Fouling and Fouling Mitigation on Heat Exchanger Surfaces

S. N. Kazi

Department of Mechanical and Materials Engineering,
Faculty of Engineering,
University of Malaya, Kuala Lumpur,
Malaysia

1. Introduction

Heating or cooling of one medium by another medium is performed in a heat exchanger along with heat dissipation from surfaces of the equipment. In course of time during operation, the equipment receives deposition (Fouling) which retards heat exchanging capability of the equipment along with enhanced pressure loss and extended pumping power. Thus accumulation of undesired substances on a surface is defined as fouling. Occurrence of fouling is observed in natural as well as synthetic systems. In the present context undesired deposits on the heat exchanger surfaces are referred to fouling. With the development of fouling the heat exchanger may deteriorate to the extent that it must be withdrawn from service for cleaning or replacement.

The overall design of heat exchanger may significantly be influenced by fouling, use of material, process parameters, and continuous service in the system or process stream are all deliberately influenced by fouling phenomena. Preventive measures of fouling are highly encouraged as it keeps the service of heat exchanger for a longer time. However many mitigation techniques of fouling are harsh to the environment. A technique involving chemicals and means benign to the environment is the most desired approach and it could elongate the cleaning interval. On the other hand unique and effective arrangements may be required to facilitate satisfactory performances between cleaning schedules. As a result fouling causes huge economic loss due to its impact on initial cost on heat exchanging operation, operating cost, mitigation measures and performance. The present study focused on fouling phenomena, fouling models, environment of fouling, consideration of heat exchanger fouling in design and mitigation of fouling.

2. Fouling

Fouling is the resultant effect of deposition and removal of deposits on a heat exchanger surface. The process of fouling could be represented by the equation (2.1).

$$\frac{dm_f}{dt} = \overset{\bullet}{m_d} - \overset{\bullet}{m_r} \tag{2.1}$$

where $\dot{dm}_f$, $\dot{m}_d$ and $\dot{m}_r$ are net deposition rates, deposition and removal rates respectively.
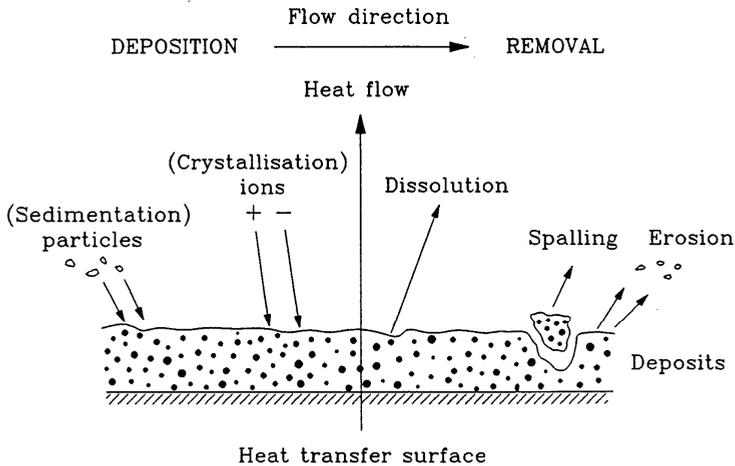

Fig. 2.1. Various deposition and removal processes during fouling.

Various deposition and removal processes for a typical system could be predicted as shown in Figure 2.1. The processes occur simultaneously and depend on the operating conditions. Usually removal rates increase with increasing amounts of deposit whereas deposition rates are independent of the amount of deposit but do depend on the changes caused by deposits such as increase in flow velocity and surface roughness. In the application of constant wall temperature or constant heat transfer coefficient boundary conditions, the interface temperature decreases as deposits build up which reduces the deposition rate.

Initiation period or time delay in heat exchanger fouling is considered the time when there is no deposition for some time after a clean heat exchanger has been brought into operation. Figure 2.2 illustrates this in detail. The initial growth of deposit can cause the heat transfer coefficient to increase rather than decrease resulting in a fouling resistance due to changing flow characteristics near the wall. At the initial stage the deposit penetrates the viscous sub-layer, the resulting turbulence increases the film heat transfer coefficient at the solid/liquid interface by changing flow characteristics near the wall. This increase in heat transfer coefficient may overcome the thermal resistance offered by the deposits and the net heat transfer coefficient may increase.

Several authors have reported negative fouling resistances [1, 2]. This process continues until the additional heat transfer resistance overcomes the advantage of increased turbulence. The time period from the beginning of the fouling process until the fouling resistance again becomes zero is called roughness delay time [3]. The time period from the beginning, when the formation of stable crystalline nuclei and their concretion to a compact fouling layer takes place is also called as induction period, which is in fact the roughness delay time and it ends up with the increase of fouling resistance above zero level.
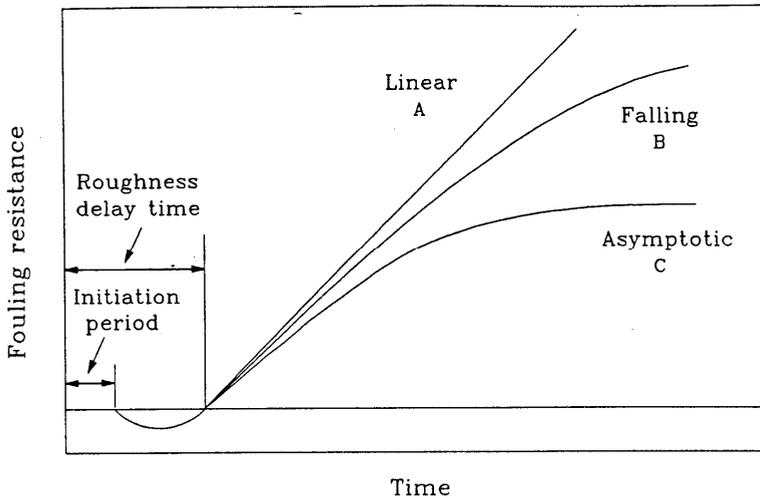
Fig. 2.2. Typical fouling curves.

The initiation period and the roughness delay time for particulate fouling are very small [4] in comparison to the fairly long delay time for crystallization fouling [5]. After the roughness delay time, the fouling curve can be classified into three categories, (a) Linear, (b) Falling, and asymptotic, as illustrated in Figure 2.2.

The linear fouling curve is obtained for very strong deposits where removal is negligible or in case where the removal rate is constant (and deposition is faster than removal). The falling rate curve is obtained from decrease in deposition and deposits with lower mechanical strength. The combined effect with time causes the net deposition or fouling rate to fall. Asymptotic fouling curve has been most commonly reported for different types of fouling. The removal rate increases with time for weak deposits and can eventually become equal to the deposition rate. The net rate is then zero as depicted in Figure 2.2.

Linear fouling curves have been presented by many authors for crystallization fouling [6-8]. However, there is some doubt as to whether the fouling rate may remain linear for a long time. For the constant heat flux situation, the net driving force may decrease with fouling. The increase in flow velocity due to the reduced cross-sectional area with deposit formation can increase the removal rate and the linear rate may change to a falling rate or even level-off completely [9]. Asymptotic behavior for crystallization fouling has reported by various authors [10, 5, 11-12]. Cooper et al. [13] found asymptotic behavior for calcium phosphate fouling (with some particulate fouling from suspended solids). For particulate fouling, asymptotic behavior is attained because particles do not adhere strongly to the wall and can be removed easily [4, 14].

A fouling process that follows a linear rate for constant heat flux can have falling or even asymptotic behaviour for constant temperature difference. The interface temperature decreases with deposit formation because of the extra resistance offered by deposit layer and enhanced flow velocities as flow passages are partially blocked by deposits. Thus the

thermal boundary conditions can result in different fouling curves which may give wrong impressions about the actual fouling mechanism.

2.1 Categories of fouling

Fouling can be categorised a number of different ways. These are (1) heat transfer service, (2) type of service fluid and (3) application. Most fouling situations are virtually unique. Fouling [15] can be classified into the following categories: (i) particulate, (ii) Precipitation, (iii) corrosion, (iv) biofouling and (v) chemical reaction.

