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Measurement of Convective Heat Transfer from a Vertical Flat Plate Using Mach-Zehnder Interferometer with Wedge Fringe Setting

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Abstract**—**Laser interferometric methods have been utilized for the measurement of natural convection heat transfer from a heated vertical flat plate, in the investigation presented here. The study mainly aims at comparing two different fringe orientations in the wedge fringe setting of Mach-Zehnder interferometer (MZI), used for the measurements. The interference fringes are set in horizontal and vertical orientations with respect to the heated surface, and two different fringe analysis methods, namely the stepping method and the method proposed by Naylor and Duarte, are used to obtain the heat transfer coefficients. The experimental system is benchmarked with theoretical results, thus validating its reliability in heat transfer measurements. The interference fringe patterns are analyzed digitally using MATLAB 7 and MOTIC Plus softwares, which ensure improved efficiency in fringe analysis, hence reducing the errors associated with conventional fringe tracing. The work also discuss the relative merits and limitations of the two methods used.

Keywords**—**MZI, Natural Convection, Naylor Method, Vertical Flat Plate.

I. INTRODUCTION

INTERFEROMETRIC methods are widely used in the temperature and heat transfer measurements. These methods provide a powerful non-intrusive tool for accurate measurement of heat transfer in convective domains. Interferometry coupled with digital image processing of the interferograms can be effectively utilized in many practical applications, for steady state and time-dependent measurements. Processing of interferograms with minimum error is of prime importance, and hence, based on the type of interferometry used, different image processing techniques have also been developed. The use of the Mach-Zehnder Interferometer (MZI) for heat transfer measurements has been widely reported in the literature. In one of the earlier investigations, this interferometric configuration has been utilized to determine the natural convection heat transfer coefficients over a uniformly heated vertical plate by Goldstein et al. [1].

Kwak and Song [2] measured free convection from a downward-facing finned plate using MZI. Gryzagoridis and White [3] have reported measurements of heat transfer characteristics of a rotating cylinder using MZI. Shimada et al. [4] also studied heat transfer characteristics of a horizontal rotating cylinder using MZI. The experiments were performed by varying the rotating Reynolds number (Re_r) and cross flow Reynolds number (Re_d). A time averaging technique was developed to measure the unsteady and turbulent heat transfer in a tall vertical enclosure using MZI by Poulad et al. [5]. Wong et al. [6] investigated the temperature field around small objects with a width to height ratio ranging from 0.33 to 1.0 using MZI coupled with digital image processing. The capability of the interferometric techniques for fluid flow measurement in small dimension passages has been demonstrated by Newport et al. [7].

An interesting interferogram analysis technique for the measurement of convective heat transfer rates has been developed by Naylor and Duarte [8], in which the local surface temperature gradients in a two dimensional temperature fields can be measured directly from a wedge fringe field. This is done by measuring the angle of intersection of a wedge fringe with isothermal surfaces. In the regions of low heat transfer rates, the fringe number near the heated surface would be insufficient to make concluding measurements, and to overcome this difficulty Naylor proposed a method to measure temperature gradients directly near the surface. Details of this measurement method can be found in literature [9]. Recently, Sajith et al. [10] have reported heat transfer measurements from electronic components using this direct gradient measurement method.

The present work utilizes the Mach-Zehnder interferometer (MZI) to obtain the heat transfer parameters associated with natural convection from a heated vertical flat plate. Two fringe analysis methods are utilized, are the conventional stepping method (Method 1) and the Naylor method (Method 2). These methods are used along with two different wedge fringe orientations, in the vertical and horizontal patterns, achieved by appropriately orienting the reflecting mirrors in the MZI. The basic theory of the two methods used is mentioned below.

II. THEORY

The resultant intensity is due to the superposition of two coherent beams is given by

$$I = I_1 + I_2 + 2(I_1 I_2)^{1/2} COS\Delta\varphi \tag{1}$$

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Considering the path difference between the test beam and the reference beam of the interferometer the phase difference between the interfering beams is given by

$$\Delta\varphi = \frac{2\pi L\left(n - n_r\right)}{\lambda} \tag{2}$$

The relation between the local refractive index and the fringe number is given by

$$n - n_r = \frac{S\lambda}{L} \tag{3}$$

where S is the fringe number. Refer [11].

