Chapter

Fouling and Mechanism

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Abstract

Fouling is the deposition of material on the heat transfer surface which reduces the film heat transfer coefficient. The impact of fouling on the heat exchanger is manifested as the reduction of thermal and hydraulic performance, in which the latter has a minor effect. This factor needs to be considered when calculating the effectiveness of the heat exchanger. During the design of heat exchangers, the fouling factor increases the required heat transfer area, which adds extra manufacturing costs. With less efficient heat exchangers, the economic cost of fouling is related to excess fuel consumption, loss of production, and maintenance or cleaning. The extra fuel consumption also damages the environment by increasing greenhouse gas production. Although much of the research work has been done on modeling and predicting fouling, it is still a poorly understood phenomenon representing the complexity of its mechanism. The common fouling mitigation action after the onset of fouling is to optimize the operating condition, e.g., increase the bulk flow velocity or decrease surface temperature. However, many quantitative and semi-empirical models have been developed to predict the fouling rate for preventive actions and optimizing cleaning schedules.

Keywords: heat exchanger, fouling, crude oil, heat transfer, thermohydraulic

1. Introduction

The deposition of foulant on the heat exchanger surface is usually in a solid or semi-solid state which gradually solidifies by the action of heat. This deposition reduces the capacity of exchangers to deliver the required outlet temperatures due to the low thermal conductivity of the deposit. The subsequent result of this reduction is the loss of thermal efficiency of the heat exchangers. Fouling is referred to the deposition of unwanted material on heat transfer surfaces resulting in the loss of thermohydraulic capacity of heat exchangers. The fouling usually occurs in most of the heat exchangers with varying severity. There are typically various sources that contribute to the development of foulants attached to the heat exchanger surface. The most common fouling precursors in crude oil are dirt particles, asphaltenes, salts, sulfur, and nitrogen compounds. It is crucial to consider the provision of fouling resistance in the heat exchanger design to compensate for the loss of efficiency due to fouling. At some point, it is desirable to take periodic shut down for mechanical cleaning of the heat transfer surface [1]. Usually, the outlet temperature of the heat exchanger is monitored, and required actions are taken to achieve the desired value.

Typically, the reduction of thermal efficiency is compensated by increasing the load on the furnace, which is manifested as an economic penalty in terms of extra fuel consumption. Van Nostrand et al. [2] divide the cost related to fouling into three categories, i.e., additional energy consumption, production loss, maintenance, and cleaning cost. They estimated the cost of fouling for a refinery processing 100,000 bbl per day at US$ 31.17 MM (extrapolated to 2022). The cost distribution for production loss, extra energy consumption, and maintenance was 40%, 10%, and <1%. Fouling mitigation strategies can reduce the cost of fouling. It is estimated that [3] 15% of energy savings can be achieved by applying fouling mitigation strategies in pre-heat trains and furnaces in oil refineries. Other options to mitigate the effect of fouling is to use retrofit of heat exchangers or to introduce tube inserts [4].

With the decrease in thermal efficiency, the flow area in the heat exchanger tube is also reduced, resulting in increased pressure drop and sometimes tube blockage. The monitoring of pressure drop and outlet temperature is therefore highly required to predict the extent of fouling and apply the mitigation actions by adjusting the operating conditions. It is also imperative to improve the heat exchanger design by incorporating the effect of operating conditions and the type of fluid used. The typical design strategy uses the fouling factor, which is merely a correction factor to compensate for the loss of heat transfer area due to fouling. The heat exchanger design also considers the ease of cleaning and elimination of hot spots to mitigate fouling. However, this scheme does not consider the dependence of fouling on the operating condition and fluid type.

In most cases, the mitigation strategy is adopted during the operation of heat exchangers. The feed is filtered to remove contaminants to minimize particle deposition, and chemical inhibitors are added. Different inhibitors used in the industry provide diverse functionality in preventing inorganic and organic fouling. Ethylenediamine tetraacetic acid (EDTA) inhibitors are commonly used against crystallization fouling. Similarly, some antioxidants and surfactants are also used to prevent fouling from polymerization and particulate matter in crude oil. An alternative to using chemical inhibitors is the application of tube inserts such as wire matrix, twisted coils, or hiTRAN. They serve as turbulence promoters to increase the removal rate of fouling by the action of wall shear forces [5].

During the operation of heat exchangers, it is sometimes desirable to promote foulant removal through operational parameters. The most common strategy is to increase the velocity to detach the foulant layer from the heat transfer surface by turbulent sweeps and bursts. These actions can work effectively against weak foulant deposits and are adopted for a longer duration, especially in refineries. For hardened deposits such as in particulate fouling, the gas rumbling is useful for promoting the dislodging of foulant. It is carried out with pressurized air or nitrogen stream introduced in the fluid for a short duration.

