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Free Convection Heat Transfer from Different Objects

Mohamed Ali and Shereef Sadek

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Abstract

Heat transfer by natural convection phenomenon has been studied by diverse researchers for several geometries and different boundary conditions. Different approaches were used such as numerical, analytical, and experimental approaches. In this chapter, we are going to review the most common published research on object shapes in natural convection heat transfer with their obtained numerical, semiempirical, and/or experimental correlations for the last two decades. These correlations are very important for engineering applications. This chapter will be stressed on cylinders in different orientations with cross sections such as circular, square, triangular, vertical, and horizontal coils and array of cylinders of different cross sections.

Keywords: natural convection, experimental heat transfer, empirical correlations, numerical heat transfer, helical coils, cylinders with different cross section, array of cylinders

1. Introduction

Many investigations have been conducted on natural convection heat transfer from single object with different cross sections such as elliptic, rectangular or square, triangular, and circular cylinders in free space. Furthermore, correlations of flat plate (vertical, horizontal, or inclined) and coils were also developed. Such correlations are those for vertical plate as reported by McAdams [1] and Churchill and Chu [2], horizontal surface by Goldstein et al. [3] and Lloyd and Moran [4], long horizontal cylinder by Morgan [5] and Churchill and Chu [6], and spheres by Churchill [7]. In Section 2, cylinders with different cross sections and orientations are presented, Section 3 reports correlations obtained from helical coils, and arrays of cylinders of different cross sections in free convection is reviewed in Section 4.

2. Cylinders of different cross sections in free convection

Atmane et al. [8] investigated experimentally the effect of vertical confinement on a single heated horizontal cylinder for a range of Rayleigh number between 3×10^4 and 3×10^6 in water. They concluded that the heat transfer nearby the cylinder and the natural convection hydrodynamics was not affected by the water surface if the distance was four times the cylinder diameter or more.

Free convection heat transfer from vertical slender cylinders has been reviewed by Popiel [9]. The classical analysis of the laminar free convection heat transfer from vertical cylinders was shown. Numerical calculations for a turbulent boundary layer flow on a vertical cylinder using a modified integral method were presented. Experimental data for laminar-turbulent transition suggested that the critical Grashof number for a vertical flat plate is $Gr_{cr} \approx 10^9$, while for a vertical cylinder is $Gr_{cr} \approx 4 \times 10^9$.

Theoretical, numerical, and experimental data for free convection heat transfer from vertical slender circular cylinders were surveyed by Popiel [9], who developed the following 3% criterion for transversal curvature effect for the average heat transfer from isothermal vertical cylinders valid in the range of Prandtl number from $Pr = 0.01$ to 100:

$$Gr_H^{0.25} \frac{D}{H} \leq a + \frac{b}{Pr^{0.25}} + \frac{c}{Pr^{0.5}} \tag{1}$$

where a = 11.474, b = 48.92, and c = 0.006085. Elsayed et al. [10] studied experimentally free convection from a constant heat flux elliptic tube cross section. They studied the effect of tube orientation on the local Nusselt number distributions as well as the average Nusselt number variation versus tube inclination angle. Results showed that the maximum average Nusselt number was achieved when the tube's major axis is vertical. An empirical correlation (Eq. (2)) has been derived to evaluate the average Nusselt number in terms of Rayleigh number based on the input heat flux:

$$Nu_{av} = 0.47(Ra^*)^{0.2}, \quad 1.1 \times 10^7 \leq Ra^* < 8 \times 10^7 \tag{2}$$

The maximum deviation between the experimental data and the correlation is about 5%. From the comparison between free convection around isothermal and constant heat flux elliptic tubes, it was found that at the steady state, the heat flux tube correlates well with $Ra^{0.25}$, similar to the isothermal tube. Ali and Al-Ansary [11] have reported experimentally steady-state natural convection heat transfer from the outer surface of vertical triangular cylinder in air. The experimental results showed the existence of laminar and transition to turbulence regimes. They observed a decrease in the local axial (perimeter-averaged) heat transfer coefficient at the lower half of the cylinder which indicated a laminar regime. On the other hand, an increase in the heat transfer coefficient along the cylinder axis was related to transition to turbulent regime at any constant heat flux. The local axial Nusselt and the modified Rayleigh numbers were used to develop two correlations for laminar (Eq. (3)) and transition regime (Eq. (4)):

$$Nu_x = 3.034(Ra^*)^{0.156}, \quad 10^7 \leq Ra_x^* < 10^{12} \tag{3}$$

with correlation coefficient $R = 91\%$:

$$Nu_x = 0.359\left(Ra_x^*\right)^{0.244}, \quad 1.0 \times 10^{10} \leq Ra_x^* < 2.0 \times 10^{12} \tag{4}$$

with a correlation coefficient $R = 91.6\%$. Another overall averaged correlation was obtained using the averaged data and the equilateral triangular side length as the characteristic length:

$$\overline{Nu_L} = 0.373\left(Ra_L^*\right)^{0.24}, \quad 4 \times 10^5 \leq Ra_L^* \leq 6.0 \times 10^8 \tag{5}$$

with a correlation coefficient $R = 93.4\%$. Critical values of the modified Rayleigh numbers were obtained and correlated for transition to turbulent:

$$(Nu_x)_{cr} = 0.457\left(Ra_x^*\right)_{cr}^{0.22}, \quad 4 \times 10^9 \leq Ra_x^* \leq 5.0 \times 10^{11} \tag{6}$$

with a correlation coefficient $R = 96.5\%$.