2.2 Particulate fouling

Particulate fouling is evolved by the accumulation of solid particles suspended in the process stream onto the heat transfer surface. Heavy particles settle on a horizontal surface due to gravity and fine particles settle onto heat transfer surfaces at different inclinations due to suction force or other mechanisms. Unburned fuels or ashes deposition on boiler tubes, dust deposition on air cooled condensers etc. are examples of particulate fouling.

2.3 Precipitation fouling (sedimentation fouling)

This kind of fouling is also called crystallization fouling. Dissolved inorganic salts are normally present in fluid used in heat exchanger. There is a maximum amount of the salt (saturated) which can be dissolved in this fluid. During heating or cooling supersaturation occurs in the dissolved inorganic salts. The inverse solubility salts such as calcium and magnesium sulphate, carbonate, silicate, etc. have less solubility in warm water up to a certain temperature than in cold water. This may occur when the process condition inside the heat exchanger is different from condition at the entrance. A stream on a wall at a temperature above that of corresponding saturation temperature for the dissolved salts allows crystal formation on the surface. Normally crystallization starts at especially active points – nucleation sites – such as scratches and pits and often after induction period spread to cover the entire surface. This type of fouling is strong and adherent and requires vigorous mechanical or chemical treatment to be removed [16]. Fouling rate increases with the increase of salt concentration or surface temperature. These are often found in heat exchangers of process industries, boilers, evaporators etc.

2.4 Chemical reaction fouling

This type of fouling occurs when the depositions are formed as a result of chemical reaction resulting to produce a solid phase at or near the surface. In the present case carbonaceous material deposits due to thermal gradation of the components of a process stream on hot heat transfer surface. This type of fouling is often extremely tenacious and need special measure to clean off the deposits from heat exchanger surfaces to provide them satisfactory operation life [16].

2.5 Corrosion fouling

This type of fouling is also caused by some chemical reaction but it is different from chemical reaction fouling. This fouling is a reactant and it is consumed. In this case, the

surface reacts with the fluid and become corroded [15]. The corrosion products can foul the surface provided it is not dissolved in the solution after formation. pH value of the solution is one of the controlling parameter. Such as, presence of sulfur in fuel can cause corrosion in gas and oil fired boilers. Corrosion is often more prone in the liquid side of the heat exchanger. In some cases the product of corrosion may be swept away to downstream of a process loop and cause deposition on surfaces there.

2.6 Accumulation of biological fouling

On a heat transfer surface the growth of biological materials results in biofouling. In this case biological micro and macro organisms are stick to the heat transfer surface. When microorganisms (e.g., algae, bacteria, molds etc.) and their products grow they form microbial fouling. Seaweeds, waterweeds, barnacles develop microbial fouling. These fouling may occur simultaneously. The growth of attached organisms is one of the common problems [15] in heat exchanger operation. Food processing industries, power plant condensers using seawater, etc. are experiencing biofouling.

2.7 Fouling process

Fouling is a complex phenomenon due to involvement of a large number of variables. From a fundamental point of view the fouling mechanism follows certain stages in developing on a surface [17]. These are: Initiation, transport, attachment, removal and aging.

2.8 Initiation

Surface is conditioned in the initiation period. The initial delay induction period is influenced by the materials surface temperature, material, surface finish, roughness and surface coating. With the increase of degree of supersaturation with respect to the heat transfer surface temperature or increase of surface temperature the induction period decreases. During the induction period, nuclei for crystallization of deposit are also formed for biological growth. This period can take a long time, may be several weeks or a few minutes or even seconds.

The delay period decreases with increasing temperature in chemical reaction fouling due to the acceleration of induction reactions. If the initial period decreases with increasing surface temperature, crystallization fouling would be changed [18]. With the increase of surface roughness the delay period tends to decrease [19]. Additional sites are developed by the roughness projections, which promotes crystallization while grooves provide regions for particulate deposition.

2.9 Transport

In this part, fouling substances from the bulk fluid are transported to the heat transfer surface across the boundary layer. This is dependent on the physical properties of the system and concentration difference between the bulk and the surface fluid interface. Transport is accomplished by a number of phenomena including diffusion, sedimentation and thermophoresis [20, 21]. The local deposition flux $\overset{\bullet}{m}_d$ on a surface can be expressed by equation (2.1).

$$\dot{m}_d = h_D \left(C_b - C_s \right)$$

(2.1)

Where, C_b and C_s are reactant concentration in the bulk fluid and that in the fluid adjacent to the heat transfer surface where as h_D is the convective mass transfer coefficient. From Sherwood number ($Sh = h_D d / D$), h_D could be evaluated. Sherwood number is dependent on the flow and the geometric parameters.

The phenomenon of transportation of a particulate matter in a fluid due to gravity on a horizontal or inclined surface is known as sedimentation. This is playing a vital roll where particles are heavy and fluid velocities are low.

2.10 Attachment

At this stage, the deposits are adhered to the surface and among itself. Salt ions approaching to the surface are attracted to it due to electro-magnetic forces and adhere to the surface to form nucleation and gradually it grows with time to form a fouling layer. Thus forces acting on the particles as they approach the surface are impotent in determining attachment. Properties of the materials, such as size, density and surface conditions are dominating the attachment phenomenon.

2.11 Removal

There is competition between removal and deposition of the foulants, up to the steady growth of the deposition on the surface. Shear forces at the interface between the fluid and deposited fouling are responsible for removal. The velocity gradients at the surface, the viscosity of the fluid and surface roughness are guiding the shear forces. Removal from the surface is performed through the mechanism of dissolution, erosion and spalling.

2.12 Aging

With the commencement of deposition ageing starts. During the ageing, there may be transformation of crystal to improve or decrease the deposition strength with time. During aging the mechanical properties of the deposit can change due to changes in the crystal or chemical structure. Alteration of the chemical composition of the deposit by a chemical reaction may change its mechanical strength. On the other hand the biofouling layer may become weak due to corrosion at the surface by slow poisoning of microorganisms.

2.13 Change in deposition thickness with time

Figure 2.3 is showing the growth rate of deposit on the surface [15]. Region A: fouling is initiated in the induction period. Region B: a steady deposit growth on the surface. The rate of removal of deposit was increased when the rates of deposition gradually retards. Region C: in this region the rate of removal and deposition seems equal and the thickness of deposition remains constant.
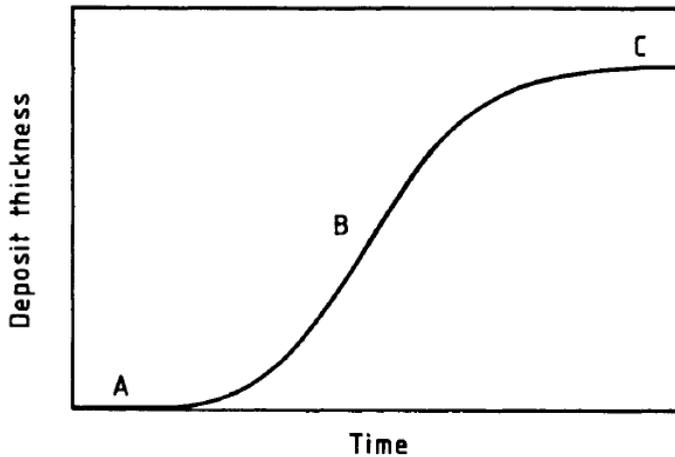
Fig. 2.3. Change in deposition thickness with time.

2.14 Composite fouling

Some of the common salts causes fouling are $CaSO_4$, $CaCO_3$ and $Mg(OH)_2$, and SiO_2. Solubility, crystal structure and strength have impact on composite scale formation in fouling. Therefore, composite fouling needs more attention and further research [17].

3. Effects of fouling

Fouling phenomena imposes retardation on heat transfer and augmentation of frictional pressure drop which degrades the effectiveness of a heat exchanger. Some basic design aspects of heat exchangers along with mitigation of fouling are discussed in the present chapter.

3.1 Effect of fouling on heat exchanger design

A fixed value of fouling resistance could be assigned during the design stage although fouling is time dependent phenomenon. The cleaning schedule and operating parameters of the heat exchanger is dependent on the design fouling factor. Depending on application some heat exchangers require frequent cleaning whereas some need rear cleaning. Fouling rate is a dominating factor in designing a particular heat exchanger.

