PART IV

RIPPLED DEPOSITS

PART IV - RIPPLED DEPOSITS

1. INTRODUCTION

Fouling is the build-up of deposits on heat transfer surfaces and usually the deposition will result in a deterioration of the thermal performance of heat exchangers. The extent to which this occurs depends largely on the processing conditions and the nature of the deposits. But fouling will also affect the pressure drop characteristics of exchangers and even influence the deposition process itself. The overall process of fouling consists of a dynamic interaction of heat, mass and momentum transfer. Chemical reaction may also be involved. The conditions existing at the interface between a deposit surface and a flowing fluid will therefore be of considerable importance.

2. DEPOSIT ROUGHNESS

2.1 Effects of Deposit

The fouling of surfaces may be considered to consist of three main effects(1). These are the insulation, diameter and roughness effects. The insulation effect is the decrease in heat transmission due to the thermal resistance of deposit layers forming on heat transfer surfaces. The extent of the insulation effect depends on the thickness and thermal conductivity of deposit.

The diameter effect is the reduction in cross-sectional area available for flowing fluids. It results in changes in the flow and pressure drop characteristics of tubes subjected to fouling. In a situation where the flowrate and friction factor remain constant, the proportionality $\Delta p \propto d^{-5}$ applies. A small decrease in diameter may therefore have a significant effect on the pressure drop or flowrate of an exchanger.

The roughness effect in fouling is of main interest in the present section. This effect arises because the transfer of heat, mass and momentum at surfaces is strongly dependent on roughness. While the insulation and diameter effects behave in a relatively predictable manner, the effects of deposit roughness are much more uncertain. Deposition on a clean surface, with commercial roughness say, may result in a deposit finish ranging from smooth to very rough. It is, therefore, difficult to quantify the contribution a given roughness will make to the overall thermal performance of a surface. The effect of roughness is usually included in the fouling resistance of heat exchangers(1).

Roughness will also affect the mass transfer at a surface. Its influence will be manifested in the deposit build-up and included in the overall character of a particular fouling system. Similarily, the effect of roughness on pressure drop will be an integral part of the changing flow environment during deposition.

In the literature, experimental work on transfer properties of surfaces with natural roughness deals mainly with pressure drop characteristics(2). Limited work has been done on heat transfer characteristics of natural roughness(1,3) and apparently nothing on mass transfer properties.

2.2 Deposits in Fouling

Deposits investigated in fouling include hardness scales, hydrocarbon materials and corrosion products. Information on roughness effects with respect to those deposits, and others, is rather limited. In most cases the experimental data is restricted to heat transfer and pressure drop performance during deposit build-up, without reference to roughness. However, a consideration of deposits encountered in fouling, should be useful.

The predominant material in water scales is calcium carbonate(4,5). These scales are usually reported as consisting of two main layers. On top there is an easily removable layer and near the tube wall there is an adherent and more crystalline layer.

Hydrocarbon deposits may be waxes or coke-like materials. The former occur during cooling, while the latter are usually some reaction products. Work on paraffin wax deposition and fouling is reported in Part II of this Thesis. There is was concluded that paraffin wax deposits exist in two layers. The outer layer was easily removable and gave rise to random fluctuations in the fouling resistance. The inner layer was adherent and more crystalline. Walker(6) found that paraffin wax deposits did not increase the pressure drop across simulated heat exchanger tubes. Watkinson(7) studied particle deposition from gas oils on heated surfaces(8). It was found that deposits were soft, powdery, black, soot-like material. The pressure drop increased during deposition.

Corrosion product deposits have given rise to different pressure drop characteristics. Hematite deposits studied by Hopkins(9) were reported as rough and granular(10). In some runs pressure drop increases occurred.

Magnetite deposits studied by Thomas(11), however, made tube surfaces smoother such that the pressure drop decreased with increased deposition(12).

2.3 Rippled Surfaces

In nature, rippled surfaces may be formed when a fluid flows over a deformable surface. Ripples are found in deserts(13-17), on beaches and in alluvial channels(18-23). They are a dynamic surface structure advancing by a continuous movement of material (sand) up and over the ripple(15).

