

PART I

HEAT TRANSFER FOULING

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1. INTRODUCTION

In industry, fouling of heat transfer surfaces has always been a recognised phenomena, although poorly understood(1,2,3). By many, fouling is considered the single most unknown factor in the design of heat exchangers(4,5). This situation exists despite the wealth of operating experience accumulated over the years and almost certainly reflects the complex nature of the phenomena in fouling problems. The vast range of process streams and conditions in industry appear to make most fouling situations unique, rendering comprehensive understanding difficult. Fouling has been described as the major unresolved problem in heat transfer(6,7,8).

Heat transfer fouling may be defined as the accumulation and formation of undesirable substances on heat transfer surfaces. It is more than a special case of deposition because it can include the effects of metal corrosion and biological growth on the performance of transfer surfaces.

Fouling affects both capital and operating costs of heat exchangers. The heat transfer area A of an exchanger can be determined from a relation of the form:

$$A = \frac{Q}{\Delta T} (R_i + R_w + R_o + R_{fi} + R_{fo}) \quad \dots (1)$$

The rate of heat transfer Q and the temperature difference are usually specified. The heat transfer resistances R_i (inside tube) and R_o (outside tube) are obtained from design correlations but R_w (tube wall) from the thermal conductivity of the tube material and its thickness. The fouling resistances inside R_{fi} and outside R_{fo} a tube wall account for the fouling and roughness of transfer surfaces(3). Fouling resistances depend on such process variables as velocity, concentration, temperature and time. When designing heat exchangers, however, fouling resistances are always assumed independent of time, with only minor contributions from other variables. These are the widely used fouling factors(9,10) that are based on previous experience and act as designers' safety factors. The extra surface area required due to fouling, in the design of heat exchangers, can be quite substantial(11,12). For a typical water/water heat exchanger, and using recommended(9) fouling factors, the heat transfer area may increase by 100 per cent(12). The effects of fouling, on capital costs, are therefore clear. Fouling increases operating costs of exchangers because;

pressure drops may increase, greater temperature differences may be required to maintain the same duty, shut-down and cleaning costs become excessive.

Heat transfer fouling involves simultaneous heat, mass and momentum transfer with chemical and biological processes also taking place. Although the literature on fouling is found in a wide variety of journals, the subject appears to fall into the discipline of chemical engineering.

Detailed reviews of heat transfer fouling are few and far between. In 1958 Badger and Banchemo⁽¹³⁾ reviewed scaling in desalination. In 1968 Watkinson⁽¹⁴⁾ reviewed the subject of fouling briefly. In 1969 Bott⁽¹⁵⁾ reviewed in detail the fouling of heat exchange equipment with special reference to cooling water systems. In 1971 Bott⁽¹⁶⁾ also reviewed gas side fouling in heat exchange systems; air-cooled heat exchangers and oil-fired heaters. In 1971 Bott and Walker⁽³⁾ discussed fouling in heat transfer equipment in general. In 1972 Taborek et al^(6,7) considered fouling in cooling water systems and mentioned the other main types of fouling.

In 1973 Hopkins⁽¹⁷⁾ and Walker⁽¹⁸⁾ reviewed fouling in general. In 1975 Bott⁽¹⁹⁾ surveyed heat transfer fouling. In 1976 Sutor et al⁽²⁰⁾ reviewed the history and status of research in fouling of heat exchangers in cooling water service.

2. CLASSIFICATION

2.1 Introduction

Most heat transfer processes at solid surfaces are subjected to fouling in one way or another. Moreover, numerous processes result in the accumulation and formation of materials at surfaces, without heat transfer even taking place. For example, particle suspensions and supersaturated solutions may result in deposition on unheated surfaces. The terms fouling and deposition are therefore used interchangeably in many instances. Fouling, as defined above, refers to the accumulation and formation of substances that affect the thermal performance of surfaces. Although the deposition of materials at unheated surfaces does not strictly constitute fouling, the basic accumulation processes in many cases, must be essentially the same.