2. Fouling estimation

Heat exchangers are designed for the required heat duty, temperatures, and flow rates of the hot and cold streams. The overall heat transfer coefficient is estimated to predict the required surface area of the heat exchanger using the following equation:

$$Q = UA\Delta T \tag{1}$$

The overall heat transfer coefficient can be calculated as follows:

$$\frac{1}{U} = \frac{1}{U_0} + R_f \tag{2}$$

There are two approaches usually adopted during the operations to estimate the extent of fouling in heat exchangers, namely thermal and hydraulic approaches.

2.1 Thermal resistance

The estimation of the extent of fouling depends on the mode of operation of the heat exchanger. If the operation has a constant temperature difference, which is usually encountered in the operation of furnace and reactor [6], then the heat flux is decreased to maintain the constant temperature difference. The fouling resistance can be estimated as follows:

$$R_f = \left(\frac{\Delta T}{q_o}\right) - \left(\frac{\Delta T}{q_t}\right) \tag{3}$$

The second mode is with constant heat flux, which is predominantly applied in lab-scale fouling experimental units [7], in which the deposition on the surface is estimated with increasing temperature difference by the following equation:

$$R_f = \left(\frac{\Delta T_t}{q_o}\right) - \left(\frac{\Delta T_o}{q_o}\right) \tag{4}$$

2.2 Hydraulic resistance

The effect of pressure drop on heat exchanger performance is also very significant, manifested as decreases in the hydraulic efficiency of the exchangers. The pressure drop increases with the thickness foulant layer. It is crucial to estimate the pressure drop changes in tubes to predict the accurate thickness of the fouling layer. Sometimes the estimation of foulant thickness based on only the thermal resistance can lead to erroneous results due to the change in thermal conductivity of the foulant with aging [8]. Commonly thin-slab approximation [9] is employed to estimate the thickness of foulant as follows:

$$R_f = \frac{x}{\lambda_f} \tag{5}$$

The aging of foulant manifested in its increasing thermal conductivity. Thus, Eq. (5) can be employed by incorporating the foulant's aging to predict the fouling rate accurately. Usually, the heat exchangers are operated at constant mass flow rate operations in which pressure drop increases with the deposition. Usually, the pumping power is increased to overcome increasing pressure drops. The velocity increases with time, affecting the film heat transfer coefficient. The pressure drop for a clean tube is given by

$$\Delta P_o = 4f \frac{L}{d_i} \frac{\rho u_o^2}{2} \tag{6}$$

Similarly, for a fouled tube, the pressure drop can be represented as

$$\Delta P_f = 4f \frac{L}{d - 2x} \frac{\rho u_f^2}{2} \tag{7}$$

If the friction factor is assumed constant, the pressure drop can be related to foulant thickness by Blasius correlation [10] as follows:

$$\Delta P_f = \Delta P_0 \left(1 - \frac{2x}{d}\right)^{-4.75} \tag{8}$$

2.3 Fouling rate

Kern and Seaton [11] considered the deposition of foulant due to two competing processes: deposition and removal. Some of the foulant material are removed from the layer by the action of turbulent eddies. The net deposition can be given as follows:

$$\frac{d\mathrm{R}_f}{dt} = \dot{\mathrm{m}}_D - \dot{\mathrm{m}}_R \tag{9}$$

The fouling rate can be determined from the slope of fouling resistance-time curves, which changes typically during the process, as shown in **Figure 1**.

Initially, with the clean surface of the heat exchanger, the fouling resistance does not increase with time due to the low strength of the deposit to stick with the surface. This period of zero fouling rate is known as the induction period. Sometimes, during the induction period, the fouling rate becomes negative, representing the enhancement of heat transfer because of increased surface roughness contributed by the initial foulant layer. After the termination of the induction period, a constant initial fouling rate is usually attained. The fouling phenomenon determines the shape of the fouling resistance-time curve. As shown in **Figure 1**, an accelerating fouling curve represents a negligible removal rate due to hard deposits.