Ali and Al-Ansary [12] carried out an experimental study to investigate the steady-state natural convection from horizontal ducts with triangular cross sections in air. Two different horizontal duct orientations were considered; in the first position, one surface was facing downward and a vertex facing upward, while in the other position, the vertex faced downward and a flat surface faced upward. All ducts had an equilateral triangle cross section with side lengths of 0.044, 0.06, 0.08, 0.10, and 0.13m. A constant-heat-flux heating element was placed inside each duct to provide the heat flux. General correlations are obtained for two duct orientations using the local perimeter-averaged heat transfer data given by Eqs. (7) and (8):

$$Nu_x = 0.429\left(Ra_x^*\right)^{0.241}, \quad 2.0 \times 10^8 \leq Ra_x^* \leq 1.0 \times 10^{12} \tag{7}$$

with a correlation coefficient of $R = 97.5\%$:

$$Nu_x = 0.688\left(Ra_x^*\right)^{0.222}, \quad 9.0 \times 10^7 \leq Ra_x^* \leq 1.0 \times 10^{12} \tag{8}$$

with a correlation coefficient of $R = 97.3\%$. A critical correlation is obtained to segregate the laminar and transition regimes when the duct vertex faces upward [Eq. (9)]:

$$Nu_x = 0.325\left(Ra_x^*\right)^{0.241}, \quad 1.0 \times 10^7 \leq Ra_x^* \leq 1.0 \times 10^{11} \tag{9}$$

with a correlation coefficient of $R = 98.2\%$.

Zeitoun and Ali [13] have studied numerically two-dimensional laminar natural convection heat transfer in air around horizontal ducts with rectangular and square cross sections. Temperature and velocity profiles were obtained close to every surface of the ducts. Different aspect ratios were used for wide ranges of Rayleigh numbers. The process procedure was based on the finite element technique. Temperature and velocity profiles are obtained near

each surface of the ducts (correlation 10) covering wide ranges of Rayleigh number for various aspect ratios (Γ), which was obtained for ducts with horizontal square and rectangular cross sections:

$$Nu = \left(0.9\Gamma^{-0.061} + 0.371\Gamma^{-0.114}Ra^{0.1445}\right)^2, \quad 700 \leq Ra \leq 1.3 \times 10^8 \tag{10}$$

with a correlation coefficient of $R = 99.8\%$.

Al-Ansary et al. [14] have presented a numerical study of laminar natural convection heat transfer from uniformly heated horizontal cylinders of a triangular cross section in air. Flow streamlines as well as temperature contours were presented around the cylinder's perimeter. Thermal boundary layer profiles were also shown for different modified Rayleigh numbers. General correlations of Nusselt numbers versus modified Rayleigh numbers were obtained for symmetric, transition, and asymmetric plumes for both positions of the cylinders. For triangular cylinders facing upward, correlations (11–12) were obtained for symmetric and asymmetric plumes around the cylinders, respectively. On the other hand, for triangular cylinders facing downward, correlations (13–14) were obtained for symmetric and asymmetric plumes around the cylinders, respectively:

$$Nu = 0.619(Ra^*)^{0.194}, \quad Ra^* < 7.0 \times 10^5 \tag{11}$$

$$Nu = 0.293(Ra^*)^{0.249}, \quad Ra^* \geq 7.0 \times 10^5 \tag{12}$$

$$Nu = 0.707(Ra^*)^{0.176}, \quad Ra^* \leq 1.0 \times 10^6 \tag{13}$$

$$Nu = 0.133(Ra^*)^{0.301}, \quad Ra^* > 2.0 \times 10^7 \tag{14}$$

Steady-state free convection heat transfer from outer surface of horizontal cylinders having rectangular cross section in air was investigated by Ali [15]. Five cylinders have been used with aspect ratios Γ (Γ = cylinder height/cylinder width) of 2, 1, and 0.5. The cylinders had a constant heat flux boundary conditions through inserting internal heating element along the centerline of each cylinder. Temperature measurements were taken along the axial and peripheral directions of the cylinder surface. Two distinct flow regimes were observed, namely, laminar and transition to turbulence. A laminar regime was obtained for low values of convection heat flux and characterized by a decrease in Nusselt numbers at any fixed longitudinal direction x on the cylinder's surface. However, Nusselt numbers increased as x increased along the cylinder's surface for any value of the heat flux, and the regime was characterized as transition to turbulence. General correlation using the local circumference average transition to turbulence heat transfer data was obtained where Nusselt numbers were correlated using the modified Rayleigh numbers (Eq. (15)):

$$Nu_x = 0.355\left(Ra_x^*\right)^{0.297}, \quad 1.9 \times 10^8 \leq Ra_x^* \leq 7 \times 10^{11} \tag{15}$$

On the overall averaged basis, correlation covering the locus of critical points segregating the laminar and transition regimes was obtained using the modified Rayleigh number (Eq. (16)):

$$\overline{Nu}_L = 0.168\left(Ra_L^*\right)^{0.287} \tag{16}$$

with a correlation coefficient of $R = 95.93\%$. In addition, laminar heat transfer data were aspect ratio and area ratio dependent, as correlated using the modified Rayleigh numbers over averaged basis (Eqs. (17) and (18)):

$$\overline{Nu}_L = 12.41\left(Ra_L^*\right)^{-0.237}\kappa^{1.259}\Gamma^{-1.226} \tag{17}$$

