Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science and Technology (RAEREST 2016)

Measurement of Temperature Distribution around a Vertical Fin by Mach-Zehnder Interferometry

Binoy Baby\textsuperscript{a}, Anooplal B\textsuperscript{b}\textsuperscript{*}

\textsuperscript{a,b} St. Joseph’s College of Engineering & Technology, Pala, 686579, India

Abstract

Interferometry is an optical non-intrusive technique becoming increasingly popular in the flow and heat transfer visualisation and measurement. In the present study, experimental investigation on heat transfer around an isothermal vertical fin using Mach-Zehnder Interferometry is carried out. The temperature of surrounding air, at a reference point, is recorded by a thermocouple placed at a distance from the heat source. Interference patterns are captured by a camera and analyzed using an image processing tool in MATLAB software. From the observations, it is pellucid that the change of air temperature in one path of the coherent laser beam results in the deformation of the interference pattern. By comparing the initial and deformed fringe patterns using the digital image processing technique, the temperature distribution around the heat source is obtained. The experimental values compared with the analytical results of vertical heated plate, show very good agreement. This indicates the reliability of interferometric measurement method.

© 2015 The Authors. Published by Elsevier Ltd.

Peer-review under responsibility of the organizing committee of RAEREST 2016.

Keywords: Isothermal; Interferometry; Heat transfer

1. Introduction

Interference of two coherent light beams is the basic principle of the interferometric measurement technique. When coherent beams are passed through regions of different densities such as those produced by a temperature field, an additional phase lag is formed in their paths which produces a deformed fringe pattern upon interference with a reference beam. This deformed fringe pattern contains information about the change in refractive
index of the medium, and the temperature distribution in the medium can be determined by digital image processing of the interferogram.

Recent advances in microelectronic field call for effective new methods which are capable of thermal management of compact heat producing devices. Due to their restricted surface area, these devices produce high heat flux. Determination of temperature distribution using a non-intrusive technique is an excellent tool to study the thermal management of compact devices. Sobhan C.B. and Peterson G.P. [1] investigated and explained the micro-scale and nano-scale heat transfers in engineering measurements. Mehandale et.al [2] studied the unresolved thermal-hydraulic issues related to ultra-compact designs. Rammohan et.al [3] measured the natural heat transfer by Mach-Zehnder Interferometer and Differential interferometer. According to Binoy and Sobhan[4], forced convection in compact mini-channel with apparent rectangular shape could be analysed with finite difference method and results validated using Michelson Interferometry. For a wide class of applications, where temperatures are not very high, interferometry could be a versatile tool for accurate measurement of three-dimensional unsteady temperature fields. Binoy Baby and Sobhan C. B. [5] investigated forced convection in a meso-channel with irregular cross section by finite difference solution and the numerical results were compared with the experimental results obtained by Mach-Zehnder Interferometry. Minnett et.al [6] measured the radiometric marine air temperature by Marine-Atmospheric Emitted Radiance Interferometer. This method deployed in a wide range of conditions could bring out some of the errors in the standard measurement.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;r&lt;/sub&gt;</td>
<td>reference temperature</td>
</tr>
<tr>
<td>T</td>
<td>temperature to be measured</td>
</tr>
<tr>
<td>T&lt;sub&gt;m&lt;/sub&gt;</td>
<td>mean temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;w&lt;/sub&gt;</td>
<td>wall temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;f&lt;/sub&gt;</td>
<td>fluid temperature</td>
</tr>
<tr>
<td>S</td>
<td>isotherm number</td>
</tr>
<tr>
<td>n</td>
<td>refractive index</td>
</tr>
<tr>
<td>λ</td>
<td>wave length of laser</td>
</tr>
<tr>
<td>C</td>
<td>Gladstone Dale constant</td>
</tr>
<tr>
<td>L</td>
<td>width of heat plate</td>
</tr>
<tr>
<td>D&lt;sub&gt;h&lt;/sub&gt;</td>
<td>hydraulic diameter</td>
</tr>
<tr>
<td>q</td>
<td>heat flux</td>
</tr>
<tr>
<td>h</td>
<td>convective heat transfer coefficient</td>
</tr>
<tr>
<td>k&lt;sub&gt;s&lt;/sub&gt;</td>
<td>thermal conductivity of solid</td>
</tr>
<tr>
<td>k&lt;sub&gt;f&lt;/sub&gt;</td>
<td>thermal conductivity of fluid</td>
</tr>
<tr>
<td>N&lt;sub&gt;u&lt;/sub&gt;</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>P&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>Ra</td>
<td>Reynolds number</td>
</tr>
</tbody>
</table>

