Fouling Effect of Geothermal Water Scale on Heat Transfer Around a Tube in a Bank

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Scales deposited onto the heating surfaces of heat exchangers seriously reduce the heat transfer performance and also increase the hydrodynamic drag. Accordingly, fouling is an important problem in the design and operation of heat exchangers. Present paper investigates the heat transfer around in-line four circular cylinders on which geothermal water scales are uniformly distributed. The cylinders are settled in tandem with equal distance between neighbouring cylinders and only the test cylinder is heated under the condition of constant heat flux. It is found that the heat transfer of the in-line tube banks greatly varies with the fouling of geothermal water scale, especially its scale height. Further, the local and average Nusselt numbers strongly depend upon the cylinder spacing and the Reynolds number.

Key Words: Fouling Effect, Geothermal Water Scale, Tube Bank, Heat Exchanger, Separation Point, Stagnation Point, Attachment Point.

Nomenclature

d : Cylinder diameter
h : Heat transfer coefficient $= q/(T_w - T_\infty)$
k : Size of scale particle
L : Longitudinal spacing between neighbouring cylinder centers
M : Mesh number
Nu : Nusselt number $= hd/\lambda$
q : Heat flux per unit area and unit time
Re : Reynolds number $= U_\infty d/\nu$
R_f : Mean fouling resistance of scale
T_∞ : Temperature of upstream uniform flow
T_w : Wall temperature
U_∞ : Velocity of upstream uniform flow
λ : Thermal conductivity of air
ν : Kinematic viscosity of air
θ : Angle from forward stagnation point

Subscript

c : Clean
f : Fouled
m : Mean
w : Wall
max : Maximum
min : Minimum

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1. Introduction

It is a very important and urgent problem to develop a system for effective use of natural energy such as solar, wind, ocean wave and geothermal one. Among many kinds of natural energy, the geothermal energy is one of the highest density of energy extracted. However, the pressure and temperature drops of the geothermal hot water through a heat exchanger bring about deposition of the geothermal water scale onto the heat transfer surfaces of heat exchangers and also onto the surfaces of flowing conduits (Rott, 1995). These depositions present a resistance to heat transfer and reduce the efficiency of heat exchangers. The growth of such deposits causes the thermal and hydrodynamic performances of heat transfer equipments to deteriorate with time.

Accordingly, the fouling affects the energy consumption of industrial processes and the amount of material employed in the construction of heat transfer equipments, because it may be necessary to provide the extra heat transfer area to compensate the effect of fouling (Melo et al., 1988 ; Somerscales and Knudson, 1981). Little attention had been paid to the fouling of heat exchangers and the associated inefficiency of heat exchanger operation till the oil crisis in 1973.

There have been numerous experimental and theoretical investigations on the fouling problems of heat exchangers during the past decade. These investigations have been performed with a model or industrial fluids in laboratories or plant equipments. For example, an attempt to derive a general fouling model was first made by Kern and Seaton (1959). They investigated the particulated fouling data and found that the fouling curves usually exhibited an asymptotic form. Watkinson (1975) reported the fouling resistance inside spirally indented and plane tubes. Chamra and Webb (1993) investigated a particulate fouling in enhanced and plane tubes. They showed that the fouling rate was higher for enhanced tubes than for plane ones. Further, experimental investigations were made on the fouling effect of the geothermal water scale upon heat transfer around single circular cylinder (Ota et al., 1984), and an elliptic cylinder (Ota and Nishiyama, 1985). They showed that the fouling resistance depends on the size of scale particle and fluid velocity. However, the fouling effect of geothermal water scale on the heat transfer in tube banks were not clarified yet. The purpose of present experimental investigation was to clarify fouling effects of geothermal water scale deposited onto the heating surface around in-line four circular cylinders in a cross flow of air. Measurements were made mainly on the temperature distribution along the cylinder surface. Nusselt numbers were estimated as functions of scale thickness, cylinder spacing and Reynolds number, and were compared with previous experimental results on the clean cylinder.

2. Experimental Apparatus and Procedure

Experiments were carried out in a low speed open circuit wind tunnel driven by a centrifugal fan at the inlet. The working section at the tunnel exit was 0.15m wide, 0.4mm high and 1.2m long. The side walls of the test section were made of plexiglass and the working section was constructed in order to insert the cylinders and vary the cylinder spacing.

