superposition of multiple self-imaging. Both the studies mentioned above, considered the case of incoherent illumination where two diffraction gratings are separated by a finite distance along the direction of illumination. Patorski [19] suggested modification to the Lau phase interferometer using the concept of multiple incoherent superposition of Talbot interferometry. He discussed the process of fringe formation when the grating separation distance is infinitely large. This case corresponds to illuminating the second grating by a multiple of mutually incoherent quasi-plane wavefronts.

In this paper, detailed experimental investigation and theoretical analysis to measure temperature and temperature profile of an axisymmetric flame using Lau phase interferometer with linear gratings and white light source is presented. We have optimized Lau phase interferometer by choosing the proper pitch of the gratings and self-image planes to achieve higher sensitivity and better contrast of fringes. From the interferogram, the angle of deflection ($\phi$) is measured and temperature is calculated. Temperature measured by Lau phase interferometer and by thermocouple and datalogger are in good agreement.

2. Theory

The schematic of the Lau phase interferometer as shown in Fig. 1 consists of three identical linear gratings $G_1$, $G_2$ and $G_3$. An incoherently illuminated linear grating $G_1$ and the collimating lens $L_C$ provide a multiple mutually incoherent plane wavefront illumination system. The grating $G_3$ is placed at the self-image plane of grating $G_2$. The phase object is inserted between $G_2$ and $G_3$. The grating $G_3$ is at a distance of $Z_k$ from the phase object. The distortion introduced in the self-images of the grating $G_2$ is proportional to the first derivative of the phase distribution [20,21]. This fringe pattern is due to interference between the distorted self-image of grating $G_2$ and detection grating $G_3$.

Let the distorted self-image of the grating $G_2$ be

$$y + \phi(x, y)Z_k = kp$$ (1)
and the equation representing the grating $G_3$ is

$$y = lp,$$

(2)

where $p$ is the pitch of the grating, $k$ and $l$ are integers representing number of rings from the center. The coordinate axis is shown in Fig. 2. The equation of moiré pattern formed by the superposition of the two gratings is given by

$$k + l = m$$

Subtracting Eq. (2) from Eq. (1), the angle of refraction $\phi$ can be written as

$$\phi = \frac{mp}{Z_k},$$

(3)

where $Z_k$ is the distance between the flame and the grating $G_3$.

Eq. (3) which relates the path of these rays to the local index of refraction is [22] given as

$$\frac{d}{ds} \left( n \frac{dr}{ds} \right) = \nabla n$$

(4)

Solving Eq. (4) for paraxial approximation and for a 2-D axisymmetric object gives

$$\phi = \frac{dy}{dx} = 2\frac{\nu}{n_0} \int_{-\infty}^{\infty} \frac{\partial n}{\partial r (r^2 + y^2)^{1/2}} dr.$$

(5)

The angle of refraction, $\phi$, of a ray passing through the flame is

$$\frac{dy}{dx} = 2\frac{\nu}{n_0} \int_{-\infty}^{\infty} \frac{\partial n}{\partial r (r^2 + y^2)^{1/2}} dr.$$

(6)

Eq. (6) has the form of an Abel transform, whose inverse is [23] gives as

$$\left( \frac{n - n_0}{n_0} \right) = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\phi dy}{(y^2 + r^2)^{1/2}}.$$

(7)

If we know $[n - n_0]/n_0$, we can calculate the temperature by using [22] the following
Fig. 2. Refraction of source light due to refractive index gradient caused by temperature field of the flame.

The equation is:

$$T = \frac{T_0}{(n - n_0)/n_0 - ((3PA + 2RT)/3PA) + 1}$$

where $T_0$ is the temperature at the reference condition for which the refractive index is $n_0$, $P$ is the atmospheric pressure, $R$ is the gas constant, and $A$ is the molar refractivity of air at 550 nm.

3. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A 250 W tungsten halogen lamp is used as an incoherent source. The incoherently illuminated grating $G_1$ and the collimating lens $L_c$ of focal length 250 mm provides a multiple mutually incoherent plane wavefront illumination system. The angular separation between the beams has to be matched to the diffraction angle of grating $G_2$. Bunsen burner flame of liquefied petroleum gas (LPG) is placed after the grating $G_2$ introduces distortion in the self-image of $G_2$, which is proportional to the first derivative of the temperature distribution. A third linear grating identical to $G_1$ and $G_2$ was placed at a distance $Z_k$ (where $Z_k = 680$ mm) from the burner. The sensitivity of the system is determined by the pitch 'p' of the grating and the distance $Z$ between the gratings $G_2$ and $G_3$. If the distance between the gratings is increased to enhance the sensitivity, the measurement accuracy reduces because of the blurring in the fringe contrast. But if the third grating is placed at a distance $Z = np^2/\lambda$, the blurring in the fringe contrast of the gratings diffraction is minimized by optimizing the self-image plane and the pitch 'p' of the grating. The fringes are formed because of the interaction of the distorted self-image of grating $G_2$ with the grating $G_3$. The fringes are recorded on photographic film by inserting a narrow slit in focal plane of
less L₁ as shown in Fig. 1. Fig. 4 shows the photograph of the fringe pattern with Bunsen burner flame. Temperature at different points of the flame is calculated by using Eqs. (6), (7) and (8) in place of Eq. 8.

4. Results

Fig. 3 shows the temperature over the entire volume of the Bunsen burner flame. The temperature profile is calculated by Lau phase interferometer using incoherent light source. Experiment is conducted with three objects: Bunsen burner, candle flame and the soldering iron. Figs. 4, 5 and 6 show the Lau interferometer fringes obtained around Bunsen burner, candle flame and the soldering iron, respectively. The value of the temperature and temperature profile is measured for axisymmetric flame of Bunsen burner LPG flame. To assess the accuracy of the method, the temperature of the LPG burner is also measured with a multilogger and a platinum–platinum–rhodium thermocouple. Good agreement is seen between the temperature values calculated by the Lau phase interferometer and that measured by thermocouple. The variation in the value measured with the Lau phase interferometer and thermocouple is within ±0.2%. Fig. 3 shows the variation of temperature as a function of distance from the center of the flame.

![Graph showing temperature vs. distance from the center of the flame.](image)

Fig. 3. Temperature vs. distance from the center of the flame.
Fig. 4. Photograph of the fringe profiles with LPG using the linear gratings.

Fig. 5. Photograph of the fringe profiles with candle flame using the linear gratings.

5. Conclusion

The Lau Phase interferometer with the linear grating is used to determine the temperature profile of the flame.
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References