Rippled surfaces may also be static. These are rippled deposits that have been observed in several process situations(G,H,I). Rippled deposits are important because they may exhibit a more pronounced effect on the transfer of heat, (mass) and momentum than any other known natural roughness shape. The rippled deposits reported in the literature occur at both isothermal and heat transfer conditions; in pipelines and boiler tubes, respectively.

3. PRESSURE DROP MEASUREMENTS

When the fouling experiments at Hveragerdi (described in Part III of the Thesis) were terminated, it was realised that the deposits were rippled. There were no facilities to measure pressure drop during the runs. Although pressure drop increases due to deposition had been expected, these increases were much greater than anticipated and reduced the flowrate with time. The problem was overcome by adjusting the flowrates regularily to the required value.

It was decided to study the pressure drop characteristics of the rippled silica deposit(G,H). A 38 cm long section was cut from the downstream end of exchanger No 1 at Hveragerdi that had been operated at Reynolds number ∿ 44,000 for 2000 hours. The clean tube ID was 1.026 cm but the diameter (determined volumetrically) with the deposit was 0.955 cm, the latter being used in all calculations. The pressure drop characteristics of the rippled silica deposit were determined from fluid flow measurements using both compressed air and demineralised water. The experimental results are given in Table 1-4. The pressure drop in a clean tube was also measured for comparison. The Fanning friction factor and the Reynolds number were determined and are plotted in Figure 1. The friction factor in the rippled tube increased with Reynolds number initially and then assumed a constant value.

The high pressure drop associated with rippled surfaces may be illustrated by comparison with the pressure drop expected from surfaces having sand grain roughness(24). The average ripple height of 0.123 mm was used as the characteristic dimension instead of the sand grain diameter. In fully turbulent flow, where the friction factor is independent of Reynolds number, sand grain roughness theory predicted a Fanning friction factor of 0.0104. The measured(G,H) friction factor at turbulent conditions was 0.028 or about 170 per cent higher. Ripple roughness, therefore, gives rise to much greater pressure drop than sand grain roughness.

The increase in pressure across heat exchanger no 1 at Hveragerdi, during the 2000 hour experimental period, must have been much greater than the difference between ripple and sand grain roughness indicates. The overall increase in pressure drop was caused by the change in tube roughness from "commercial-rough" to "ripple-rough", and the reduction in tube diameter. The measured friction factor was about 5x that of hydrodynamically smooth tube at Reynolds number 44,000.

The pressure drop characteristics of each roughness type or geometry, can be expressed by a single curve by plotting the roughness function ϕ against the dimensionless roughness height e^+(24,25). In fully turbulent flow ($e^+ > 70$) the friction function becomes constant and for sand grain roughness, $\phi = 8.5$. Haller et al(26,27) studied pressure drop in tubes with rippled magnetite deposits(1). They found that the shape of the friction factor against Reynolds number curve was similar to that of sand grain roughness. The measured friction factor, however, was higher than that expected from sand grain roughness theory. The data indicated that for rippled magnetite $\phi \sim 5$ in fully turbulent flow(1).

The friction function ϕ for the rippled silica deposit was calculated in Tables 2 and 4 and plotted against the dimensionless roughness height e^+ in Figure 2. The shape of the curve is similar to that of sand grain roughness. In the fully turbulent region the friction function was constant $\phi \sim 3$. Ripple roughness, therefore, shows the same qualitative behaviour as sand grain roughness, although the friction function is much lower. Because $f \propto \phi^{-2}$ the pressure drop of ripple roughness is greater than sand grain roughness for the same dimensionless roughness height.

Figure 3 shows the rippled silica deposit found in heat exchanger No 1 at Hveragerdi.

4. MECHANISM OF FORMATION

While the literature on rippled deposits gives instances of pressure drop increases, there has been very little discussion about a possible mechanism of formation. Rippled deposits may form at ambient temperatures in large diameter pipelines and at near-critical temperatures in small diameter evaporator tubes. The main similarity between these widely different conditions, appears to be that the fluid concerned was water. To gain an understanding of the conditions at which rippled deposits have formed, the available literature on ripples in supercritical once-through boilers was reviewed(1). The less extensive literature on ripples in pipelines was also reviewed(G). Based on these reviews, the work on silica fouling (Part III of Thesis), the present pressure drop measurements and the general literature on flow over roughness elements, a mechanism of formation has been suggested(H).