(for) $\kappa < 100, \quad 8 \times 10^6 \leq Ra_L^* \leq 6 \times 10^7$

$$\overline{Nu}_L = 33,633.84\left(Ra_L^*\right)^{-0.241}\kappa^{0.86}\Gamma^{0.0779} \tag{18}$$

for $\kappa \geq 100, 1.0 \times 10^6 \leq Ra_L^* \leq 7 \times 10^6$ where κ is the area ratio (κ = surface area of the cylinder/ cross section area of the cylinder). Ali [16] has investigated experimentally the steady-state free convection from vertical and horizontal cylinders with square or rectangular cross section. Four and three cylinders had square and rectangular cross sections, respectively. The cylinders had constant heat flux boundary conditions where the heating elements were inserted internally along the center of the cross section. Temperature measurements were taken on the cylinder's peripheral direction and on the axial direction of the cylinders. General correlation using the local perimeter-averaged transition to turbulence heat transfer data was obtained where Nusselt numbers were correlated using the modified Rayleigh numbers (Eq. (19)). Furthermore, the laminar local perimeter-averaged data were correlated using the axial distance as a parameter (Eqs. (20) and (21)):

$$Nu_x = 0.14\left(Ra_x^*\right)^{0.269}, \quad 5.0 \times 10^9 \leq Ra_x^* \leq 1.5 \times 10^{11} \tag{19}$$

with a correlation coefficient $R = 94\%$:

$$Nu_x = 1.7\left(Ra_x^*\right)^{0.164} \tag{20}$$

For area ratio $\kappa < 0.01, 1.0 \times 10^7 \leq Ra_x^* \leq 4.0 \times 10^{10}$, with a correlation coefficient $R = 97.3\%$:

$$Nu_x = 6.02\left(Ra_x^*\right)^{0.113} \tag{21}$$

For area ratio $\kappa = 0.01, 1.0 \times 10^7 \leq Ra_x^* \leq 1.0 \times 10^{11}$, with a correlation coefficient $R = 93.4\%$. In addition, on the overall averaged basis for laminar heat transfer, data were correlated using the modified Rayleigh numbers as seen by Eqs. (22) and (23):

$$\overline{Nu}_L = 1.52E + 11\left(Ra_L^*\right)^{-0.283}\kappa^{4.077}\Gamma^{0.392} \tag{22}$$

which is valid for

$$\kappa > 0.01, 4.0 \times 10^6 \leq Ra_L^* \leq 4.0 \times 10^8 \tag{23}$$

$$\overline{Nu}_L = 4.283E + 8\left(Ra_L^*\right)^{-0.0365}\kappa^{2.42} \tag{24}$$

which is valid for

$$\kappa \leq 0.01, 1.0 \times 10^6 \leq Ra_L^* \leq 1.5 \times 10^8 \tag{25}$$

Natural convection from inclined circular cylinders to air was reported experimentally by Oosthuizen [17] using a transient cooling technique. Oosthuizen pointed out that the flow over the inclined cylinder was in general three-dimensional and obtained a correlation for Nusselt numbers as a function of Grashof number and the cylinder's aspect ratio:

$$\frac{Nu_D}{\left(G_D \cos\phi\right)^{0.25}} = function\left(\frac{l}{D\tan\phi}\right) = function(l^*) \tag{26}$$

where D, l, and ϕ are the diameter, length, and angle of inclination of the circular cylinder. He observed that for l^* greater than about 10, the flow over the cylinder is the same as that over a horizontal cylinder, while for l^* less than about 1, the flow is the same as that over a vertical cylinder. Similar experiment was done by Stewart [18], and using the same technique followed by Oosthuizen [17], a constant heat flux was applied by inserting a heating element along the centerline of the cylinder. Stewart reported a general correlation valid for horizontal, vertical, or inclined cylinders at any angles:

$$\frac{Nu_D}{\left(Ra_D \cos\phi\right)^{0.25}} = 0.53 + 0.555\left[\left(\frac{D}{l\cos\phi}\right)^{0.25} - \left(\frac{D}{l}\right)^{0.25}\right] \tag{27}$$

Local heat transfer coefficient profiles were experimentally obtained by Al-Arabi and Salman [19], for inclined circular cylinder subject to boundary condition of constant heat flux. In their experiment, the laminar regime was characterized by a decrease in the local heat transfer coefficient up to the middle of the cylinder, and the transition regime was indicated by an increase of the local heat transfer coefficient in the other half of the cylinder. Experimental correlations were obtained for each angle of inclination. Another experiment was done for isothermal inclined cylinders. Al-Arabi and Khamis [20] reported that the average heat transfer coefficient decreased with increasing the cylinder diameter for constant inclination and cylinder length. General local (Eqs. (26) and (27)) and average (Eqs. (28) and (29)) Nusselt number correlations were suggested for laminar (Eqs. (26) and (28)) and turbulent (Eqs. (27) and (29)) convection heat transfer:

$$Nu_x = \left[2.3 - 1.72\left(\sin\phi\right)^{0.8}\right](Gr_D)^{-1/12}[Gr_x Pr]^{0.25 + 1/\left(12\sqrt{\sin\phi}\right)} \tag{28}$$

$$Nu_x = \left[0.42 - 0.16\left(\sin\phi\right)^{0.8}\right](Gr_D)^{-1/12}[Gr_x Pr]^{1/3} \tag{29}$$

$$Nu_l = \left[2.9 - 2.32\left(\sin\phi\right)^{0.8}\right](Gr_D)^{-1/12}[Gr_l Pr]^{0.25 + 1/\left(12\sqrt{\sin\phi}\right)} \tag{30}$$

$$Nu_l = \left[0.47 + 0.11\left(\sin\phi\right)^{0.8}\right](Gr_D)^{-1/12}[Gr_l Pr]^{1/3} \tag{31}$$