Because fouling is such a complex phenomenon, it must be worth while to attempt some classification, to identify areas of concern and stimulate further experimental studies. This was recognised by Bott and Walker⁽³⁾ and Taborek et al⁽⁶⁾ that listed some broad categories of fouling and mentioned the main variables. An important consideration must also be the field of activity or industry, where deposition and fouling occur.

2.2 Types of Fouling

One factor that is important in fouling, is the mode of heat transfer; involving sensible or latent heats. Fouling by a single phase fluid is likely to differ from that of a boiling one. However, for the present purposes, fouling at boiling and non-boiling surfaces will be considered together. It should be appreciated that most real deposits contain foulants arising from several sources; solubility, particulate, reaction etc. Nevertheless, it is convenient to distinguish between the following main types:

Solubility fouling occurs when a substance comes out of solution due to heating or cooling. The deposition of inverse solubility inorganic salts on heated surfaces, usually called 'scaling', belongs to this type of fouling. Scaling is common in boilers⁽²¹⁾, cooling water systems^(6,7,20,22-27,38), desalination processes⁽²⁸⁻³⁷⁾ and oil well operations⁽³⁹⁻⁴⁴⁾. Substances investigated include calcium carbonate^(6,7,27,32,45-48), calcium sulphate⁽⁴⁹⁻⁵⁴⁾ and magnesium hydroxide⁽³²⁾. Inorganic substances with normal solubility deposit on cooled surfaces; silica in geothermal waters is such a system⁽⁵⁵⁻⁵⁸⁾. Paraffin waxes in crude oils and hydrocarbon solvents also display normal

solubility and give rise to both deposition and fouling problems(18,59-72). Methods to reduce fouling are both chemical and mechanical in nature(73-80).

Particulate fouling is where particles suspended in liquids or gases deposit out and adhere to surfaces. Considerable work has been done on aerosol deposition on unheated surfaces(81-85). Studies at heated surfaces have also been performed(86,87,88). The deposition and fouling of particulate corrosion products in boiler waters and reactor coolants have been extensively studied(89-94). Particulate fouling systems studied include sand-water suspensions(14,95), particles in gas oils(14,96), hematite in water(17,97), and some desalination systems(98-100,128). Particulate deposition includes sedimentation.

Reaction fouling occurs when a chemical reaction (transformation) occurs at heat transfer surfaces and form deposits. Coking, the thermal decomposition of heavy hydrocarbons, occurs widely in industry(101-106). Reaction fouling is common in the petroleum industry(1,10,108,109). Freons are known to form deposits by thermal decomposition in pool boiling(110).

Biological fouling is when organisms grown at heat transfer surfaces. This type of fouling is common in cooling water systems(111-114).

Corrosion fouling occurs when heat transfer surfaces corrode and change their thermal characteristics.

2.3 Variables

The main variables that affect deposition and fouling have been discussed by several authors(3,6,7,18,20). The most general observation is that fouling of heat exchangers increases with time, usually in an asymptotic fashion. In most of the published studies, fouling is directly proportional to foulant concentration. However, the strength of cooling water deposits has been shown to decrease with decreasing deposit purity(27). The effects of temperature in deposition and fouling depend greatly on the type of fouling occurring. In solubility fouling, for example, the temperature difference between bulk and surface result in the concentration driving force causing deposition(47,115). Temperature often enters deposition rates in an Arrhenius-type expression(6,7,14,27,95).

Fluid velocity is probably the most important variable when studying deposition

and fouling. It effects both the convective transport of foulants toward surfaces and the shear stresses which deposits are subjected to. The overall effect is therefore complex as will be indicated in Section 3 below. Other variables of interest include heat flux, tube diameter and surface roughness, particle diameter, fluid and foulant chemistry and the usual physical properties.

