RIPPLED SILICA DEPOSITS IN HEAT EXCHANGER TUBES

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ABSTRACT

Rippled deposits have been observed during the removal of heat from geothermal water. The effect of the ripples is to produce enhanced heat transfer in the early stages of the fouling process and pressure losses of 170% greater than for equivalent sand grain roughness under similar conditions.

NOMENCLATURE

- e = height of roughness, m (unless otherwise stated)
- f = friction factor, dimensionless
- r = radius, m
- R = fouling resistance, $(kW/m^2K)^{-1}$
- U = overall heat transfer coefficient kW/m^2K
- x = ripple spacing, m (unless otherwise stated)
- ϕ = roughness function, dimensionless
- λ = ripple ratio, x/e, dimensionless.

Subscripts

- o = clean

Superscripts

- + = dimensionless

INTRODUCTION

The formation of deposits on heat transfer surfaces results in changes of their heat transfer (1) and pressure drop characteristics. The extent to which this occurs depends largely on the associated roughness.

Rippled deposits were encountered during an investigation into the fouling behaviour of silica laden geothermal waters (2). When geothermal waters are extracted from the ground they contain dissolved silica corresponding to the solubility at the base temperature and pressure of the reservoir. During utilisation the waters are cooled and become highly supersaturated with respect to silica. The excess silica deposits rapidly on all surfaces and is not easily removed by mechanical or chemical means. It has been suggested that deposition is the major constraint on the utilisation of geothermal energy (3).

EXAMPLES OF RIPPLED DEPOSITS

Rippled deposits have been observed in a number of different situations. Wiederhold (4) and Seiferth and Kruger (5) reported that excessive pressure loss increase occurred in a pipeline carrying fresh water. In three years the pressure drop increased by about 57%. The pipeline was 80 km long with a diameter of 0.5m. The pressure drop increases were due to the formation of transversely rippled deposits. The ripples were 0.5 - 1 mm high and spaced at 3-8 mm. The deposit consisted mainly of alumina and other inorganic oxides. Pressure measurements were performed on a 178m section and of the pipeline after 3 years of operation. The friction factor was found to decrease with Reynolds number.

Gessner (6) reports observations on increased pressure loss in a large diameter water duct associated with a small hydroelectric scheme. The increased pressure drop was due to the formation of rippled deposits. In eighteen years the output of the plant decreased from 10.1 MW to 8.6 MW or about 1% per year. The average diameter of the duct was 1.95m. The height of the ripples was 0.5 - 4 mm and their spacing 4-16 mm.

Experience with some supercritical once-through boilers has shown that unacceptably high pressure drops can occur in the evaporators such that frequent chemical cleaning is required (7-14). In one instance the pressure drop increased about 70% in 10,000 hours (10). Examination of tubes removed from these boilers has shown that transversely rippled corrosion products (mainly magnetite) on the walls are responsible for the high pressure drops encountered. The effect on heat transfer has been negligible. The phenomenon of rippled deposits has only been observed in those sections of evaporator tubes carrying water in the liquid phase. In other sections, such as economiser tubes and steam tubes, all corrosion products are evenly distributed as thin films with no evidence of ripples. Haller et. al. (13,14) observed that the structure of the corrosion product film was transversely rippled. Other workers (7,8,10), however, stated that the structure ranged from a transverse ripple effect to a crater-like form where the transverse ripples were connected by longitudinal ripples. Schuster (9) concluded that the crater-like structure was more likely to be associated with high Reynolds numbers. The average spacing between the transverse ripples has been reported as 0.2 - 0.3 mm (8) and 0.18- 0.3 mm (10) with ripple heights of 0.025 - 0.040 mm and 0.02 - 0.04 mm respectively.

Rippled deposits formed in a 0.61 m pipeline conveying saturated brine at 15°C have been examined (15). Exceptionally high pressure drops resulted which could not be explained simply in terms of increased velocity due to the reduction in flow area. The thickness of the deposit was only 5-7 mm. Measurements on a 2692m section of the pipeline after approximately five years of operation showed that the pressure drop was 0.365 bar at a Reynolds number of 139,000 (bulk velocity 0.5 m/s). The measured friction factor f was 0.0148. A section of the deposit with four transverse ripples was measured and gave an average ripple spacing of 4.73 mm and an average ripple height of 1.08 mm. The pressure drop calculated for the pipeline was only 0.140 bar, or 38% of the measured pressure drop. The calculation was performed by using the average ripple height of 1.08 mm in the relation given by Schlichting (16) for sand grain roughness. The deposit consisted mainly of calcium carbonate and magnesium hydroxide.