Fouling allowance: Provisions are during the design stage once fouling is anticipated. Different approaches are used to provide an allowance for fouling resistance. They all result into an excess heat transfer surface area. Updated methods include, specifying the fouling resistances, the cleanliness factor, or the percentage over surface.

A fouling resistance is prescribed on each side of the surface where fouling is anticipated. A lower overall heat transfer coefficient is resulted. To achieve the specified heat transfer, excess surface area is provided. Until the specified value of the fouling resistance is reached, the performance of the heat exchanger will be satisfactory. Depending on this fact, maintenance schedule could be planned to avoid unprecedented shut down for cleaning.

Tubular Exchanger Manufacturers Association (TEMA) [22] is referenced source of fouling factors used in the design of heat exchangers. Plant data, proprietary research data, personal and company experience etc. are other sources of fouling resistance data could be used in design.

Minimize Fouling by considering Design Features: Extent of fouling could be minimized by good design practice. Direct contact heat exchangers are considered where excess fouling is desired. In general a fouling prone fluid stream should be placed on the tube side as cleaning is easier. Generally higher fluid velocity and lower tube wall temperature retard fouling accumulation. Velocity of 1.8 m/s is a widely accepted figure for tube side flow of a heat exchanger. Heat Exchangers, operating over dew point for acid vapor and above freezing for fluids containing waxes prevent corrosion and freezing fouling. Fouling deposits are always found heavy in the region of low velocity at the vicinity of baffles in the shell side of the shell and tube heat exchangers.

Design features to facilitate fouling control: Full elimination of fouling may not be possible by good design practice alone. So, heat exchangers require cleaning at certain intervals. On-line cleaning can be employed to control fouling by extending cleaning cycle. Continuous fouling can ensure minimized fouling allowance. At construction and installation phase of a plant on-line cleaning system could be installed at ease. A heat exchanger with removable head and straight tube would be easy to clean and maintain. Space and provision for removal and cleaning of tube bundles are required to be available. On site cleaning facilities are to be provided with options of keeping isolation valves and connection provisions for cleaning hoses which could lead to chemical cleaning.

Fouling and operation of heat exchangers: Provision of excess surface area in heat exchangers for curbing fouling may lead to operation problem and fouling build. Generally high heat transfer area enhances total heat transfer which raises the out let temperature. By changing process parameters such as flow, surface temperature leads to higher fouling.

Fouling control strategies: A number of strategies are applied for fouling control. In operating condition additives are added. On-line or off-line surface cleaning techniques are other options. To control fouling under different consequences are consolidated by some researchers as stated in Table 3.1 [23].

On-line techniques	Off-line techniques
Use and control of appropriate additives: Inhibitors, Antiscalants, Dispursants, Acids, Air jet	Disassembly and manual cleaning: Lances: Liquid jet, Steam, Air jet. Mechanical Cleaning:
On-line cleaning: Sponge balls, Brushes, Sonic horns, Soot blowers, Chains and scrappers, Thermal shock, Air bumping	Drills, Scrapers Chemical cleaning

Table 3.1. Various techniques adapted to control fouling.

Heat Exchanger with green additives: Many additives were developed for retardation of fouling but many of them found carcinogenic in nature. Now researchers are heading towards green additives. Chemistry and analysis are underway. Lab analysis and performances will be subsequently achieved. In near future users are looking for a breakthrough in this field.

3.2 Fouling effect on heat transport

Mineral scales deposited on heat exchanger surfaces are a persistent and an expensive problem in process industries, cooling water systems, steam generation units, desalination by evaporation etc. and also house hold equipment. Precipitation of mineral salts as a scale on the surface of the conduit and cause obstruction of fluid flow, impedance of heat transfer, wear of metal parts, localized corrosion attack and unscheduled equipment shutdown.

The deposit layer provides an additional resistance to heat transfer. Generally, the thermal conductivity of the deposit layer is very low compared with that of the material of the heat exchanger which may result in a much higher thermal resistance than the wall or film resistances. The deposit layer also reduces the flow area, which increases the pressure drop. This problem is quite severe and is further enhanced by the rough surface of the deposit. Both effects reduce the heat exchanger performance significantly. Additional energy requirements in terms of more heating or pumping power can hamper the economics of the process.

In a circular tube, fouling builds on the inside or outside of the tube depending on the flowing fluid. Fouling adds an insulating cover to the heat transfer surface. The overall heat transfer coefficient for a smooth tubular heat exchanger under deposited conditions, U_f can be obtained by adding the inside and outside thermal resistances:

$$U_f = \frac{1}{A_o / A_i h_i + A_o R_{fi} / A_i + A_o \ln(d_o / d_i) / 2\pi k L + R_{fo} + 1 / h_o} \tag{3.1}$$

where R_{fi} and R_{fo} represent resistances for the outer and inner surfaces of the tubes.

The thermal resistance due to fouling is evaluated generally based on experiments as difference in the overall specific resistances of the fouled and clean wall:

$$R_f = \left(\frac{1}{U_f} - \frac{1}{U_{cl}} \right) \tag{3.2}$$

Where, the overall heat transfer coefficient U_f can also be evaluated by using the rate equation:

$$U_f = \frac{\dot{Q}}{\left(A \times \Delta T_f \right)} \tag{3.3}$$

The heat flow rate $\dot{Q}_f$ and temperature difference ΔT_f (the temperature difference between heated surface and the bulk liquid) are experimentally obtained. A is the exposed area of the heat exchanging surface to the liquid. The net rate of deposition of $CaSO_4.2H_2O$ on metal

surface is estimated as $\dfrac{m}{t}$, where m is the total mass accumulation on a unit area and t refers to the amount of time the surface was exposed to the solution of the foulant.

Using the definition of heat transfer coefficient and fouling resistance, the equation (3.4) can be derived for constant heat duty.

$$\frac{A_{fouled}}{A_{clean}} = 1 + U_{clean}R_f \tag{3.4}$$

The required excess heat transfer area usually becomes excessive due to the higher clean heat transfer coefficients. It is often recommended that the additional surface should not exceed 25 percent of the heat transfer surface requirement for clean operation.

3.3 Effect of fouling on pressure drop

In heat exchangers pressure loss is considered more critical than loss in heat transfer due to fouling. Fouling results in a finite layer. Flow field, pressure drop are affected by the change in geometry of the flow passage. Thus in a tubular heat exchanger, the deposited layer roughens the surface, diminishes the inner and raises the outer dimension of the tubes. The inside diameter of the tube decreases and roughness of the tube increases due to fouling which, causes an increase in pressure drop. Pressure drop inside a tube of a heat exchanger under fouled and clean state can be correlated as follows:

$$\frac{\Delta P_f}{\Delta P_c} = \frac{f_f}{f_c}\left(\frac{d_c}{d_f}\right)\left(\frac{u_{mf}}{u_{mc}}\right)^2 \tag{3.5}$$

Considering that the mass flow rates under clean and fouled conditions are the same, the mass flow rate can be represented as:

$$\dot{m} = \rho u_m A_{cr} \tag{3.6}$$

Equation (3.5) thus becomes:

$$\frac{\Delta P_f}{\Delta P_c} = \frac{f_f}{f_c}\left(\frac{d_c}{d_f}\right)^5 \tag{3.7}$$

The magnitude of d_f of scaled tube can be obtained from equation (3.8).

$$d_f = d_c \exp\left(-\frac{2k_cR_f}{d_c}\right) \tag{3.8}$$

The thickness t_f of deposit layer can be obtained from:

$$t_f = 0.5 d_c \left[1 - \exp\left(-\frac{2k_f R_f}{d_c} \right) \right] \qquad (3.9)$$

For a known total fouling resistance, the tube diameter under fouled conditions can be evaluated on knowing the thermal conductivity of the deposits. Non-uniform thermal conductivity may result from the multi layers of fouling deposits. Approximate thermal conductivities of pure materials constituting fouling deposits are often used for estimation of thermal conductivity of the total deposits. Depending on situations the fouling layer is considered composed solely of one material. In some occasions to ease calculations f_f is considered equal to f_c.

4. Conditions influencing fouling

The conditions influencing fouling can be classified as: (A) operating parameters, (B) heat exchanger parameters, and (C) fluid properties. Among the operating parameters the important events which influencing fouling at a significant level are: (1) velocity, (2) surface temperature, and (3) bulk temperature.