2.4 Industries of Interest

Since fouling occurs in so many industries (probably all process industries) it is perhaps relevant to consider the main fields of activity where the phenomena may act as a constraint on the central process. Deposition and fouling occur in the following main fields: Power generation where high quality feed waters give rise to fouling when subjected to high temperature conditions. Combustion products may also cause fouling. Desalination, where raw or treated sea-waters give rise to fouling at most conditions. Petroleum industry, where deposition occurs in flowlines and fouling in the various hydrocarbon processes. Cooling service, as practiced in almost every industry. Raw and treated cooling waters are used extensively and give rise to fouling at normal operating conditions. Air cooled exchangers may give rise to particulate fouling.

In recent years energy conservation has become more and more important in industry⁽¹¹⁶⁻¹¹⁷⁾. One way of conserving energy is to exchange heat between process streams; hot reject heats cold inlet. Various wastes may also be combusted to extract energy. However, many energy conservation measures may be subject to fouling. Fouling may also put a constraint on alternative energy sources. Geothermal fluids contain considerable amounts of silica that deposit on cold surfaces during heat extraction⁽⁵⁸⁾. The extraction of energy from ocean thermal gradients could be limited by sea-water fouling⁽¹¹⁸⁾. The main fouling effects in industry; pressure drop increases and greater temperature differences required for some duty, will in some cases also result in increased use of energy. Therefore, fouling must be an important constraint on energy conservation.

In the dairy industry fouling in milk treatment processes is of great practical importance⁽¹¹⁹⁾.

3. PREVIOUS STUDIES

3.1 Introduction

In the present section, only those studies dealing specifically with heat transfer fouling will be considered. Non-fouling studies such as aerosol deposition, are better considered separately. Previous studies on heat transfer fouling will be considered in two groups; deposition-release studies and general studies. The former group deals with heat transfer fouling where the foulant build-up may be represented by a simple mass balance in the form of two functions; deposition and release. The general studies group deals with the remaining situations.

The deposition-release approach has met with some success in predicting heat transfer fouling. This success seems to argue for further developments of suitable models.

3.2 Deposition-release

Kern and Seaton⁽¹²⁰⁾ observed that the fouling resistance of many heat exchangers in oil refineries appeared to increase asymptotically with time. They suggested that the time dependence of the fouling resistance could be approximated by the empirical expression:

$$R_f = R_f^* [1 - \exp(-\beta t)] \quad \dots (2)$$

where R_f and R_f^* were the fouling resistances at any time t and at asymptotic conditions $t \rightarrow \infty$, respectively, and β a constant. No experimental data were presented but it was stated that the fluid velocity was an important variable effecting fouling.

Kern and Seaton⁽¹²⁰⁾ proposed a theoretical fouling model where the net rate of fouling was expressed as the difference between the rate of deposition and the rate of release. The model was essentially a mass balance expression:

$$\frac{dx}{dt} = k_1 c W - k_2 x \tau \quad \dots (3)$$

where: k_1 = deposition coefficient
 k_2 = release coefficient
 x = deposit thickness

- c = foulant concentration
 W = mass flowrate
 τ = shear stress at wall

By assuming c and W constant and $x \ll d$ (tube diameter), Kern and Seaton were able to integrate Equation 3 and obtained an expression that gave the deposit thickness as a function of time:

$$x = \frac{k_1 c W}{k_2 \tau} [1 - \exp(-k_2 \tau t)] \quad \dots (4)$$

This expression is of the same general form as Equation ~~3~~².

The initial rate of deposition and the asymptotic fouling resistance were obtained by putting $x = 0$ and $(dx/dt) = 0$ in Equation 3, respectively.

$$\left(\frac{dx}{dt}\right)_{t=0} = k_1 c W \quad \dots (5)$$

$$x^* = \frac{k_1 c W}{k_2 \tau} \quad \dots (6)$$

Kern and Seaton⁽¹²⁰⁾ showed that when the deposit thickness x was significant in relation to tube diameter d , Equation 3 is not directly integrable. Kern⁽¹²¹⁾ has derived the appropriate solution of the deposition-release expression for the case of constant pressure drop and concentration but variable mass flowrate.