The proposed mechanism is based on the phenomena of flow separation and reattachment at roughness elements. For rippled deposits to be formed, two conditions must be fulfilled : The depositing material (foulant) must be close to or at saturation, such that the deposition driving force is very small. Also, the depositing material must be relatively adherent and not easily removed by fluid shear.

Flow over roughness elements separates and reattaches 6-8 roughness heights downstream(28). On heat transfer surfaces, the local rate of heat transfer is greater at the reattachment point. If follows, that the local rate of mass transfer must also be greatest at the reattachment point. In situations where the tendency for deposition is minimal and the deposit material highly adherent, it is suggested that ripples will be formed at sites of reattachment. Typical values for the reattachment distance (measured at heights e of roughness elements) are 7.2(29) and 7.5(30). The rippled silica deposit examined from heat exchanger no 1 at Hveragerdi had an average ripple ratio (ripple spacing/height) of 7.1(H). Therefore, the ripple spacing corresponded to the above values for the reattachment distance. This was taken to indicate that the growth of the silica ripples was controlled by flow separation and reattachment.

5. DISCUSSION

In the present section the importance of roughness in fouling was discussed and illustrated in terms of rippled deposits. Pressure drop measurements on a rippled silica deposit showed that rippled surfaces increase the transfer of momentum considerably above that of commercially rough surfaces. Heat and mass transfer at the solid-liquid interface (tube wall) must be affected, similarily.

A separation reattachment mechanism was proposed for the formation of rippled deposits, where it was assumed that the foulant was at saturation and the deposit highly adherent. In a great number of deposition and fouling situations, very little can be done to eliminate the foulant from the system and deposition becomes inevitable; the foulant concentration is set by the system conditions. Where ripples are formed, therefore, the deposit adherance appears to be the one parameter that might be manipulated to prevent ripples forming. Additives might possibly provide the answer as with some desalination scales.

The pressure drop characteristics of the rippled silica deposit showed qualitative agreement with rippled magnetite deposits and other roughnesses exhibiting the same behaviour as sand grain roughness. However, the work of Wiederhold(3) and Seiferth and Krüger(32) on rippled deposits in pipelines, showed the friction factor to decrease with Reynolds number. This behaviour was explained in terms of experimental work with right angles on flat surfaces, where the friction factor decreased with Reynolds number when the spacing of the right angles was below some critical value that was less than the reattachment distance(G).

An examination of the Wiederhold(31) pressure drop data shows the friction factor curve (against Reynolds number) to be almost parallel to that of smooth tubes, except that it is much higher. This qualitative agreement appears to suggest that rippled deposits in large diameter pipes (d ∿ 50 cm) and small diameter tubes (d ∿ 2cm) behave differently. It has already been shown how the ripple spacing decreases with tube diameter(G). The exact friction factor behaviour depends, therefore, on the relative roughness e/d, while the friction factor value depends on the type of roughness; which might be sand grain or rippled, for instance.

The rippled silica deposit was obtained at the end of a 2000 hour run. The pressure drop measurements reported above refer only to the, presumably, fully developed deposit structure. What is required is some information about the initial stages in the growth of the ripples; their geometry and pressure drop characteristics. This would provide the necessary data to show if the proposed separation-reattachment model hold for both the initiation and propagation of rippled structures.

6. CONCLUSIONS

1. Deposit roughness is an important consideration in fouling.
2. Rippled deposits exhibit a more pronounced effect on fouling than any other natural roughness shape.
3. Silica ripples formed in 2000 hours at Reynolds number 44,000 resulted in a friction factor 5x that of a smooth tube.
4. Rippled deposits are probably formed due to flow separation and reattachment when the deposition driving force is minimal and the deposit strongly adherent.
5. The friction factor of rippled surfaces behaves differently at small and large values of the relative roughness.

7. RECOMMENDATIONS FOR FURTHER STUDY

1. Detailed examination of deposit roughness and its effect on heat, mass and momentum transfer, should be an integral part of any fouling study.
2. Experiments should be carried out to investigate the geometry and transfer properties of rippled deposits from initiation to propagation. The effect of foulant concentration and deposit adherance should also be investigated.