In-line tube banks examined were schematically shown in Fig. 1. All the cylinder diameters are 34mm and their spanwise length 0.15m. They were made of hard vinyl chloride tube and four circular cylinders were settled in tandem with equal distance between neighbouring centers. The first cylinder was located 0.18m downstream from the nozzle outlet. Their in-line pitch ratio L/d was varied from 1.5 to 4.0 and the Reynolds number from 13000 to 50000. The velocity of upstream uniform flow was measured with a pitot tube at the nozzle exit. The scales were picked up in geothermal water power plant. These scales were crushed and classified by sieves of various mesh number. Five size of particles were examined; that is, $M=150$, 48, 35, 28, 20 (scale size $k=0.085$, 0.257, 0.460, 0.756, 1.077). The relative roughness k/d were 0.0025, 0.0076, 0.014, 0.022, 0.032 respectively. The particles of silica scale deposited from geothermal hot water were uniformly distributed on the four circular cylinders. For the heat transfer measurements, a stainless steel sheet of 23.5 mm wide and 0.03mm thick was helically wound around the central section of the tube and was electrically heated. The inside of the tube was filled with rigid urethane foam to minimize the heat loss and the measurements were conducted by heating only the measured cylinder

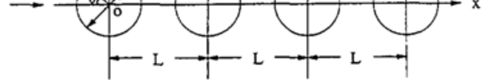


Fig. 1 Arrangement of cylinders and coordinates system

under the condition of constant heat flux. The supplying heat flow rate was determined from the measured electric current and voltage. The heat flux to the test cylinder was ranged from 1.2 to 4. 5 kW/m^2 depending on the Reynolds number. The temperature distributions along the cylinder surface were measured at intervals of 10° with 0. 07 mm copper-constantan thermocouples which were struck onto the cylinder surface. The heat loss by conduction and radiation was neglected in the following results. The local heat transfer coefficient and the corresponding Nusselt number were defined respectively, as followed (Aiba and Yamazaki, 1976; Aiba et al., 1980).

$$h=\frac{q}{(T_w-T_\infty)},\quad Nu=\frac{h\cdot d}{\lambda}$$

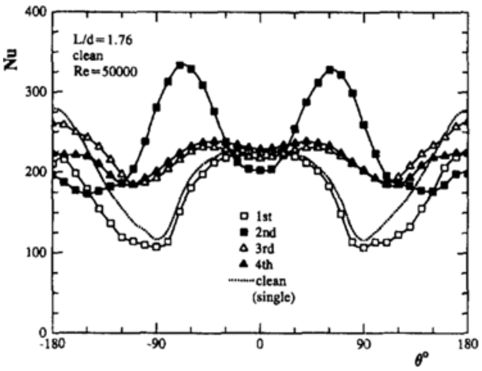
3. Experimental Results and Discussion

The local Nusselt number distribution is presented for the four cylinders of clean surface in the cases of L/d=1.76, 3.0 and Re=50000 in Fig. 2.

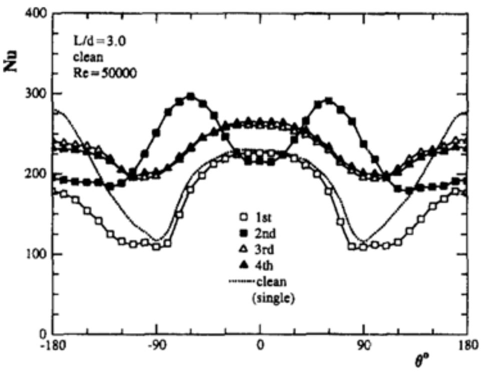
Figure 2(a) shows the symmetric distribution of the local heat transfer coefficient on the four cylinders. The first cylinder shows similar trend to the single clean cylinder but the Nusselt number on the downstream surface is a little lower than the upstream one due to effects of the downstream cylinder. Nu attains a maximum at the upstream stagnation point, decreases with surface distance as a laminar boundary layer develops, reaches a minimum around $\theta=\pm 90°$, and subsequently increases to the downstream in the separated flow region.