EXPERIMENTAL WORK

Experimental work was carried out at Hveragerdi in the south-west of Iceland. A double walled heat exchanger was manufactured from 316 stainless steel with a 0.12 cm thick wall. The main tube of the exchanger was nominal 1.27 cm O.D. and 2 m long. The first 0.5 m acted as an entry section and a further 1.5 m was surrounded by a 1.91 cm O.D. cooling jacket. The exchanger was mounted vertically, thermally insulated and operated in a counter-current mode. Temperatures were measured at the inlet and outlet of both streams by mercury-in-glass thermometers. The hot and cold streams from the exchanger were fed to a weighing tank and drain.

The geothermal water giving rise to deposition and fouling was taken directly from the district heating mains of the town of Hveragerdi. The temperature of the water was 80°C and it contained 777 ppm total dissolved solids of which 305 ppm was silica. The water was saturated with respect to silica with a pH of 9.5 at room temperature. The cooling water was taken from the water mains of the town.

The operation of the tubular heat exchanger consisted of maintaining the geothermal and cooling water flowrates as constant as possible and measuring their inlet and outlet temperatures.

Heat Transfer

The fouling of heat exchangers may be expressed by the fouling resistance

$$R_f = \frac{1}{U} - \frac{1}{U_o} \quad \text{........ (1)}$$

in the present studies a pseudo U_o - value was calculated for each experimental U-value to ensure that the difference between the two overall coefficients gave a more representative fouling resistance. The same approach has been used by other workers (17). The physical properties used in all calculations were estimated from expressions derived for sea-water solutions (18).

For a clean experimental heat exchanger as used in the present studies it was found (2) that measured overall heat transfer coefficients were about 10 per cent greater than the calculated smooth tube coefficients when the Reynolds number was greater than 10,000. This was probably due to the commercial roughness of the exchanger tubes. However, in the calculation of the pseudo clean tube overall heat transfer for coefficient U_o, no correction was made for the effect of commercial roughness.

The cooling water flowrate remained constant during the experimental period. The hot water flowrate, however, had to be adjusted frequently to compensate for increased pressure drop in the heat exchanger and associated pipework as a result of deposition and fouling. Visual observation at the end of the experimental period revealed that deposition had only occurred on the geothermal water side of the exchanger tube. The change in the measured overall heat transfer coefficient U was therefore the result of fouling by silica on the hot side. The average Reynolds number of the geothermal water was 44,000. All heat transfer calculations were based on the clean tube diameter of 1.026 cm.

The fouling resistance of the exchanger, as expressed by Equation 1, is the difference between the inverse of the two overall heat transfer coefficients. The fouling resistance is plotted in Figure 1 and is shown to be "spoon" shaped. For the first 50 hours the fouling resistance remains constant at -0.04 $(kW/m^2\ ^oC)^{-1}$ and at 650 hours it has reached unity. After that the fouling resistance increases linearily to reach 0.4 $(kW/m^2\ ^oC)^{-1}$ at 2000 hours. However, the true fouling resistance was lower or 0.36 $(kW/m^2\ ^oC)^{-1}$. The "spoon" shaped fouling curve of Figure 1 consists of three periods of interest. The first 50 hours constituted an induction period followed by an enhancement period from 50 to 600 hours. The enhanced heat transfer was attributed to the increased roughness produced by the rippled silica deposit. At 600 hours the enhancement in heat transfer becomes equal to the reduced heat transmission due to deposition and the linear period begins.

Pressure Drop

At the end of the 2000 hour experimental period a 38 cm section of the heat exchanger tube was removed for accurate pressure drop measurements. The inside diameter of the clean tube was 1.026 cm