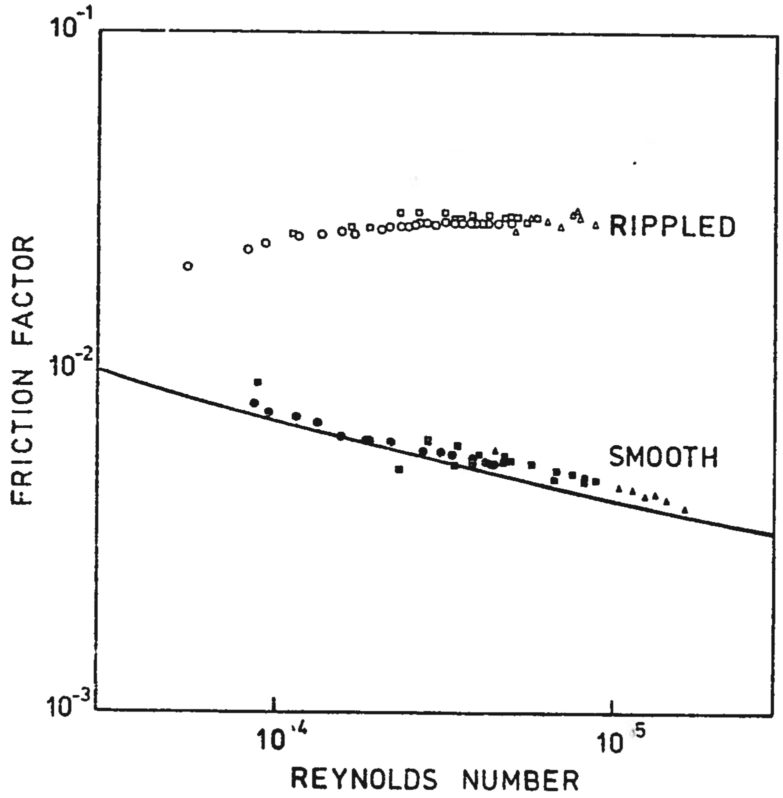

FIGURE I - Friction factor against Reynolds number. ● Table 1, ▲ and ■ Table 3, o Table 2, Δ and □ Table 4.

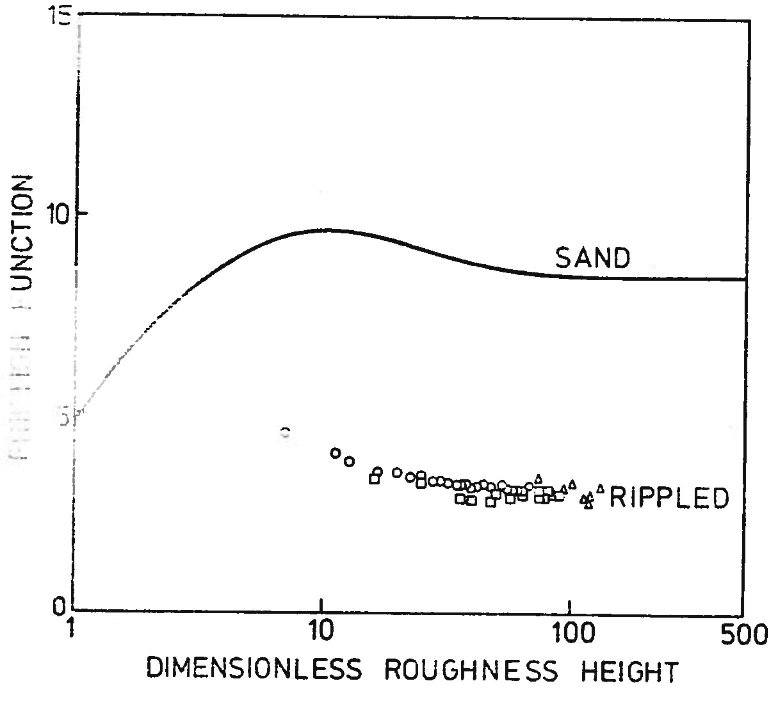

FIGURE 2 - Friction function against dimensionless roughness height. o Table 2, Δ and □ Table 4.

