The effect of particle concentration on ferric oxide fouling of water in tubes having a two-dimensional repeated rib geometry

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Abstract
The effect of ferric oxide concentration on particulate fouling in two-dimensional repeated rib tubes is investigated. Three repeated rib tubes with the range of roughness configuration $0.015 \leq e/D_i \leq 0.030$ and $10 \leq p/e \leq 20$ are tested. The fouling curves show an asymptotic behavior. The fouling resistances of repeated rib tubes are higher than that of the plain tube. At low concentration of 750 ppm, however, they are approximately the same. The repeated rib tubes show stronger concentration dependencies compared with the plain tube. Within the test range, the repeated rib tube fouling resistance increases as $p/e$ increases and $e/D_i$ decreases. The deposit inspection supports this trend. The effect of the deposit non-uniformity on fouling resistance and the effect of deposit on heat transfer performance are additionally examined.

Key words: Fouling, Particulate, Ferric oxide, Repeated rib, Tube, Concentration

Nomenclature

\begin{align*}
A_i & \quad \text{internal heat transfer area, m}^2 \\
B(e^+) & \quad \text{friction roughness function} \\
C & \quad \text{concentration} \\
c_{pw} & \quad \text{specific heat of water, J/kg}\cdot\text{s} \\
D_i & \quad \text{internal tube diameter to the fin root, m} \\
d_p & \quad \text{particle diameter, m} \\
e & \quad \text{rib height, m} \\
e^+ & \quad \text{roughness function} \\
f & \quad \text{friction factor} \\
k_f & \quad \text{foulant thermal conductivity, W/mK} \\
k_m & \quad \text{mass transfer coefficient, m/s} \\
L & \quad \text{length of the tube, m} \\
m_w & \quad \text{water flow rate, kg/s} \\
n_s & \quad \text{number of start} \\
p & \quad \text{rib pitch, m} \\
Pr & \quad \text{Prandtl number} \\
Q & \quad \text{heat transfer rate, W} \\
R_f & \quad \text{fouling resistance, m}^2\text{K/W} \\
R_f^* & \quad \text{asymptotic fouling resistance, m}^2\text{K/W} \\
Re & \quad \text{Reynolds number} \\
St & \quad \text{Stanton number}
\end{align*}
**Variables**

- \( T_{\text{sat}} \) saturation temperature, K
- \( T_{\text{w, in}} \) water temperature at test section inlet, K
- \( T_{\text{w, out}} \) water temperature at test section outlet, K
- \( U_c \) clean overall heat transfer coefficient, W/m\(^2\)K
- \( U_f \) fouled overall heat transfer coefficient, W/m\(^2\)K
- \( \nu^* \) friction velocity, m/s
- \( u_m \) mean water velocity, m/s
- \( w \) rib width, m
- \( x \) distance, m

**Greek symbols**

- \( \alpha \) helix angle, deg
- \( \Delta x \) deposit thickness, m
- \( \mu \) dynamic viscosity, kg/m\(\cdot\)s
- \( \nu \) kinematic viscosity, m\(^2\)/s
- \( \rho_p \) particle density, kg/m\(^3\)
- \( \tau' \) non-dimensional particle relaxation time
1. Introduction

Fouling can be defined as the accumulation of undesired deposits on heat transfer surfaces. This accumulation of deposits adversely affects the thermal and hydraulic performance of the surfaces, and increases both the initial and operational costs of a heat exchanger. It is common to categorize fouling according to the principal process which causes the phenomenon (Bott, 1988). They are particulate fouling, precipitation fouling, chemical reaction fouling, corrosion fouling and biological fouling. With these categories, the problem of fouling becomes more manageable, which otherwise will be hopelessly complicated in a real situation. For particulate fouling especially, much progress has been made in the understanding of fouling mechanisms. As a result, several fouling models are available (Epstein, 1988). However, it is still impossible to predict the fouling resistance for a given condition, primarily because too many parameters - flow condition, tube material, fouling material, etc. - are involved, and moreover, most of the effects of these parameters are not known yet. The processes which govern particulate fouling are the transport of particles to the wall, the adhesion of particles at the wall and the removal of deposits from the wall. The mechanism of particle transport is rather well understood, and the transport rate is predictable. However, the mechanisms of the adhesion and the removal processes are not well understood and the rates are not predictable at all (Epstein, 1988). Particulate fouling is a great concern for, electric utility condensers or chiller condensers, for example, where particle-contaminated water is circulated in the tube-side.

