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Interferometric study of natural convection heat transfer phenomena around array of heated cylinders

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ABSTRACT

Interferometric measurements of natural convection-based heat transfer rates around array(s) of heated cylinders have been presented. Experiments have been performed with single, two cylinders placed adjacent to each other with varying centre-to-centre distances and three cylinders arranged in a triangular configuration. Mach-Zehnder interferometer has been employed for recording the projection data of temperature field. The interferograms have first been qualitatively interpreted to understand the influence of buoyant plume of one cylinder on the convective phenomena of the other cylinder(s) of the array. Images have then been quantitatively analyzed to retrieve the whole field temperature distributions. Results have been presented in the form of interferometric images, temperature contours, local distribution of heat transfer rates as a function of Rayleigh numbers. Experiments involving two cylinders showed a strong dependence of the net convective phenomena on the relative spacing of the cylinders. While the buoyant plumes originating from each cylinder were almost independent of each other for larger centre-to-centre distances, the plumes were seen to be strongly coupled as the spacing between the cylinders was reduced. Wall heat transfer rates were found to be comparable with those of single cylinder for large cylinder centre-to-centre distances and showed a decreasing trend as the relative spacing is reduced. Experiments on the triangular array of cylinders revealed that the heat transfer rates from the top cylinder were strongly influenced by the thermal plumes rising from the bottom cylinders. The average Nusselt number around the top cylinder in triangular configuration was found to be significantly smaller than that of the single cylinder.

1. Introduction

Natural convection based heat transfer has been a subject of considerable interest due to its potential applications in areas such as electronic cooling, nuclear reactor cooling, condensers tube, air conditioning cooling system, solar collectors, etc. [1–5]. With increasing demand of effective power dissipation in modern applications, understanding the phenomenon of buoyancy-driven heat transfer and various ways for enhancing the heat transfer rates have become an immediate necessity. Depending upon the application, various geometric configurations and sets of necessary boundary conditions have been studied by a range of researchers. Some of the prominent geometric configurations include flat or curved surfaces, single and/or array of heated surfaces confined in an enclosure or kept in an infinite surrounding medium in which they are allowed to cool down. The reported studies have also covered different orientations of these thermally active surfaces including horizontal, vertical and inclined configurations [6,7]. Of all the possible configurations, heat transfer phenomena around horizontally placed single as well as multiple circular cylinders has drawn the attention of various researchers in the past. Efforts have been made both experimentally as well as through numerical simulations to study the heat transfer phenomenon around a single and array of circular cylinders and related flow physics under natural convection regime [8,9]. Churchill and Chu [10] proposed an empirical expression for the mean value calculation of Nusselt Number (Nu) over the cylinder for a wide range of Rayleigh numbers (Ra) and Prandtl numbers (Pr). Experimental investigations to capture the turbulent transition mechanism for natural convection flows around large horizontal cylinders have been presented by Misumi et al. [11]. The study employed smoke-based flow visualization scheme to qualitatively understand the turbulent transition mechanisms. Kitamura et al. [12] investigated the phenomena of turbulent transition for a Rayleigh number range of $3 \times 10^8 \leqslant Ra \leqslant 3.6 \times 10^{13}$ with uniform flux heating of cylinders of diameter varying from 60 to 800 mm. Morgan [13] and Mcadams [14] proposed correlations for a wide range of

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Nomenclature

D	diameter of the cylinder (mm)
Nu	Nusselt number
h	heat transfer coefficient (W/m^2 K)
I	intensity
k	thermal conductivity (W/m K)
L	optical path Length of the test cavity (m)
n	refractive index
ΔT	temperature difference (°C)
T	temperature of fluid (°C)
r	radial coordinate
s	separation distances, scales
W	wavelet coefficients
x, y, z	coordinate axes

Greek symbols

θ	angle (°)
φ	phase (radians)
λ	wavelength (nm), Fringe period

Subscripts

avg	average
amb	ambient fluid
s	cylinder surface
S	small diameter
L	large diameter

