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Interferometry based whole-field heat transfer measurements of an impinging turbulent synthetic jet☆

Udaysinh S. Bhapkar, Sharika Mohanan, Amit Agrawal, Atul Srivastava *

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Powai 400076, Mumbai, India

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ABSTRACT

The present work is concerned with exploring the potential of refractive index-based imaging techniques for investigating the heat transfer characteristics of impinging turbulent synthetic jets. The line-of-sight images of the convective field have been recorded using a Mach Zehnder interferometer. Heat transfer experiments have been conducted in infinite fringe setting mode of the interferometer with air as the working fluid. The effect of the excitation frequency of the synthetic jet on the resultant temperature distribution and local heat transfer characteristics has been studied. The fringe patterns recorded in the form of interferograms have first been qualitatively discussed and thereafter, quantitatively analyzed to determine the two-dimensional temperature field. Local heat transfer coefficients along the width of the heated copper block have been determined from the temperature field distribution thus obtained from the interferograms. The results have been presented in the form of interferometric images recorded as a function of frequency of the synthetic jet, corresponding two-dimensional temperature distributions and local variation of heat transfer coefficients. Interferometric measurements predicted maxima of the heat transfer coefficient at the resonance frequency of the synthetic jet and at a jet-to-plate surface spacing (z/d) of 3. These observations correlate well with the thermocouple-based measurements of temperature and heat transfer coefficient performed simultaneously during the experiments. The interferometry-based study, as reported in the present work for the first time in the context of synthetic jets, highlights the importance of refractive index-based imaging techniques as a potential tool for understanding the local heat transfer characteristics of synthetic jets.

1. Introduction

Recent advancements in miniaturizing the size of electronic equipments have led to the challenging task of finding more efficient and economical ways for maintaining the operating temperatures of the devices below the prescribed levels. Taking into account the high power densities involved with the operation of these miniaturized systems and the associated chances of their degradation/failure over a period of time, it becomes imperative to design appropriate cooling systems. In this context, the concept of synthetic jets has attracted the attention of various researchers in the recent past due to their inherent advantages over other conventional cooling techniques e.g. air cooling based on fans/impinging jets and liquid cooling using micro-channels, liquid metal cooling etc.

Synthetic jet is a device in which the jet is produced in the form of train of vortices by successive ejection and suction of the ambient fluid. The fact that the synthetic jets are made up of the surrounding fluid itself with which they interact, there is no requirement of input piping or complex fluidic packaging which makes them particularly suited for space constrained applications. Moreover, due to better mixing properties, synthetic jets have a number of potential engineering applications, such as flow control, thrust vectoring of jets, and creation of local turbulence. In view of these potential advantages, a large spectrum of experimental as well as numerical studies on synthetic jets and their performance comparison with continuous jets has been reported in the literature by various researchers [1–3]. Of notable interests are the studies reported by M. Arik wherein the author investigated the local heat transfer characteristics of high-frequency synthetic jets during impingement cooling over flat surfaces and also explored the feasibility of employing meso-scale synthetic jets for such applications [4]. A series of experimental studies have been presented by Chaudhari et al. reporting the effects of various operating parameters on the performance characteristics of synthetic jets [5–7]. In recent years, efforts have also been made to further develop the understanding of the inherent flow physics associated with the heat transfer characteristics of synthetic jets [8–10] and feasibility of inclined synthetic jets for space-constrained applications [11].

The available literature in the field of synthetic jet reveals that though the importance of the flow physics responsible for the enhancement of heat transfer coefficients has been realized by various researchers,

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* Corresponding author.
E-mail addresses: atulsr@iitb.ac.in, atuldotcom@gmail.com (A. Srivastava).

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necessary efforts in mapping the whole field temperature distribution and local heat transfer rates have not been adequately made. Majority of the researchers have employed either intrusive ways of surface temperature measurements (e.g. thermocouples) or limited their investigations to infrared thermal imaging-based surface temperature measurements. However, in order to understand the detailed effects of flow physics on heat transfer processes, it is necessary to carry out local field measurements in the vicinity of the target plate cooled by the synthetic jets. In view of this, refractive index-based imaging techniques e.g. interferometry, schlieren and shadowgraph become important as they are capable of providing the whole-field distribution of the quantity of interest in a purely non-intrusive manner [12,20]. When coupled with the principles of tomography, the entire three-dimensional temperature field distribution and hence the local variation of heat transfer rates can be retrieved based on the images recorded from different directions (projection angles) [21]. A survey of literature in the field of synthetic jets reveals that in spite of these inherent advantages, the potential of refractive index-based optical imaging techniques has not yet been explored fully for determining the local field information of temperature and heat transfer rates. To the best of the knowledge of the authors, the only available studies in the literature are the ones reported by Smith and Glezer [13] and Qayoum et al. [14] wherein the authors have employed laser schlieren technique for visualizing the structure of the synthetic jet impinging on the target surface. However, these studies are restricted only to the qualitative visualization of the flow field; quantitative evaluation of the recorded images for determining the local variation of fluid temperature and/or heat transfer coefficient in the vicinity of the heated surface has not been reported with an exception of [15] wherein the authors reported the application of digital holographic interferometry (DHI) for the measurement of temperature fields in moving fluids.