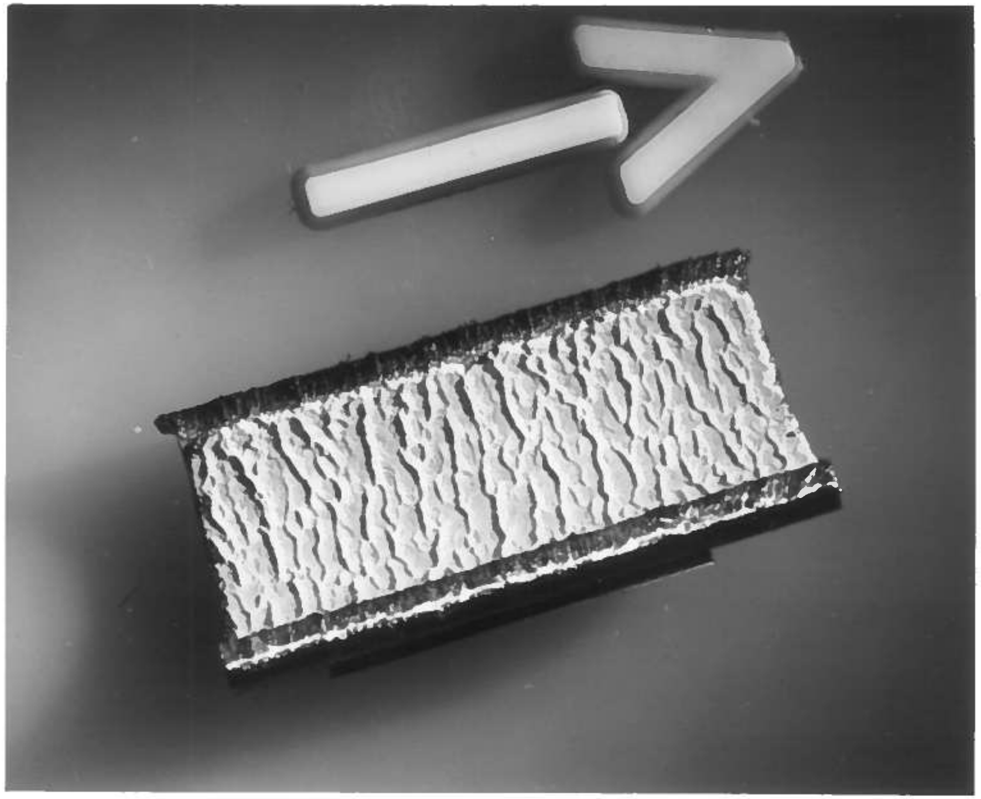

FIGURE 3

Rippled Silica Deposit in Tubular Exchanger No 1 at Hveragerdi

TABLE I

Pressure Drop Data and Calculations; Smooth Tube, Compressed Air

No	V_{atm} (l/s)	Δh (cm H_2O)	T (^oC)	p (bar)	Re	f x 10^3
1	1.04	1.4	19.2	1.0068	8642	8.04
2	1.40	2.3	19.4	1.0156	11618	7.36
3	1.85	3.5	19.4	1.0296	15409	6.42
4	2.28	5.0	19.4	1.0464	18990	6.14
5	2.63	6.6	19.4	1.0633	21912	6.22
6	3.25	9.3	19.4	1.0936	27104	5.88
7	3.64	11.3	19.4	1.1213	30307	5.84
8	4.08	14.4	19.4	1.1506	34028	6.08
9	4.56	15.4	19.2	1.1792	37965	5.34
10	4.98	18.0	18.3	1.2207	41463	5.42
11	5.39	20.4	18.1	1.2516	44895	5.38
12	5.65	21.9	17.9	1.2819	47052	5.40
13	5.68	22.8	17.8	1.2837	47314	5.56
14	5.21	19.3	18.1	1.2427	43413	5.40
15	4.57	16.1	18.9	1.1880	38073	5.58
16	4.00	13.0	19.4	1.1447	33316	5.68
17	3.26	9.3	19.4	1.0944	27178	5.84
18	2.22	4.9	19.6	1.0445	18494	6.34
19	1.60	2.9	19.7	1.0214	13278	7.10
20	1.14	1.6	19.7	1.0088	9534	7.54