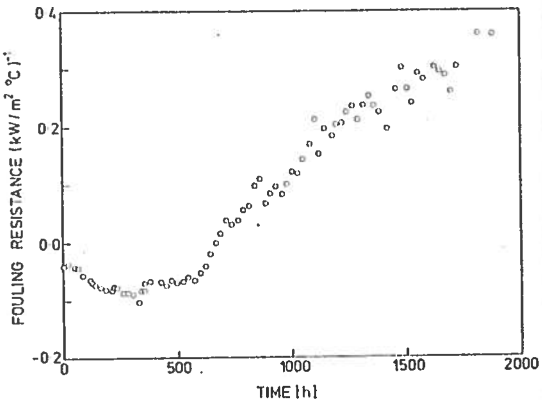

FIG 1 Fouling resistance variation with time

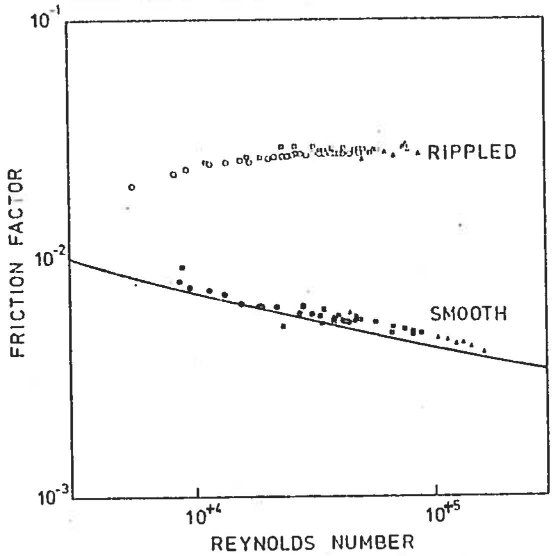

FIG 2 Friction factor and Reynolds number

but the diameter of the tube with the deposit was estimated volumetrically as 0.955 cm. The volumetric diameter was used in the pressure drop calculations.

The experimental apparatus consisted of a 90 cm long, 1.026 cm ID, entry section connected to the test section. The ID of both tubes was flush to a 6.4 mm bridge between them having two radially-opposite pressure tappings in the centre. Similarily, there was a 40 cm long tube downstream from the test section.

Experiments with both compressed air and demineral-ised water were performed. In the air experiments the flowrate was measured by a gas meter downstream at atmospheric pressure. The temperature of the air was measured between the 40 cm outlet section and the gas meter. The pressure tappings at the inlet and outlet were connected to water manometers with the other leg open to atmosphere. In this way the average absolute pressure and pressure drop in the test section could be determined. In the water experiments the pressure drop was measured by a manometer, the flowrate in a weighing tank and the temperature downstream from the 40 cm outlet section by a mercury-in-glass thermometer. The physical properties of air and water used in the pressure drop calculations were obtained from standard texts.

To test the validity of the experimental procedure a smooth test section was inserted and the pressure drop characteristics determined. The friction factor values derived from the measured pressure drops were found to be just above those of a hydrodynamically smooth tube (19), when plotted against Reynolds number. This is to be expected for a commercially rough tube (see Figure 2).

The compressed air experiments were carried out at ambient temperatures only but the water experiments at ambient and higher (70-90°C) temperatures. The silica deposit showed no signs of being eroded when subjected to the air and water pressure drop measurements.

The friction factor in rough pipes can be related to the roughness function ϕ by the expression (16,20).

$$\phi = \sqrt{\frac{2}{f}} + 2.5 \ln \left(\frac{e}{r}\right) + 3.75 \qquad \ldots\ldots\ldots (2)$$

The roughness function depends on the geometry of a rough surface (20). For the well known sand grain roughness the friction function has been correlated to the dimensionless roughness height e^+.

In the hydraulically smooth region ($e^+ \leq 5$) and the transition region $5 \leq e^+ \leq 70$) the friction function ϕ varies with e^+. In the completely rough region ($e^+ > 70$), however, the friction function is constant at $\phi = 8.5$ such that the friction factor calculated from Equation 2 becomes independent of Reynolds number.

The friction factor against Reynolds number for the rippled rube is shown in Figure 2. The friction factor increases with Reynolds number to an apparently constant value. This is in qualitative agreement with tubes having sand grain roughness (16). However, the friction factor is much higher than predicted from sand grain roughness theory using the rippled height as the characteristic dimension. The average ripple height was measured as 0.123 mm. Assuming fully turbulent flow, sand grain roughness theory predicts a friction factor of 0.0104, while the experimental value obtaind in this work is approximately 0.028, or 170% higher. To compare the experimental results with the semi-empirical sand grain roughness theory the friction function ϕ has been calculated and is shown plotted in

Figure 3 against the dimensionless roughness height e^+. In the fully rough region, where ϕ is independent of e^+, the value of the friction function becomes $\phi = 3$.