For the case of the second cylinder, the Nusselt number attains a maximum around $\theta=\pm 70°$ since the shear layers separte from the first cylinder attach there. Its velocity gradient is much larger than that on the further downstream cylinders, resulting in a high heat transfer rate near the attachment point on the second cylinder.

The third and fourth cylinders represent very similar behaviors, which are much different from those for the first and second cylinders. Maximum values of Nu locate at about $\pm 30°$, which locate



(a) L/d=1.76



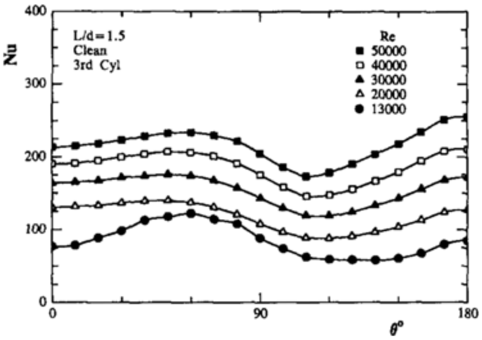
(b) L/d= 3.0

Fig. 2 Local Nusselt number distribution

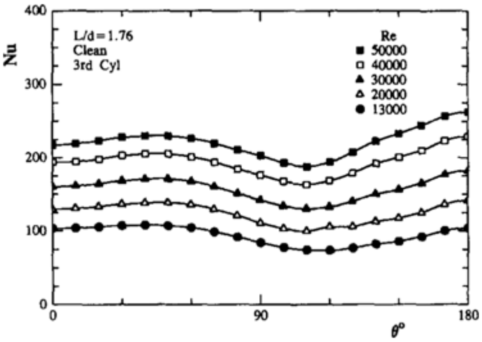
upstream as compared to that for the second cylinder, and Nu at the upstream stagnation point is higher than that of the second cylinder. This may be due to the fact that on the second and downstream cylinders, the shear layer separates around $\theta=\pm 120°$ and consequently the wake width upstream of the third and fourth cylinders becomes smaller (Aiba et al., 1981).

Figure 2(b) shows a case of L/d=3.0. The characteristic variation of Nu for the first and second cylinders is very similar to that for L/d=1.76, through its value is generally lower compared to the latter (Aiba et al., 1980). In the case of the third and fourth cylinders, as the cylinder spacing increases, the entrainment of the main flow around the upstream of cylinder increases, then attains a maximum at the upstream stagnation point($\theta=0°$), and reaches a minimum around $\theta=\pm 90°$ where the flow separates.

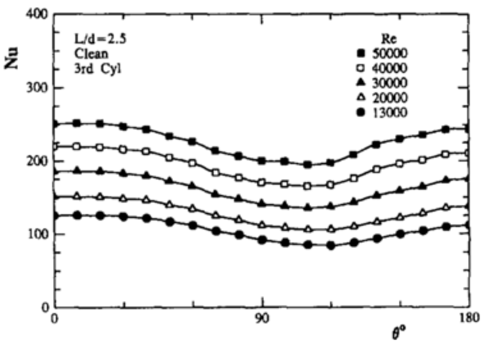
Variations of the local Nusselt number on the



(a)



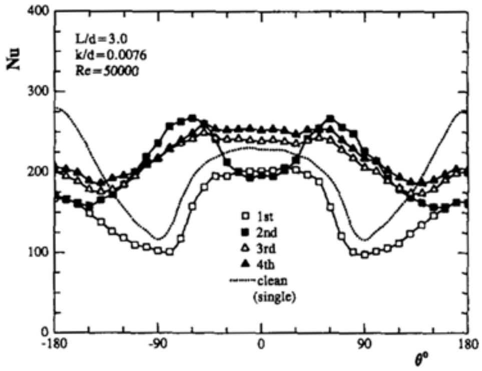
(b)



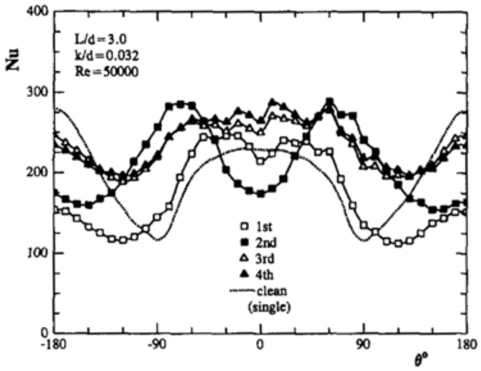
(c)