Enhanced tubes have been used widely because of their superior heat transfer performance. The inside geometries of the enhanced tubes are usually helical-rib, three-dimensional roughness or corrugated (Webb and Kim, 2005). The effect of fouling on enhanced tubes could be worse than that on smooth tubes because it may degrade the superior heat transfer performance by filling the gap of the roughness elements with foulants. The literature contains very little data on fouling in enhanced tubes. The few investigations that have been carried out address particulate and precipitation fouling. Kim and Webb (1991) performed accelerated particulate fouling tests of three repeated rib tubes (0.015≤e/Di≤0.030 and 10≤p/e≤20) and a smooth tube for 14,000≤Re≤26,000 using ferric oxide and aluminum oxide particles. They found that the fouling resistance of the repeated rib tubes was higher than those of the smooth tubes at low Reynolds number. It increased as e/Di decreased and as p/e increased. However, at high Reynolds number of 26,000, the fouling resistance was approximately the same as that of the smooth tube. They developed the particulate fouling model for enhanced tubes, which accounted for effect of enhancement geometry on the fouling rate. Somerscales et al. (1991) compared the fouling characteristics of five enhanced tubes (two helical fin, one axial fin, one corrugated and one helical rib) from accelerated fouling tests using magnesium oxide. Unexpectedly, they found that corrugated tube was less susceptible to fouling than a smooth tube. Their results suggest that certain geometries (e.g., corrugated surface) may mitigate the effects of particulate fouling. Chamra and Webb (1993) investigated the effect of particle size and concentration on particulate fouling of corrugated or rippled tubes using silt and clay of 2.0, 4.0 and 16.0 μm diameter for 1200≤C≤2000 ppm. The fouling resistance increased as particle diameter and Reynolds number decreased or concentration increased. Of the two enhanced geometries, rippled tube fouled faster than the corrugated tube. Chamra and Webb (1994) extended the repeated rib tube particulate fouling model of Kim and Webb (1991) to enhanced geometries of Chamra and Webb (1993). Li (2007) obtained accelerated fouling data in helically ribbed tubes having different number of rib start (18≤n≤35), helix angle (25°≤α≤45°) and rib height (2.8≤p/e≤9.9). Aluminum oxide particles were used as the foulant. The test range covered 16,000≤Re≤24,000 and 1300≤C≤2900 ppm. The fouling resistance increased as Reynolds number decreased or concentration increased. Within the test range, the fouling resistance increased as p/e decreased, which is in contradiction with the finding of Kim and Webb (1991), who reported that the fouling resistance increased as p/e increased for repeated-rib tubes having 10≤p/e≤20. Different range of p/e between the two investigations may be responsible for the contradiction. Webb (2009) performed particulate fouling tests of a three-dimensional truncated cone tube using the same foulant (aluminum oxide particles of 3.0 μm diameter) of Li (2007), and compared the results with those of the internally ribbed tubes of Li (2007). Significantly higher fouling resistance was obtained for the truncated cone tube. The truncated cone tube yielded approximately 50% higher heat transfer coefficients than those of the internally ribbed tubes. Additional data on cooling tower water fouling in enhanced condenser tubes, where both precipitation and particulate fouling are major fouling mechanism, have been provided by Webb and Li (2000), Li and Webb (2000, 2002) and Shen et al. (2015a, 2015b).

The above literature survey reveals that most of the particulate fouling studies have been performed using commercially enhanced (rippled, corrugated and helically ribbed) tubes. One exception is Kim and Webb (1991), who
investigated particulate fouling in two-dimensional repeated ribbed tubes. Two-dimensional repeated rib is the basic geometry for the tube-side enhancement, and may provide fundamental understanding on fouling in enhanced tubes. Kim and Webb (1991) investigated the effect of Reynolds number for three repeated rib tubes having $0.015 \leq \frac{e}{D_i} \leq 0.030$ and $10 \leq \frac{p}{e} \leq 20$. This is a continuing study of Kim and Webb (1991). In this study, the effect of foulant concentration on particulate fouling in two-dimensional repeated rib tubes is investigated. Ferric oxide is used as the foulant, and the concentration is varied from 750 to 2500 ppm. The tube-side Reynolds number is fixed at 19,000. This Reynolds number was chosen because previous study by Kim and Webb (1991) has shown that this was the highest Reynolds number where measurable fouling occurred at a reasonable amount of time (approximately 20 hours).

