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Fluid flow and heat transfer of natural convection induced around a vertical row of heated horizontal cylinders

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ABSTRACT

Natural convective flow and heat transfer induced around a vertical row of heated horizontal cylinders were investigated experimentally. The experiments were carried out with the 10-cylinder rows of diameters $d = 8.4$, 14.4, 20.4 mm. The cylinder rows were placed in air with vertical gaps ranging from $G = 3.6$ mm to 150.6 mm. These enabled the experiments in the wide ranges of the modified Rayleigh numbers $5 \times 10^2 < Ra_d^* < 10^5$, and the non-dimensional gaps $(G/d) = 0.176$–17.9. The flow fields around the row were first visualized using a smoke. The results depicted that the plumes arising from the upstream cylinders remain laminar throughout the rows when the gaps between cylinders are smaller than 20.6 mm. While when the gaps are larger than 30.6 mm, the plumes begin to sway and undergo the turbulent transition on the halfway of the rows. The average heat transfer coefficients from the individual cylinders in the row were subsequently measured. They showed a monotonous decrease toward downstream when the flow remains laminar. While when the turbulent transition occurs, they turn to increase. The coefficients were next arranged with various parameters to obtain non-dimensional heat transfer correlations. Among those parameters, the parameter $Ra_G^*\ (G/d)$ was found to best correlate the present Nusselt numbers Nu_G, where, Ra_G^* and Nu_G are the gap-based modified Rayleigh and the average Nusselt numbers. Moreover, the non-dimensional heat transfer correlations were proposed both for the laminar and turbulent flows based on the data plots in Nu_G–$Ra_G^*\ (G/d)$ plane. The proposed correlations are very simple but can predict the Nusselt numbers quite satisfactory.

1. Introduction

Natural convective flows induced around arrays or banks of cylinders are encountered in many engineering applications, such as heat exchangers for air conditioning and refrigeration, pin–fin-type heat sinks for electronics cooling, solar heating system, nuclear reactor safety and heat removal from nuclear wastes and so on. These applications have motivated a considerable body of research on the natural convective flows and heat transfer from the arrays of cylinders. Among various orientations of the arrays, a single vertical row of heated horizontal cylinders, which is schematically illustrated in Fig. 1, has been treated most frequently in the prior studies. This is because an interaction of natural convection occurs typically in this configuration, and that the interaction may alter the heat transfer substantially from that of the single cylinder.

The one of the pioneer studies on this configuration was made by Lieberman and Gebhart [1], who have investigated the natural convection heat transfer from heated horizontal wires 0.127 mm-diameter placed in the same plane of inclination angles 0°, 30°, 60° and 90° from vertical. They have reported that the wires, in particular, set in the vertical plane show a monotonous decrease in the Nusselt numbers toward downstream when the spacing S between cylinders is relatively small $S = 4.76$ mm, whereas the Nusselt numbers turn to increase for larger spacing, $S = 9.52$, 14.28, 19.05 mm. The above variations in the Nusselt numbers are attributed to the following two distinct effects. The one is a temperature effect of the buoyant plume. When the spacing between cylinders is small, the temperature of the plume arising from the lower cylinder remains high and a high-temperature plume covers the upper cylinders. This results in the reduction in the heat transfer. The second is a velocity effect of the buoyant plume. When the spacing is large, the temperature of the plume is reduced to be low-enough, still, the velocity exists and this will enhance the heat transfer from the upper cylinders. The above

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opposite effects of the temperature and velocity will exert complex influences on the heat transfer from the downstream cylinders and make it uncertain whether their heat transfer coefficients will be higher or lower than that of the single cylinder.

After the above pioneer work, a number of experiments have been carried out on the heat transfer from the rows of cylinders. Those are listed in Table 1, where the diameter d and the number of test cylinders N set in the row, the vertical spacing between cylinders (S/d) and the experimental ranges of Rayleigh numbers Ra_d are presented. Marsters [2] have conducted the heat transfer experiments on the vertical row of three, five and nine cylinders 6.35 mm-diameter. He has reported that the Nusselt numbers from the cylinders decrease toward downstream when the spacing is small as $(S/d) = 2$ and 4, whereas the numbers show gradual increase for the spacing larger than $(S/d) = 6$. Similar results were also obtained by Sparrow and Niethammer [3], who have carried out the heat transfer experiment for a pair of isothermal cylinders 37.9 mm-diameter with the spacing $(S/d) = 2$–9. They showed the Nusselt numbers of the upper cylinder are lower than those of the single cylinder for small spacing $(S/d) = 2$ and vice versa for the spacing larger than $(S/d) = 5$. Tokura and co-workers [4] have also investigated the effect of spacing on the heat transfer from the row of two, three and five cylinders. They showed that the Nusselt numbers from the cylinders decrease toward downstream for the spacing (S/d) less than 2, while the numbers increase for (S/d) larger than 3. Although the critical spacing (S/d) that enhances or deteriorates the heat transfer from the downstream cylinders is somewhat different, Sadegh Sadeghipour and Ashegi [5], Chouikh and co-workers [6] have also reported similar results.