Fig. 3 Local Nusselt number for third cylinder with clean surface

third cylinder with the Reynolds number are shown for L/d=1.5, 1.76 and 2.5 in Figs. 3(a) through 3(c). In the case of L/d=1.5, in a region of Re≥20000, Nu distribution is not much different from that for L/d=1.76 though Nu_{max} locates at about θ=50°. Nu distribution changes its form at Re=13000. The position of Nu_{max} shifts downstream to θ=60°, the heat transfer on the front face deteriorates, and the location of Nu_{min} becomes obscure. Therefore it becomes difficult to determine the separation point from the local Nusselt Number distribution. In the case of the L/d=1.76 and 2.5, the variation of Nu with Re is small. It is noticed that the separation point exists at about θ=110°. Especially at L/d=1.76, Nu_{max} and Nu_{min} always occur at about θ=50° and 110°, respectively, independently of Re. At a wider spacing of L/d=2.5, an entrainment of main flow into the front surface increases and it causes the position of Nu_{max} to be identical with the forward stagnation point. The results of the fourth cylinder at L/d=1.5, 1.76 and 2.5 show similar trends to those for the third one.



(a) k/d=0.0076



(b) k/d=0.032

Fig. 4 Local Nusselt number distribution

Figure 4 shows the results of the fouled cylinder for k/d=0.0076, 0.032 and Re=50000. Figure 4(a) presents the local Nusselt number for k/d=0.0076. It decreases nearly uniformally on the whole circumference compared to that for the clean cylinder shown in Figure 2(b) because of the thermal resistance of the scale.

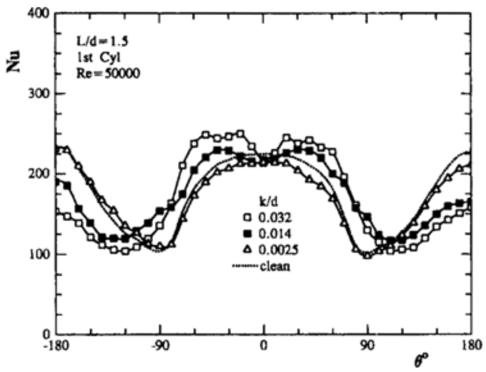
Figure 4(b) presents the results for k/d$=$0.032. In the first cylinder, the laminar boundary grows from the upstream stagnation point transits to the turbulent one because the scale roughness increases. This brings about two maxima on the upstream part of the cylinder, the separation point moves downstream to around $\theta=\pm 120°$, and the turbulent separation occurs. Nu at $\theta=0°$ is lower compared to that on the clean surface because of insulation effect of the scale layer. However, from the transition point to the separation one, Nu is higher compared to that on the clean surface. On the second cylinder, Nu shows an increase of the maximum compared to that for k/d$=$0.0076, since the separated shear layer from the first cylinder attaches. However, Nu on the upstream surface drastically decreases because of the insulation effect of the scale layer. For the cases of the third and fourth cylinders, the symmetry of Nu disappeared, since the turbulent boundary layers on two sides of the upstream cylinder develop somewhat differently. The highly turbulent flow approaches to the upstream surface, resulting in a higher value of Nu there. Further Nu in the separated flow region increases similarly.

Figure 5 shows the effects of the scale size on the local Nusselt number for the first and second cylinders. In the case of the smallest scale(k/d$=$0.0025) shown in Fig. 5(a), the result is almost the same as for the clean cylinder, but Nu is slightly lower because of the insulation effect of the scale layer.