TABLE 2

Pressure Drop Data and Calculations; Rippled Tube, Compressed Air

No	V_{atm} (l/s)	Δh (cm H_2O)	T (^oC)	p (bar)	Re	$f \times 10^3$	e^+	ϕ
1	0.63	1.5	20.0	1.0001	5540	20.2	7.1	4.55
2	1.05	4.8	20.0	1.0083	9206	23.6	12.9	3.81
3	1.56	11.1	20.0	1.0238	13700	25.1	19.8	3.53
4	1.95	17.6	20.0	1.0396	17161	25.8	25.1	3.41
5	2.33	25.0	19.7	1.0567	20478	26.1	30.1	3.36
6	2.64	32.4	19.4	1.0740	23204	26.8	34.6	3.25
7	2.94	39.0	19.4	1.0902	25636	26.8	38.2	3.24
8	3.15	45.2	19.4	1.1056	27698	27.0	41.5	3.21
9	3.39	51.7	19.4	1.1214	29758	27.0	44.7	3.23
10	3.60	58.5	19.4	1.1378	31602	27.5	47.7	3.14
11	4.05	71.4	19.2	1.1716	35575	27.2	53.4	3.18
12	4.42	84.0	18.9	1.2047	38817	27.7	58.8	3.10
13	4.80	96.0	18.3	1.2375	42136	27.6	63.8	3.12
14	4.25	77.9	19.2	1.1870	37349	27.3	56.3	3.16
15	5.06	106.8	18.3	1.2638	45304	27.3	68.1	3.20
16	4.63	90.4	18.3	1.2210	40658	27.5	61.4	3.13
17	3.82	65.4	19.2	1.1546	33515	27.7	50.8	3.10
18	3.03	42.5	19.4	1.0985	26591	27.4	40.0	3.15
19	2.77	35.3	19.4	1.0817	24309	26.8	36.2	3.25
20	2.46	28.3	19.4	1.0647	21584	26.8	32.2	3.24
21	2.15	21.6	19.4	1.0487	18854	26.4	27.9	3.31
22	1.79	14.9	19.4	1.0325	15689	26.9	23.0	3.39
23	1.32	8.0	19.4	1.0160	11567	25.1	16.7	3.52
24	0.94	3.7	19.2	1.0057	8268	22.7	11.3	3.99

TABLE 3

Pressure Drop Data and Calculations; Smooth Tube, Demineralised Water, Hot and Cold Conditions

No	W (kg/s)	Δh (cm H_2O)	T (°C)	Re	$f \times 10^3$
1	0.220	40.9	21	28000	6.34
2	0.267	57.5	21	34030	6.04
3	0.309	73.3	21.2	39470	5.77
4	0.365	96.1	21.2	46680	5.41
5	0.368	97.8	23	48980	5.43
6	0.400	112.9	23.2	53530	5.29
7	0.420	126.3	23.4	56480	5.37
8	0.500	167.5	24	67770	5.08
9	0.592	232.0	24	80600	4.97
10	0.649	268.2	24.5	89450	4.77
11	0.547	199.3	24.5	75250	5.00
12	0.476	147.5	25.0	6632	4.87
13	0.339	86.0	25.0	47220	5.61
14	0.162	25.0	26.0	23020	5.18
15	0.063	4.8	25.5	8801	9.22
1	0.704	265.7	52	163700	3.98
2	0.625	222.1	51.5	144100	4.22
3	0.585	202.0	51.5	134900	4.39
4	0.550	176.3	51.2	126100	4.34
5	0.500	150.3	51	113800	4.51
6	0.455	125.9	51	103900	4.53
7	0.359	83.7	51	81990	4.84
8	0.197	30.0	50.5	44650	5.96

TABLE 4

Pressure Drop Data and Calculations; Rippled Tube, Demineralised Water, Hot and Cold Conditions