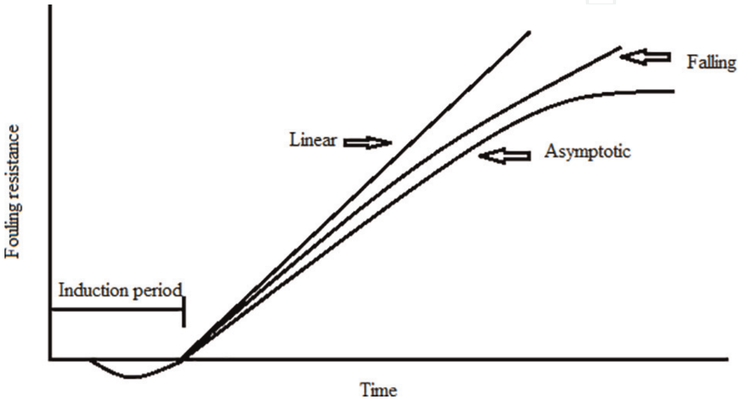


Figure 1.
Fouling resistance-time curves for different fouling mechanisms [11].

The linear fouling curve is the most common behavior in heat exchangers; it represents constant deposition and removal rate, while the deposition dominates over the removal. It is usually associated with crystallization fouling, but some studies also showed the asymptotic behavior for crystallization fouling [12, 13]. The falling and asymptotic curves depict the existence of the removal rate. As the deposit builds up, the flow area is reduced, and the velocity increases, allowing the foulant removal by shear forces. This retardation phenomenon is the cause of the asymptotic behavior of the fouling resistance-time curve and is proportional to the thickness of the foulant layer. This behavior is most familiar with particulate fouling and constant heat flux operations. The sawtooth behavior is typical in crude oil fouling, where the sudden removal of the deposits causes a negative fouling rate.

This initial fouling rate was represented by Ebert and Panchal [14] as a semi-empirical threshold model for crude oil fouling as:

$$\frac{dR_f}{dt} = \alpha\, Re^{-\beta} \exp\left(\frac{-E}{RT_f}\right) - \sigma\tau_w \tag{10}$$

They described the threshold point where the induction period is terminated. The above model was developed to predict the film temperature for a particular velocity to achieve a zero initial fouling rate, i.e., threshold point. They found that if this condition is maintained during the operation, there would be negligible or no fouling. If the left-hand side of Eq. (10) is taken to be zero, then a set of data appoints can be generated as shown in **Figure 2** for different values of film temperatures. The developed curve in **Figure 2** can be employed to estimate the corresponding film temperature in the non-fouling zone for a particular velocity.

The fouling prediction models are modified to produce a similar behavior caused by complex interaction of different mechanisms existing in the crude oil fouling process. The feedstock composition also plays a critical role in defining the fouling behavior. The presence of inorganic and asphaltenes molecules in crude oil makes it difficult to predict feedstock composition effects on fouling rate.

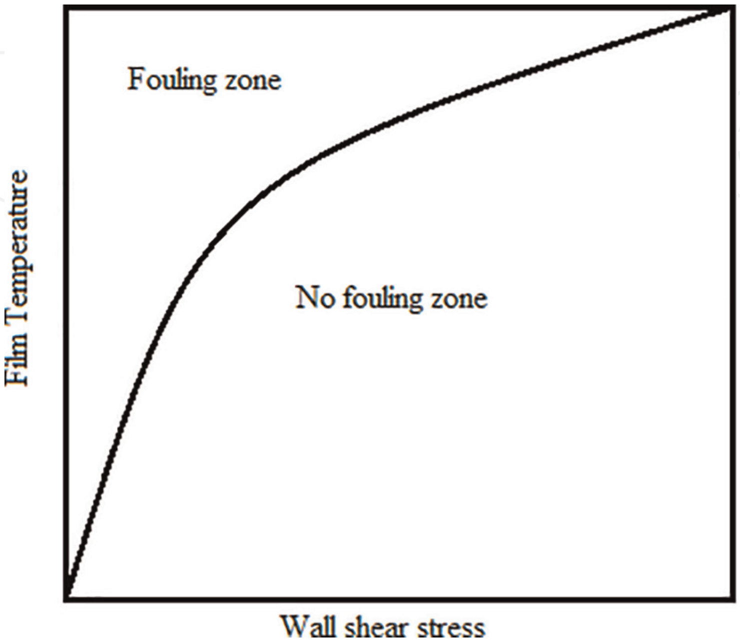


Figure 2.
Data curve to estimate film temperature for corresponding shear stress at zero fouling rate [14].

3. Types of fouling

Fouling phenomena depend on the type and concentration of foulant precursors in the bulk fluid entering the heat exchanger. There are several types of fouling based on the feedstock handled by the heat exchanger. Typically, foulant material consists of organic and inorganic constituents with deposition rates proportional to each other [15]. The following paragraphs are devoted to explaining different types of fouling.