A. Stepping Method (Method 1)

The Lorenz-Lorentz relation connects the density of a homogenous medium with its refractive index as follows:

$$\frac{n^2 - 1}{\rho\left(n^2 + 2\right)} = G \tag{4}$$

with air as the medium, n ≈ 1. Incorporating the ideal gas equation and utilizing (3)

$$\frac{T}{Tr} = \frac{1}{1 - aS} \tag{5}$$

where,

$$a = \frac{2\lambda R T_r}{3LG\mathrm{P}_\mathrm{r}} = \frac{2\lambda}{3LG\rho}$$

Equation (5) provides a method to step through a temperature field to obtain the temperature corresponding to every fringe, if the temperature corresponding to a reference fringe (T_r) is known. A detailed derivation of the above expression can be found in [12].

Equating the convective and conductive heat transfer rates at a heated surface,

$$h\left(T_s - T_\infty\right) = -k\left.\frac{\partial T}{\partial x}\right|_{x=0} \tag{6}$$

$$h = -k\left.\frac{\partial T}{\partial x}\right|_{x=0}\frac{1}{\left(T_s - T_\infty\right)} \tag{7}$$

B. Naylor Method (Method 2)

Naylor method is used in analyzing wedge fringe patterns. The interfering beams are slightly misaligned by an angle ϴ to produce the wedge fringe pattern. The fringe angle can be related to the temperature field, to obtain the following expression for h:

$$h = \frac{2R\lambda \mathrm{T}_s^{\,2} k}{3rZp(T_s - T_\infty)d\tan\alpha} = \frac{C}{\tan\alpha} \tag{8}$$

where,

$$C = \frac{2R\lambda \mathrm{T}_s^{\,2} k}{3rZp(T_s - T_\infty)d}$$

The steps in the derivation of the above expression can be seen in [8].

III. EXPERIMENTAL DETAILS

A. Mach-Zehnder Interferometer (MZI)

The Mach-Zehnder interferometer used in the present study employs a He-Ne laser (2mW, 632.8nm wavelength) as the illuminating light source. A schematic of the arrangement is shown in Fig. 1 and a photograph of the experimental system is shown in Fig. 2. The collimated and expanded laser beam is allowed to fall on a beam splitter (B1), where the beam is divided into reflected and transmitted beams. These beams of equal amplitude strike the plane mirrors M1 and M2, and get combined at the second beam splitter (B2), with a constant phase relationship. This produces interference fringes, which are captured at the transmitting beam of the second splitter, using a CCD camera (AVT Marlin F033C) and further analyzed digitally. The fringe patterns give the information about the test section, if it is placed at one of the two arms of the interferometer.

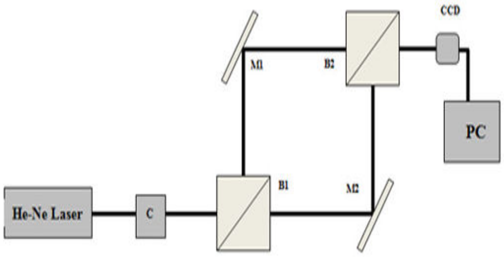

Fig. 1 Schematics of Mach-Zehnder interferometer

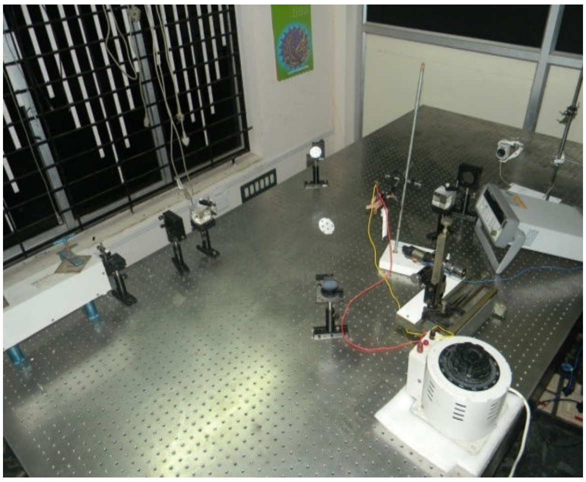

Fig. 2 Photograph of the experimental set up

B. Digital Image Processing

Digital image processing of the interferograms is employed in analyzing the convective field, as this sophisticated method reduces the errors, provides accurate location of the fringe centers and accurate determination of the fringe angles, compared to conventional manual fringe processing methods. The fringe centers and the angle can be determined within an error limit of ± 3 pixels by employing digital image processing methods. The details of the image processing technique used in the present study are given in the following sections.