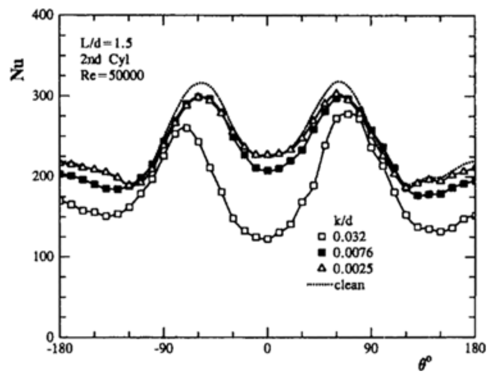
For the case of k/d$=$0.014, the laminar boundary layer transists to the turbulent one near the upstream stagnation point because of the scale roughness, resulting in an increase of Nu. It reaches maximum around $\theta=\pm 30°$, decreases to the downstream, and attains minimum at about $\theta=\pm 120°$ where the turbulent boundary layer separates. In the case of k/d$=$0.032, the maximum of Nu is higher than that at the upstream stagnation point of the clean surface. In the separated flow region, Nu exhibits the lowest value due to an increase of the insulation effect of scale layer.

Figure 5(b) shows the case of the second cylinder for k/d$=$0.0025, 0.0076 and 0.032. The maximum of Nu appears around $\theta=\pm 70°$, since the separated shear layer attaches there. Nu is lower than that for the clean surface due to the scale. It is worth to note that in the case of k/d$<$0.032, the minimum value of Nu exists at the separation point, in contrast to the case of k/d$=$0.032, in which the minimum value of Nu exists at the upstream stagnation point.

A variation of the mean Nusselt number with the scale size k is shown in Fig. 6. In the case of Fig. 6(a), it is clearly shown that Num shows no essential change for a very small scale size at relatively low Reynolds number. However in the case of the first cylinder at Re$>$40000, Nu_m attains a minimum at k/d$=$0.0076, after that increases slightly as the scale size increases Num of the third cylinder are shown in Fig. 6(b). There is no essential change at the small scale

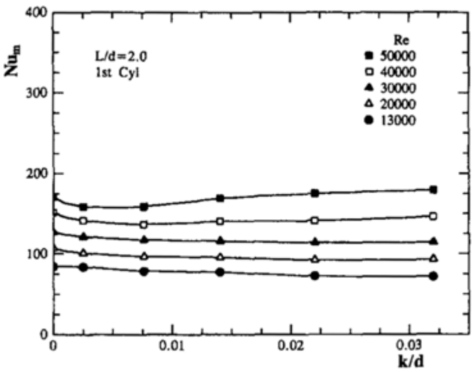


(a) First cylinder

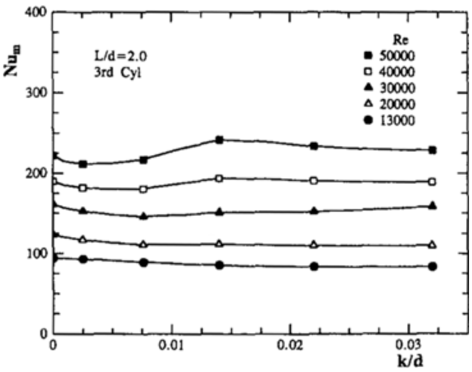


(b) Second cylinder

Fig. 5 Local Nusselt number distribution of fouled cylinder

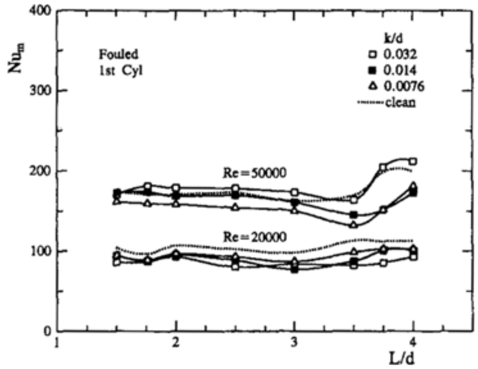


(a) First cylinder

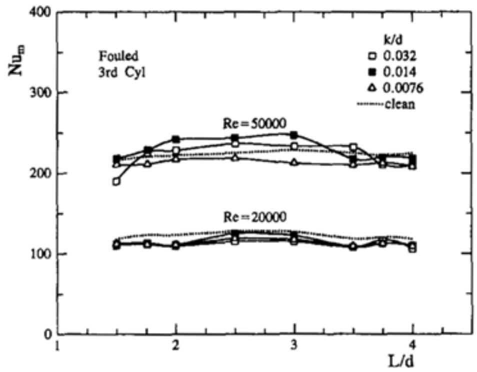


(b) Third cylinder

Fig. 6 Mean Nusselt number for L/d=2.0



(a) First cylinder



(b) Third cylinder

Fig. 7 Mean Nusselt number at Re=50000 and 20000

size, but in the range of Re>30000, Nu_m attains a maximum at k/d=0.014, after that Nu_m decreases with increasing the scale size. Such a tendency is also observed for other cylinder spacings, though the results are omitted.