Li and Tarasuk [21] have presented a universal correlation in terms of Nusselt and Rayleigh numbers for circular cross-sectional inclined cylinder from 0 to 90°. Their results show a direct proportion of the average Nusselt numbers with the Rayleigh numbers and inversely

proportional to the inclination angle of the cylinder to the horizontal for the Rayleigh number range (104 to 106). A copper electroplating system was used to simulate the free convection heat transfer using a mass transfer system based on the analogy between heat and mass transfer by Heo and Chung [22]. They have used that method to determine the heat transfer from inclined cylinders. Numerical and experimental investigation on free convection heat transfer was reported by Kalendar and Oosthuizen [23] using inclined isothermal square cylinders. Those cylinders had been exposed to the top surface. Their results for the average Nusselt number and for inclination angle range from 0 to 180° were correlated as

$$\frac{\overline{Nu}}{Ra^{0.28}} = 0.27 + \frac{0.65}{\left(W \cdot Ra^{0.25}\right)^{0.95}} \tag{32}$$

where W is the width ratio (width/height). Experimental study has been made on local and averaged natural convection heat transfer from inclined square cylinders in air at 30°, 45°, and 60° inclination angle to the horizontal by Ali [24]. His results showed that the correlation obtained for each inclination angle indicated that the natural convection has a weak dependence on the inclination angle; therefore, overall correlations were obtained to cover all cylinders at all inclination angles for laminar regime: one for local laminar profiles (Eq. (31)) and the other for averaged profiles (Eq. (32)):

$$Nu_x = 1.109\left(Ra_x^*\right)^{0.193}, \quad 1.0 \times 10^7 \leq Ra_x^* \leq 2.0 \times 10^{12} \tag{33}$$

$$Nu = 0.452(Ra^*)^{0.224}, \quad 4.0 \times 10^4 \leq Ra^* \leq 1.0 \times 10^8 \tag{34}$$

The corresponding local correlation for transition regime was obtained as

$$Nu_x = 0.842\left(Ra_x^*\right)^{0.209}, \quad 9.0 \times 10^9 \leq Ra_x^* \leq 1.0 \times 10^{12} \tag{35}$$

3. Helical coils in free convection

Natural convection heat transfer from helical coils is very important for its large surface area per unit volume. Helical coils are used in many engineering applications such as heating, ventilation, and air-conditioning systems. The first reference to deal with the subject of helical coils that tried to get empirical correlation is an experimental study by Ali [25]. In this study, a correlation is developed for natural convection from vertical helical coils in water for a range of Prandtl number, $3.44 \leq Pr \leq 5.30$. In his experiment, ten coils were used corresponding to four various coil diameters to tube diameter ratios and to five different ratios of pitch to tube diameter. It was observed that the average heat transfer coefficient is inversely proportional with the coil length for tube diameter of $d = 0.012$m but directly proportional with the coil length for $d = 0.008$m. The correlation for $d = 0.012$m, using the coil length as a characteristic length, is

$$Nu_L = 0.685Ra_L^{0.295}, \quad 3 \times 10^{12} \leq Ra_L \leq 8 \times 10^{14} \tag{36}$$

where L is the length of the helical coil. Free laminar convection heat transfer from coils in air was studied by Xin and Ebadian [26] for vertical and horizontal positions. Three test coils were

used in their experiment. The coils had a constant heat flux boundary condition. Averaged Nusselt numbers were obtained in correlation form for the two positions of the coils.

For the horizontal coils, the study was concentrated on the middle turn of each coil only, and they conclude that the peripheral average Nusselt number distribution around the middle turn is almost periodic. Their correlation for the three middle turns of the three test coils (did not include the coil end effect) was given by

$$Nu_d = 0.318 Ra_d^{0.293}, \quad 5 \times 10^3 \le Ra_d \le 1 \times 10^5 \tag{37}$$

where d is the tube diameter of the helical coil. Ali [27] has studied experimentally the effect of laminar natural convection heat transfer from horizontal helical coils in air. Four coils of different diameters were used and heated using constant heat flux in the range of $500 - 5000 \, W/m^2$. In his results, the transition regime was characterized by a wavy variation in Nusselt numbers as a function of the number of turns. His laminar-averaged correlation obtained for the heat transfer coefficient indicated a decrease in the heat transfer coefficient with increasing the number of coil turns.

His overall averaged Nusselt numbers vs. Rayleigh numbers for all turns of the four test coils for $q'' = 500$ and $1000 \, W \cdot m^{-2}$ were shown. Least square power law fit through his data set obtained the following correlations for a heat transfer flux q'' of 500 and $1000 \, W \cdot m^{-2}$, respectively.

$$Nu_d = 10824.2 Ra_d^{-1.196}, \quad 340 \le Ra_d \le 645 \tag{38}$$

$$Nu_d = 187508 Ra_d^{-1.526}, \quad 728 \le Ra_d \le 938 \tag{39}$$

Using the horizontal coil axial distance x as a characteristic length, Ali [27] showed that an overall correlation for all heat fluxes for all coils in air can be obtained as

$$Nu_x = 0.913 Ra_x^{0.301}, \quad 3 \times 10^3 \le Ra_d \le 7 \times 10^6 \tag{40}$$

Another constant heat flux experimental work using vertical helical coils in air for two different groups of coils was studied by Ali [28]. He used the coil tube diameter and the coil axial length as two different characteristic lengths for analyzing his data. His obtained Nusselt number correlation, using the tube diameter as a characteristic length, showed heat flux dependence when Rayleigh number was used in the correlation. However, using the axial distance of the coil as a characteristic length in both Nusselt and Rayleigh numbers correlation made all the data to collapse on one unique curve independent of the heat flux. Prabhanjan et al. [29] have presented an experimental investigation using three vertical coils in water using various characteristic lengths. The correlation they got was not accurate enough to be considered for a wide rage and different orientations. Therefore, they recommend that more study should be made to develop an accurate correlation for Nusselt numbers. On the other hand, their experiment was good in predicting the outer surface temperature of the coil. In order to obtain correlations for natural convection heat transfer from coils in high Prandtl number medium, Ali [30] investigated experimentally that case for laminar and transition natural convection heat transfer using vertical helical coils with various pitches in 57% glycerol-water

solution by mass. That experiment was for a range of Prandtl number of 28–36. For both diameter ratio and Rayleigh numbers fixed, he showed increases of the overall heat transfer coefficient with decreasing the number of coil turns. Accordingly, keeping the diameter ratio constant and increasing the Rayleigh numbers led to increase in heat transfer coefficients. On the other hand, enhancement was obtained in heat transfer coefficients corresponding to lower diameter ratio of the coils for both constant number of turns and Rayleigh number. The overall averaged empirical correlations for coils with five and ten turns were reported, respectively, as

