SRPioneers
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2nd International Conference on New Frontiers in Physics (ICNFP 2014), 9-11 July 2014, Istanbul, Turkey

Measurement of Convective heat transfer coefficient and temperature distribution around axisymmetric objects using moiré deflectometry technique

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***Abstract*— The spatial temperature distribution and heat transfer coefficient have been measured by moiré deflectometry. This technique can be applied to measure temperature distribution, refractive index of transparent axisymmetric plasmas and for optimum design of instruments.**

Keywords-component; Metrology; Moiré technique;

I. INTRODUCTION

Measurement of temperature distribution around an axisymmetric heated object and its heat transfer coefficient can be used in different works like determination of the temperature profile of burner flames and plasma medium and the heat transfer coefficient from cylindrical tanks.

In several optical methods such as interferometry and deflectometry, temperature distribution is obtained by refractive index gradient or its spatial derivatives [1].Schlieren, shadowgraphy and moiré are deflectometric methods consist in refractive index gradients. Moiré deflectometry is a technique of wave front analysis which in both Talbot effect and moiré technique is applied for measuring and test phase objects or reflection surfaces [2-3].

In the last works, temperature distribution around an axisymmetric heated object was evaluated by interferometric method s [4-5]. Interferometric methods require high mechanical stability and high-quality optical components. They are very sensitive to vibration and noise of environment and inefficient in large refractive index gradient. Their data is analyzed using wave theory.

In this paper, moiré deflectometry method is used in which the equations are interpreted by the ray optics and spatial coherence of probe beam is only essential. This method is not sensitive to environmental vibrations and noises. In large temperature gradient deflectometry methods are more precise.

II. THEORY

Light beam deflection in inhomogeneous medium can be used in study of spatial distribution of that inhomogeneity. The collimated light propagating through phase object is deflected, Fig.1, and imaging lines of grating G_1 on grating G_2 is displaced equals δd . Therefore, moiré pattern displacement in each point with respect to δd equals δd_M . According to Fig. 1, the ray deflection angle can be calculated by:

$$\alpha(y,z) = \frac{\delta d}{Z_k} = \frac{d}{Z_k}\frac{\delta d_M(y,z)}{d_M} \qquad (1)$$

where d and d_M are the pitch of gratings and moiré fringe spacing, Z_k is k th Talbot distance given by kd^2/λ . For an axisymmetric object, the

refractive index can be written in cylindrical coordinate as [1]:

$$n(r,z)-n_f=-\frac{n_f}{\pi}\int_r^{r_f}\frac{\alpha(y,z)}{\sqrt{y^2-r^2}}dy, \qquad (2)$$

n_f is the refractive index of the air(ambience). By numerical solution of this Abel integral, the refractive index distribution is determined. For solution, the integration range is divided into N zones of equal size.

$$\Delta n(r_i)=-\frac{n_f}{\pi}\int_r^{r_f}\frac{\alpha(y)}{\sqrt{y^2-r_i^2}}dy=-\frac{n_f}{\pi}\sum_{j=i}^{N-1}\int_{r_j}^{r_{j+1}}\frac{\alpha(y_j)}{\sqrt{y^2-r_i^2}}dy \qquad (3)$$

To simplify considerations, $\alpha(y_j)=\alpha_j$ and α_j in the each zone is assumed constant. The refractive index gradients are obtained as fallow:

$$\Delta n(r_i)=-\frac{n_f}{\pi}\sum_{j=i}^{N-1}b_{ij}\alpha_j, \qquad (4)$$

Where,

$$b_{ij}=\int_{r_j}^{r_{j+1}}\frac{dy}{\sqrt{y^2-r_i^2}}=Ln\left(\frac{r_{j+1}+\sqrt{r^2{}_{j+1}-r_i^2}}{r_j+\sqrt{r^2{}_j-r_i^2}}\right), \qquad (5)$$

The temperature distribution versus refractive index gradients is equal to:

$$\Delta T=\frac{1}{dn/dt}\Delta n \qquad (6)$$

Where, dn/dt is the thermo- optic coefficient which is $0.927*10^{-6}\ 1/C^{\circ}$ for He- Ne laser light in air. The convective heat transfer coefficient is obtained by temperature gradient on the wire surface:

$$H=-\frac{k_w}{(T_w-T_f)}\frac{dT}{dr}\bigg|_{r=a}, \qquad (7)$$

where r is distance from the wire center, a is the radius of axisymmetric object, T_w , T_f are the wire surface and ambient temperature, respectively and k_w is air thermal conductivity in the wire surface temperature calculated by semi-experimental equation[6] and ambient refractive index n_f can be evaluated by Edlen equation[6].

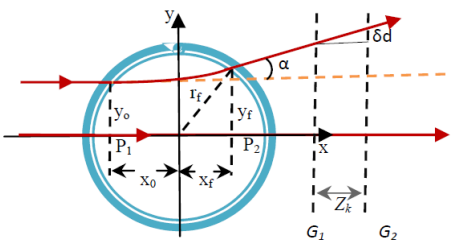

Fig.1. Light beam deflection, passing through phase object and grating G_1 and G_2.

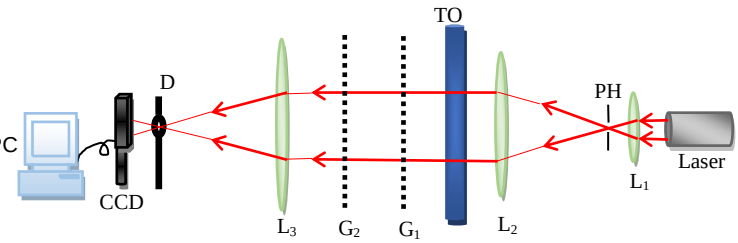

Fig.**2.** Schematic Set-up.L_1, L_2, L_3, G_1, G_2, PH, TO, D, CCD and PC stand for lenses, gratings, pin hole, test object, diaphragm, camera and computer, respectively.