2. Experiments

2.1 Tube geometries tested

The same repeated rib tubes and a plain tube tested by Kim and Webb (1991) were used in the present study. The roughness dimensions are provided in Table 1. The tube inside diameter ($D_i$) is defined as the diameter to the base of the repeated ribs. Figure 1 shows photos of the repeated rib tubes and a plain tube. The repeated rib tubes were made from hard drawn copper tubes of 19.05 mm O.D. and 17.02 mm I.D. The ribs were made manually by applying a localized pressure on the outer surface of the tube. A tubing cutter with a dull edge was used to form the roughness. As a consequence, the cross-section of the rib was arc-shaped as shown in the enlarged cross-sectional photo (Figure 2). The smooth tube was a integral fin tube which has a smooth inner surface with 14.1 mm I.D. and integral fins (1024 fins/m, 1.5 mm fin height) on the outer surface.

![Figure 1](image_url)

(a) plain

(b) 30/20

(c) 30/10

(d) 15/10

Fig. 1  Photographs of the tubes; (a) plain, (b) 30/20, (c) 30/10 and (d) 15/10

| Tube  | $D_i$ (mm) | $\frac{e}{D_i}$ | $\frac{p}{e}$ | $\frac{w}{e}$ |
|-------|------------|----------------|--------------|--------------|
| 30/20 | 17.0       | 0.030          | 20           | 3.0          |
| 30/10 | 17.0       | 0.030          | 10           | 3.0          |
| 15/10 | 17.0       | 0.015          | 10           | 4.6          |
| plain | 14.1       | -              | -            | -            |

Table 1  Roughness dimensions of the tubes
2.2 Fouling apparatus

Figure 3 shows a schematic drawing of the experimental apparatus, and Figure 4 shows the test section and its instrumentation. The apparatus is capable of testing four tubes simultaneously. The apparatus was designed to operate and record data 24 hour/day unattended, with heat input to the test section. Heat is transferred to the 3.05 m long test section by condensing R-114 on the annulus side of the test section. R-114 is used because the test section operates above atmospheric pressure (215 kPa at 25°C), so non-condensibles cannot enter the system during operation or during shut-down periods. Condensed R-114 is returned to electric heated boilers. Each test section has its own boiler, where R-114 is heated by three electric band heaters (1200 W each). Power to the band heaters is controlled by individual auto-transformers. The heat is removed from the test water in a plate heat exchanger, and to the constant water temperature reservoir.

Three temperatures - water inlet, water outlet and R-114 saturation - are measured using thermistors, whose accuracy is ±0.03°C. The saturation pressure is measured using a pressure transducer of ±0.15% accuracy. The water flow rates are measured using pre-calibrated orifices and differential pressure transducers, whose accuracy is ±0.2%. The test section pressure drops are measured using differential pressure transducers of ±0.3% accuracy. The refrigerant saturation pressure is compared against the saturation temperature to verify the absence of non-condensibles. When the saturation pressure is converted to saturation temperature, it agrees with the measured saturation temperature within 0.3°C. The resultant uncertainties of the fouling resistance were ±13.2%. Means are provided to collect samples of the fouling deposit for visual inspection. This is accomplished using the deposit sections shown in Figure 3. The deposit sections are 0.3 m long, and are installed just downstream from the test section.
2.3 Data reduction

The fouling resistance is calculated as follows. First, the overall heat transfer coefficient ($U_f$) based on inside surface area ($A_i$) is measured for clean tube condition. The $A_i$ is defined as $\pi D_i L$. Then, the overall heat transfer coefficient ($U_f$) is measured for the fouled condition. It is intended that the data for $U_f$ and $U_c$ are taken at the same velocity, heat flux and water inlet temperature. The fouling resistance is obtained by

$$R_f = \frac{1}{U_f} - \frac{1}{U_c}$$  \hspace{1cm} (1)

$$U_f = \frac{Q}{A \Delta T_{LM}}$$  \hspace{1cm} (2)

$$Q = \dot{m}_w c_p (T_{w,in} - T_{w,out})$$  \hspace{1cm} (3)

$$\Delta T_{LM} = \frac{T_{w,in} - T_{w,out}}{\ln \frac{T_{sat} - T_{w,in}}{T_{sat} - T_{w,out}}}$$  \hspace{1cm} (4)