With this background, the present work is concerned with exploring the application of one of the refractive index-based optical imaging techniques namely interferometry for the determination of two-dimensional temperature field distribution during the synthetic jet-based cooling of the heated target plate. The study holds its importance in view of the fact that the whole field temperature distribution of ambient fluid would provide local field information of the heat transfer coefficient over the entire two-dimensional plane above the top surface of the target plate. Though the current study is two-dimensional in nature, it is expected that when coupled with the principles of tomography, the technique would prove to be useful for generating local field information required for understanding the detailed effects of underlying flow physics on heat transfer processes in the context of synthetic jets. The heat transfer experiments have been carried out for a range of frequencies of the synthetic jet. A Mach–Zehnder interferometer has been employed to record the line-of-sight images of the convective field in the form of interferograms. The recorded interferometric fringe patterns have first been qualitatively discussed to understand the effect of synthetic jet frequency on the resultant convective field. Subsequently, the interferograms have been quantitatively analyzed to retrieve the two-dimensional temperature field distribution and local variation of heat transfer coefficient along the width of the heated target plate.

2. Apparatus and instrumentation

The experimental setup for conducting heat transfer experiments using synthetic jets has schematically been shown in Fig. 1(a). The target heated surface is constructed from a copper plate of size of 40×40 mm^2 and a thickness of 5 mm and is heated by a nichrome foil heater attached below the copper plate. The heater is supported by Bakelite plate to provide proper surface contact between the heater and the copper plate. Electrical power supplied to the heater is controlled by a rheostat and a step down transformer. The copper plate is heavily insulated using glass-wool below the Bakelite plate and sides of the heater in order to minimize the heat loss from the side and bottom surfaces. The plate surface temperature is measured using pre-calibrated K-type thermocouples, which are placed at two opposite sides of the copper plate and 10 mm inside the side surfaces. The ambient air temperature is monitored using a separate thermocouple positioned at a sufficiently large distance from the heated target surface so as to avoid any influence of the heating zone on its readings. The synthetic jet assembly is mounted on a traversing stand such that the axial distance between the jet orifice and the heated copper block can be varied. The jet emerging from the orifice directly impinges at the centre of the copper plate. The diaphragm of an acoustic actuator is used for generating the synthetic jet flow. The diaphragm is fitted with circular orifice with sharp edges and a diameter of 12 mm. At resonance, the excitation frequency is equal to either the diaphragm frequency or the Helmholtz frequency. As the same actuator is employed in the present study, the diaphragm frequency is same for all the cases considered. A function generator and an amplifier (*Syscon Instruments*) have been used to supply constant input power to the acoustic actuator. The frequency of excitation and voltage to the actuator are varied for obtaining the desired velocity. The frequency of excitation and voltage supplied to the actuator can be varied as per the requirement.

A Mach–Zehnder interferometer (Fig. 1(b)) has been employed to record the projection data of the convective field in the vicinity of the top surface of the target heated plate. Experiments have been carried out in infinite fringe setting mode of the interferometer. In this setting, the interferometric fringes are representative of the lines of constant temperature i.e. isotherms. Changes in the refractive index field due to the temperature gradients near the top surface of the heated target plate result in a difference in path lengths of test and the reference beams of the interferometer. The two beams on superposition at the second beam splitter BS2 produce an interference pattern, which can be observed and recorded. This pattern contains information on the variation of refractive index and hence the temperature field distribution. To avoid ground vibration from reaching the optics, the entire interferometer is placed over a pneumatic vibration isolation table. Once the mounts of the vibration isolation table are pressurized, the entire interferometer floats over the mounts. This stabilizes the interferometric images and facilitates image acquisition. The interferometric images produced are recorded at video rate (25 frames/s) using a monochrome CCD camera (*Thorlabs*) with a spatial resolution of 1024×768 pixels.

3. Data reduction

The theory of interferometry and the related data reduction steps have been briefly described below:

The intensity distribution $I(x, y)$ of an interferogram in (x, y) plane can be expressed by a sinusoidal function as

$$I(x,y) = A(x,y) + B(x,y)\cos\left[2\pi \vec{f}_0 \vec{r} + \Delta\phi(x,y,t)\right] \tag{1}$$

where $\vec{f}_0$ is a constant vector corresponding to the tilt of the reference mirror and $\Delta\Phi$ is the phase difference induced due to the difference in the optical path lengths of the two arms of the interferometer in the absence of any test medium. In the context of the present experiments, as the thermal gradients set up in the vicinity of the target heated surface, the phase difference i.e. $\Delta\Phi$ can be expressed in terms of the difference in the refractive index distribution $n(x, y)$ of the fluid i.e. air in the vicinity of the heated plate and the reference refractive index n_0, that is

$$\Delta\phi(x,y) = \frac{2\pi}{\lambda}\int_0^L (n(x,y) - n_0)dz \tag{2}$$

Here L is the geometrical path length covered by the test and the reference beams. In the present work, principles of Windowed Fourier Transform (WFT) technique have been employed for extracting the phase