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Numerical investigation of the laminar natural convection heat transfer from two horizontally attached horizontal cylinders

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ABSTRACT

In this work, natural convection heat transfer from two horizontally attached cylinders in air has been studied numerically over the range of Rayleigh number $10 \leqslant Ra \leqslant 10^5$. A new model proposed by Bejan et al. (1995) is applied here, and it has been proved to be a more accurate and effective method for the numerical simulation of the natural convection in free space than other models used previously. Furthermore, the representative results for streamlines, isothermal contours, local Nusselt number and local drag coefficients have been presented with different Rayleigh numbers. It can be observed that there form two recirculation vortexes in the wake region when the two plumes begin to merge, and their sizes grow with the increasing Rayleigh number due to the downstream movement of the front stagnation point and the upstream movement of the separation point. Owing to the interactions of their plumes, the location of the maximum value of local Nusselt number moves downstream along the cylinder surface, i.e., it displaces to 133–150° depending on the Rayleigh number whereas it always occurs at the front stagnation point corresponding to 90° for a single cylinder. However, because the thinnest boundary layer in this work still hardly penetrates the small clearance between them and then influences their heat transfer, their interactions are independent of the Rayleigh number. Finally, a new correlating equation of the average Nusselt number with the Rayleigh number for the present configuration, has been proposed.

1. Introduction

Natural convection heat transfer exists in the situations that there is no forced velocity and it is induced by the buoyancy force resulting from the temperature-dependent density gradients in the fluid [1]. It is commonly encountered in industrial and environmental applications such as heat exchangers, nuclear and chemical reactors, and electronic devices, with the common fluids, e.g., air and water, even with the hot nanofluids in recent years [2–4]. Especially, the external flow and heat transfer around the horizontal cylinders by natural convection, due to their pragmatic significance, have been abundantly implemented in detail over the past several decades.

In the early stage of the field, most of researchers concentrate on the investigations of the flow and heat transfer characteristics for a single cylinder in free space [5–21], on account of their fundamental significances. They mainly concerned about the correlating equations for the average Nusselt number as a function of Rayleigh number, or both Rayleigh number and Prandtl number, to provide an accurate prediction on the heat transfer coefficients in the process of engineering calculations.

However, in most practical applications, especially in heat exchangers, refrigeration condensers, etc., it is the most commonly encountered multiple cylinders arranged in vertical, inclined or horizontal arrays. Intuitively, in such configurations, the characteristics of heat transfer from each cylinder in the arrays are affected by the others because of their interactions with each other. As a result, its heat transfer characteristics are not predicted by simple superposition of single cylinder behavior [22]. Nevertheless, there is no doubt that the studies for the single cylinder have provided fundamental and academic insights into the mechanisms of the natural convection heat transfer and flow from cylinders. In such background, the studies conducted on the effect of their interactions thus also have been a basic work for the heat transfer from cylinders cooling by natural convection over the past several decades. For the case of a pair of or more equal-diameter heated horizontal cylinders arranged in a vertical configuration, there are abundant results to be available [23–38]. A detailed review of these previous literatures is presented by Shyam et al. [39], who have numerically analyzed the laminar natural convection heat transfer from a pair of horizontal cylinders aligned vertically in power-law fluids, spanning the range of Grashof number from 10 to 10^4, the

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Nomenclature

C	a constant
C_D	drag coefficient (dimensionless)
C_f	friction drag coefficient (dimensionless)
C_p	pressure drag coefficient (dimensionless)
D	diameter of cylinder (m)
D_∞	width of computational domain (m)
g	gravitational acceleration (m/s^2)
Gr	Grashof number (dimensionless)
h	convective heat transfer coefficient (W/m$^2\cdot$K)
k	thermal conductivity (W/m·K)
n	power-law index (dimensionless)
Nu	average Nusselt number (dimensionless)
p	gauge pressure (Pa)
Pr	Prandtl number (dimensionless)
R	radial distance from cylinder surface (m)
r	unit normal vector on the surface of cylinder (dimensionless)
Ra	Rayleigh number (dimensionless)
s	surface area of each cylinder (m^2)
S	center-to-center cylinder distance (m)
T	temperature of fluid (K)
T_m	film temperature of fluid (K)
T_∞	temperature of fluid far away from cylinder (K)
T_w	temperature of the surface of the cylinder (K)
ΔT	temperature difference, $\Delta T = T_w - T_\infty$
u, v	x and y components of the velocity (m/s)
V_θ	tangential velocity (m/s)
V_R	radial velocity (m/s)
U,V	x and y components of the velocity (dimensionless)
u_{ref}	reference velocity (m/s)
x, y	Cartesian coordinates (m)
X, Y	Cartesian coordinates (dimensionless)