### 2. Experimental Studies

The basic components of the Mach-Zehnder Interferometry are shown in the line diagram at Fig.1. The laser beam from the source is passing through a collimating lens and split into two coherent beams by a beam splitter (prism) BS1. Then, one of the beams (Test Beam) is passed around the vertical fin to the mirror M1 and reflected to a second beam splitter BS2, whereas the other beam (Reference Beam) goes through the reference section (air) to mirror M2 and is reflected to BS2. The two reflected beams combine together in BS2 and produce the fringe pattern, which is captured by the CCD camera.

The constituent parts of the experimental set up, incorporating the Mach-Zehnder Interferometry are shown in Fig.2. A 1.5 mW Helium-Neon laser of wave length 632.8 nm is used as the light source. Fringe patterns, after focusing through a plano-convex lens are captured by a (AVT Marlin) CCD camera with a PC interface, supported by AVT (Allied Vision Technology) software packages. A single fin is placed in the vicinity of Test section beam and the heat dissipation from the vertical fin to the surrounding air medium is measured by the interferometric technique. The refractive index of the air surrounding the vertical fin is changed due to the heat dissipation from the
fin surface to the surrounding air medium. The vertical fin is fabricated with a nickel-chromium alloy heater sandwiched between two thin steel plates of dimension 100 mm x 60 mm. This vertical fin is placed in the test section. The width of the fabricated fin assembly is 3 mm. Heat is transmitted uniformly from the heater to the plate and the heating level is controlled using a variable transformer in the heater circuit. In this measurement method, it is required to find the temperature of a reference fringe in the field, in order to calculate the temperature distribution of the field. Thus, a T-type thermocouple is kept at a measured distance from the fin surface. The thermocouple reading is monitored using an Agilent Bench Link Data Acquisition Unit (A34970). Initial (without heating) and final (with heating) fringe patterns are captured by the camera and analyzed by digital image processing techniques. Intensity profile is obtained by processing the image using MATLAB software. The only phase lag introduced between the test and reference beams is due to the effect of heat dissipation from the vertical fin, and upon interference, the fringe patterns can be analyzed to obtain the temperature distribution around the vertical fin.

Fig. 1. Line diagram of Mach-Zehnder Interferometer.

Fig. 2. Experimental setup.
3. Results and Discussions

Fig. 3. Initial fringe pattern (without heat dissipation)

Fig. 4. Deformed fringe pattern (with heat dissipation)

Fig. 5. Isotherms in the vicinity of isothermal vertical fin.
For the experimentation, wedge fringes were set by aligning the optical components in order to get the fringes parallel to the surface of the vertical fin. When heat is dissipated from the fin surface, the fringes near to it get dislocated. Fringe spacing changes due to the density variation of air surrounded by fin. The refractive index of a medium depends on the density of the medium. Initial (without heat dissipation) and deformed fringes (with heat dissipation) are obtained. The initial and deformed fringe images captured with and without heat dissipation are shown in Fig.3 and Fig.4 respectively. Isotherms or Moire fringes are obtained by digitally subtracting the initial parallel fringe from the deformed fringe pattern. The narrow dark bands among them are called isotherms since they are constant temperature regions. The isotherms around the vertical fin and the position of the thermocouple are shown in the Fig.5. The intensity profile of the resultant image is measured over the distance between isothermal vertical fin surface and the thermocouple by digital image processing using MATLAB. The intensity profile plotted between surface of the fin and thermocouple is shown in Fig.6. By analysing this intensity plot neglecting its sharp fluctuations, it can be seen that the crests represent the high light intensities and the troughs the dark isotherms. Length of one pixel is determined by dividing the known distance between the fin and the thermocouple by the pixel count between the two.