The experiments mentioned in the above were all concerned with the natural convection of air. While Reymond et al. [7], Persoon et al. [8], and Grafsrønningen and Jensen [9] have investigated the natural convection of water induced around a pair of isothermal cylinders. Since their experiments were conducted in the range of high-Rayleigh numbers $Ra_d = 10^6$–10^8, their main concerns were directed to a turbulent transition of plume arising from the bottom cylinder. In particular, Persoon and co-workers [8], and Grafsrønningen and Jensen [9] have carried out PIV measurements of the velocity field around the cylinders. Based on their PIV data and also on the output-signals of the heat-flux-sensor embedded to the surface of the top cylinder, Persoon and co-workers reported that the turbulent transition of plume occurs when the spacing (S/d) is larger than 2. While, Grafsrønningen and Jensen reported the critical spacing for the transition as $(S/d) = 3$. Their critical spacing $(S/d) = 2$ and 3 is far smaller than those of the prior experiments with air. The difference will be attributed to the Rayleigh numbers between the water and air experiments.

Aside from these experimental investigations, a few numerical analyses have been conducted on the laminar heat transfer from the vertical row of horizontal cylinders. Farouk and Gűçeri [10] have investigated the heat transfer from double horizontal rows of isothermal cylinders numerically. In their analysis, a sufficiently large number of cylinders were considered in each horizontal row such that a symmetrical flow field can be assumed. They have presented the average Nusselt numbers from the bottom and top cylinders placed with identical horizontal and vertical spacing of $(S/d) = 4$. Chouikh and co-workers [11] have also performed the numerical analysis on the laminar heat transfer from a pair of cylinders using a finite-difference method. They have presented the analytical Nusselt numbers from the bottom and top cylinders in the range of Rayleigh numbers, $Ra_d = 10^2$–10^4 and spacing $(S/d) = 2$–6. Moreover, Corcione [12] has carried out intensive numerical analysis on the laminar natural convection around the vertical row of two to six cylinders. The analysis covered the wide ranges of Rayleigh numbers $Ra_d = 5 \times 10^2$–5×10^5 and spacing $(S/d) = 2$–50. His analytical Nusselt numbers show significant variations with the locations x, spacing (S/d) and Rayleigh numbers Ra_d of the cylinder. With using these parameters, he has proposed Nusselt number correlations for the individual cylinders in the row.

The above literature survey depicts that a variety of experiments and analyses have been carried out on the natural convection induced around the vertical rows of cylinders, and also that their main concerns were focused on the problem whether the heat transfer from the downstream cylinders is enhanced or not with the spacing. For the sake of this, heat transfer coefficients or Nusselt numbers from the downstream cylinders were compared with those from the bottom cylinder. However, we could extract little information from those comparisons. When considering the engineering applications of the cylinder rows, the authors suppose a quantitative prediction of the heat transfer from the downstream

Table 1
List of experiments on the natural convection around single vertical row of horizontal cylinders.

Worker(s) (year)	Ref.	Experiment & measurement (test fluid)	Test cylinder			Range of Rayleigh No. Ra_d	Remarks (specific interest)
			Diameter d (mm)	Number N	Spacing (S/d)		
Lieberman and Gebhart (1969)	[1]	Heat transfer exp., visualization of temperature field (air)	0.127	10	37.5–225	Order of 10^{-1}	Effect of inclination of cylinder row
Marsters (1972)	[2]	Heat transfer exp. (air)	6.35	3,5, 9	2–10	750–2000	
Sparrow and Niethammer (1981)	[3]	Heat transfer exp. (air)	37.87	2	2–9	2×10^4–2×10^5	Effect of temperature imbalance between two cylinders
Tokura et al. (1983)	[4]	Heat transfer exp. visualization of temperature field (air)	22, 28.5	2,3,5	1.1–40	4×10^4–4×10^5	Effect of parallel confining walls
Sadeghipour and Asheghi (1994)	[5]	Heat transfer exp. (air)	6.6	2–8	3.5–27.5	300–1000	
Chouikh et al. (2000)	[6]	Heat transfer exp. (air)	6.5	2	2–6	300–5000	Temperature and velocities between cylinders
Reymond et al. (2008)	[7]	Heat transfer exp. (water)	30	2	1.5–3	$(2–6) \times 10^6$	Local Nu No. and their fluctuation
Persoons et al. (2011)	[8]	Heat transfer exp. PIV measurements (water)	30	2	2–4	$(1.8–5.5) \times 10^6$	Oscillation of plume
Grafsrønningen and Jensen (2012)	[9]	Heat transfer exp. PIV measurements (water)	54	2	2–4	1.82×10^7–2.55×10^8	Local and average Nu No. and fluctuation, Velocity field above cylinder
Present		Heat transfer exp. visualization of flow field (air)	8.4, 14.4, 20.4	10	1.176–18.9	250–$2.0 \times 10^{4*}$ (*converted from modified Ra^* numbers)	Correlation for the average Nu. No.