3.1 Particulate fouling

The deposition of particles on the heat transfer surface is known as particulate fouling. These particles include originally suspended particles in the feedstock before entering the heat exchanger and particles formed within the heat exchanger by reaction or flocculation. The concentration of filterable solids in crude oil indicates the potential of particulate fouling. Wang and Watkinson [16] found that iron sulfide particles in crude oil were formed by the chemical reaction of hydrogen sulfide with iron oxides which resulted in particulate fouling. These particles can be inorganic, organic, or a mixture of both. For example, the salt contained by the boiler water and crude oils, corrosion products, and sand and dirt particles in cooling water is commonly referred to as inorganic particle fouling. Similarly, the deposition of organic particles produced by the aggregation and flocculation of asphaltenes in crude oils is known as organic particle fouling. The thermophoretic forces sometimes govern the particle deposition, which act on particles when there is a temperature difference between the hot surface and bulk fluid.

3.2 Chemical reaction fouling

Under a favorable condition, the soluble reactants present in the fluid tend to react to form insoluble products, which are then deposited on the heat transfer surface. The reaction in the bulk fluid is often polymerization of organic molecules, which results in products with high molecular weights. The presence of transition metals and heteroatoms such as nitrogen, sulfur, and oxygen tend to catalyze the reaction by polarizing other organic molecules, leading to lower activation energies for the reaction to occur. The oxygen reacts with organic molecules to form peroxides, increasing the polymerization reaction rate. The formation of highly viscous organic foulant from the deformation of organic molecules is also an example of chemical reaction fouling in refinery pre-heat train and furnace. Some reactions take place on the heated surface to transform them into harder products that are not easily removed, such as coke formation at high temperatures. The presence of unsaturated hydrocarbons, acidic compounds, mercaptans, and amines in crude oils induce polymerization reactions. Commonly, the acid number of crude oil is estimated to indicate its susceptibility to fouling. Temperature is also an important factor in chemical reaction fouling which promotes the fouling process. Therefore, it is desirable to operate the process at lower temperatures to mitigate the fouling phenomena.

3.3 Corrosion fouling

The reaction of metal surfaces with the fluid stream in contact to produce deposits is called corrosion fouling. This type of fouling is highly dependent on the surface roughness, composition, and impurities in the fluid stream. The most common impurity is sulfur, nitrogen, and chlorine compounds such as ammonia, hydrogen sulfide, and hydrogen chloride. The salt present in crude oils in the from sodium, calcium and magnesium chlorides sometimes enters the heat exchanger due to less efficient desalter process. When heated in the form of chlorides, these salts break down to hydrogen chloride, which is very toxic for steel. The hydrochloric acid deposits on the heat transfer surface and form corrosion product such as iron chloride. The reaction is incessant with the continuous production of hydrogen chloride.

$$CaCl_2 + H_2O \rightarrow CaO + 2HCl$$

$$2HCl + Fe \rightarrow FeCl_2 + H_2$$

$$FeCl_2 + H_2S \rightarrow FeS + 2HCl$$

The sulfur present in crude oils also reacts with iron to form iron sulfide, which is toxic to the metal surface. Mostly, the organic acids such as naphthenic acids present in crude oils tend to react with iron to form iron-organic acids, which then react with hydrogen sulfide to form iron sulfide.

$$Fe + 2RCOOH \rightarrow Fe(RCOO)_2 + H_2$$

$$Fe(RCOO)_2 + H_2S \rightarrow FeS + 2RCOOH$$

The amount of naphthenic acid present in crude oils is represented by total acid number (TAN), which indicates crude oil susceptibility to corrosion. The iron sulfide is insoluble in water and crude oil which act as protection from further corrosion at low shear stress regions. Sulfur compounds like mercaptans decompose to hydrogen sulfide in the presence of hydrogen gas and become highly corrosive [16]. Temperature is also plays a major role in the corrosion process. The decomposition of mercaptans into H_2S, called sulfidation, occur in the presence of hydrogen gas at temperatures higher than 230°C. If temperature exceeds 370°C the H_2S decompose into elemental sulfur which is the most toxic state of sulfur.

3.4 Biofouling

This type of fouling can be caused by microorganisms (bacteria, algae, or fungus) or macroorganisms (barnacles, mussels, or seaweeds). These organisms colonize the metal surface by taking the nutrition from the interface between biofilm and fluid. Initially, the aerobic species consume the available oxygen and lead to anaerobic conditions, which only require nutrition to thrive [17]. This condition results in the rapid growth of biofilm. Biofouling is commonly found in sea and wastewater systems. The biofilm deposition by the microorganisms and their products served as the resistance to heat transfer in recirculation systems. The flow reduction and blockage of fluid passage are directly related to macroorganisms' growth in once-through systems. These organisms can trap the silt and other suspended particles, which reduce the thermal efficiency of heat exchangers. Due to the depletion of oxygen near biofilm, the metal surface beneath biofilm becomes anodic, which results in an enhanced corrosion rate [18]. Biofouling can also result in corrosion by supplying ion-concentrated sites. The most common industries affected by biofouling are food, marine, water, medicine, and mining. Biofouling is highly concerned in power plants where condenser operations are highly susceptible to biofouling and corrosion. Chlorine is added to the water to overcome this difficulty.