During the test, the water velocity reduced a small amount due to fouling. To account for the reduced water velocity, the clean tube $U$ value ($U_c$) was adjusted. The adjustment was done as follows. First, the clean tube $U$ value was measured as a function of water velocity. These data were then curve-fitted as a function of water velocity. The $U_c$ was then calculated at the actual velocity in the fouled tube using the curve-fit equation. The asymptotic fouling resistance ($R^*_f$) was calculated by curve-fitting the reduced fouling data into following form. Figure 5 shows a schematic drawing of the asymptotic fouling curve.

$$R_f = R^*_f (1 - e^{-b t})$$  \hspace{1cm} (5)

2.4 Test operation

After each fouling test, once-through city water was run through the apparatus piping for approximately 24 hours to clean the test sections and the apparatus piping. Then, the test section was mechanically cleaned using a hand-operated nylon brush. Before brushing, a weak solution of detergent was added to the test section to aid deposit removal. After brushing, the apparatus was filled with clean city water. The apparatus was run for two hours with clean water to reach steady state. After it reached a steady state, the amount of particulate required for the desired concentration was added.
This was taken as time zero for the next fouling test series, which was approximately 20 hours. During a test, which started at 1500 ppm concentration for example, the foulant concentration decreased to approximately 1200 ppm. No foulant was added during the test period. This was done to prevent instabilities that could affect the fouling rate, or the retention of the foulant deposit. The flow velocity was almost constant during the test period. The foulant concentration was measured by a weighing method. Approximately one liter of fouled water was taken from the apparatus in a glass beaker, and was thoroughly evaporated using an electric heater. The foulant concentration was determined from the weight of the fouled water and that of the remained deposit in the beaker after evaporation.

3. Results and Discussions

3.1 Foulant material

The particle size is an important factor affecting the deposition mechanism. According to Bott (1995), three main deposition regimes may be identified - diffusion, inertia and impaction. In the diffusion regime ($\tau'<0.1$), Brownian motion controls the particle deposition, where $\tau'$ is a non-dimensional particle relaxation time, which is defined as

$$\tau' = \frac{\rho_p d_p^2 u^2}{18\mu
'}$$

The $\tau'$ may be interpreted as a non-dimensional particle stopping distance. In the inertia regime (0.1<$\tau'<10$), turbulence eddies give the particle a radial velocity which penetrates the viscous sublayer, and particles are carried to the wall by their inertia. In the impaction regime ($\tau'>10$), the deposition velocity (particle velocity toward the wall) is the same order of magnitude as the friction velocity, and remains approximately constant independent of the magnitude of $\tau'$. Figure 6 shows the widely accepted deposition curve by Epstein (1988). The ordinate $k_m/u*$ is the non-dimensional mass transfer coefficient. Here, the foulant deposition rate on the wall will depend on the particle size in addition to the foulant concentration and fluid velocity. For the case of a ferric oxide-water suspension flowing at $Re = 19,000$ in the plain tube with 14.1 mm I.D., the diffusion regime extends up to $d_p = 16 \mu m$. Thus, this regime is probably the most important regime in industrial applications. The mean particle diameter of the present ferric oxide is 2.11 $\mu m$, which is well within the diffusion regime.

The ferric oxide (Fe$_2$O$_3$) particle size was measured using a particle size analyzer (HORIBA CAPA 500). Figure 7 shows the particle size distribution of the "as-delivered" ferric oxide particles. Figure 8 shows the particle size distribution of a foulant sample that was removed from the fouling apparatus and dried. A comparison of Figures 7 and
Fig. 6  Particle deposition behavior onto smooth tubes

Fig. 7  Ferric oxide particle (as delivered) size distribution.