Velocity influences fouling at a significant level. In diffusion controlled processes, increasing the fluid velocity causes more fouling [24]. In most cases, fouling decreases at higher fluid velocities [4, 13, 25]. Increasing flow velocity increases the fluid shear stress which causes more removal. This results in lower fouling rates which resulting to lower fouling resistance. For weak deposits (particulate fouling), increasing the flow velocity may completely eliminate fouling. For stronger deposits, increasing the flow velocity beyond a particular point may not decrease fouling significantly [25]. For very strong deposits, increasing the flow velocity may not have any effect at all [6].

Surface temperature may increase, decrease or have no effect on fouling [26]. The rates of chemical reaction and inverse solubility crystallization increase with an increase in temperature. For inverse solubility salts, higher surface temperature increases fouling due to higher concentration gradients and higher reaction rate constants. In case of normal solubility salts cooling results in more fouling.

The bulk temperature also effects on increase of fouling rate. In inverse crystallisation, when precipitation happens in the fluid bulk, increasing the temperature increases the rate of crystal formation and hence deposition. Thus bulk temperature has effects on chemical reaction rate and polymerisation rate.

The important heat exchanger parameters are classified as: surface material, surface structure (roughness), heat exchanger type and geometry [27]. Surface material is considered seriously for corrosion fouling because of the potential to react and form corrosion products. Different materials have different catalytic action and may promote or reduce fouling for different processes. The initial fouling rate and scale formation depends significantly on the surface roughness. Junghahn [28] proved theoretically that the free energy change associated with crystal nuclei formation was much less on a rough surface than on a smooth surface. Rough surfaces result in higher deposition due to protected zones in the cavities or pits where flow velocities are very low.

According to Rankin and Adamson [29], it is not the rate of nucleation but the nuclei attachment which is strongly dependent on the surface roughness. Chandler [30] also observed similar results. In general the rough surface causes more fouling which reduces the delay time for all types of fouling. Surface roughness increases turbulence near the surface, which in turn increases the removal rate of fouling on the surface. Better performance occurred due to the increase in surface roughness with deposit formation and has been reported by some authors [1, 2]. Marriott [31] reiterated that mirror finished surfaces in heat exchangers are used to reduce fouling in practice.

5. Heat exchanger type, geometry and process fluid influencing fouling

Shell and tube heat exchangers are used most commonly but they are not particularly suitable for fouling conditions. Fouling can be reduced with special baffle and tube design. Several studies [32-35] have shown that finned tubes foul less than plain tubes. Non-uniform thermal expansion leads to lower deposit strength and hence less deposition. Freeman et al. [36] found that tubes with longitudinal grooves on the outside had less particulate fouling (by alumina particles) than the plain tubes.

Fluidised-bed heat exchangers are used in several applications to reduce or even eliminate fouling completely. Fluidised particles remove deposits from the heat transfer surface. They also enhance the heat transfer efficiency as they interrupt the viscous sub-layer. These heat exchangers have been used successfully to reduce fouling by hard, adhering silica deposits [37]. Graphite heat exchangers are also reported to have less fouling. Direct contact heat transfer may be another alternative to reduce fouling [38]. Properties of the process fluid such as the nature and concentration of the dissolved constituents or suspended particles, presence of any living organisms, solution pH etc. affect fouling significantly.

Excessively high over-concentration of solids in the evaporating liquid may lead to carry-over in the steam and cause fouling in process heat transfer equipment. Corrosion is very important on the steam side of process equipment. Water pH, over-concentration of treatment chemicals in evaporating liquids and dissolved gases (mainly oxygen and carbon dioxide) are very important contributors to corrosion fouling [39]. The presence of living organisms causes biological fouling and makes biofilms. This can sometimes enhance other fouling mechanisms too, as microbial deposits may trap suspended particles. They may also change the chemistry of water and can cause scaling or corrosion [39].

6. Fouling models

A number of models have been proposed for different types of fouling. Analysis and model improvement is still progressing as there are difficulties due to the complex nature of deposit formation and lack of reproducible measurement of fouling resistance. Most of the models have been simplified with many assumptions [40] as stated below:

- Surface roughness is neglected.
- Change in surface roughness with deposit formation is also neglected.
- Only one type of fouling is usually considered.
- Changes in physical properties of the fluids are neglected in most of the cases.
- The fouling layer is assumed to be homogeneous.

- Changes in flow velocity with changing cross-sectional area due to fouling are usually neglected.
- The shape of deposits, e. g. crystals or particles is ignored.

It is also observed that few attempts have been made to model the initiation or roughness delay period. Almost all the models predict fouling (scaling) after the delay period. Some other notable parameters are neglected in modelling such as: (a) effect of simultaneous action of different fouling mechanisms, (b) equipment design, (c) surface parameters e.g. surface material and surface roughness, (d) increase in surface area with deposition, (e) properties of foulant stream, (f) nature of process, and the (g) fluctuations in operation.

Modelling is usually done taking into consideration only (a) flow velocity, (b) concentration, (c) wall and bulk temperature, and (d) time.

Watkinson and Martinez [11] developed a model, based on the fundamental material balance equation (2.1). For the deposition rate the following expression is adopted:

The deposition rate is expressed as shown in equation (6.1).

$$\frac{dx_f}{dt} = \frac{K_R}{\rho_f}(c_F - c_{Sa})^n \tag{6.1}$$

For sparingly soluble salts with inverse solubility (e.g. $CaCO_3$), the deposition rate is controlled by the slow reaction rate and the constant of reaction rate K_R that obeys the Arrhenius equation:

$$K_R = A_0 e^{(\frac{-E}{R_g T_f})} \tag{6.2}$$

with T_f as the interface temperature.

Kern and Seaton [43] recommend for the removal rate the equation:

$$\dot{m}_r = a_8 \tau_f x_f \tag{6.3}$$

Where τ_f is the shear stress exerted by the liquid flow on the fouling film. Even though $CaCO_3$ deposits are much stronger than the particulate deposits considered by Kern and Seaton [43] the removal rate was assumed to be directly proportional to deposit thickness, which may not be correct for all the cases.

Kern and Seaton [41] proposed a model for particulate fouling which takes into account removal or re-entrainment of deposits. The mathematical model is based on a general material balance equation (2.1). Deposition and removal rates act separately and combine into a net deposition rate. The rate of deposition is expressed as:

$$\dot{m}_d = a_9 c' w \tag{6.4}$$

Where, c' is dirt concentration and w is constant weight flow of fluid. The removal rate is roughly proportional to the total depth of dirt deposited on the heat transfer surface as stated below.

$$\overset{\bullet}{m}_r = a_{10}\tau_f x_f \tag{6.5}$$

Combining the equations for deposition and removal rates (6.4) and (6.5) with the material balance equation (2.1), the fouling resistance expression is obtained:

$$R_f = \overset{*}{R}_f (1 - e^{-\theta t}) \tag{6.6}$$

where θ is a time constant and $\overset{*}{R}_f$ is the asymptotic value of the fouling resistance. For these also the following equations are obtained.

$$\overset{*}{R}_f = \frac{a_9 c'w}{a_{10}\lambda_f \tau_f} \tag{6.7}$$

$$\theta = a_{10}\tau_f \tag{6.8}$$

Here, λ_f is the thermal conductivity of the deposits, a_9 and a_{10} are proportionality constants. This model predicts asymptotic fouling behaviour with $\overset{*}{R}_f$ being the fouling resistance after an infinite time of operation. According to this model, no matter what the conditions, i.e. type of fluid, heat exchanger surface, temperature driving force, an asymptotic fouling value will be obtained sooner or later with removal rates becoming equal to deposition rates.

7. Cost imposed due to fouling

An additional cost is imposed by fouling of heat transfer equipment in industries. Few studies have been undertaken to determine the fouling related costs in industry. Fouling costs can generally be divided into four major categories, such as (1) increased capital expenditure, (2) energy costs, (3) maintenance costs, (4) cost of production loss and (v) extra environmental management cost.