Watkinson⁽¹⁴⁾ studied the fouling of a heated stainless steel tube by a heavy gas oil⁽⁹⁶⁾ and a sand-water suspension⁽⁹⁵⁾. The main purpose of the experiments was to investigate the effect of mass flowrate W on fouling. Watkinson⁽¹⁴⁾ found that, at the experimental conditions given in Table 1, the heated tube fouled in an asymptotic fashion. The fouling resistance was correlated to Equation 2, and in Table 2 the main relationships are given. The heat flux was not specified. Additional experiments were carried out to investigate the effect of tube wall temperature on gas oil fouling at constant mass flow conditions. The initial rate of deposition was correlated to temperature by an Arrhenius-type expression. The effect of flowrate on sand-water fouling was found to be more complex than indicated in Table 2. When $W > 0.136$ kg/s, both β and $(dR_f/dt)_{t=0}$ were found to decrease drastically with flowrate. This critical flowrate was equivalent to bulk velocity 2.29 m/s and mass flux

2341 kg/m²s. However, R_f^* showed the same flowrate dependence at all values.

TABLE 1

Experimental Conditions(14,95,96)

Property	Gas Oil	Sand-water
c (mg/kg)	~15	~5
\bar{T}_i (°C)	100	60
\bar{T}_w (°C)	146	77
W (kg/s)	0.081 - 0.353	0.067 - 0.248
t_{max} (h)	390	132
d (mm)	8.6	8.6
d_p (µm)	~50	~15

TABLE 2

Experimental Relationships(14,95,96)

Term	Gas Oil	Sand-water
β	W	$W^{1.9}$
$\left(\frac{dR_f}{dt}\right)_{t=0}$	W^{-1}	$W^{0.92}$
R_f^*	W^{-2}	$W^{-1.2}$

Watkinson⁽¹⁴⁾ developed a new deposition-release model in an attempt to rationalize the experimental results. The following model was proposed:

$$\frac{dx}{dt} = k_1 sN - k_2 x\tau \quad \dots (7)$$

where the deposition function includes particle stickability s and mass flux towards the wall N. Other symbols as before. The release function is that of Kern and Seaton^(120,121). The terms in the deposition function were expressed by:

$$s = \frac{k_3 \exp(-E/R_g T_w)}{f u^2} \quad \dots (8)$$

$$N = h (c_b - c_w) \quad \dots (9)$$

$$h = \frac{u \sqrt{\frac{f}{2}}}{12 Sc^{\frac{2}{3}}} \quad \dots (10)$$

- where:
- k_3 = constant
 - E = activation energy
 - R_g = universal gas constant
 - T_w = tube wall temperature
 - f = friction factor
 - u = fluid bulk velocity
 - h = mass transfer coefficient
 - c_b = foulant bulk concentration
 - c_w = foulant wall concentration
 - Sc = foulant Schmidt number

Watkinson⁽¹⁴⁾ assumed $x \ll d$ and derived a general expression that gave the deposit thickness x as a function of time. Two limiting cases were considered; mass transfer controlled and adhesion controlled. In the former $s \sim 1$ and $c_w \sim 0$ such that:

$$x = \frac{k_1 u \sqrt{\frac{f}{2}} c_b}{k_4 12 Sc^{\frac{2}{3}} f u^2} \left[1 - \exp(-k_4 f u^2 t) \right] \quad \dots (11)$$

where $k_2 \tau$ in the release function has been replaced by $k_4 f u^2$. In the latter, the deposition process was controlled by the chemistry of adhesion and:

$$x = \frac{k_5 \exp(-E/R_g T_w)}{k_4 f u^2} \left[1 - \exp(-k_4 f u^2 t) \right] \quad \dots (12)$$

where k_5 is a concentration dependent coefficient. Table 3 shows how the main

relationships depend on the fluid bulk velocity. The corresponding relationships from the Kern-Seaton model are also given. The sand-water fouling was therefore mass transfer controlled and the gas oil fouling more adhesion controlled. Watkinson⁽¹⁴⁾ has also developed deposition-release expressions where deposit thickness was sufficient to affect fouling.