Rayleigh numbers.In the context of horizontally placed cylinders, the interaction of buoyant thermal plumes of one cylinder with that of the neighboring cylinders strongly influences the resultant heat transfer phenomena of the system. Since the temperature and the associated buoyant flow field of the individual cylinders interact with each other, the heat transfer coefficient for a cylinder in an array is generally different from that of a single cylinder. The net effect of this interaction is either a reduction or an enhancement of the average heat transfer coefficient for a given cylinder that depends on the relative position of the cylinder in the array assembly. One of the first investigations of natural convection heat transfer from an array of cylinders was conducted by Eckert and Soehngen [15]. This study considered three cylinders with uniform surface temperature arranged in a vertical line as well as in staggered configuration. The authors reported that the net heat transfer from the middle cylinder reduces and this reduction is even more for the case of top cylinder. Liberman and Gebhart [16] conducted experiments using ten wires of diameter 0.127 mm arranged in a vertical and inclined array to explain that with the varying cylinder spacing, the two opposing effects caused by the interaction of buoyancy plumes leads to a decrease in average heat transfer rates in the subsequent cylinders along the direction of plume propagation. Marsters [17] used three, five and nine cylinders in various configurations including vertical and inclined arrays to show that the heat transfer rate from the upper cylinders could reduce to as low as 50% as compared with the lower cylinder. Sparrow and Niethammer [18] studied natural convection heat transfer from two horizontal cylinders of diameter 37.9 mm arranged in a vertical array for Rayleigh numbers in the range of 2×10^4 to 2×10^5. The study reported that there is no noticeable change in the heat transfer rate from the lower cylinder when compared with the single cylinder. However, the heat transfer rate of the upper cylinder was greatly affected by the cylinder to cylinder temperature difference and also the separation distance. In the case of the cylinders maintained at the same temperatures, heat transfer from the upper cylinder decreases at small separation distances and increases at larger ones. Tokura et al. [19] considered two, three and five horizontal cylinders of diameter 28.5 mm in vertical array, in the range of Rayleigh numbers 2.8×10^4 to 2.8×10^5 between two parallel confining walls. The authors recommended optimum cylinder spacing, separation distance between the walls and number of cylinders to enhance the total heat transfer rate from an array. Farouk and Güçeri [20] numerically investigated laminar and turbulent natural convection heat transfer from single and two cylinders in line and staggered rows of cylinders maintained at same temperature. Ashjaee and Yousefi [21] did an experimental study of laminar free convection heat transfer from vertical and inclined arrays of horizontal isothermal cylinders in air using Mach-Zehnder interferometer. The authors found that the heat transfer from an individual cylinder in the array depends upon the relative position of the other cylinders. In the same context, Ashjaee and co-workers further made use of the potential of the interferometric technique for investigating natural convection-based heat transfer phenomena from a horizontal isothermal cylinder as well as for an array of inline cylinders located underneath an adiabatic ceiling [22,23]. Herraez and Belda employed the technique of holographic interferometry for the determination of heat transfer coefficients and the Nusselt numbers around heated cylinders of varying diameters [24]. Primary findings of an experimental study carried out using interferometry for investigating the effects of separation distances on the resultant heat transfer coefficients around an array of vertically placed heated cylinders was reported by Razelos [25] for a wide range of Rayleigh numbers. Tokanai et al. [26] obtained a correlation for a three cylinder array through experiments. Using the same correlations, the authors presented a way to estimate heat flux on five cylinders maintained at different surface temperatures. Very recently, Sadeghifar and co-workers demonstrated the applicability of integral method to develop closed form relationships for the determination of heat transfer rates (heat transfer coefficients and/or Nusselt numbers) in the context of forced convection heat transfer through cylinders [27,28].

Survey of various studies available in the literature in the context of heat transfer phenomena associated with an array of multiple horizontally placed heated cylinders reveals that the subject has generated considerable interest among the researchers in the past. In view of this, a whole range of studies, experimental as well as numerical, have been reported. However, compared to a large number of numerical studies, the amount of experimental data reported in open literature is still quite limited. Moreover, a majority of these experimental works have primarily employed the intrusive ways of temperature measurement, e.g. thermocouples, which provide temperature data only at select points and hence generating the whole field information about the temperature field and/or heat transfer rates becomes quite challenging. With this background, we report a purely non-intrusive real-time experimental investigation of heat transfer phenomena around a single as well as array of multiple cylinders arranged in various configurations, using laser interferometric technique. A Mach-Zehnder interferometer has been employed for recording the line of sight projection data of the convective field around the cylinder assembly in the form of two-dimensional interferometric images. For a given cylinder diameter, the choice of the differences in the cylinder(s) surface temperature and that of the ambient fluid (T_s-T_∞) has been made in such a way that the resultant magnitudes of Rayleigh numbers are relatively on a lower side and hence one