Country	Fouling costs US $ million	GNP (1984) US $ million	Fouling costs % of GNP
USA (1982)	3860-7000	3634000	0.12-0.22
	8000-10000		0.28-0.35
Japan	3062	1225000	0.25
West Germany	1533	613000	0.25
UK (1978)	700-930	285000	0.20-0.33
Australia	260	173000	0.15
New Zealand	35	23000	0.15
Total Industrial World	26850	13429000	0.20

Table 7.1. Estimated fouling costs incurred in some countries.

The heat transfer area of a heat exchanger is kept exaggerated to compensate retardation imposed by fouling. Oversized pumps and fans are selected to compensate design over-surfacing the enhanced pressure loss from reduction in the flow area.

In some occasions standby heat exchangers are kept in process design in order to ensure uninterrupted operation while a fouled heat exchanger is taken under cleaning maintenance. In-situ cleaning in some cases are recommended while chemical cleaning is preferred for others. All together, cost of cleaning, cleaning equipment, chemicals all are imposing extra to the capital cost of the plant.

Muller-Steinhagen [37] reported that total annual costs for highly industrialised countries such as the United States and the United Kingdom are about 0.25 percent of the countries gross national product (GNP). Even for a relatively less industrialised country like New Zealand, the total fouling costs are around 0.15 percent of its GNP. Muller-Steinhagen [37] has summarised the total fouling costs for various countries based on 1984 in Table 7.1.

8. Fouling mitigation

Gilmour [42] reported that the degradation of heat transfer performance due to fouling in shell and tube heat exchangers occurs mainly due to poor shell-side design. In recent years numerous methods have been developed to control fouling. These methods can be classified as: (1) chemical methods, (2) mechanical methods and (3) changing the phase of the solution. By adding foreign chemicals in a solution, reduction of fouling is achieved by chemical methods of fouling mitigation. Chemical additives developed by many companies have been extensively used to mitigate fouling in the industrial sector. Various additives can be used to prevent scaling [43-44]. Bott [45] specified that the additives used act in different ways, such as (a) sequestering agents, (b) threshold agents, (c) crystal modifiers and (d) dispersants. Some of the common water additives are EDTA (sequestering agent), polyphosphates and polyphosphonates (threshold agents) and polycarboxylic acid and its derivatives (sequestering and threshold treatment). Sequestering agents such as EDTA complex strongly with the scaling cations such as Ca^{++}, Mg^{++}, and Cu^{++} in exchange with Na^+, thus preventing scaling as well as removing any scale formed previously. They are used effectively as antiscalants in boiler feed water treatment. Troup and Richardson [46] claimed that their use is uneconomical when hardness levels are high.

Polyphosphates and polyphosphonates as threshold agents are also used to reduce scaling in boilers and cooling water systems. Bott [45] said that they prevent the formation of nuclei thus preventing the crystallisation and mitigate fouling. Very small quantities of these agents are effective in reducing scaling from supersaturated salt solutions.

Crystal modifying agents (e.g. Polycarboxylic acid) distort the crystal habit and inhibit the formation of large crystals. The distorted crystals do not settle on the heat transfer surface, they remain suspended in the bulk solution. If their concentration increases beyond a certain limit, particulate fouling may take place. This is prevented either by using techniques to minimise particulate fouling or using dispersing agents along with crystal modifying agents.

Though crystallisation fouling may not be prevented completely using additives, the resulting crystalline deposits are different from those formed in the absence of any

additives. The layer looses its strength and can be removed easily. By controlling pH, crystallisation fouling can furthermore be minimised. The solubility of deposit forming components usually increases with decreasing pH. In many water treatment plants, sulphuric acid is added to maintain a pH between 6.5 and 7.5 [47]. In this case, addition of corrosion inhibitors may also be required which may enhance fouling again.

Seeding is used commercially to reduce crystallisation fouling. This method involves addition of seeds to the scaling fluid. Crystallisation takes place preferentially on these seeds rather than on the heat transfer surface. Calcium sulphate seeds are generally used to avoid calcium sulphate scaling [48-49]. These seeds need not be of the crystallising material, but they should have similar crystallographic properties, i. e. atomic agreement and lattice spacing [50].

To mitigate particulate fouling by chemical means, dispersants are used to reduce the surface tension of deposits. It helps in disintegrating the suspended particles into smaller fragments that do not settle so readily.

Addition of certain chemicals can slow down or terminate chemical reactions. Dispersants are very helpful in keeping the foulants away from the surface. Some particles such as corrosion products may act as catalysts. Chemical reaction fouling could be suppressed by reducing the number of these particles. Corrosion inhibitors (chromates and polyphosphates) can be used to reduce corrosion fouling [47]. Usually a passivating oxide layer is desired to prevent corrosion of the surface. Corrosion fouling may promote other fouling mechanisms e. g. higher roughness of the corroded surface may enhance crystallisation fouling. The corrosion products may act as catalysts and promote chemical reaction fouling and also augments particulate fouling by depositing on the heat transfer surface.

Mitigation of fouling by chemical methods has several drawbacks. Fouling and corrosion inhibitors usually contain considerable amount of chlorine, bromine, chromium, zinc etc. Therefore, their concentration has to be monitored carefully. Treatment of fluid released from the plant to natural waterways is necessary to prevent harmful effects. Higher concentrations can be used in closed systems but overdosing may have negative effects and some components may precipitate. Using different additives at the same time may result in dangerous chemical reactions. Some additives have limited life and some degrade with time and loose activity.

Pritchard [51] has broadly classified mechanical methods into two categories according to their ways of action. (1) Brute force methods such as high-pressure jets, lances, drills etc. (2) Mild methods such as brushes and sponge balls. Muller-Steinhagen [37] has reported that several mechanical methods have been developed in recent years. The following mechanisms predict the modern methods:

- Breakage of deposits during brief overheating due to differential thermal expansions of heat transfer surface and deposits,
- Mechanical vibration of the heat transfer surfaces,
- Acoustical vibration of the surface,
- Increased shear stress at the fluid/deposit interface, and
- Reduced stickiness of the heat transfer surface.

Most liquid-side fouling mitigation techniques have been developed for the tube-side of shell and tube heat exchangers. The relevant techniques include:

1. increase in flow velocity,
2. reversal of flow direction,
3. heat transfer surface such as, surface roughness and surface materials,
4. fluidised bed heat exchangers,
5. pulsating flow,
6. turbulence promoters, and
7. transport of cleaning devices through tubes.

The deposits which are not strongly adhere to the surface can be removed by increasing the flow velocity. Muller-Steinhagen and Midis [4] reported that alumina deposits were removed completely when the flow velocity was increased for a short period of time after a fouling run. At higher flow velocity, the wall shear stress increases and causes more removal of deposits from the surface.

At a regular interval of time, the reversal of flow direction on the heat transfer surface could be another effective method of reducing fouling. This technique needs several modifications in the existing set-up. Muller-Steinhagen [37] stated that mitigation of fouling by increasing the flow velocity could be more effective than reversal of flow direction.

Surface material and surface roughness play an important role on fouling mitigation. Thus lowering the surface roughness retards the adhesion of deposits and the number of nuclei growth sites. Lower deposition rate also experienced with lowering surface energy of the material of heat exchanger. Using inert particles is an effective way of reducing or even eliminating fouling completely as practiced in fluidized bed heat exchangers. Pulsating flow in heat exchangers is a strategy to increase the level of turbulence [52-58]. Where, as a matter of fact heat transfer coefficient increases with the enhancement of deposit removal. Higher heat transfer reduces fouling by reducing the interface temperature which is beneficial for certain fouling mechanism such as crystallization fouling of inverse solubility salts. The higher level of turbulence augments the deposit removal rate.

Fracture of deposits by fatigue is enhanced by higher turbulence due to pulsation resulting to increase of removal rate. Generally the deposition rate of fouling phenomena [3] depends on the thickness of viscous and thermal sub-layers. Muller-Steinhagen [37] reported that by inserting turbulence promoters inside tubes or by using tube corrugations, the heat transfer coefficient can be increased by a factor of 2 to 15 by reducing the thickness of average thermal boundary layer. Turbulence promoters may reduce both the crystallisation and reaction fouling. Muller-Steinhagen [37] informed that particulate fouling will be enhanced if particulate or fibrous material already exists in the solution.