TABLE 3
Model Relationships^(14,95,96,120,121)

Term	Kern-Seaton	Mass transfer	Adhesion
β	fu^2	fu^2	fu^2
$\left(\frac{dR_f}{dt}\right)_{t=0}$	u	$\sqrt{f} u$	-
R_f^*	$(fu)^{-1}$	$(\sqrt{f}u)^{-1}$	$(fu^2)^{-1}$

Charlesworth⁽⁸⁹⁾ studied the deposition of particulate corrosion products in a boiling water reactor. It was suggested that a modified Kern-Seaton expression might describe the build-up of corrosion products on heated and unheated surfaces.

$$\frac{dw}{dt} = k_1 c - k_2 w \quad \dots (13)$$

where w was the weight of deposit per unit area and other symbols as before. In this model fluid velocity does not affect the deposit build-up.

Taborek et al^(6,7) performed extensive and systematic experimental work on pure inverse solubility salt solutions and a variety of cooling waters. A deposition-release model was developed for fouling by treated cooling tower water with low suspended solids content. The model described mixed crystallisation fouling of inverse solubility salts. The main solid depositing was calcium carbonate. The following deposition-release expression was proposed:

$$\frac{dR_f}{dt} = k_1 s \lambda^n \exp(-E/R_g T_s) - k_2 \frac{\tau}{\delta} x^m \quad \dots (14)$$

where: s = stickability
 λ = water characterization factor
 n = exponent
 T_s = deposit surface temperature
 δ = deposit characterization factor
 m = exponent

No practical experimental data were given nor any values of the various terms involved in the deposition and release functions. The foulant concentration was characterised by λ the Langelier saturation index and the stickability was determined empirically as:

$$s = k_3 \exp(-u^{\frac{2}{3}}) \quad \dots (15)$$

The deposit structure was assumed to depend on the fluid velocity such that:

$$\frac{\tau}{\delta} = k_4 u^a \quad \dots (16)$$

where the exponent $a < 2$. The fouling resistance against time was given by:

$$R_f = \frac{k_1 k_3 \lambda^n \exp\left(\frac{-E}{R_g T_s} - u^{\frac{2}{3}}\right)}{k_2 k_4 u^b} \left[1 - \exp(-k_2 k_4 u^b t) \right] \quad \dots (17)$$

where the exponent $b < 2$. According to this model the dependence of β , $(dR_f/dt)_{t=0}$ and R_f^* on fluid velocity are more complex than in previous models. The exponent m was assumed unity when correlating the model to experimental data.

Watkinson and Martinez⁽⁴⁷⁾ have studied the fouling of a constant wall temperature exchanger by a synthetic calcium carbonate solution. The variables investigated were fluid velocity, bulk temperature and tube diameter. The water contained 3000 mg/kg dissolved solids and 400 mg/kg particulate matter. It was established that calcium carbonate deposited from solution. In the experiments investigating the effects of velocity and diameter, the bulk inlet temperature was 57°C and the tube wall temperature 103°C. Asymptotic conditions were reached in less than 5 hours, during which the deposit surface temperature

decreased 15°C typically. Experimental data at constant bulk and wall temperature for $Re < 12000$ were correlated to the asymptotic fouling resistance by:

$$R_f^* \propto d^{-0.23} u^{-1.33} \quad \dots (18)$$

Watkinson and Martinez⁽⁴⁷⁾ developed a deposition-release model where the deposition function was written in terms of inverse solubility salt crystallization while the release function was as in the Kern-Seaton model.

$$\frac{dx}{dt} = k_1 (c_b - c_s)^n - k_2 x \tau \quad \dots (19)$$

The constant k_1 was a crystallization rate constant and n an exponent. Foulant concentration in bulk and at deposit surface were given by c_b and c_s , respectively. It was assumed that the solubility of calcium carbonate was linear with temperature:

$$c_b - c_s = k_3 (T_s - T_b) \quad \dots (20)$$

and the heat transfer situation that of a steam condenser such that:

$$R_i \gg R_w + R_o \quad \dots (21)$$

This meant that:

$$T_s - T_b = \frac{T_w - T_b}{1 + R_f/R_i} \quad \dots (22)$$

where T_s , T_b and T_w refer to the temperature at deposit surface, fluid bulk and tube metal wall, respectively.