Figure 7 shows a variation of Nu_m with L/d at Re=50000 and 20000 for the first and third cylinders. Nu_m of the first cylinder shown in Fig. 7(a) exhibits complicated variation compared to the third cylinder. At Re=50000, Nu_m for all scale sizes decreases with increasing the cylinder spacing, and it attains a minimum at L/d=3.5. However, as L/d further increases over L/d=3.5, Nu_m of the first cylinder discontinuously increases. The reason for such a change is that a vortex street is formed in the wake of the first cylinder and then an approach of the main flow at low temperature brings about an increases of Nu. On the other hand, Nu_m of the third cylinder decreases after the jumping phenomenon.

In general, as the scale size increases, Nu_m decreases, but such a trend is reversed due to the highly turbulent flow at the high Reynolds number. In the case of k/d=0.032, Nu_m of the fouled cylinder is a little bit higher than that of the clean cylinder. These results show that in some range of the Reynolds number, there exists a region of the scale size in which the heat transfer capability of the fouled surface is augmented by the scale roughness compared with the clean surface.

The results of the third cylinder are shown in Fig. 7(b). Nu_m at Re=20000 exhibits no essential variation with L/d. There is no discontinuous increase even at Re=50000, and in the case of k/d=0.032, Nu_m rather decreases for L/d=3.75 and 4.0 compared to that for L/d=3.5. The fourth cylinder exhibits a similar variation as the third cylinder though the results are not illustrated. These present results clarify that as the third