$$Nu_L = 2.53 \times 10^{-5} Ra_L^{0.739} \left(\frac{D}{d_0}\right)^{-1.313}, \quad 10^{12} \leq Ra_L \leq 10^{14} \tag{41}$$

$$Nu_L = 1.535 \times 10^{-5} Ra_L^{0.671} \left(\frac{D}{d_0}\right)^{-0.702} \tag{42}$$

$$for \quad 7 \times 10^{12} \leq Ra_L \leq 8 \times 10^{14}$$

where D is the coil diameter and d_0 is the outer tube diameter. The overall average Nusselt numbers for all coils used was correlated using Rayleigh number as

$$Nu_L = 0.106 Ra_L^{0.335}, \quad 2 \times 10^{12} \leq Ra_L \leq 8 \times 10^{14} \tag{43}$$

$$Nu_L = 0.555 Gr_L^{0.301} Pr^{0.314} \tag{44}$$

For $10^8 \leq Gr_L \leq 5 \times 10^{14}$ and $4.4 \leq \overline{Pr} \leq 345$.

An experimental study has been made on steady-state natural convection heat transfer from vertical helical coil tubes in heat transfer oil of Prandtl number range $250 - 400$ by Ali [31]. He used five sets of coils; each set consisted of three coils with constant coil diameter to tube diameter ratio. Each set had two, five, and ten turns. The helical coil-to-tube diameter ratios were 30, 20.83, 17.5, 13.33, 10, and 10. The coil length was used as a characteristic length in the dimensionless groups where correlation obtained Eq. (42) for high Prandtl number and compared to that of low Prandtl number fluids of [25].

An alternative correlation was obtained using the Rayleigh number as

$$Nu_L = 0.714 Ra_L^{0.294}, \quad 5 \times 10^{10} \leq Ra_L \leq 8 \times 10^{14} \tag{45}$$

Natural convection heat transfer phenomena for an inclined helical coil were investigated experimentally by Moon et al. [32] for $Ra_D = 4.55 \times 10^6$. An electroplating system was used to measure mass transfer instead of heat transfer, based on the analogy concept.

4. Arrays of cylinders in free convection

To increase the surface area of the heat transfer, thermally interacting multiple horizontal and vertical cylinders have been investigated by different researchers. Most of the analyses for

those types of geometries are circular. A pair of vertically aligned horizontal cylinders in water is investigated by Reymond et al. [33] for a Rayleigh numbers 2×10^6, 4×10^6, and 6×10^6 and for a range of cylinder spacing of 1.5, 2, and 3 diameters. They observed that the heat transfer from the bottom cylinder in the array was unaffected by the upper cylinder for the used spacing between cylinders. It was also found that the presence of unheated lower cylinder had no effect on the upper cylinder heat transfer. For that reason they did the experiment for both heated cylinders with different spacings. Their experiment showed that the rising plume from the lower cylinder had large effect on the upper cylinder's surface heat transfer. Their results showed that increasing the Rayleigh number increases the area-averaged heat transfer in line and the following correlation is suggested:

$$\overline{Nu} = 0.48(Ra_L)^{0.25}, \quad 10^4 < Ra_L < 10^7 \tag{46}$$

Experimental investigation on natural convection at high Rayleigh numbers from a pair of evenly spaced cylinders in water for five different center-to-center separation distances was reported by Grafsrønningen and Jensen [34]. Their results showed that at small separation distance of the upper cylinder, the increase in average Nusselt number was about 6% and for large one was about 15 to 40%. The effect of dissimilar cylinder spacing between horizontal cylinders in vertical arrays of two or three cylinders was investigated by Grafsrønningen and Jensen [35]. Their results have shown that the Nusselt number on the middle cylinder in a three-cylinder array increased compared to the lower cylinder and that of the upper cylinder increased too with no much difference than that of the middle cylinder.

Experimental investigation was performed on laminar natural convection from two cylinders arranged in vertical array with a spacing range 2 and 6 of the tube diameter by Chouikh et al. [36]. The cylinders were kept isothermal with Rayleigh numbers range 10^2 and 10^4. Their results were consistent with those in the literature. They found that the bottom cylinder's heat transfer was unaffected by the downstream cylinders and was equal to that of a single cylinder. It was also observed that the upper cylinder in the array of large spacing had an enhanced numbers, but at close distances, it had a reduced Nusselt numbers. On the other hand, for the same spacing, a direct enhancement of heat transfer from the upper cylinder with Rayleigh number was obtained. Their observation about the heat transfer from cylinders in the array agreed with the flow field around the cylinders.

Numerical work was reported on natural steady-state laminar convection heat transfer from horizontal cylinders arranged in vertical array by Corcione [37] in air. Cylinders were isothermal, and numerical simulations were done for arrays of $2 - 6$ with separation distance between cylinders of 2 up to more than 50 cylinder diameters. The simulation was done for Rayleigh number range 5×10^2 and 5×10^5. He has reported numerical correlations valid for the whole array of cylinders and also for any individual cylinder in the array. He compared his numerical results with those in the literature, and it was found satisfactory. In addition, it was found that at any investigated Rayleigh number, degradation was generally the rule at the smaller tube spacing, while enhancement predominated at the larger ones. Two distinct numerical correlations were obtained, as shown below, for the average Nusselt number Nui

of any ith cylinder in the array in terms of Rayleigh number Ra, the cylinder location measured from the center of the bottom cylinder x/H, and the number of cylinders in the array Ni (where $H = S \times (N - 1)$):

$$Nu_{ith} = Ra^{0.25} \left\{ 0.364 \ln \left[(x/D)^{0.4} / N_i^{0.9} \right] + 0.508 \right\} \tag{47}$$