The crystallization rate constant was given by:

$$k_1 = k_4 \exp(-E/R_g T_s) \quad \dots (23)$$

The following deposition-release model resulted.

$$\frac{dx}{dt} = k_4 (k_3 \alpha)^n \exp\left(\frac{-E/R_g}{T_b + \alpha}\right) - k_2 x \tau \quad \dots (24)$$

where:

$$\alpha = \frac{T_w - T_b}{1 + R_f/R_i} \quad \dots (25)$$

The deposition-release model was not integrated, but an expression for the asymptotic fouling resistance R_f^* was given and used to compare the experimental data to the model. It was found that the model correlated the data well when $n = 2$.

3.3 General

Experimental studies into heat transfer fouling not specifically dealt with elsewhere in the Thesis, will be considered briefly in the present section.

McCabe and Robinson⁽¹²²⁾ proposed that the amount of scale formed in evaporators was proportional to the amount of liquid evaporated. It was assumed that the temperature difference $\Delta T = T_w - T_b$ remained constant with time. The following equation gives the overall heat transfer resistance with time:

$$R^2 = R_c^2 + k_1 A \Delta T t \quad \dots (26)$$

where R_c is the overall heat transfer resistance at clean conditions and k_1 a constant. This equation has been verified for evaporator scaling.

Hasson⁽¹²³⁾ has developed an expression for heat exchanger scaling. The expression correlated calcium carbonate deposition data at low fluid velocities where no deposit release occurred. Reitzer⁽¹¹⁵⁾ has derived a similar expression.

Reitzer⁽¹¹⁵⁾ assumed that heat exchanger scaling depended on the foulant supersaturation, raised to the power n . At constant $\Delta T = T_s - T_b$ the overall heat transfer resistance was given by:

$$R^{n+1} = R_c^{n+1} + (n + 1) \left(\frac{k_1}{k_2 \rho} \right) \left(\frac{k_3 \Delta T}{h_i} \right) t \quad \dots (27)$$

and at constant heat flux conditions:

$$R = R_c + \left(\frac{k_1}{k_2 \rho} \right) \left(\frac{k_3 q}{h_i} \right)^n t \quad \dots (28)$$

where: k_1 = diffusion-reaction coefficient
 k_2 = deposit thermal conductivity
 k_3 = constant
 ρ = deposit density
 h_i = inside heat transfer coefficient

Gonionskiy et al⁽¹²⁴⁾ have discussed the above relationships and developed an expression for the overall heat transfer resistance with time. The scaling process was assumed to depend on the average fluid temperature in the boundary layer. Calcium sulphate deposition data was correlated by the derived expression.

Hasson et al⁽⁴⁵⁾ studied the formation of calcium carbonate scales in a constant heat flux exchanger. Experiments were performed at Reynolds number 13000 to 42000. Deposition increased linearly with time. It was found that the rate of deposition was diffusion controlled and that:

$$\frac{dw}{dt} \propto Re^{0.68} \quad \dots (29)$$

Hasson and Zahavi⁽⁵¹⁾ studied the deposition of calcium sulphate on heated surfaces. It was found that deposition was greatest at the downstream end of the exchanger, decreasing rapidly toward the upstream region.