No	W (kg/s)	Δh (cm H_2O)	T (^oC)	Re	f x 10^3	e^+	ϕ
1	0.171	129	37.5	33030	28.1	50.0	3.02
2	0.236	251	43.4	50890	28.6	77.7	2.95
3	0.222	223	44.5	48890	28.6	74.6	2.95
4	0.214	204	45.5	47850	28.2	72.6	3.00
5	0.196	172	46.2	42000	28.5	64.1	2.96
6	0.161	119	47.5	37390	28.9	57.4	2.90
7	0.134	83	48.0	31240	29.3	48.3	2.84
8	0.111	57	48.6	26250	29.1	40.4	2.87
9	0.097	44	49.5	23290	29.1	35.9	2.88
10	0.047	9	50	11360	25.7	16.4	3.41
11	0.141	88	52	35100	27.9	53.0	3.04
12	0.192	162	54	49620	27.6	74.4	3.10
13	0.208	189	55.2	54780	27.4	81.9	3.12
14	0.226	231	55	59280	28.4	90.3	2.97
15	0.065	18	54.5	16770	26.5	24.6	3.28
1	0.217	210	54	56070	28.0	84.7	3.03
2	0.260	284	56	69140	26.5	101.7	3.27
3	0.278	356	57	75140	29.0	115.6	2.88
4	0.284	367	59	79260	28.6	121.0	2.95
5	0.303	396	61	87110	27.1	129.5	3.17
6	0.263	328	62	76800	29.7	119.6	2.78
7	0.208	190	64	62380	27.7	93.7	3.08
8	0.161	108	67	50660	26.0	73.7	3.36

NOMENCLATURE

d : Tube diameter (cm)

e : Roughness height (mm)

e^+ : Dimensionless roughness height (= eu^*/ν)

f : Friction factor (= $\tau_w/\frac{1}{2}\rho u^2$)

Δh : Pressure drop (cm H_2O)

p : Absolute pressure (bar)

Δp : Pressure drop (N/m^2)

Re : Reynolds number (= ud/ν)

T : Temperature (^oC)

u : Bulk velocity (m/s)

u^* : Friction velocity (= $u\sqrt{f/2}$)

V_{atm} : Volumetric flowrate at atmospheric pressure (l/s)

W : Mass flowrate (kg/s)

ϕ : Friction function (= $\sqrt{\frac{2}{f}} + 2.5 \ln \frac{2e}{d} + 3.75$)

τ_w : Shear stress at wall (N/m^2)

ρ : Fluid density (kg/m^3)

ν : Kinematic viscosity (m^2/s)

REFERENCES

1. Bott, T R, Walker, R A, "Fouling in Heat Transfer Equipment", Chem Engr, No 251, 391-395, (Nov 1971).

2. Robertson, J M, Martin, D J, Burkhart, T H, "Turbulent Flow in Rough Pipes", Ind Eng Chem Fundamentals, 7(2), 253-265, (May 1968).

3. Smith, J W, Epstein, N, "Effect of Wall Roughness on Convective Heat Transfer in Commercial Pipes", AIChE Journal, 3(2), 242-248, (June 1957).

4. Taborek, J, Aoki, T, Ritter, R B, Palen, JW, Knudsen, J G, "Fouling : The Major Unresolved Problem in Heat Transfer", Chem Eng Prog, 68(2), 59-67, (Feb 1972), "Predictive Methods for Fouling Behaviour", Chem Eng Prog, 68(7), 69-78, (July 1972).

5. Watkinson, A P, Martinez, O, "Scaling of Heat Exchanger Tubes by Calcium Carbonate", J Heat Transfer, 97(4), 504-508, (Nov 1975).

6. Walker, R A, "Fouling of Heat Exchanger Tubes", PhD Thesis, University of Birmingham, (1973).

7. Watkinson, A P, "Particulate Fouling of Sensible Heat Exchangers", PhD Thesis, University of British Columbia, (1968).

8. Watkinson, A P, Epstein, N, "Particulate Fouling of Sensible Heat Exchangers", 4th Int Heat Transfer Conf, Versailles, (Sept 1970).

9. Hopkins, R M, "Fouling of Heated Stainless Steel Tubes with Ferric Oxide from Flowing Water Suspensions", PhD Thesis, University of British Columbia, (1973).

10. Hopkins, R M, Epstein, N, "Fouling of Heated Stainless Steel Tubes by a Flowing Suspension of Ferric Oxide in Water", 5th Int Heat Transfer Conf, 2, 180-184, Tokyo, (1974).

11. Thomas, D, "Experimentelle Untersuchung über die Ablagerung von suspendientem Magnetit bei Rohrströmungen in Dampferzeugern und über den Einfluss der Magnetitablagerungen auf den Wärmeübergang", Dr-Ing dissertation, Technischen Universität München, (1973).