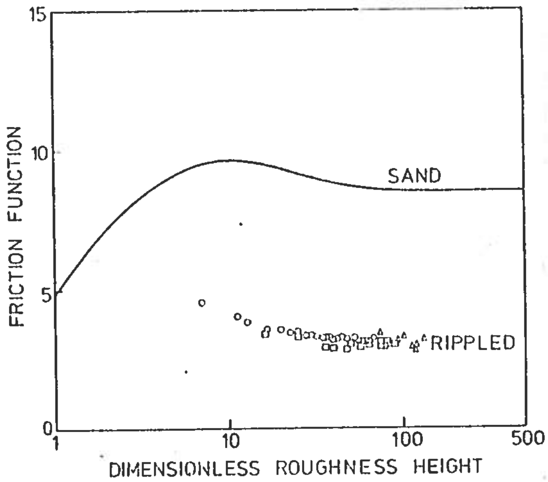

FIG 3 Friction function and roughness height

Deposit Examination

At the end of the experimental period (2000 hours) the silica deposit was examined. Figure 4 shows the appearance of the deposit in a section of the 0.5 cm OD heat exchanger tube.

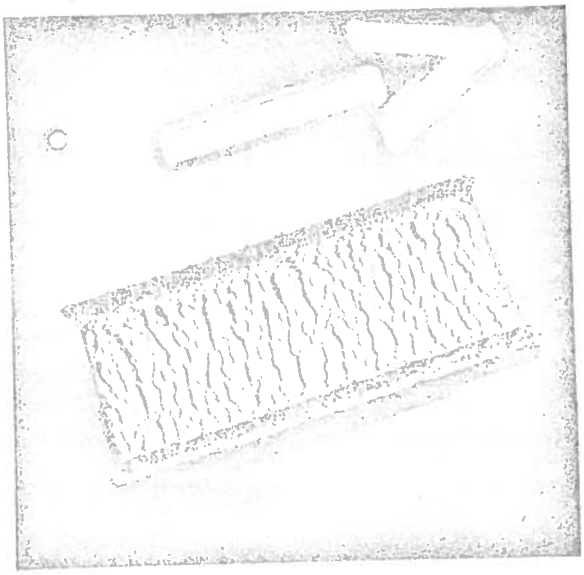

FIG 4 Section of tube showing transverse ripples

The surface of the deposit consisted of narrow ridges rising above a relatively uniform but rough area. The ripples were transverse to the direction of flow and apparently evenly spaced.

A section of the silica deposit was removed to measure the dimensions of the ripples. This was done in an optical microscope on a polished cross-section of the deposit. Figure 5 shows the ripple profile. The ripples are apparently not symmetrical but lean slightly against the direction of flow which is from left to right. The deposit thickness in the uniform trough area between the ripples was estimated as 0.25 - 0.3 mm.

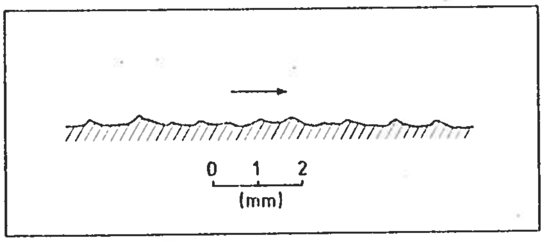

FIG 5 Ripple profile

From a photograph of the polished cross-section magnified 50x the height and spacing of 38 ripples were measured. The average spacing was found to be 0.87 mm and the average ripple height 0.123 mm. The standard deviation of the spacing and height measurements was 36.5% and 33.1% respectively. These values correspond well with the standard deviation of normal distribution which characterises many naturally occurring phenomena.

Gravimetric analysis of the rippled deposit showed that it consisted of about 60% silica. Other elements present included aluminium, calcium, potassium, sodium, iron and titanium. X-ray diffraction showed the deposit to be completely amorphous.

FORMATION OF RIPPLED DEPOSITS

It has been postulated that rippled deposits might be caused by an interaction of deposition/erosion processes (7,8,10), by high pressure/temperature/flow oscillations or the action of sublayer bursts in the boundary layer (21). These suggestions, however, have no experimental support and are therefore very speculative (15).

The available data on the length scales of rippled deposits are given in Table 1. An examination of these data shows that the spacing x and height e of naturally-occurring ripples range from 0.193 to 10 mm and 0.0142 to 2.3 mm, respectively. The ripple ratio $\lambda = x/e$, however, ranges from 4.3 to 13.6. The ripple ratio is therefore confined to a relatively narrow range while the spacing and height show a greater range of values. This suggests that naturally-occurring rippled deposits might be characterised by the ripple ratio rather than the actual length scales.