Middis [10] also reported fouling mitigation by adding natural fibre in the supersaturated solutions of concentration 3.6 g/L $CaSO_4$. He observed that the rate of $CaSO_4$ fouling on heated metal tube surface decreases with the increase of fibre concentration in the fouling solution. Kazi [59] also got similar results by adding different types and concentrations of natural fibre in supersaturated solutions of $CaSO_4$.

Some novel methods which do not fall under well reported categories, such as magnetic or electric treatment are also available in the market to reduce fouling. Usually magnetic treatment is carried out by inserting permanent magnets in a pipe before the heat exchanger.

Parkinson and Price [60] have reported significant reduction in fouling by the magnetic treatment as it helps in precipitating the salts. These salts stay suspended in the bulk liquid and are removed later. On the other hand Hasson and Bramson [61] informed that there is no effect of magnetic treatment at all on fouling. They observed that magnetic treatment neither decreased nor increased the rate of scaling. The nature of the deposits also remained unchanged. Bernadin and Chan [62] have also reported no influence of magnetic treatment on silica fouling. Muller-Steinhagen [37] has stated that magnetic mitigation devices in some cases actually increased fouling. Thus from the available information no conclusion can be made about the influence of the magnetic field on the scaling process.

9. Cleaning of heat exchangers

A decrease in the performance of a heat exchanger beyond acceptable level requires cleaning. In some applications, the cleaning can be done on line to maintain acceptable performance without interruption of operation. At other times, off-line cleaning must be used.

Garrett-Price et al. [27] presented some cleaning approaches for fouled heat exchangers. They specified on-line cleaning generally utilises a mechanical method designed for only tube side and requires no disassembly. In some applications flow reversal is required. Chemical feed can also be used as an on-line cleaning technique but may upset the rest of the liquid service loop.

On-line mechanical cleaning techniques are also in practice. On line tube side cleaning techniques are the sponge-ball and brush systems. The advantage of on-line cleaning is the continuity of service of the exchanger and the hope that no cleaning-mandated downtime will occur. The principal disadvantage is the added cost of a new heat exchanger installation or the large cost of retrofits. Furthermore there is no assurance that all tubes are being cleaned sufficiently.

Off-line chemical cleaning is a technique that is used very frequently to clean exchangers. Some refineries and chemical plants have their own cleaning facilities for dipping bundles or re-circulating cleaning solutions. In general, this type of cleaning is designed to dissolve the deposit by means of a chemical reaction with the cleaning fluid. The advantages of chemical cleaning approach include the cleaning of difficult-to-reach areas. Often in mechanical cleaning, there is incomplete cleaning due to regions that are difficult to reach with the cleaning tools. There is no mechanical damage to the bundle from chemical cleaning, although there is a possibility of corrosion damage due to a reaction of the tube material with the cleaning fluid. This potential problem may be overcome through proper flushing of the unit. Disadvantages of off-line chemical cleaning include corrosion damage potential, handling of hazardous chemicals, use of a complex procedure.

Off-line mechanical cleaning is a frequently used procedure. The approach is to abrade or scrap away the deposit by some mechanical means. The method includes high-pressure water, steam, lances and water guns. In off-line mechanical cleaning there are some advantages such as excellent cleaning of each tube is possible, good removal potential of very tenacious deposits. Disadvantages include the inability to clean U-tube bundles successfully, usual disassembly problem and the great labour needed.

Frenier and Steven [63] describe general methods for cleaning heat exchanger equipment, including both mechanical and chemical procedures. They have given guidelines for selecting between chemical and mechanical cleaning, and among the various types of chemical cleaning processes. They stated that water-based fluids can transport and deposit a wide variety of minerals, and corrosion products form due to the reaction of the aqueous fluids with the metals of construction. Hydrocarbon and petrochemical fluids transport and deposit a variety of organic scales. Common inorganic scale forming compound includes various iron oxides, hardness deposits (carbonates and silicates). They stated that the entire cleaning situation must be considered when choosing between mechanical and chemical cleaning, as well as the specific technique within the general category. The general categories of mechanical cleaning are abrasive, abrasive hydraulic, hydraulic and thermal [64].

Frenier and Barber [63] stated that, for chemical cleaning of the heat exchanger tubes, it is very beneficial to obtain a sample of the deposit so that its composition can be determined. Based on the chemical analysis of the deposit, an optimal treatment plan can be developed and the best solvent selected. They have classified the deposits generically, as organic (process-side) or inorganic (water-side).

They stated that the process side deposits may range from light hydrocarbon to polymers and generally they are similar to the fluids from which they originate. They mentioned that the general categories of solvents for process side scales include aqueous detergent solutions, true organic solvents and emulsions. Aqueous detergent formulations always contain a surfactant-type component. In addition they can contain alkaline agents, such as sodium hydroxide, sodium silicate, or sodium phosphate. Builder molecules such as ethylenediaminetetraacetic acid (EDTA) suppress the effects of hard water, and coupling agents such as glycol ethers, improve the dissolution of some organic deposits.

Detergent formulations are effective only for removing the lighter deposits. Refinery fluids, aeromatics and terpenes are used to dissolve the organic deposits. N-methyl-2-pyrrolidinone also is a very effective polar solvent with low toxicity characteristics. They reiterated that the effectiveness of the application depends greatly on proper application conditions, such as flow rate and temperature. Combination of surfactants, organic solvents and water emulsions are good cleaning agents. Emulsions with an organic outer phase are particularly useful for cleaning large vessels. Oily rust deposits having both organic and inorganic compositions can be removed by acidic emulsions combining an acid and an organic solvent.

Water-side deposits usually contain minerals, such as iron oxides (corrosion products), hardness (Ca and Mg carbonates) and silica, in individual cases other minerals can also be found. The solvents for removing inorganic deposits usually contain mineral acids, organic acids or chelating agents.

Mineral acids used in chemical cleaning include hydrochloric acid (HCl), hydrofluoric acid (HF), sulphuric acid (H_2SO_4), phosphoric acid (H_3PO_4), nitric acid (HNO_3) and sulfamic acid (H_2NSO_3H). Hydrochloric acid is the most common and most versatile mineral acid. It is used on virtually all types of industrial process equipment at strengths from 5 percent to 28 percent (5-10 percent is the most usual range). It can be inhibited at temperatures up to about 180 °F. HCl will dissolve carbonates, phosphates, most sulphates, ferrous sulphide,

iron oxides and copper oxides. By using with appropriate additives, fluoride deposits, copper and silica can also be removed from surfaces with inhibited HCl. HCl is corrosive, so it has restricted use. HCl is not used to clean series 300 SS, free-machining alloys, magnesium, zinc, aluminium, cadmium, or galvanised steel because of the potential for generalised or localised attack. It is not desirable to contact the fouled metal with a strong mineral acid, because of the danger of damage to the equipment during or after cleaning. An alternative solvent family consists of aqueous solutions of chelating agents and organic acids with pH values of about 2 to 12.

Citric acid was one of the first organic acids used in industrial cleaning operations [65]. For removing iron oxide from steel surfaces, citric acid and a mixture of formic and citric acid could be used [66]. The mixture could hold more iron in solution than either of the acids alone could do. Ammonium citrate and sodium citrate solvents are currently used to clean a wide variety of heat transfer equipment, including boilers and various types of service water systems. The advantage of citric acid formulation is their low toxicity and ready biodegradability. EDTA is a versatile chemical that forms metal ion complexes with higher equilibrium constants than citric acid. As a result chemical cleaning solvents with pH values from 4.5 to about 9.2 have been formulated that can remove Fe and Cu, as well as Ca, Ni and Cr. The major advantage of the EDTA solvents is that they are much more aggressive than citric salts for removing very heavy iron oxide deposits especially if they contain copper. The disadvantage includes high cost per pound of metal removed and low biodegradability.

All of the chelating agents are also organic acids. Eberhard and Rosene [67] taught the use of solvents consisting of formic acid or citric acid for cleaning nondrainable tubes in super heaters. Reich [66] used a mixture of formic acid and citric acid to a proportion of 3:1, to remove iron oxide deposits. The advantage of these mixtures is that they avoid the precipitation of solids that formed in pure formic or citric acid solutions. Formulations of formic acid with hydroxyacetic acid and citric acid with hydroxyacetic acid can be used as a cleaning agent. Bipan [3] used acetic acid of concentration 3 percent to remove $CaSO_4.2H_2O$ deposit on plate type SS heat exchangers. He said that with the increase in acid solution temperature the removal efficiency increases. Similar results were obtained by Kazi [68]. It reveals that a complete and systematic study of fouling on different metal surfaces and their mitigation by additives have been required to be done along with study of introducing a benign to environment technique for chemical cleaning of fouling deposits.