8 shows that the mean particle size of the dried foulant material is 2.11 μm, as compared to 0.64 μm for the as-delivered ferric oxide sample. This suggests that the particles become agglomerate in the fouling apparatus. SEM (Scanning Electron Microscope) pictures were taken of the foulant sample removed from the apparatus. One of these photos is shown in Figure 9. Figure 9 shows that the particles are heavily agglomerated. The single particle size shown in Figure 9 is in the 0.2 ~ 0.4 μm range. Figure 9 also shows agglomerated particles, whose size is in the range of 2 ~ 3 μm. This is in good agreement with the 2.11 μm size shown in Figure 8.

3.2 Fouling curves

Clean tube data were taken prior to initiate the fouling test (Figure 10). This test yielded the overall heat transfer coefficients of the clean tube ($U_c$), which were curve-fitted as a function of Reynolds number. The clean tube data were taken at velocities between $13,000 \leq \text{Re} \leq 30,000$. During the test, the fouling water inlet temperature was maintained at 24°C and the heat flux to the test tube was maintained at 13.0 kW/m². In Figure 10 and following figures, repeated rib tubes are designated as $e/D_i$ and $p/e$. For example, 30/20 tube has $e/D_i = 0.030$ and $p/e = 20$. Figure 10 shows that $U_c$ of the repeated rib tubes increases as $e/D_i$ and $p/e$ decreases. Figure 10 also shows that $U_c$ of the plain tube is higher than those of the repeated rib tubes. This is expected because the plain tube has high performance integral fins on the condensing side whereas repeated rib tubes have widely spaced grooved on the condensing surface.
Fouling tests were conducted at three different concentrations (2500, 1500, 750 ppm). Throughout the test, tube-side Reynolds number was fixed at 19,000. Figure 11 shows the fouling curves at 2500 ppm. The foulant
concentration decreased to 2000 ppm at the end of the test. The shape of the curves shows an asymptotic behavior. The repeated rib tubes show higher fouling resistances than the plain tube. The highest fouling resistance is observed for the 15/10 tube, followed by 30/20 and 30/10 tubes. Figures 12 and 13 show the fouling curves at 1500 and 750 ppm. The foulant concentration decreased to 1200 and 600 ppm respectively at the end of the test. The fouling curves show an asymptotic behavior. At 750 ppm, however, the fouling resistances are very small.

The asymptotic fouling resistance ($R_f^*$) was calculated by curve-fitting the data to the form of Equation (5). Figure 14 shows the $R_f^*$ plotted against concentration. The figure shows that the concentration effect on $R_f^*$ is much stronger for repeated rib tubes than for the plain tube. At 2500 ppm, the repeated rib tubes show much higher $R_f^*$ than the plain tube. However, at 750 ppm, the $R_f^*$ of the repeated rib tubes are almost the same as that of the plain tube. The $R_f^*$ values were correlated using a least square fit program. The concentration, $e/D_i$ and $p/e$ were chosen as functional groups. The result is

$$R_f^* \propto (e / D_i)^{0.27} (p / e)^{2.1} C^{6.5}$$

(7)

Fig. 11 Fouling curves, ferric oxide concentration 2500 ppm, Re = 19,000

Fig. 12 Fouling curves, ferric oxide concentration 1500 ppm, Re = 19,000
Equation (7) shows that the $R_f^*$ is strongly dependent on concentration. The strong dependency was reported for other commercial enhanced, which have helical ribs [Chamra and Webb (1993), Li (2007)]. Equation (7) also shows that $R_f^*$ increases as $p/e$ increases and $e/D_i$ decreases. The sketch of the deposit of the $p/e = 20$ tube (Figure 15) shows that deposit gets thicker as the flow develops downstream from $x/e = 3.0$ (which may be the reattachment point). We may define the average deposit thickness as the value averaged between the ribs. Then, the average deposit thickness becomes larger as $p/e$ gets larger. The average of the $p/e = 20$ tube (Figure 15) is indeed thicker than that of the $p/e = 10$ tube (Figure 16). Turbulence intensity measurement between the ribs [Hijikata et al. (1988)] show that the turbulent intensity is maximum at the reattachment point, and decreases as the flow develops downstream. The decreasing turbulence intensity may result in thicker fouling deposit. Hijikata et al. (1988) also showed that the turbulence intensity increased as the rib height increases. The increased turbulence intensity may result in a thinner deposit. The sketches of the fouling deposit (Figures 16 and 17) show a thinner deposit on the $e/D_i = 0.030$ tube than on $e/D_i = 0.015$ tube. This may explain the decreasing $R_f^*$ for increasing $e/D_i$ as shown in Figure 14.
Fig. 15  Deposit distribution between ribs (tube 30/20)