The interference fringes can be made parallel to the heated surface by appropriate adjustment of one of the mirrors in the MZI setup. When an isothermal flat plate dissipating heat is placed in one of the arms of the interferometer, the fringes gets deformed due to the temperature field. The resulting fringe pattern is captured and stored in the PC using a CCD camera and AVT MARLIN image grabbing software. In a standard image format, the data is stored as an array in a MATLAB 7 platform and the intensity profiles are drawn by employing suitable image processing procedures. The deformed fringe pattern and the corresponding intensity profile at a particular section are shown in Figs. 3 (a) and (b) respectively. The intensity profile shows the variation of intensity, as maximum and minimum peaks, as well as the pixel distances of fringe locations which can be converted to real distances by multiplying with a scaling factor. The image processing technique utilized is explained in detail by Malacara [13]. By locating the fringe centers, in the present study, the centers of the dark fringes are utilized, which correspond to the minimum intensity points in the intensity plot and by obtaining the temperature corresponding to each fringe using (5) the temperature gradient in the convective field can be obtained. In the present investigation, the convective field is that around a heated isothermal flat plate. The test specimen for this is fabricated with a Nickel-Chromium alloy heater sandwiched between two thin plates of copper. The heat input to the heater is regulated using an autotransformer. The reference surface temperature, T_r in the stepping procedure using (5) is determined using a calibrated T type thermocouple attached to four different location in the surface of the heated plate. When the heated section is introduced in the interferometer the initial fringes gets deformed, thus producing fringes due to the density gradient or temperature in the field of measurements.

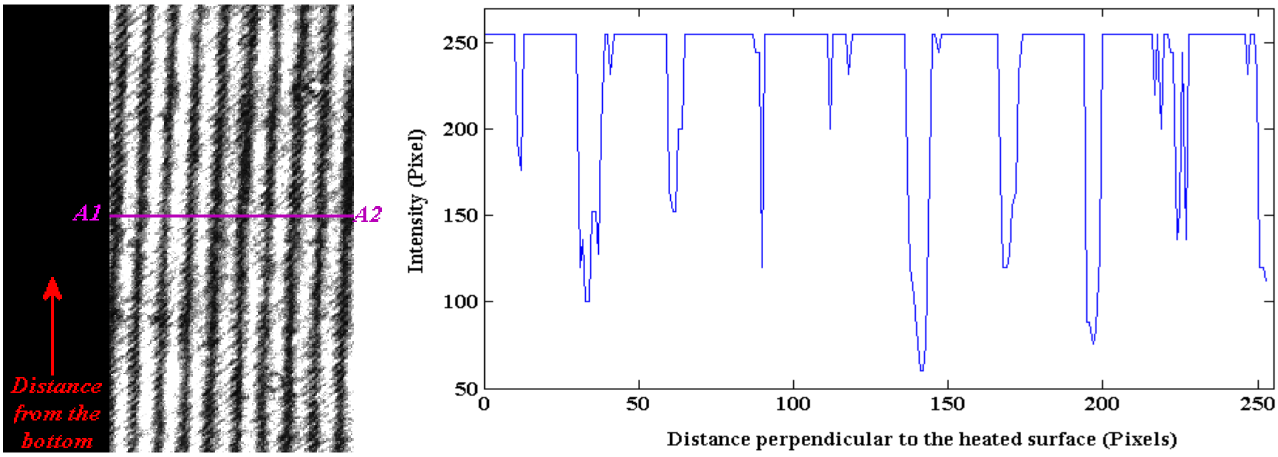

Fig. 3 (a) Typical interferogram obtained at a surface temperature of 40^{o}C (b) intensity profile drawn along the horizontal line

Fig. 4 shows the temperature variation in the vicinity of the dissipating surface, for a surface temperature of 40^{o}C. The plot gives the variation of non-dimensional temperature along a non-dimensional distance. In Fig. 4, the experimental result is also shown compared with the theoretical result available in the literature [14], which emphasizes the applicability and accuracy of the measurement method for convective fields.