12. Thomas, D, Grigull, U, "Experimental Investigation of the Deposition of Suspended Magnetite from the Fluid Flow in Steam Generating Boiler Tubes", Brennst-Wärme-Kraft, 26(3), 109-115, (1974), AERE Translation LB/G/407/21, (August 1974).

13. Bagnold, R A, "The Physics of Blown Sand and Desert Dunes", Methuen & Co, London, (1941).

14. Sharp, R T, "Wind Ripples", J Geol 71(5), 617-636, (1963).

15. Wilson, I, "Sand Waves", New Scientist, 53(788), 634-637, (1972).

16. Cook, R U, Warren, A, "Geomorphology in Deserts", B T Batsford Ltd, London, (1973).

17. Ellwood, J M, Evans, P D, Wilson, I G, "Small Scale Aeolian Bedforms", J Sedimentary Petrology, 45 (2), 554-561, (June 1975).

18. Allen, J R L, "Current Ripples", North-Holland Publishing Co, Amsterdam, (1968).

19. Allen, J R L, "On the Geometry of Current Ripples in Relation to Stability of Fluid Flow", Geografiska Annaler, 51, 61-96, (1969).

20. Allen, J R L, "Bed Forms Due to Mass Transfer in Turbulent Flows : A Kaleidoscope of Phenomena", J Fluid Mech, 49 (1), 49-63, (1971).

21. Kennedy, J F, "The Mechanics of Dunes and Antidunes in Erodible-Bed Channels", J Fluid Mech, 16 (4), 521-544, (1963).

22. Raudkivi, A J, "Bed Forms in Alluvial Channels", J Fluid Mech, 26 (3), 507-514, (1966).

23. Simons, D B, Richardson, E V, Nordin, C F, "Sedimentary Structures Generated by Flow in Alluvial Channels", in "River Morphology", edited by S A Schumm, Published by Dowden, Hutchinson and Ross Inc, Stroudsburgh, Pennsylvania, (1972).

24. Schlichting, H, "Boundary-Layer Theory", McGraw-Hill, (1968).

25. Baumann, W, Rehme, K, "Friction Correlations for Rectangular Roughnesses", Int J Heat Mass Transfer, 18 (10), 1189-1197, (1975).

26. Haller, K H, Mravich, N J, Seifert, J W, "Nature and Behaviour of Corrosion Products in Once-Through Boilers", Mat Prot Perf, 10 (8), 27-31, (August 1971).

27. Haller, K H, Lee, R A, Slotnik, J S, "Heat Transfer and Friction Characteristics of Porous Magnetite Layers in Once-Through Boilers", ASME Paper No 71-WA/HT-45, (1971).

28. Webb, R L, Eckert, E R G, Goldstein, R J, "Heat Transfer and Friction in Tubes with Repeated-Rib Roughness", Int J Heat Mass Transfer, 14, 601-617, (1971).

29. Wilkie, D, "Forced Convection Heat Transfer from Surfaces Roughened by Transverse Ribs", 3rd Int Heat Transfer Conf, Chicago, (1966).

30. Lewis, M J, "an Elementary Analysis for Predicting the Momentum- and Heat-Transfer Characteristics of a Hydraulically Rough Surface", J Heat Transfer, 97 (2), 249-254, (May 1975).

31. Wiederhold, V W, "Über den Einfluss von Rohrablagerungen auf den hydraulischen Druchabfall", Gas-u Wasserfach, 90 (24), 634-641, (December 1949).

32. Seiferth, R, Krüger, W, "Überraschend hohe Reibungsziffer einer Fernuasserleitung", VDI-Zeitschrift, 92 (8), 189-191, (März 1950)

G. Gudmundsson, J S, Newson, I H, Bott T R, "Rippled Deposits : Formation and Pressure Drop Effects", AERE-R 8703, (March 1977).

H. Bott, T R, Gudmundsson, J S, "Rippled Silica Deposits in Heat Exchanger Tubes", 6th Int Heat Transfer Conference, Toronto, (1978).

I. Gudmundsson, J S, "A Review of Rippled Magnetite Deposits in Supercritical Once-Through Boilers", AERE-R 8738, (April 1977).