Greek symbols

α	thermal diffusive coefficient (m^2/s)
β	coefficient of thermal expansion (K^{-1})
θ	circumferential angle (degree)
ϑ	kinematic viscosity (m^2/s)
δ	distance between two grid points on the surface of cylinder (m)
ρ	density of the fluid (kg/m^3)
τ	wall shear stress per unit length of cylinder (Pa)

Superscript and subscripts

$*$	dimensionless quantities
θ	local value
L	lower cylinder
U	upper cylinder
0	single cylinder

Prandtl number ranging from 0.72 to 100, the center-to-center separation distances as $2 \leqslant S/D \leqslant 20$, and the power-low index $0.3 \leqslant n \leqslant 1.5$, where the values for $n < 1$ correspond to the shear-thinning fluids, $n = 1$ represents the Newtonian behavior, whereas $n > 1$ is the shear-thickening fluids. Their conclusions are similar to the prior results where the arrays of cylinders are immersed in Newtonian fluids, e.g., air and water, i.e., the heat transfer characteristics of the lowest cylinder in a vertical array are almost same as a single horizontal cylinder when $S/D \geqslant 2$, instead, the heat transfer phenomena for the upper cylinders are complex, which is either enhanced or degraded with respect to that for a single cylinder, depending on the spacing between two consecutive cylinders and Rayleigh number. All else being equal, for the small spacing, the Nusselt numbers for the upper cylinders are reduced, which should be attributed to the preheating effect by the lower cylinders. In other works, the temperature difference between the working fluid and the upper cylinders decreases owing to the working fluid heated by the lower cylinders. However, as the separation distance increases, the heat transfer rate of the downstream cylinders increases. That trend stems from the combined results of the dominating velocity effect and the weakening preheating effect, i.e., these upper cylinders are submerged in the plumes rising from the lower cylinders, experiencing a mixed convection regime due to the initial velocity imposed by the plumes of the lower cylinders, whereas the preheating effect, due to the large number of entrainment of the cold surrounding fluid from both sides, is so weak that it hardly contributes anything to the heat transfer from the upper cylinders. Finally, it can be enhanced up to approximately 1.24 times that of a single cylinder. Aside from the similar characteristics of the heat transfer to that reported in Newtonian fluids, Shyam et al. [39] have found that the shear-thinning fluids facilitate the heat transfer relative to that for the Newtonian fluids, while the shear-thickening fluids have an adverse influence on the heat transfer rate. Analogous phenomena have been reported in molten salts in a successive paper by Yuanwei Lu et al. [40], who investigated the natural convection from the vertical arrays of 2–8 horizontal cylinders for the Rayleigh number in the range between 2×10^3 and 5×10^5 and the separation distances increasing from 2 to 9 times cylinder diameter. More recently, Kitamura et al. [41] have conducted an experimental analysis on the natural convection heat transfer and flow from a single vertical row of heated horizontal cylinders consisting of ten cylinders in air, with the purpose of deriving the heat transfer correlating equations for any individual cylinder in the array, in particular, also presenting the correlation for the turbulent flows. Besides, the effect of the temperature imbalance ratio (define as $\Delta T_L/\Delta T_U$) on natural convection heat transfer from the upper cylinder in a vertical array consisting of a pair of cylinders has been investigated experimentally and numerically by Sparrow and Niethammer [24], and Park and Chang [26], via considering the temperature imbalance ratio to be one and two, respectively. Their consistent results have proved that the heat transfer rate for the upper cylinder is impaired with the increasing ratio, because of the reinforcing preheating effect, i.e., for the ratio of one, the ratio of the Nusselt number for the upper cylinder to a single cylinder varies from 0.8 to 0.104 over the range of S/D as $2 \leqslant S/D \leqslant 4$ at $Ra = 2 \times 10^4$ and the corresponding range for the temperature imbalance ratio of two was found to be 0.3 to 0.73.

On the other hand, in pursuit of the maximization in the value of heat transfer rate in structure design, the optimization of heat transfer from arrays of cylinders in a given space has been a classical topic. It differs from those previous studies [22–41] that are restricted to the arrays of cylinders in free space, where the optimal spacing in the arrays must take the volumetric heat transfer into account, rather than simply maximize the value of Nusselt number for the upper cylinders or the whole arrays. Bejan et al. [42] proposed a metric for measuring the heat transfer volumetric density to optimize the spacing of a staggered tube bank with the centers of any three consecutive cylinders forming equilateral triangles in a fixed volume. As a result of the symmetry of flow, a