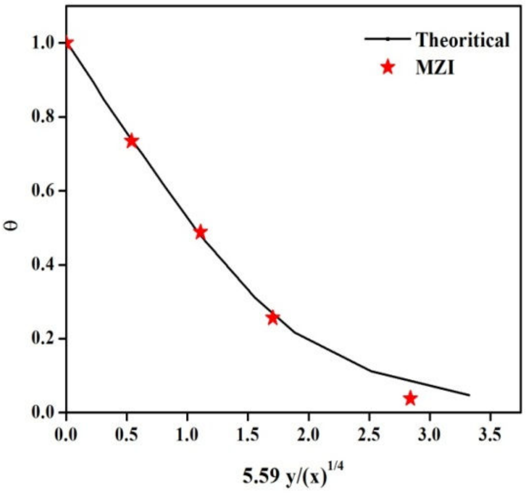

Fig. 4 Comparison of the temperature distribution in the vicinity of a heated surface, obtained using MZI with theoretical [14]

To obtain the temperature gradients directly, to be used in the method proposed by Naylor and Duarte [8], the fringes are set normal to the heated surface and the fringe shift at the heated surface is obtained by measuring the bending angle. This is done by processing the deformed fringes using MOTIC Plus software. The deformed fringe pattern corresponding to 40^{o}C surface temperature is shown in Fig. 5.

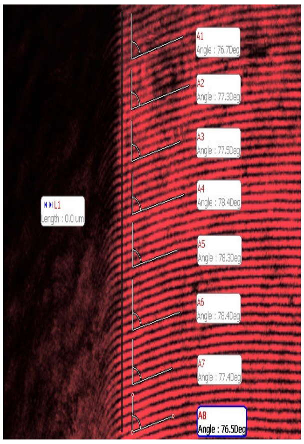

Fig. 5 Typical Interferogram obtained for a surface temperature of 40^{o}C. The bending angles are marked in the figure

IV. RESULTS AND DISCUSSION

The digital interferometric measurement methods explained in the above sections can be effectively utilized to determine the heat transfer parameters characterizing convective dissipation from a vertical flat plate, namely the heat transfer coefficients and Nusselt numbers. In the present investigation, the surface temperatures of the plate are set at 40ºC, 50ºC and 70ºC degrees so as to obtain a low, moderate and high heat dissipation levels, corresponding to a versatile application of such systems, namely thermal management of micro electronics. Measurements have been carried out on a heat dissipating surface made using two copper plates with a sandwiched heating element. The location at which the observation has been made is around a height 1.3cm above the bottom edge of the plate. The surface temperature measurements are done using a calibrated T type thermocouple and an Agilent Data Logging System, for temperature monitoring. The heat input is given to the heater using stabilized electric supply, which was monitored and kept constant with the help of a wattmeter. The experiment was set up on a optical table in a vibration free environment.

Fig. 6 shows the variation of the parameter h/C as a function of the fringe bending angle in degrees. The heat transfer coefficient shows a decreasing trend with an increase in the bending angle. The Initial fringes are set at an angle of 90 degree with the plate and when the plate is heated, the fringes bend so that the magnitude of the angle is decreased. Thus the decrease in the fringe angle corresponds to the magnitude of the heat transfer from the surface to the surrounding medium. It is clear that an increase in the measured fringe angle corresponds to a reduction in the value of the heat transfer coefficient.