Table 1. Length scales and ripple ratio of rippled deposits

Types of Fluid	x (mm)	e (mm)	$\lambda = \frac{x}{e}$	Ref
Fresh Water	5.5	0.75	7.3	4
" "	10	2.3	4.3	6
Boiler Water	0.45	0.09	5	8
" "	0.24	0.03	8	10
" "	0.35	0.045	7.8	15
" "	0.8	0.1	8	15
" "	0.193	0.0142	13.6	14
" "	0.201	0.0165	12.2	14
Saline Water	4.73	1.08	4.4	15
Geothermal Water	0.87	0.123	7.1	Present Work

Webb et al. (22) have presented a catalogue of flow patterns downstream from a rectangular rib roughness for several pitch to height ratios. They show that separation occurs at the rib, forming a widening free shear layer which reattaches 6-8 rib heights downstream from the separation point. A reverse flow boundary layer originates at the reattachment point and grows in thickness in the upstream direction. Measurements have shown that local heat transfer coefficients reach a maximum in the vicinity of the reattachment point. Wilkie (23) and Lewis (24) have shown that reattachment occurs probably at pitch to height ratio x/e of 7.2 and 7.5 respectively.

The hydrodynamics of ripples and rectangular roughness are probably very similar. Separation and reattachment is therefore likely to occur on a rippled surface. The ripple ratio $\lambda = 7.1$ measured at Hveragerdi for the silica deposit corresponds well with the values for reattachment behind rectangular roughness elements. It is suggested here that the phenomena of flow separation and reattachment is responsible for the formation of rippled deposits, provided certain conditions are fulfilled.

For any deposition to occur there must be some driving force such as concentration difference. Observations in Iceland on pipelines carrying geothermal waters have shown that rippled deposits are more likely to be found where the deposition driving force is almost non-existent. This appears also to be a common feature of other systems where rippled deposits are found as shown by the slow deposit build-up. The absence of a strong deposition driving force could therefore be a major factor causing deposition to assume a rippled profile. When the driving force is large deposition will occur on sites evenly distributed over the surface. However, when the driving force is limited deposition will occur preferentially at sites in regions of enhanced mass transfer.

In most deposition and fouling situations deposit build-up consists of two competing processes; deposition and removal. The extent to which a surface becomes fouled depends largely on the relative importance of these two processes. At sites where enhanced mass transfer occurs it is to be expected that wall shear stresses are the greatest. For the separation-reattachment hypothesis to be right, therefore, the removal process must be insignificant in comparison to the deposition process. The fact that silica deposits adhere very strongly to surfaces and are notoriously difficult to remove, support the above arguments.

In commercial tubes naturally-occurring roughness exists as a result of the manufacturing process. Such roughnesses will project into the fluid and promote deposition at the tip. At these locations the deposits will most likely grow faster than in the areas around them. At a certain distance downstream from the roughness the deposition rate will also be enhanced due to the phenomena of boundary layer separation and reattachment. In these regions of enhanced mass transfer a new roughness element will grow and in turn give rise to further enhancement sites further downstream. In this way the mechanism of formation becomes self-perpetuating.

Rippled deposits have been shown to form under both isothermal and heat transfer conditions and circumferential heat flux appears to have no effect on the structure of the ripples. This suggests that the mechanism giving rise to rippled deposits is a hydrodynamic phenomenon of the type discussed above.

CONCLUSIONS

1. Rippled deposits are formed when geothermal waters saturated with silica are cooled in simulated heat exchanger tubes:
   (a) In 2000 hours the plotted fouling resistance of a heat exchanger at Reynolds number 44,000 showed a "spoon" shaped curve consisting of induction, enhancement and linear periods. The final fouling resistance was 0.36 $(kW/m^2\ ^{o}C)^{-1}$.
   (b) The rippled silica pressure drop after 2000 hours was 170% greater than expected from sand grain roughness. The friction function in the fully turbulent region was constant at $\phi = 3$.
   (c) The 60% silica deposit consisted of ripples 0.123 mm high and spaced at 0.87 mm. The ripple ratio was therefore $\lambda = 7.1$.

2. It is postulated that rippled deposits are formed due to the phenomena of flow separation and reattachment when:
   (a) The deposition driving force is almost non-existent.
   (b) The deposit material (silica) adheres strongly to surfaces.

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