Fig. 16  Deposit distribution between ribs (tube 30/10)

Fig. 17  Deposit distribution between ribs (tube 15/10)
3.3 Wet deposit structure

The wet deposits of the ferric oxide were inspected visually. The ferric oxide yielded a red muddy deposit that appears similar to "red oxide paint". The wet deposit may be transferred to a person's hand by rubbing the external surface of the deposit. To remove the deposit from the hand, one must scrub it well with soap and water. The outer layer of the deposit was easily removed from the surface. This exposed a surface layer that was more tenacious. Relatively hard rubbing pressure was required to remove the surface layer. The entire test apparatus was cleaned with once-through city water after each fouling test. To clean out the ferric oxide deposits from the apparatus, it took more than a day of water circulation. Even after a day, the water still had a light tint.

3.4 Deposit distribution between ribs

The fouling apparatus is equipped with deposit sections which are installed at the downstream end of each test section. The 230 mm long sample tube was installed in the deposit section prior to the fouling run. During the test, no heat transfer occurred in the deposit section, whereas the heat flux in the test section was maintained at 13.0 kW/m². This heat flux induced approximately 2°C temperature difference between the wall and the bulk stream. At this small temperature difference, the effect of temperature gradient on the particle deposition (thermophoresis) is believed to be negligible. So, the distribution in the deposit section should represent that in the test section. As the end of the fouling test, the sample tube was carefully removed from the deposit section and dried in the open air. Then, the sample tube was cut in half using a band saw. Figures 15 to 18 show the photographs of the ferric oxide deposit for the four sample tubes. The run time was about 15 hours at 1500 ppm.

Figure 15 shows the photograph and sketch of the deposit cross-section of the 30/20 tube. The figure also shows the flow direction and the non-dimensional distance ($x/e$). The sketch shows that the deposit thickness varies along the flow direction. The deposit just behind the rib is fairly thick compared with that on the other parts of the tube. Then, the deposit gets thinner until it reaches $x/e \approx 3.0$, where the thickness is the smallest. The photograph shows a dark line near $x/e \approx 3.0$. The dark line may have been formed when the separated flow reattached. Hijikata et al. (1988) showed that the flow reattached at $x/e \approx 4.5$. Downstream from the separation point, the deposit thickness increases as the flow develops, and reaches a maximum value at the front of the rib. Hijikata et al. (1988) also showed that the turbulent intensity reaches the maximum at the reattachment point, and decreases as the flow develops downstream. Lavallee and Popovich (1974) measured the wall shear stress distribution between the ribs, and showed that it has a peak at $x/e \approx 8.3$, and decreases thereafter. This decreasing wall shear stress, coupled with decreasing turbulence intensity, seems to cause the deposit thickness to increase. The photograph in Figure 15 shows a fairly smooth deposit until $x/e \approx 10$. Downstream from $x/e \approx 10$, however, the deposit surface shows ripples. The formation of ripples may be attributed to the turbulent nature of the flow. It was reported by Seban (1964) that the reattached flow adjusts itself to the wall and
eventually develops to the standard turbulent boundary layer far downstream of reattachment. The ripples may indicate the presence of the turbulent bursts. However, no definite explanation for the formation of the ripples is provided here. The smooth deposit surface in the recirculation zone may be related with the large wall shear stress existing in the region (Lavallee and Popovich, 1974). The cracks shown in Figure 15 occurred when the deposit dried.

Figure 16 shows the photograph and cross-section sketch of the 30/10 tube. The sketch shows that the deposit thickness varies along the flow direction. The variation of the deposit thickness is quite similar to that of the 30/20 tube - thick deposit behind the rib. The thinnest deposit is at \( x/e \approx 3.0 \), increasing deposit thickness downstream of the reattachment with maximum thickness at the front of the rib. The picture also shows a fairly smooth deposit for all the regions between the ribs. This is consistent with the results from the 30/20 tube, where ripples occurred beyond \( x/e \approx 10 \). The \( p/e \) value of the 30/10 tube is 10. The figure shows several cracks which occurred during dry-out. The figure also show bare tube surface which occurred from the loss of the dry deposit.