![Intensity profile between thermocouple and fin surface.](image)

Density variation of air with temperature is plotted and a polynomial is fitted as shown in Eq. (1). This polynomial is used to find the isotherm temperatures using Lorentz-Lorenz equation.

\[-6T^3 \times 10^{-8} + 7T^2 \times 10^{-5} + 0.0317T + 5.65 = 0\]  

(1)

\[\frac{-6T^3 \times 10^{-8} + 7T^2 \times 10^{-5} + 0.0317T + 5.65}{-6T_r^3 \times 10^{-8} + 7T_r^2 \times 10^{-5} + 0.0317T_r + 5.65} = \frac{1}{(1-aS)}\]  

(2)

\[a = \frac{(n+1) \lambda}{(n^2+1) \lambda C L (-6T^3 \times 10^{-8} + 7T^2 \times 10^{-5} + 0.0317T + 5.65)}\]  

(3)

\[n = 1.000272, \lambda = 0.000000632 \text{ meter}, C = 0.0002257, L = 0.003 \text{ m}.\]
By counting the number of pixels from the thermocouple to each isotherm its distance (in mm) from the thermocouple can be calculated using the length of a pixel determined earlier. The temperature of each isotherm around the vertical fin is determined by the stepping process. Fig.7 shows the temperature distribution around the fin surface along the horizontal direction. Temperature increases from the thermocouple position (Reference point) to the surface of the fin.

![Temperature distribution](image)

**Fig.7.** Temperature distribution along the distance from reference point to fin surface.

The heat flux, heat transfer coefficient and Nusselt number at different sections can be obtained as follows:

\[
q''(z) = -k_s \left( \frac{dT}{dy} \right)_w \tag{4}
\]

\[
h_z = k_s \left( \frac{dT}{dy} \right)_w \left( \frac{1}{T_w - T_m} \right) \tag{5}
\]

\[
\text{Nu}_z = \frac{k_s}{k_f} \left( \frac{D_h}{T_w - T_m} \right) \left( \frac{dT}{dy} \right)_w \tag{6}
\]

\[
T_f = \left( \frac{T_w + T_m}{2} \right) \tag{7}
\]

Here, \(T_m\) is an integral average fluid temperature, calculated from the temperature profile by the digital image analysis of the fringe pattern.
4. Validation

The temperature at each fringe is determined using a stepping procedure with the interferometric relation for air and the digital image analysis. The temperatures of the ambient air and the surface of the fin are measured by a T-type thermocouple, and are used in the calculation of the theoretical Nusselt number. The experimental values of the local Nusselt number along the height are compared with the analytical formula given by Churchill and Chu which is described in Incropera [7] for an isothermal vertical flat plate given by the Eqn. (4).

$$\overline{Nu_L} = 0.68 + \frac{0.670Ra_L^{1/4}}{\left[1+(0.492/Pr)^{9/16}\right]^{4/9}}, Ra_L \leq 10^9$$  \hspace{1cm} (8)

For comparison the theoretical and experimental Nusselt number values are plotted as shown in Fig. 8, which indicates a fine agreement, thereby proving the dependability of the experimental method using the interferometric measurement procedure.

![Graph showing variation of Nusselt number around vertical fin](image)

**Fig. 8. Variation of Nusselt number around vertical fin**

5. Conclusion

A simple Mach-Zehnder interferometry has been aligned to detect the measurement of air temperature. A single thermocouple for measurement of the temperature at a point far from the heat source is the only essential requirement. Thus, the non-intrusive temperature measurement is made possible without disturbing the medium. The deformed interference pattern containing the data regarding the heat distribution is captured as an image. This is analysed on MATLAB to obtain an intensity plot and a resultant image shows the positions of isotherms. Lorenz-Lorentz relation is used to determine the temperatures at these isotherms. Positions of the isotherms are determined...
using data cursor on MATLAB. From the temperature and position, temperature plots are drawn. The temperature of any point between reference and heat source can be determined using the temperature plot. These temperatures are used to find out local Nusselt number and validate the results. This measurement technique can be used to measure the heat dissipation of any heat exchanging device without the measuring instruments disturbing the surrounding medium.

6. References