for $2 \leq N_i \leq 6$, $2(N_i - 1) < x/D \leq 8 + N_i$, and $5 \times 10^2 \leq Ra \leq 5 \times 10^5$, with percent standard deviation of error $Esd = 3.19\%$ and range of error from -5.07 to $+7.97\%$. N_i cylinder's index in an array

$$Nu_i = Ra^{0.25} \left\{ 0.587 \ln \left[(x/D)^{0.33} / N_i^{0.5} \right] + 0.35 \right\} \tag{48}$$

for $2 \leq N_i \leq 6$, $(8 + N_i) < x/D \leq \left(10^9 / Ra \right)^{0.333}$, and $5 \times 10^2 \leq Ra \leq 5 \times 10^5$ with percent standard deviation of error $Esd = 3.27\%$ and range of error from -5.93 to $+7.96\%$, and S is the center-to-center distance and D is the cylinder diameter. Another average numerical correlation for Nusselt numbers Nua for all cylinders in the array was obtained in terms of the cylinder spacing ratio S/D, the Rayleigh numbers Ra, and the total number of cylinders N in the array as

$$Nu_a = Ra^{0.235} \left\{ 0.292 \ln \left[(S/D)^{0.4} \times N^{-0.2} \right] + 0.447 \right\} \tag{49}$$

which is valid for

$$2 \leq N \leq 6, \quad 5 \times 10^2 \leq Ra \leq 5 \times 10^5, \quad S/D \leq 10 - \log(Ra)$$

with percent standard deviation of error $Esd = 2.25\%$ and range of error from -4.79 to $+5.27\%$:

$$Nu_a = Ra^{0.235} \left\{ 0.277 \ln \left[(S/D)^{0.4} \times N^{0.2} \right] + 0.335 \right\} \tag{50}$$

which is valid for

$$2 \leq N \leq 6, \quad 5 \times 10^2 \leq Ra \leq 5 \times 10^5, \quad S/D \leq 10 - \log(Ra)$$

with percent standard deviation of error $Esd = 2.72\%$ and range of error from -6.40 to $+6.09\%$. Sadeghipour and Asheghi [38] have reported an experimental study for natural convection heat transfer from horizontal isothermal cylinders in vertical arrays of 2–8 at a low Rayleigh number of 500, 600, and 700. Their results showed that the heat transfer coefficient for the lowest cylinder is the same as that of a single horizontal cylinder. They found that the Nusselt numbers reached a maximum enhancement of 24% for the second cylinder, in an array of two cylinders, at a cylinder spacing of $S/D > 20$. For arrays of more cylinders, they observed a maximum enhancement at distance of $S/D > 15$ from the upper cylinder in the array, but that enhancement is a little bit higher as the number of cylinders in the array increased. Therefore, they found a direct proportional between the number of cylinders in the array and the Nusselt numbers of the array. The following correlation presents their array's Nusselt numbers as a function of Ra, S/D and N:

$$\overline{Nu}_N = Ra^{1/4}\left[0.823 + \exp\left(-1.5(S/D)^{0.05N}\right)\right] \tag{51}$$

which is valid for

$$2 \leq N \leq 8, \quad 500 \leq Ra \leq 700, \quad 3.5 \leq S/D \leq 27.5$$

Park and Chang [39] have studied numerically the interactive natural convection heat transfer from a pair of vertically separated horizontal circular cylinders of equal diameter. The flow was assumed to be laminar, and each cylinder was kept isothermal. In their study, zone-dependent grid systems were successfully employed with grid overlapping in between. Results were presented, the velocity profiles and the local and overall Nusselt numbers for the Rayleigh number ranged $10^4 \sim 10^5$, Prandtl number fixed at 0.7, and for different cylinder spacings.

Corcione [40] studied steady-state laminar free convection from a pair of vertical arrays of equally spaced, horizontal isothermal cylinders set in free air, numerically. Simulations were obtained for $1 - 4$ circular cylinders arranged in tube arrays for vertical and horizontal center-to-center distance of the range 2–12 and 1.4–24 of cylinder diameters, respectively. The Rayleigh numbers used in his simulation was in the range 10^2–10^4, where he used the cylinder diameter as a characteristic length. He has concluded that the Nusselt numbers of any cylinder in the array may be reduced or enhanced compared to that of a single tube depending on the location of the cylinder in the array, the array geometry, and the investigated Rayleigh numbers. He also proposed some dimensionless correlations for the heat transfer.

Persoons et al. [41] have discussed the near interaction between local fluid dynamics and natural convection heat transfer from a couple of isothermally heated horizontal cylinders plunged in water. The presence of the next heated cylinder induced heat transfer improvements of up to 10% and strong variations in local heat transfer rate. Therefore, specific attention was motivated on how the local heat transfer characteristics of the upper cylinder were affected by buoyancy-induced fluid flow from the lower cylinder. The paper studied a variety of Rayleigh numbers between 1.8×10^6 and 5.5×10^6 and a vertical cylinder gaps between $2D$ and $4D$. A joint temporal analysis of the data has provided new insights into the governing mechanisms, which enables further optimization of the heat transfer performance. They concluded that there was no significant heat transfer fluctuations associated with the single cylinder for the range of investigated Rayleigh number $\left(1.8 \times 10^6 \leq Ra \leq 5.5 \times 10^6\right)$. This result was consistent with the average heat transfer rate correlation. On the other hand, for a vertical array of two horizontal cylinders with center spacing from $2D$ to $4D$, a strong periodicity associated with the local heat transfer rate was found. It was observed that fluctuations were highest around the bottom of the upper cylinder where the lower plume impinged and also at the top of it where the plume detached. Furthermore, an increase up to 10% of the average heat transfer rate was observed at the upper cylinder which depends on the separation distance and the Rayleigh number. However, a reduction of -5% in heat transfer was also obtained at low Rayleigh numbers and small separation distance $\left(Ra = 1.8 \times 10^6, S/D = 2\right)$, respectively.