3.5 Crystallization fouling

In this type of fouling, the inorganic salts become insoluble in the fluid at supersaturated state and form deposits on the heat transfer surface. These salts can behave with normal solubility or inverse solubility. With normal solubility behavior, the solubility increases with temperature and vice versa with inverse solubility. The nuclei of the salt crystal can be formed in the bulk fluid and on the heated surface with inverse solubility at high temperatures. These nucleation sites may be corrosion products, impurities like crystals, or irregular sites on the surface. The crystals formed in the bulk fluid are deposited on the heated surface. The fouling grows by the deposition of the crystal layer over another layer. This fouling is common in desalination systems, boilers, and evaporators [19]. The crystallization fouling from inorganic salts from water is known as scaling. These salts usually are sulfates and carbonates of calcium and magnesium.

3.6 Precipitation fouling

The deposition of asphaltenes separated from crude oils is categorized as precipitation fouling. Asphaltenes are considered the major foulant in crude oil fouling. When precipitated and flocculated from the crude oil, the asphaltenes molecules form large particles. These particles are aggregated and deposited on the surface of the heat exchanger. The chemical formula for asphaltenes is not specific; the number of atoms a molecule contains varies depending upon the source. Also, the molecular weight of asphaltenes differs in a wide range. The average molecular weight of asphaltene is 750 amu [20]. The structure of the asphaltene molecule contains polycyclic aromatic rings with alkyl side chains. The presence of heteroatoms, e.g., oxygen, nitrogen,

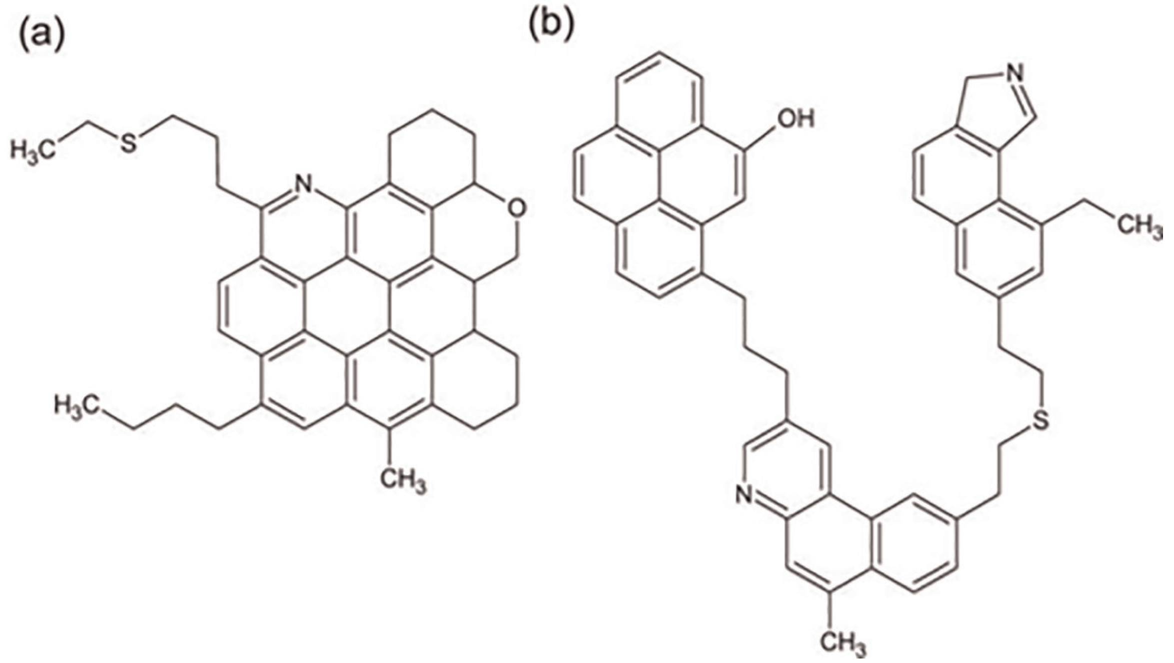


Figure 3.
Structure of asphaltenes molecule: Yen–Mullins island model (a) and archipelago model (b) [23].

sulfur, nickel, and vanadium, renders its polarity. There are two suggested structure types of asphaltene molecule, i.e., island and archipelago. The island structure is comprised of a monomer containing six or more rings, while the archipelago is a polymeric structure with polycondensed groups of rings linked by aliphatic side chains [21]. A rough estimate suggested about 7–8 fused rings in a single polycyclic aromatic hydrocarbon (PAH) [22] which favors the proposed island structure.