Palen and Westwater⁽⁵³⁾ studied calcium sulphate deposition in a pool boiler and found it proportional to the heat flux squared. Galloway⁽¹¹⁾ has studied the formation of inorganic scales by an electrochemical method and obtained an expression for the dimensionless deposit thickness with time. Walker and Bott⁽¹²⁵⁾ have applied curve fitting methods to fouling data. Konak⁽¹²⁶⁾ has discussed the prediction of fouling curves in heat transfer equipment. Fisher et al⁽¹²⁷⁾ have discussed some techniques used to measure fouling. Morse and Knudsen⁽²⁷⁾ studied the effect of alkalinity on the scaling of simulated cooling tower water. Fouling increased asymptotically with time and was greater at high alkalinity values. Deposit strength was found to be a function of the non-calcium carbonate components.

Hopkins(17) and Hopkins and Epstein(97) investigated the fouling of heated stainless steel tubes by ferric oxide in water. The experimental conditions were as follows:

concentration 15-3750 mg/kg
Reynolds number 10100 - 37600
heat flux 0-292 kw/m²
average bulk temperature 60⁰C
tube wall temperature 60-90⁰C
tube internal diameter 8.71 mm
pH 6.2

The ferric oxide (hematite) consisted of ~0.2 μm fundamental particles that agglomerated into particles > 10 μm in diameter. No measurable fouling occurred at concentrations c<750 mg/kg and reproducible results were obtained only if c>1750 mg/kg. Most runs were performed at a standard concentration of 2130 mg/kg. Fouling increased with concentration. The build-up of deposits was asymptotic and reached steady conditions in 2-4 hours. The following relationships were derived:

$$R_f^* \propto W^{-0.9} \quad \dots (30)$$

$$\left(\frac{dR_f}{dt} \right)_{t=0} \propto W^{0.3} \quad \dots (31)$$

It was found that deposition decreased with heat flux; deposition was greatest at zero heat flux conditions. It was suggested that thermophoresis might play an important role in the deposition process. A hypothesis was presented according to which the fouling behaviour is controlled by the rate at which crevice corrosion of the stainless steel occurs.

NOMENCLATURE

A	:	Heat transfer area (m^2)
a	:	Exponent
b	:	Exponent
c	:	Foulant concentration (mg/kg)
D	:	Diffusivity of particulate foulant (m^2/s)
d	:	Tube diameter (m or mm)
d_p	:	Particle diameter (m or μm)
E	:	Activation energy (kJ)
f	:	Friction factor ($= \tau / \frac{1}{2} \rho u^2$)
h	:	Heat transfer coefficient ($kW/m^2 \text{ } ^\circ C$)
k	:	Constants and coefficients
m	:	Exponent
N	:	Mass flux ($kg/m^2 s$)
n	:	Exponent
Q	:	Rate of heat transfer (kW)
q	:	Heat flux (kW/m^2)
R	:	Heat transfer resistance ($kW/m^2 \text{ } ^\circ C$) ⁻¹
R_f	:	Fouling resistance ($kW/m^2 \text{ } ^\circ C$) ⁻¹
R_g	:	Universal gas constant ($= 8.3143 \text{ J/mole } ^\circ K$)
Re	:	Reynolds number ($= ud/\nu$)
s	:	Stickability
Sc	:	Schmidt number of particulate foulant ($= \nu/D$)
T	:	Temperature ($^\circ C$ or $^\circ K$)
t	:	Time (s)
ΔT	:	Temperature difference ($^\circ C$)
u	:	Fluid bulk velocity (m/s)
W	:	Mass flowrate (kg/s)
w	:	Weight of deposit (mg/cm^2)
x	:	Deposit thickness (mm or μm)

α	:	Heat transfer factor ($^{\circ}\text{C}$)
β	:	Constant
δ	:	Deposit characterization factor
λ	:	Water characterization factor
ν	:	Kinematic viscosity (m^2/s)
ρ	:	Fluid density (kg/m^3)
τ	:	Shear stress at wall (N/m^2)

Subscripts

b	:	Bulk
c	:	Clean
i	:	Inside
o	:	Outside
s	:	Surface
w	:	Wall

Superscript

*	:	Asymptotic
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PART II
PARAFFIN WAX DEPOSITION
AND FOULING