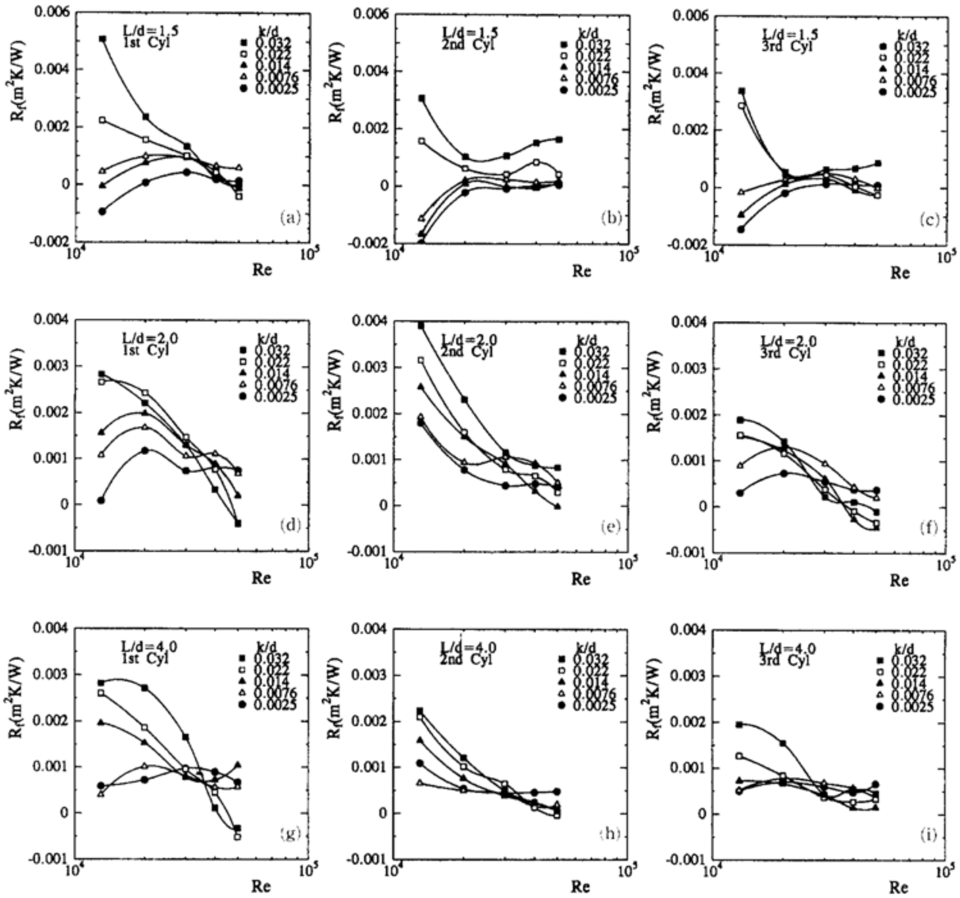


Fig. 8 Fouling resistance of first, second and third cylinders

cylinder though the results are not fouling of geothermal water scale deposited onto the heating surface complicatedly affects its heat transfer capability depending on the Reynolds number, the thickness of the scale and the cylinder spacing.

Shown in Fig. 8 is a variation of the mean fouling resistance over the whole circumference R_f of the first, second and third cylinders among four cylinders with the Reynolds number for the cylinder spacing of L/d=1.5, 2.0 and 4.0. R_f is estimated from the following equation under the assumption, in which the heat flux, the free stream velocity and the free stream temperature are constant respectively (Ota and Nishiyama, 1985).

$$R_f = \frac{T_{wm_f} - T_{wm_c}}{q} = \frac{1}{h_{m_f}} - \frac{1}{h_{m_c}}$$

Characteristic variation of R_f for the first cylinder strongly depends on the scale size and the Reynolds number. In the case of the large scale such as k/d=0.032 and 0.022, R_f steeply decreases with an increase of the Reynolds number. However, as for the small scale such as k/d=0.0075 and 0.0025, the variation of R_f with the Reynolds number is relatively small, and R_f exhibits a maximum at some Reynolds number depending on the cylinder spacing and the scale size. R_f of the second cylinder shows slightly different variations from that of the first cylinder. In the case of L/d=1.5, R_f becomes negative at low Reynolds number since the heat transfer is augmented by the scale layer. Except such case, R_f of the second cylinder, in general, decreases with the Reynolds number. In the case of L/d=1.5 and k/d=0.032, R_f attains a minimum at about Re=20000. The third cylinder shows similar variation with the second cylinder. However, the separation point of the second cylinder shifts to the downstream and then the wake width becomes narrow. In the cases of $L/d=2.0$, $k/d=0.0025$ and 0.0076, R_f reach a maximum value at Re=20000 and subsequently decreases. That is, since the downstream cylinder locates in the flow of high turbulence which is formed by the upstream cylinder, the effect of the scale layer becomes small. On the contrary, the first cylinder located in the uniform flow, the insulating effect of the scale layer is very large.

In general, the effect of the scale layer is the greatest for the first cylinder.

4. Concluding Remarks

It is found that heat transfer characteristics around in-line tube banks are greatly affected by fouling of geothermal water scale, especially its scale size. Further, the local and mean Nusselt numbers strongly depend on the cylinder spacing and the Reynolds number. The main results obtained are summarized as follows.

(1) In the case of the first cylinder, characteristic variations of the local and mean Nusselt numbers are similar to that of a single cylinder. A large scale promotes the transition of the boundary layer to the turbulent one, resulting in an increase of Nu on the upstream surface and a decrease of Nu on the downstream one. When Re ≥ 40000 and $k/d \leq 0.0076$, Nu_m becomes lower than that for the clean cylinder. The fouling effect of scale is the greatest among four cylinders and R_f rapidly decreases with an increase of Re when the scale is large.

(2) In the case of the second cylinder, the local Nusselt number distribution strongly depends upon the character of the shear layers separated from the first cylinder. That is, Nu reaches a maximum at the attachment point of the separated shear layer, and Nu near the upstream stagnation point is quite low. The fouling effect is small compared with the first cylinder, since the second cylinder locates in the highly turbulent flow which is formed by the first cylinder.

(3) In the cases of the third and fourth cylinders, the local and mean Nusselt number distributions show qualitatively similar with each other, and they exhibit weak dependency on the cylinder spacing.

Acknowledgements

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