The concentration of peptizers such as aromatics and resins in the crude oil should be enough to hold the asphaltenes soluble in the crude oil (**Figure 3**). The saturates present in the crude oils are considered as flocculants for the asphaltenes [24]. The ability of crude oils to maintain asphaltenes soluble is called stability. Sometimes the combination of different crude oils induces the precipitation of asphaltenes which cause deposition in the heat exchangers. The Colloidal Instability Index (CII) is considered as a good indication of the fouling propensity by asphaltenes precipitation.

4. Fouling mechanism

Fouling is a complex phenomenon that involved multiple processes. These processes occur in a sequential manner, and sometimes one process dominates over another. The general sequence can be shown in the steps below:

Precursors → Foulant → Hard Deposit

Initially, the fouling precursors enter the heat exchanger or formed within the heat exchanger. These fouling precursors are then reacted to form insoluble deposits on the heat transfer surface. After the deposition, the foulant is transformed into a hard material by aging, which is difficult to be removed. It is still debatable whether the formation of precursor and foulant is in the bulk fluid or on the heat transfer surface. However, it is evident from the experimental work [25, 26] that the solubility of precursors and temperature have a high impact on fouling and both of these factors can affect fouling in the bulk fluid as well as on the heat transfer surface.

Epstein [27] categorized the fouling in the five stages known as the 5 × 5 matrix, as shown in **Figure 4**. This matrix relates the fouling stages with the type involved in the process.

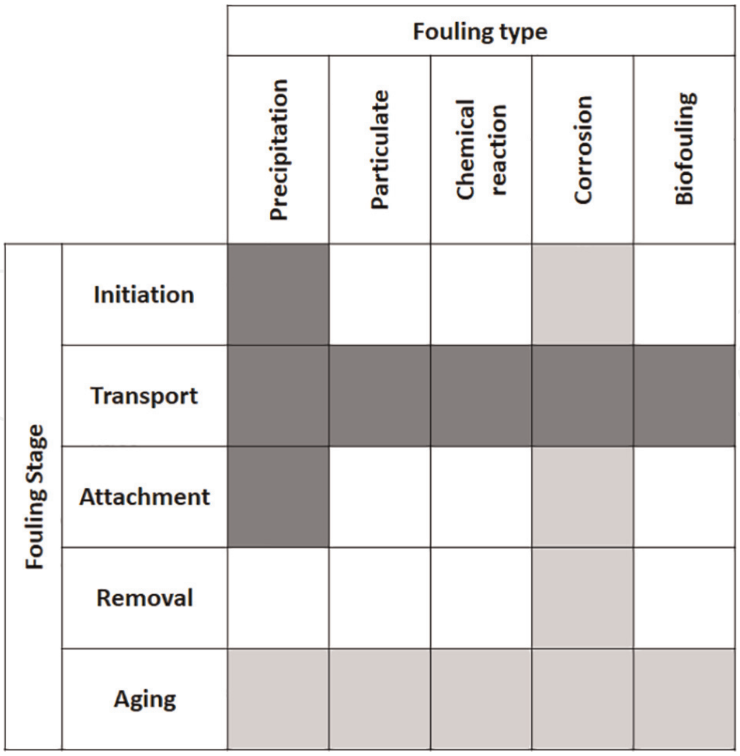
The details of these main five events, i.e., initiation, transport, attachment, removal, and aging, are described in the subsequent paragraphs.

4.1 Initiation or formation of foulant material

The fouling phenomenon starts with a delay or induction period with no increase in the resistance to heat transfer. On the contrary, the fouling resistance sometimes becomes negative due to an increase in surface roughens, which enhances heat transfer by turbulence [28]. The surface roughness is caused by the initial deposition of particles on the clean surface present initially in the bulk fluid or formed by polymerization or corrosion reaction.

Only a few studies were done on predicting the length induction period. Yang et al. [29] developed a model for fractional surface coverage (θ) of the clean surface. The model relates the surface coverage with time using a sigmoidal function as:

$$\theta = \frac{k_1 - k_2}{k_1} \frac{1}{1 + we^{-(k_1 - k_2)t}} \tag{11}$$



Fouling Stage	Fouling type: Precipitation	Particulate	Chemical reaction	Corrosion	Biofouling
Initiation	■			▒	
Transport	■	■	■	■	■
Attachment	■			▒	
Removal				▒	
Aging	▒	▒	▒	▒	▒

Figure 4.
The current standing of the 5 × 5 fouling matrix by Epstein [27]. The color change from lighter to darker indicates the increase in the degree of understanding.