Figure 17 shows the photograph and cross-section sketch of the 15/10 tube. The sketch shows that the deposit thickness varies along the flow direction. The variation of the deposit thickness is quite similar to that of the 30/10 tube - i.e., thick deposit behind the rib, the thinnest deposit at \( x/e \approx 4.5 \), and increasing deposit thickness downstream of the reattachment with maximum thickness at the front of the rib. This tube shows the thinnest deposit at \( x/e \approx 4.5 \) whereas the 30/20 and 30/10 tubes showed the thinnest deposit at \( x/e \approx 3.0 \). The \( x/e \approx 4.5 \) matches with the reattachment point suggested by Hijikata et al. (1988). Figure 17 shows a fairly smooth deposit for all regions between the ribs. The deposits on top of the rib were fairly thick compared with those for the other tubes. The figure also shows several cracks and the bare tube surface which seems to have occurred during dry-out and handling. The cracks only occurred at the downstream portion of the reattachment where the deposit thickness is rather thick. The 30/10 tube also experienced this phenomenon.

Figure 18 shows the photograph and cross-section sketch of the plain tube. The sketch shows that the deposit thickness is fairly uniform along the flow direction. The figure also shows that the deposit surface is not smooth. It shows rippled structure. The rippled structure was also reported by Bott and Gudmundsson (1978) from their experiment on geothermal silica fouling. The figure shows several cracks and the bare tube surface which seems to have occurred during dry-out and handling.

### 3.5 Effect of non-uniform deposit

In the previous section, it is shown that, for repeated rib tubes, the deposit thickness varies along the flow direction. It is suspected that the fouling resistance of the non-uniform deposit may be different from that of the uniform deposit. Consider two extreme cases shown in Figure 19. The uniform deposit is shown as Case 1, and the extremely non-uniform deposit with the deposit thickness suddenly decreasing to half of the other side is shown as Case 2. In both cases, the total deposit mass is the same. For Case 1, the thermal resistance becomes

\[
R_{f1} = \frac{Ax}{k_f} \tag{8}
\]

For Case 2, the thermal resistance for each region becomes

\[
R_{f2,1} = \frac{8Ax}{3k_f} \quad \text{and} \quad R_{f2,2} = \frac{4Ax}{3k_f} \tag{9}
\]

Then, the total thermal resistance becomes

\[
R_{f2} = \frac{1}{1/R_{f2,1} + 1/R_{f2,2}} = \frac{9}{8} R_{f1} \tag{10}
\]
which shows that the thermal resistance is 13% higher for Case 2. The non-uniformity of the actual fouling deposit between the ribs seems to be much favorable than the Case 2. Thus, it is anticipated that the error caused by the on-uniformity of the deposit is less than 13%.

### 3.6 Effect of deposit on heat transfer performance

During the fouling experiment of the repeated rib tubes, the effective rib height may decrease as the deposit build up between the ribs. This decrease of rib height has an effect of decreasing heat transfer performance of the repeated rib tubes. In the calculation of the fouling resistance using Equation (1), the heat transfer performance of the repeated rib tube was assumed to be constant during the fouling test. This assumption needs to be verified. The highest fouling resistance obtained during the entire test is about $5 \times 10^{-5}$ m$^2$K/W, which occurred for the 15/10 tube at 2500 ppm concentration. It would be reasonable to assume that the thermal conductivity of the ferric oxide deposit layer is smaller than solid ferric oxide and larger than pure water. The thermal conductivity of ferric oxide was not readily available, and thus was assumed to be the same as that of aluminum oxide. The thickness of the deposit which yields $5 \times 10^{-5}$ m$^2$K/W is 2300 μm if the deposit has the thermal conductivity of aluminum oxide ($k_f = 46$ W/mK), and 30 μm if the deposit has the property of water ($k_f = 0.6$ W/mK). If the deposit thickness had been 2300 μm, whole rib would have been covered with the deposit considering that the rib height of the 15/10 tube is 255 μm. When the fouled tube was inspected visually, relatively thin deposits were indentified between the ribs. This suggests that the thermal conductivity of the deposit is close to that of water. Thus, in the calculations that follow, the deposit thermal conductivity is assumed to be that of water, which yielded the deposit thickness of 30 μm at $5 \times 10^{-5}$ m$^2$K/W fouling resistance. Then, the effective rib height will be 225 μm at the end of the fouling test, which shows 13% decrease from the initial value.