10. Nomenclature

A	Heat transfer area	m^2
A_0	Arrhenius constant	$m^3/kg.s$
a_1-a_{13}	Proportionality constant	-
c	Concentration	g/L or kg/m^3
c_P	Specific heat capacity	J/molK
d	Pipe diameter	m
E	Activation energy	J/mol
ΔH	Head loss	$m\ H_2O$
h_c	Heat transfer coefficient	W/m^2K
K_R	Reaction rate constant (dimension depend on the order of n)	$m^4/kg.s$
L	Length	m

$\dot{m}$	Mass flux	kg/m²s
$\dot{m}_d$	Increase of solids mass present in the fouling film	kg/m²s
$\dot{m}_r$	Decrease of solids in the fouling film	kg/m²s
m_f	Solids deposited in the fouling film per unit area	kg/m²
P	Pressure	kPa
P	Perimeter	m
P_c	Intercrystalline cohesive force	N
ΔP	Pressure drop	kPa/m
$\dot{Q}$	Heat flow	W
$\dot{q}$	Heat flux	W/m²
R	Ratio of the radius of inner and outer tubes of annulus	-
R_b	Bonding resistance	-
R_g	Universal gas constant	J/mol.K
R_f	Fouling resistance	m²K/kW
R_f^*	Asymptotic value of the fouling resistance	m²K/kW
r	Radius	m
r_H	Hydraulic radius	m
T	Temperature	ºC
T_f	Temperature at the surface of the fouling film	ºC
ΔT	Temperature difference	K or ºC
t	Time	s
t_{ind}	Induction time	s
U	Overall heat transfer coefficient	W/m²K
u	Velocity	m/s
$\bar{u}$	Local mean velocity	m/s
u*	Friction velocity, $\sqrt{(\tau_w/\rho)}$	m/s
u⁺	Dimensionless velocity, $\bar{u}/$u*	-
u_t	Turbulent friction or shear velocity, $\bar{u}\sqrt{f/2}$	m/s
w	Constant weight flow of fluid	kg/s
x	Distance in x direction	m
x_f	Fouling film thickness	m
y	Distance in y direction	m

Greek

α	Constant	-
β	Individual mass transfer coefficient	m/s
θ	Time constant	s
ε	Height of roughness	m

ε/d	Roughness ratio	-
f	Fanning friction factor	-
λ	Thermal conductivity	W/mK
λ_f	Thermal conductivity of the deposits	W/mK
μ	Dynamic viscosity	kg/ms
ρ	Density	kg/m³
ρ_f	Density of the deposits	kg/m³
τ	Shear stress	N/m²
τ_w	Wall shear stress	N/m²
τ_f	Shear stress exerted by the liquid flow on the fouling film	N/m²
ν	Kinematic viscosity	m²/s
ϕ	Friction factor	-
δ	Hydrodynamic boundary layer thickness	m
δc	Linear thermal expansion coefficient of the fouling film porosity	1/K
δ_t	Thermal boundary layer thickness	m
ξ	Ratio of thermal to hydrodynamic boundary layers	m

Dimensionless Numbers

Nusselt Number
$$Nu = \frac{h_c \cdot d}{\lambda}$$

Prandtl Number
$$\Pr = \frac{c_p \cdot \mu}{\lambda}$$

Reynolds Number
$$\mathrm{Re} = \frac{\rho \cdot u \cdot d}{\mu}$$

11. References

[1] Bott, T. R. and Gudmundsson, J. S., Rippled Silica deposits in Heat Exchanger Tubes. 6th International Heat Transfer Conference. 1978.

[2] Crittenden, B. D. and Khater, E. M. H., Fouling From Vaporising Kerosine. Journal of Heat Transfer, 1987. 109: p. 583-589.

[3] Bansal, B., Crystallisation Fouling in Plate Heat Exchangers, PhD thesis, Department of Chemical and Materials Engineering, 1994, The University of Auckland: Auckland, New Zealand.

[4] Muller-Steinhagen, H. M. and Middis, J., Particulate Fouling in Plate Heat Exchangers. Heat Transfer Engineering, 1989. 10(4): p. 30-36.

[5] Bohnet, M., Fouling of Heat Transfer Surfaces. Chemical Engineering Technology, 1987. 10: p. 113-125.

[6] Ritter, R. B., Crystallisation Fouling Studies. Journal of Heat Transfer, 1983. 105: p. 374-378.

[7] Reitzer, B. J., Rate of Scale Formation in Tubular Heat Exchangers. I & EC Process Design and Development, 1964. 3(4): p. 345-348.

[8] Hasson, D., Rate of Decrease of Heat Transfer Due to Scale Deposition. DECHEMA Monograph, 1962. 47: p. 233-282.

[9] Bott, T. R. and Walker, R. A., Fouling in Heat Transfer Equipment. The Chemical Engineer, 1971: p. 391-395.

[10] Middis, J., Heat Transfer and Pressure Drop For Flowing Wood Pulp Fibre Suspensions, PhD thesis, Chemical and Materials Engineering. 1994, The University of Auckland: Auckland, New Zealand.

[11] Watkinson, A. P. and Martinez, O., Scaling of Heat Exchanger Tubes by Calcium Carbonate. Journal of Heat Transfer, 1975: p. 504-508.

[12] Augustin, W., Verkrustung (Fouling) Von Warmeubertragungsflachen, in Institut fur Verfahrens- und Kerntechnik. 1992, Technische Universitat Braunschweig: Germany.

[13] Cooper, A., Suitor, J. W. and Usher, J. D., Cooling Water Fouling in Plate Heat Exchangers. Heat Transfer Engineering, 1980. 1(3): p. 50-55.

[14] Muller-Steinhagen, H. M., Reif, F., Epstein, N. and Watkinson, A. P., Influence of Operating Conditions on Particulate Fouling. The Canadian Journal of Chemical Engineering, 1988. 66: p. 42-50.

[15] Bott, T.R., Fouling of Heat Exchangers. 1995: Elsevier Science & Technology Books. 529.

[16] Bell, K.J. and A.C. Mueller, Wolverine Heat Transfer Data book II. 2001, Wolverine Tube, Inc.

[17] Epstein, N., Heat Exchanger Theory and Practice, in: J. Taborek, G. Hewitt (eds.) heat exchangers in Heat Exchanger Theory and Practice, McGraw-Hill, 1983.

[18] Epstein, N., Thinking about Heat transfer fouling: a 5 x 5 matrix. heat Transfer Engineering, 1983. 4: p. 43-46.

[19] Epstein, N. (1981) Fouling in heat exchangers. In Low Reynolds Number Flow Heat Exchangers, S. Kakac, R. K. Shah, and A. E. Bergles (eds.). Hemisphere, New York.

[20] Somerscales, E. F. C., and Knudsen, J. G. (eds.) (1981) Fouling of Heat Transfer Equipment. Hemisphere, New York.

[21] Melo, L. F., Bott, T. R., and Bernardo, C. A. (eds.) (1988) Fouling Science and Technology. Kluwer, Dordrecht.

[22] Standards of the Tubular Exchanger Manufacturers Association 7th ed. Tubular Exchanger Manufacturers Association, New York, 1988.

[23] Chenoweth, J. M. (1988), General design of heat exchangers for fouling conditions. In Fouling Science and Technology, L. F. Melo, T. R. Bott, and C. A. Bernardo (eds.), pp. 477-494. Kluwer, Dordrecht.

[24] Brusilovsky, M., Borden, J. and Hasson, D., Flux Decline due to Gypsum Precipitation on RO Membranes. Desalination, 1992. 86: p. 187-222.

[25] Walker, G., Degradation of Performance, Industrial Heat Exchangers- A Basic Guide. 1982: Hemisphere Publishing Corporation. 213-272.