To maintain a long induction period, the value of deposition rate constant (k_1) should be equal to removal rate constant (k_2). They defined the induction period length as the time to reach 50% of the maximum surface coverage. A good agreement of model found with experimental data of deposition from crude oil, protein, and salt. They found very short induction periods with initially not cleaned surfaces. The length of the induction period depends on various factors such as fluid composition, surface roughness, temperature, and velocity. However, the temperature is the most significant parameter that affects the induction period length because the other factors, such as solubility of precursors and reaction rate, are also temperature-dependent. High temperature and low velocity significantly reduce the length of the induction period.

4.2 Transport to the heat transfer surface

The transfer of fouling precursors from the body of the fluid to the heat transfer surface occurs in many ways, e.g., diffusion, sedimentation, thermophoresis, or impaction. The migration of the precursor from bulk fluid to the surface boundary layer due to the concentration difference is called diffusion [30]. The deposition rate by diffusion can be described as

$$\dot{m}_D = k_m(c_b - c_s) \tag{12}$$

where k_m is the deposition rate constant. The mass transfer coefficient, k_m, can be estimated using the correlations of Sherwood number.

The sedimentation process by the action of gravitational force is common for large deposit particles such as sand, clay, or rust material [31]. The drag force on the particle should be lower than the gravitational force to settle it down on the surface. Thermophoresis, also known as thermodiffusion or Soret effect, is caused by the diffusion due to temperature gradient [32]. The particles are transferred from the hot zone to the cold zone by the thermophoretic force. This phenomenon is common in gas phase deposition, where particles are derived towards the colder regions of the heat exchanger. The deposition of particles by impaction is also significant as some particles achieve high velocity with respect to the fluid and reach the hot surface by inertial force.

4.3 Attachment or formation of the deposit at the heat transfer surface

The attachment of particles transported to the surface is highly dependent on the condition of the surface. The rough surface contains the potential to bind with the particles due to the availability of nucleation sites. The protective coatings on the heat exchanger surface provide a low-energy surface, reducing its wettability and preventing fouling. The sticking probability of the particles, defined as the residence time of the particles on the heat transfer surface, is also a function of velocity and surface temperature. The experimental studies suggest increased deposition with low velocity and high surface temperature [33]. Considerable work has been performed to model foulant deposition on heat transfer surfaces [34]. Many empirical or semi-empirical models were proposed to describe the deposition mechanism. Kern and Seaton [35] were the first to propose the deposition model as a competing phenomenon between deposition and removal as follows:

$$dx/dt = \alpha c_b J - \beta \tau x \tag{13}$$

The first and second terms on the left-hand side represent the rate of deposition removal. They consider the removal rate to be the function of the thickness of the fouling layer. Paterson and Fryer [36] proposed a model for fouling by skimmed milk. They assumed the laminar sub-layer as a differential chemical reactor in which the foulant is produced, and the deposition rate is the product of the foulant production rate and sticking probability. The proposed model is given as

$$\frac{dR_f}{dt} = \alpha \, \exp\left(-E/RT\right)/\mathrm{u}_o \tag{14}$$

Polley et al. [37] suggested a fouling prediction model which relates the sticking probability (S) with shear stress as:

$$\frac{dR_f}{dt} = \frac{A_o}{\alpha} e^{-E/RT_f} S \tag{15}$$

The sticking probability was defined as the function of shear stress

$$S = 1 - \left(\frac{\tau_w - 2}{98}\right)^{0.5} \tag{16}$$

Other forces can influence particle residence time on the heat transfer surface, such as London–van der Waals force, electric double-layer structure, and viscous hydrodynamic force [38].

4.4 Removal of material from the heat transfer surface

It is possible that the part of the deposited material loses its bonding with the surface or the deposition layer. The net deposition of the foulant is the result of the difference between the deposition rate and the removal rate. These two mechanisms occur simultaneously during the fouling process. Several factors affect the removal process, such as erosion, diffusion, or dissolution [39]. The shear forces generated by the interaction of moving fluid and the static foulant layer cause the breakup of the foulant particles from the deposited layer. These shear forces can also be generated from the turbulent sweeps and bursts. As the deposited layer becomes thicker, the cross-sectional area reduces, resulting in increased velocity and shear stress at the fluid-layer interface, referred to as the auto-retardation process [40]. This phenomenon leads to the removal of foulant particles by spalling or erosion. There is also a possibility that the deposit is removed by diffusion back to the bulk fluid. It is only possible if the foulant is a reaction product transformed into a soluble product or by the concentration gradient between the foulant layer and the bulk fluid. Kern and Seaton [35] related the deposition rate with the thickness of the foulant layer as:

$$\dot{\mathrm{m}}_R = \mathrm{k}_r \tau x \tag{17}$$

Polley et al. [41] modified the model by suggesting the controlling mechanism of removal as mass transfer dependent rather than shear stress. They replaced the shear stress parameter with $\mathrm{Re}^{0.8}$ as:

$$\dot{\mathrm{m}}_R = \mathrm{k}_r \, Re^{\,0.8} \tag{18}$$

The removal term is also referred to as entrainment because initially, there is no fouling layer on the clean surface to be removed [42].

4.5 Aging

After the foulant deposition, physical and chemical transformation occurs, which results in its mechanical and thermal properties known as the aging process. As time passes, the foulant becomes hard and thermally more conductive by the action of heat. In a few cases, such as in biofouling, the deposit becomes weaker in strength due to the corrosive decay of microorganisms. The organic deposit becomes harder in crude oil fouling as the coking process starts after the deposition. The thermal conductivity of the deposit also increases with aging, which also enhances the heat transfer resulting in a lower fouling rate. The change in thermal conductivity due to the conversion of organic deposit into a coke-like material was reported to be from 0.2 to 1 W/m K [43]. This mechanism is crucial in estimating the accurate thickness of the foulant layer. Therefore, aging plays a key role in describing the thermohydraulic behavior of heat exchangers. A long time is required for aging to occur, rendering its measurement impossible in laboratory experiments. The aging phenomenon was incorporated in the fouling prediction models by Ishiyama et al. [44]. They correlated the foulant thermal conductivity with a youth factor, y, which gradually decreases from 1 to 0 as aging takes place. The deposit thermal conductivity was represented as:

$$\lambda_f = \lambda_f^{\infty} + \left(\lambda_f^{o} - \lambda_f^{\infty}\right) y \tag{19}$$

The youth factor was modeled using a first-order kinetics as:

$$\frac{dy}{dt} = ky \tag{20}$$

where k is the rate constant for aging, which depends on temperature by Arrhenius law.

They assumed that the overall fouling resistance is the sum of resistance by individual sublayers with different aging histories. The thickness of each sublayer was assumed constant; however, the thermal conductivities were varied with time. This modeling scheme enabled to produce a close to the real behavior of the fouling process.

5. Conclusion

Fouling is still a long-standing problem in heat transfer research. It is related to the economic and environmental penalties in heat transfer operations. The complexity of the fouling mechanism entails difficulty in its understanding. However, recent development in fouling prediction models has enabled researchers to estimate the fouling rate accurately. A successful design of a heat exchanger requires a deep understanding of the fouling mechanism. This understanding is promising in improving the accuracy of mitigation actions to optimize the operation of the heat exchanger. Similarly, it also assures cost-effective cleaning and production planning.

Nomenclature

A_o	Arrhenius coefficient
A	Heat transfer area, m^2
c_b	Concentration of foulants in bulk fluid, mol/m^3
c_s	Concentration of foulants on surface, mol/m^3
d	diameter of tube, m
E	Activation energy, J/mol
f	fanning friction factor
J	mass flux, kg/s
k_1, k_2	lumped rate constants, s^{-1}
L	length of tube, m
$\dot{m}_D$	deposition flux, kg/m^2 s
$\dot{m}_R$	removal flux, kg/m^2 s
P	pressure, atm
Q	rate of heat transfer, J/s
q	heat flux, J/m^2s
q_o	initial heat flux, J/m^2s
q_t	heat flux after time t, J/m^2s
R	Gas constant, J/mol K
R_f	thermal resistance, m^2K/W
Re	Reynolds number
S	sticking probability

t	time, s
T	temperature, K
T_f	film temperature, K
U	overall heat transfer coefficient, W/m^2K
U_o	clean overall heat transfer coefficient, W/m^2K
u_o	initial flow velocity, m/s
u_f	flow velocity in fouled tube, m/s
w	wettability parameter
x	deposit thickness, m
y	youth factor
Greek	
$\alpha, \beta, \gamma, \sigma$	model fitting parameters.
λ_f	foulant thermal conductivity, W/m K
λ_f^o	fresh foulant thermal conductivity, W/m K
λ_f^∞	aged foulant thermal conductivity, W/m K
ρ	density, kg/m^3
τ	shear stress, N/m^2
τ_w	wall shear stress, N/m^2
μ	dynamic viscosity, Pa s
θ	fractional surface coverage

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