The degradation of the tube-side heat transfer coefficient will be studied using a simplified model shown in Figure 20. A repeated rib tube with rectangular cross-section ($e/D_i = 0.015$, $p/e = 10$) is considered, and the deposit is assumed to be uniform between the ribs. The deposit on top of the rib is neglected. A rectangular cross-section is chosen because of the availability of the heat transfer and friction correlation (Webb et al., 1971). After the fouling, it is assumed that the rib height is decreased 13%, which yields the rib configuration $e/D_i = 0.013$ and $p/e = 11.5$. The tube-side heat transfer coefficients before fouling ($e/D_i = 0.015$ and $p/e = 10$) and after fouling ($e/D_i = 0.013$ and $p/e = 11.5$) will be compared. The Reynolds number is assumed to remain the same (Re = 19,000) during the test. Through the experiments of repeated rib tubes (0.01≤$e/D_i$≤0.04, 10≤$p/e$≤40), Webb et al. (1971) found that all the friction data are reasonably correlated by the following equations for $e^+≥20$.

$$B(e^+)\left(\frac{p}{e}\right)^{0.55} = 0.95$$  \hspace{1cm} (11)
Fig. 20  Model adopted to show the effect of heat transfer degradation

\[ B(e^+) = \sqrt{\frac{2}{f} + 2.5 \ln \left( \frac{2e}{D_i} \right) + 3.75} \]  \tag{12}  \\
\[ e^+ = \frac{e}{D_i} \sqrt{\frac{f}{2} Re} \]  \tag{13}  

For the tube before fouling \((e/D_i = 0.15, p/e = 10)\), the calculated results are \(B(e^+) = 3.22\) and \(e^+ = 25.3\). The heat transfer coefficient (or Stanton number) may be obtained from the following equation,

\[ St = \frac{f / 2}{1 + \sqrt{f / 2 [4.5(e^+)^{2/3} Pr^{0.7} - B(e^+) ]}} \]  \tag{14}  

which yields \(St = 3.2 \times 10^{-3}\).

The heat transfer coefficient after fouling \((e/D_i = 0.013, p/e = 11.5)\) may be obtained using the same procedure, and the result is \(St = 3.1 \times 10^{-3}\). This shows that the tube-side heat transfer coefficient decreases about 3% after fouling.

This degradation of tube-side heat transfer coefficient may also be expressed as a fouling resistance, which turns out to be \(3 \times 10^{-6} \text{m}^2\text{K/W}\). This is about 6% of the total fouling resistance \((5 \times 10^{-5} \text{m}^2\text{K/W})\). Thus, we may neglect the degradation of tube-side heat transfer coefficient by fouling. Then, the measured fouling resistances in this study may be interpreted as a pure deposit resistance without much error. If the calculation is repeated assuming the doubled deposit thickness of 60 \(\mu\text{m}\), the decrease of the tube-side heat transfer coefficient becomes 7%.

4. Conclusions

In this study, the effect of ferric oxide concentration on particulate fouling in two-dimensional repeated rib tubes was investigated. The concentration was varied from 750 to 2500 ppm. The tube-side Reynolds number was fixed at 19,000. The range of roughness configuration was \(0.015 \leq e/D_i \leq 0.030\) and \(10 \leq p/e \leq 20\). The fouling curves showed asymptotic behavior. Listed below are major findings.

1) The fouling resistances of repeated rib tubes were higher than that of the plain tube. At low concentration of 750 ppm, however, they were approximately the same.
2) The repeated rib tubes showed stronger concentration dependencies compared with the plain tube.
3) Within the test range, the repeated rib tube fouling resistance increases as \(p/e\) increases and \(e/D_i\) decreases. The deposit inspection supports this trend.
4) Evaluation of the deposit non-uniformity on fouling resistance reveals that the effect is not significant (less than 13%).

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