Marstrrs [42] has studied experimentally the heat transfer properties of a vertical array of heated cylinders in steady-state natural convection. The results for a variety of combinations

of spacing and number of cylinders were reported. The cylinder temperature in a vertical array is a function of spacing and position for a given dissipation rate. For close spacing, the temperature rises, generally, but for wide spacing, the temperature decreases monotonically. For closely spaced arrays, individual tube Nusselt numbers were found to be smaller than for a single cylinder (as much as 50% smaller). However, for wide spacing, individual tube Nusselt numbers were higher (up to about 30%) than for a single cylinder. A similar experiment was done by Sparrow and Niethammer [43] for two-cylinder array. The distance between the two cylinders was changed between 2–9 the cylinder diameter, and it was found that degradation of the Nusselt number of the upper cylinder occurred at small separations and enhancement at large ones if compared to the lower cylinder. It was also found that the maximum enhancement observed at a separation distance range of 7–9 cylinder diameters.

Basit et al. [44] numerically investigated natural convection heat transfer from an assembly of vertical cylinders of Pakistan Atomic Research Reactor. They solved the two-dimensional axisymmetric case and presented the temperature, velocity profiles, and Nusselt number variations at different heat flux values. The normalized Nusselt number decreased along the axial distance. They observed an increase of maximum temperature along the length of the fuel pin but still far below the melting point. On the other hand, a decrease in local heat transfer coefficient was obtained along the length of the fuel pin.

Yousefi and Ashjaee [45] have studied experimentally laminar natural convection heat transfer from vertical array of horizontal isothermal elliptic cylinder. In their experiment, they studied two to five cylinder major axis at Rayleigh number between 10^3 and 2.5×10^3. They concluded that:

a.   At any Rayleigh number and for each spacing between cylinders, the heat transfer rate from the bottom cylinder in the array was unaffected by the rest of the cylinders, and it was equal to that of a single cylinder.

b.   For the spacing between cylinders used in their study, they observed a direct proportion between the heat transfer from the topmost cylinder in the array and the spacing between cylinders.

c.   At large separation between cylinders, the buoyant flow effect was very limited, and Nusselt numbers of the downstream cylinders in the array were almost the same unaffected by the large separation between cylinders. [Where S and a are the vertical center-to-center separation distance and the minor axis, respectively].

d.   The average Nusselt number of the arrays increased with increasing the Rayleigh number and the cylinder spacing. Also, for large cylinder spacing, the difference between the average Nusselt number and that for single cylinder decreased by increasing the Rayleigh number.

The experimental data for the average Nusselt number of any individual ith cylinder in the array $\overline{Nu_i}$, excluding the lowest one, were correlated to the Ra, Y/a, and N_i, by the following equation:

$$\overline{Nu_i} = Ra^{0.25}\left\{0.321\ln\left[(Y/a)^{0.695}/N_i^{1.4}\right] + 0.575\right\} \tag{52}$$

which is valid for

$$2 \leq N_i \leq 8, \quad 10^3 \leq Ra \leq 2.5 \times 10^3, \quad N_i \leq Y/a \leq 4N_i$$

with percentage standard deviation of error $Esd = 2.91\%$ and range of error from -6.01 to $+6.91\%$. The experimental data for the average Nusselt number of all the cylinders in the vertical array may be correlated to the Ra and S/a, by the following equation:

$$\overline{Nu}_a = Ra^{0.25}[0.183 \ln (S/a) + 0.28] \tag{53}$$

which is valid for

$$2 \leq N \leq 5, \quad 10^3 \leq Ra \leq 2.5 \times 10^3$$

with percentage standard deviation of error $Esd = 1.34\%$ and range of error E from -2.6 to 2%. Ashjaee and Yousefi [46] have experimentally studied steady-state two-dimensional natural convection heat transfer from the vertical and inclined array of five horizontal isothermal elliptic cylinders with vertical major axis which confined between two adiabatic walls. Their correlation for any individual ith cylinders in the vertical array using the average Nusselt numbers $\overline{Nu}_{iv}$ excluding the lowest one can be correlated to the Ra, S_y/d, and Ni by the following equation:

$$\overline{Nu}_{iv} = Ra^{0.25}\left\{0.45 \ln \left[(S_y/d)^{0.45}/N_i^{0.92}\right] + 0.51\right\} \tag{54}$$

which is valid for

$$2 \leq N_i \leq 5, \quad 10^3 \leq Ra \leq 3 \times 10^3, \quad N_i \leq S_y/d \leq 4N_i$$

with percent standard deviation of error equal to 4.1% and range of error from -7.01 to 6.72%, where S_y, d, and the $\overline{Nu}_{iv}$ stand for vertical center-to-center distance of the ith cylinder from the bottom cylinder, diameter of the cylinders, and average Nusselt number of the ith cylinder in vertical array, respectively. On the other hand, their correlation for the vertical array presented by Nusselt number $\overline{Nu}_{av}$ was correlated to the Ra and P_y/d, by the following equation:

$$\overline{Nu}_{av} = Ra^{0.235}\left[0.47 \ln (P_y/d)^{0.4} + 0.27\right] \tag{55}$$

which is valid for

$$N = 5, \quad 10^3 \leq Ra \leq 3 \times 10^3, \quad 2 \leq P_y/d \leq 5$$

where P_y and N stand for vertical center-to-center separation distance and number of cylinders in the array, respectively. Eq. 53 had a percent standard deviation of error equal to 2.37% and range of error from -2.86 to 1.58%. Furthermore, for inclined array, the following correlation was obtained for individual cylinder where the variation of Nusselt number with Ra, S_y/d, N_i, P_x/d, and P_y/d are as follows:

$$\overline{Nu}_{ii} = Ra^{0.25}\left\{0.67 \ln \left[(S_y/d)^{0.45}/N_i^{0.83}\right] + 0.7\right\} \times \left\{0.95(P_x N_i/d)^{0.41}/(P_y/d)^{1.88} + 0.65\right\} \tag{56}$$

which is valid for

$$2 \leq N_i \leq 5, \quad 10^3 \leq Ra \leq 3 \times 10^3, \quad N_i \leq S_y/d \leq 4N_i \quad 0 \leq P_x/d \leq 2$$

and with percent standard deviation of error equal to 4.19% and range of error from -9.6 to 10.8%, and P_x stands for horizontal center-to-center separation distance. Moreover, their correlation of the average Nusselt number of the inclined array was obtained as

$$\overline{Nu}_{ai} = 0.572Ra^{0.235}\left[(P_x/d) + 0.0256\exp\left(0.24/\eta^{1.07}\right)\right]^{\eta} \tag{57}$$

where η is defined as $\eta = \left(3.115P_y/d\right)^{-0.934}$. Ali et al. [47] have investigated experimentally natural convection heat transfer from the outer surface of a vertical array of horizontal square cylinders in air. Five cylinders equally spaced were used with cross section of $0.02 \times 0.02 m^2$. The cylinders were subject to constant heat flux boundary condition using internal constant heat flux heating elements. Experiment was done for arrays of 2–5 square cylinders and for four center-to-center separation distances to equivalent diameter ratios (S/D). Their study concentrated on the effect of cylinder location in the array and on the geometry of the array, where D was the cross-sectional side length of the square cylinder and Y was the vertical distance measured from the lower cylinder. Local and averaged results showed that the lowermost cylinder was uninfluenced by the downstream cylinders and its Nusselt number is identical to that of a single cylinder in free space. It is also shown that any cylinder in the array was influenced only by the upstream cylinders and unaffected by the downstream ones. Furthermore, the top (downstream) cylinder in each array always degraded the Nusselt number the most than that of a single cylinder followed by other cylinders upstream toward the lower cylinder at small $S/D = 2.5$. This degradation is generally depended on the center-to-center distance ratio S/D of the cylinders in the array. As S/D increases the degradation changed to enhancement in Nusselt numbers, and critical S/D was obtained for the upper (downstream) cylinder in each array. This enhancement depends on the number of cylinders in the array as well as on the S/D ratio. Local and averaged correlations are obtained for each cylinder in different arrays in terms of Nusselt numbers and the modified Rayleigh numbers for $S/D = 2.5$ where the degradation occurred (Eq. (56) for local and Eq. (57) for averaged). **Figure 1** shows the setup used in their experiment holding the array of square cylinders and the cross section of the cylinders filled with sand to insure uniform conduction from the heating element to the surface of the cylinders. Furthermore, general local and averaged correlations, where enhancement in heat transfer occurred, are obtained by Eqs. (58) and (59), respectively, for $S/D = 5$, 7.5, and 10 as shown below:

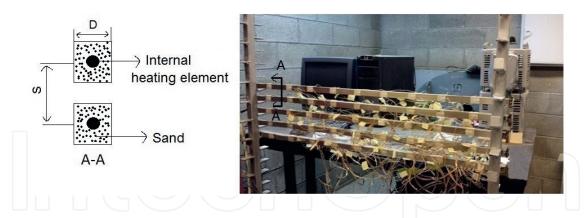$$Nu_x = 0.253\left(Ra_x^*\right)^{0.254}N^{-0.099}M^{0.048}, \qquad R^2 = 95.20\% \tag{58}$$

$$Nu_D = 0.425\left(Ra_D^*\right)^{0.213}N^{-0.98}M^{0.049}, \qquad R^2 = 94.20\% \tag{59}$$

$$Nu_x = 0.247\left(Ra_x^*\right)^{0.246}N^{0.147}(S/D)^{0.084}M^{-0.058}, \qquad R^2 = 94.66\% \tag{60}$$

$$Nu_D = 0.379\left(Ra_D^*\right)^{0.205}N^{0.147}(S/D)^{0.084}M^{0.069}, \qquad R^2 = 90.40\% \tag{61}$$

where N and M stand for the number of cylinders in the array (2, 3, 4, or 5) and the sequence of the cylinder in the array (1, 2, 3, or 4), respectively.

M Sequence of cylinder in an array.

Figure 1. Setup used to hold the arrays of square cylinders and cross sections at A-A showing the center-to-center distance S and the side length D of the square cylinders.

5. Conclusion

Natural convection from individual cylinder of different cross sections is reviewed in this chapter. Circular, square, triangular, and elliptic cylinders are considered. Empirical, numerical, or experimental correlations are mentioned for such cross-sectional cylinders. Helical coils are also reviewed, and experimental correlations for vertical and horizontal coils are presented by different authors in various environments. Correlations for horizontal, vertical, and inclined array of cylinders with different cross sections are also shown either for individual cylinder in the array or as the average Nusselt numbers for the whole array of cylinders.

Acknowledgements

Nomenclature

Γ cylinder aspect ratio

κ area ratio ($As = Ac$)

ϕ cylinder inclination angle

a minor axis of the elliptic

D cylinder diameter

d_0 coil outer tube diameter

G_D Grashof number based on D

Gr_{cr} critical Grashof number based on H

Gr_H Grashof number

H cylinder height

L cylinder length

M sequence of cylinder in an array

N number of cylinders in an array

N_i cylinder's index in an array

N_u Nusselt number

P_y vertical center-to-center distance

P_r Prandtl number

q heat transfer flux

R correlation coefficient

R_a Rayleigh number

Ra^* modified Rayleigh number

S center-to-center distance in an array

x distance along cylinder

Y distance of any cylinder from the lower cylinder

l cylinder length

W width-to-height ratio

Author details

Mohamed Ali* and Shereef Sadek

*Address all correspondence to: mali@ksu.edu.sa

Mechanical Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia

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