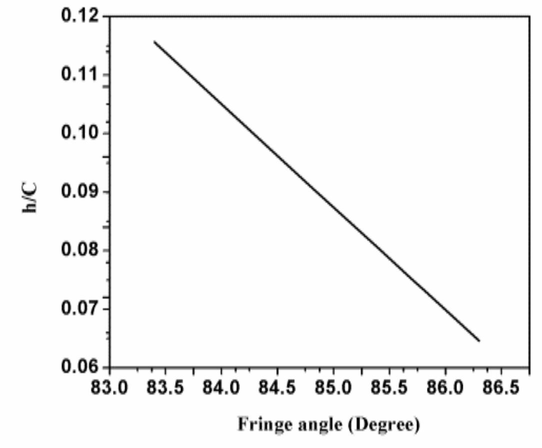

Fig. 6 The local variation of h/C with the bending angle

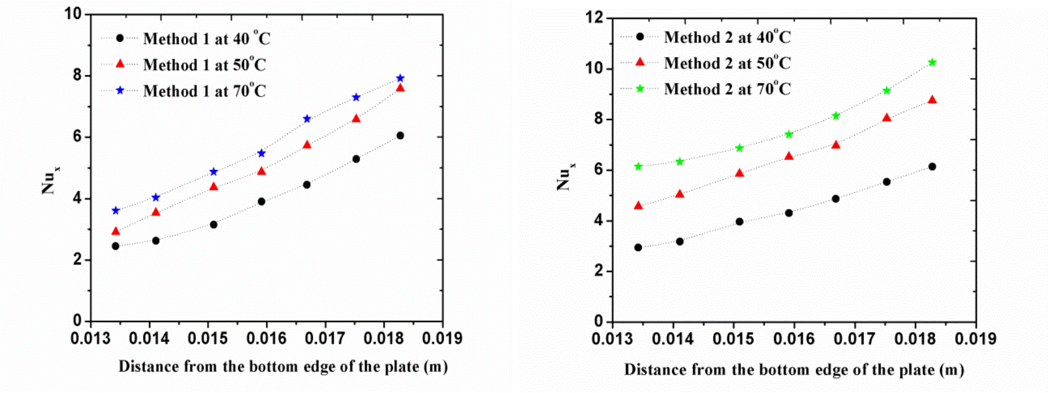

Fig. 7 Variation of Nu_x for three different surface temperatures, obtained using Method 1 & Method 2

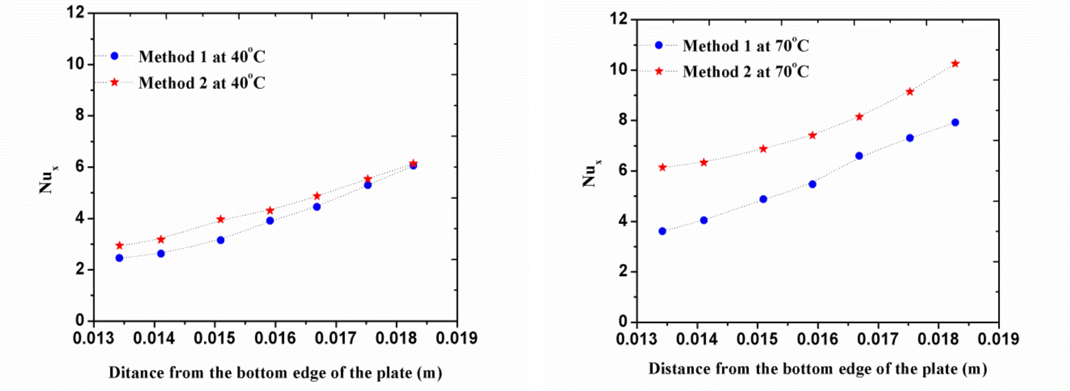

Fig. 8 Comparison of Nu_x at low and high heat dissipation levels using Method 1 &Method 2.

Fig. 7 shows the variation of local Nusselt number within in the field of vision, for different surface temperatures, obtained using the two analysis methods explained before. It is found that the distributions in the Nusselt number obtained using the two methods agree fairly well at lower temperatures, but at higher temperatures, they are considerably different. The comparison shown in Fig. 8 further depicts this. This difference can be attributed to the inefficiency of Method 2 to predict heat transfer parameters at high heat dissipating levels.

The results shown above suggest that stepping method would be a more accurate method to obtain heat transfer for a wider range of surface temperature, with less inherent inaccuracies, though the method is more laborious due to the analysis, starting from temperature distributions. This makes the Naylor and Duarte method more attractive while dealing with low heat dissipation level, as it can directly measure the heat transfer from the fringe patterns. The heat transfer coefficients obtained here is a function of bending angle as seen in (8).

V. CONCLUSION

Interferometric methods have been demonstrated to be powerful non-intrusive tools to determine the convective fields without disturbing the test field. The present work focused on different wedge fringe orientations of the Mach-Zehnder interferometer. The method is benchmarked with respect to the theoretical results, and two methods for heat transfer estimation have been presented in the paper. From the results it is understood that the stepping method can be used in a wide range of temperature levels, whereas the Naylor and Duarte method is an easier method of measurement, provided the heat dissipation levels are low. Both the fringe settings are easier to set up, compared to infinite fringe settings in conventional interferometry, and therefore attractive in the implementation point of view.

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