III. Experiments and Results

As shown in the Fig. 2, a He-Ne laser with wavelength 632.8 nm is the probe light source and lenses L_1 , L_2 with 4, 180mm focal lengths and a pin hole with diameter 8 μm are used as a beam expander. For measuring the ray deflection, two gratings with a pitch 0.1mm is applied such that G_2 lies on the 4-th Talbot distance of G1 equals 126.5mm. For eliminating the lines of gratings, a diaphragm placed at the focus of L_3. In the set-up of measurement, Fig.3, by applying 5 volts voltage, the wire as a test object becomes warm and the temperature gradient is created.

By focusing lens L_3 with 180mm focal length, CCD records reference fringes and deflection fringes by temperature gradient that deflection of moiré pattern is obvious, Fig.4. The moiré fringe deflection versus the moiré fringe spacing $\delta d_M/d_M$ is obtained by Fig.4-b in each point of the image. The ray deflection is evaluated from Eq. (1) as illustrated in Fig.5-a. The laboratory temperature, pressure and relative humidity was recorded 21°*C, 650mmHg and 58%, respectively. Therefore ambient refractive index is calculated from Edlen equation* n_f*=1.000231131* .

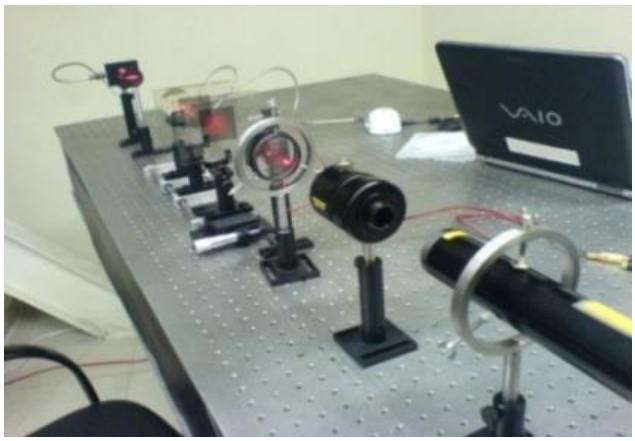

Fig.3. Experimental set-up

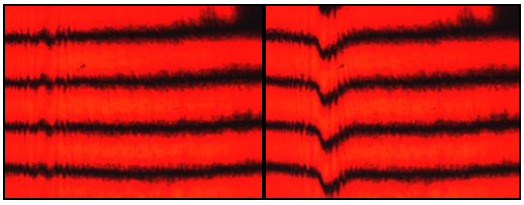

Fig.4. (a) Reference fringes,
(b) deflected fringes by temperature gradient.

The refractive index gradient can be given by Eq.(4) and the refractive index distribution versus distance from the wire center is shown in Fig.5-b. As can be seen, the rafractive index approach to a fix value equal to 1.000231 that is compatible with ambient refractive index n_f=1.000231131. By Eq.(6), the temperature profile versus distance from the wire center is evaluated, shown in Fig.6. As one can see from the plot, temperature on the wire surface is maximum value and equals $89°C$. The convective heat transfer function is given $H = 0.3988 W/m^2.°K$ by Eq.(7).

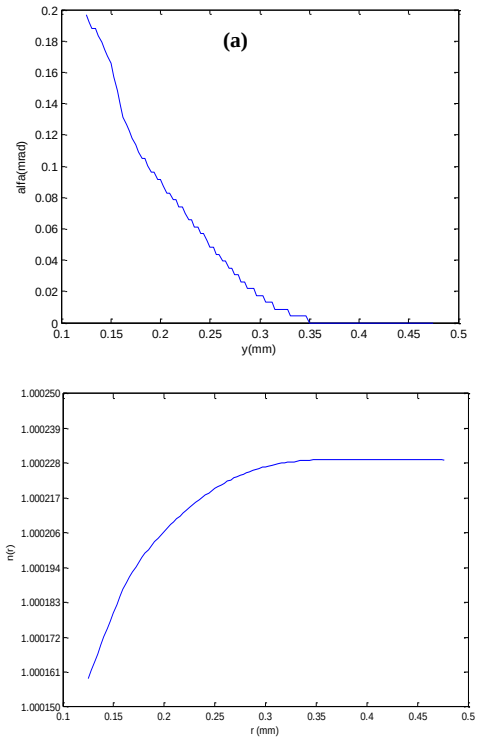

Fig.5. (a) The ray deflection angle and (b) Refractive index distribution versus distance from the wire center

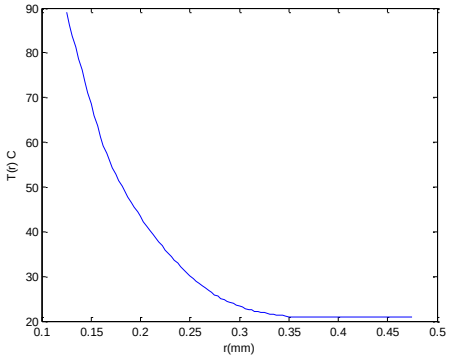

Fig.6. Temperature profile versus distance from the wire center.

IV.Conclusion

The temperature and refractive index distribution and the convective heat transfer function around a vertical axisymmetric heated wire is obtained that experimental results is reasonably in agreement with ambient parameters. This technique is simple and not sensitive to noise with no complicated and expensive set-up. The probe light wavelength does not affect the measurement results and just the test object should be transparent with respect to probe light. For large temperature gradients that interferometry is limited and can produce erroneous information, moiré deflectometry is able to use with more certainty.

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