[26] Gudmundson, J. S., Particulate Fouling, in Fouling of Heat Transfer Equipment, E.F.C. Somerscales and J.G. Knudsen, Editors. 1981, Hemisphere Publishing Corporation. p. 357-387.

[27] Garrett- Price, B. A., Smith, S. A., Watts, R. L., Knudsen, J. G., Marner, W. J. and Suitor, J. W., Overview of Fouling, Fouling of Heat Exchangers- Characteristics, Costs, Prevention, Control, and Removal. 1985, Noyes Publications: New Jersey. p. 9-20.

[28] Junghahn, L., Methoden Zum Herabsetzen oder Verhindern der Krustenbildung. Chemie Ingenieur Technik, 1964. 36: p. 60-67.

[29] Rankin, B. H. and Adamson, W. L., Scale Formation as Related to Evaporator Surface Conditions. Desalination, 1973. 13: p. 63-87.

[30] Chandler, J. L., The Effect of Supersaturation and Flow Conditions on the Initiation of Scale Formation. Transactions of Institution of Chemical Engineers, 1964. 42: p. T24-T34.

[31] Marriott, J., Where and How to Use Plate Heat Exchangers. Chemical Engineering, 1971. 78(8): p. 127-134.

[32] Knudsen, J. G. and McCluer, H. K., Hard Water Scaling of Finned Tubes at Moderate Temperatures. Chem. Eng. Progress Symp. series, 1959. 55(9): p. 1-4.

[33] Katz, D. L., Knudsen, J. G., Balekjian, G. and Grover, S. S., Fouling of Heat Exchangers. Petroleum Refiner, 1954. 33(4): p. 121-125.

[34] Webber, W. O., Under Fouling Conditions Finned Tubes can Save Money. Chemical Engineering, 1960. 67(6): p. 149-152.

[35] Sheikholeslami, R. and Watkinson, A. P., Scaling of Plain and Externally Finned Tubes. Journal of Heat Transfer, 1986. 108: p. 147-152.

[36] Freeman, W. B., Middis, J. and Muller-Steinhagen, H. M., Influence of Augmented Surfaces and of Surface Finish on Particulate Fouling in Double Pipe Heat exchangers. Chemical Engineering Processing, 1990. 27: p. 1-11.

[37] Muller-Steinhagen, H. M., Fouling: The Ultimate Challenge for Heat Exchanger Design. The sixth International Symposium on Transport Phenomena in Thermal Engineering. 1993. Seoul, Korea.

[38] Muller-Steinhagen, H. M., Introduction to Heat Exchanger Fouling. Proceedings of Fouling in Heat Exchangers. 1988. The University of Auckland, Centre for Continuing Education, Auckland, New Zealand.

[39] Garrett- Price, B. A., Smith, S. A., Watts, R. L., Knudsen, J. G., Marner, W. J. and Suitor, J. W., Generic Industrial Fouling, in Fouling of Heat Exchangers- Characteristics, Costs, Prevention, Control, and Removal. 1985, Noyes Publications. p. 21-37.

[40] Pinheiro, J. D. D. R. S., Fouling of Heat Transfer surfaces, Heat Exchanger Source Book, J.W. Palen, Editor. 1986, Hemisphere Publishing Corporation. p. 721-744.

[41] Kern, D. Q. and Seaton, R. E., A Theoretical Analysis of Thermal surface Fouling. Brit. Chem. Eng., 1959. 4(5): p. 258-262.

[42] Gilmour, C. H., No Fooling- No Fouling. Chem. Eng. Progr., 1965. 61(7): p. 49-54.

[43] Harris, A. and Marshall, A., The Evaluation of Scale Control Additives, Conference on Progress in the Prevention of Fouling in Industrial Plant. 1981. University of Nottingham.

[44] Krisher, A. S., Raw Water Treatment in the CPI. Chemical Engineering, 1978: p. 79-98.

[45] Bott, T. R., The Fouling of Heat Exchangers. DSIR, Wellington, New Zealand., 1981.

[46] Troup, D. H. and Richardson, J. A., Scale Nucleation on a Heat Transfer Surface and its prevention. Chemical Engineering Communications, 1978. 2: p. 167-180.

[47] Muller-Steinhagen, H. M., Fouling of Heat Transfer Surfaces. VDI Heat Atlas, English Edition, VDI- Verlag GmbH, 1993: p. OC1-OC22.

[48] Gainey, R. J., Thorp, C. A. and Cadwallader, Calcium Sulphate Seeding Prevents Calcium sulphate Scaling. Industrial and Engineering Chemistry, 1963. 55(3): p. 39-43.

[49] Rautenbach, R. and Habbe, R., Seeding Technique for Zero-Discharge Processes, Adaption to Electrodialysis. Desalination, 1991. 84: p. 153-161.

[50] Telkes, M., Nucleation of Supersaturated Inorganic Salt Solutions. Industrial and Engineering Chemistry, 1952. 44(6): p. 1308-1310.

[51] Pritchard, A. M., Cleaning of Fouled Surfaces: A Discussion, in Fouling Science and Technology, NATO ASI Series, Series E: Applied Science, Melo, L. F., Bott, T. R. and Bernardo, C. A., Editors. 1988. p. 721-726.

[52] Keil, R. H., Enhancement of Heat Transfer by Flow Pulsation. Industrial Engineering Chemistry: Process Design and Development, 1971. 10(4): p. 473-478.

[53] Ludlow, J. C., Kirwan, D. J. and Gainer, J. L., Heat Transfer with Pulsating Flow. Chemical Engineering Communications, 1980. 7: p. 211-218.

[54] Karamercan, O. E. and Gainer, J. L., The Effect of Pulsations on Heat Transfer. Industrial Engineering Chemistry Fundamentals, 1979. 18(1): p. 11-15.

[55] Herndon, R. C., Hubble, P. E. and Gainer, J. L., Two Pulsators for Increasing Heat Transfer. Industrial Engineering Chemistry: Process Design and Development, 1980. 19: p. 405-410.

[56] Edwards, M. F. and Wilkinson, W. L., Review of Potential Applications on Pulsating Flow in Pipes. Transactions of Institution of Chemical Engineers, 1971. 49: p. 85-94.

[57] Gupta, S. K., Patel, R. D. and Ackerberg, R. C., Wall Heat /Mass Transfer in Pulsatile Flow. Chemical Engineering Science, 1982. 37(12): p. 1727-1739.

[58] Thomas, L. C., Adaptation of the surface Renewal Approach to Momentum and Heat Transfer for Turbulent Pulsatile Flow. Journal of Heat Transfer, 1974: p. 348-353.

[59] Kazi, S. N., Heat Transfer to Fibre Suspensions-Studies in Fibre Characterisation and Fouling Mitigation, PhD thesis, Chemical and Materials Engineering. 2001, The University of Auckland: Auckland, New Zealand.

[60] Parkinson, G. and Price, W., Getting the Most out of Cooling Water. Chemical Engineering, 1984: p. 22-25.

[61] Hasson, D. and Bramson, D., Effectiveness of Magnetic Water Treatment in Suppressing Calcium Carbonate Scale Deposition. Industrial Engineering Chemistry: Process Design and Development, 1985. 24: p. 588-592.

[62] Bernardin, J. D. and Chan, S. H., Magnetics Effects on Similated Brine Properties Pertaining to Magnetic Water Treatment. Fouling and Enhancement Interactions, 28th National Heat Transfer Conference. 1991. Minneapolis, Minnesota, USA.

[63] Frenier, W. W. and Barber, J. S., Choose the Best Heat Exchanger Cleaning Method. Chemical Engineering Progress, 1998: p. 37-44.

[64] Gutzeit, J., Cleaning of Process Equipment and Piping. 1997, MTI Publication, Materials Technology Institute, St. Louis.

[65] Loucks, C. M., Organic Acids for Cleaning Power- Plant Equipment. Annual Meeting of ASME. 1958. New York.

[66] Reich, C. F., Scale Removal. 1961: U. S. A.

[67] Eberhard, J. F. and Rosene, R. B., Removal of Scale Deposits. 1961: U. S. A.

[68] Kazi, S. N., Duffy, G. G. And Chen, X. D., Mineral scale formation and mitigation on metals and a polymeric heat exchanger surface. Applied Thermal Engineering, 30 (2010): p. 2236-2242.