



Towards a common taxonomy for heat exchanger fouling

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Abstract

A literature search on the term ‘fouling’ shows that it arises in several, very different, contexts. In process engineering, fouling often refers to the loss in heat exchanger performance resulting from the deposition and/or growth of unwanted layers of material at the heat transfer surface. In 1978 *Epstein* (Epstein In: Proceedings of the 6th International Heat Transfer Conference (held in 1978). Hemisphere Publishing, New York, 6:701–732, 1981) proposed a characterisation of fouling processes in heat transfer according to the dominant formation mechanism, which was accompanied by a careful classification of terms to describe the different feature. This resulted in Epstein’s seminal paper on the 5×5 fouling matrix (Epstein in Heat Transf Eng 4:43–56, 1983). The subsequent 40 years of research in heat exchanger fouling and cleaning have introduced more terms and, on occasion, introduced some confusion in terminology. This is also evident in quantitative treatments of fouling, and recent conferences have featured helpful discussions of terminology for particular cases. There is a case for a systematic review of fouling taxonomy. We present a review of current and previous fouling taxonomies, both written and mathematical, and propose a modification of *Epstein*’s matrix. We present a suggested formalisation which could be used as a ‘common language’ to guide understanding for future meetings and publications.

Abbreviations

DFI Degree of fouling increase, -
THE Thermohydraulic efficiency, -

Latin letters

A Area, m²
 \tilde{A} Hamaker constant, J
 a Surface coverage, %
 Bi Biot number, -
 C_f Fanning friction factor, -
 E Energy, N
 F Configuration factor, -
 F_S Surface shear force, N
 h Film heat transfer coefficient, W m² K⁻¹

m Mass coverage, kg m⁻²
 Nu Nusselt number, -
 P Pressure, bar
 Q Heat transfer rate, W
 R Thermal resistance, m² K W⁻¹
 R_i Surface roughness, m
 St Stokes number, -
 T Temperature, K
 t Time, s
 U Overall heat transfer coefficient, W m⁻² K⁻¹
 u Mean velocity, m s⁻¹
 x Wall thickness, m

Greek letters

β Mass transfer coefficient, m s⁻¹
 γ Surface energy, N m⁻²
 δ Thickness, m
 θ Contact angle, °
 ζ Zeta potential, V
 ξ Friction coefficient, -
 λ Thermal conductivity, W m⁻¹ K⁻¹
 ρ Density, kg m⁻³
 τ Shear stress, Pa

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Subscripts

0	Clean state
C	Cold side
d	Deposition
f	Fouling
H	Hot side
HE	Heat exchanger
HT	Heat transfer
ind	Induction
ini	Initiation
LM	Log-mean
m	Mass based
r	Removal
s	Shear
th	Thermal
w	Wall

1 Introduction

In general, the term fouling can be described as the accumulation of unwanted deposits on surfaces, particularly those used for heat transfer [1]. Fouling is a major challenge across the process industries. Surveys have shown that more than 90% of heat exchangers used in industry have problems due to deposits [2, 3]. The consequences of the formation of deposits in heat exchangers and other system components are manifold [4]: firstly, the presence of a deposit layer on a heat transfer surface represents an additional thermal resistance and thus progressively deteriorates the heat transfer performance of an apparatus. In addition, the presence of the layer alters the fluid dynamics via narrowing of flow channels, enhances surface roughness, or both, resulting in increased pressure losses in the system. Fouling layers can encourage undesirable reactions such as corrosion or harbour microorganisms that can promote corrosion and/or contaminate the product stream. Fouling can also reduce the service life of apparatus and plant equipment, resulting in higher maintenance costs.

The negative effects of fouling in heat exchangers are often countered in the design phase by increasing the heat transfer surface area over the value for a clean, non-fouled unit. Various studies have estimated the corresponding oversizing to be between 10% and 67%, with corresponding extra capital investment for the unit and its supporting structures [2, 5, 6]. In order to compensate for the poorer heat transfer performance and the increased pressure loss, the energy requirement of a process also increases. The regular cleaning of equipment that is prone to fouling also leads to downtime and thus production losses, or additional capital for standby units. These all result in additional costs. According to one extrapolation, the cost of fouling in a

strongly industrialized country is about 0.25% – 0.3% of gross domestic product [2]. The magnitude of these impacts has prompted the scientific investigation of fouling for several decades [7]. The authors have found no recent surveys or calculations on the economic significance of fouling, nor its impact on the environment and health. There is a strong need for a review of this type.

Research has considered methods for minimizing fouling and developing or optimizing cleaning processes, as well as gaining a better understanding of the various basic deposition mechanisms involved in order to be able to predict the formation and growth of fouling more accurately. Detailed knowledge of the likely deposition behaviour allows targeted counteraction and thus a reduction in the costs arising from fouling at the design stage.

In the academic and industrial fouling (& cleaning) communities, different terms and definitions are often used for the same topic, or the definition is either not clear or ambiguous. This is already evident when considering the different names for fouling layers, as shown in Table 1.

This taxonomy is intended to help people working on fouling to employ a common language for an easier and precise communication. The focus here is on fouling in heat exchangers and makes no claim to be complete, as it can be revised regularly. It does not consider fouling in other process engineering devices such as membranes, separation and absorption columns, and piping. It focuses on deposition in heat transfer systems, where the presence of a temperature gradient is essential for the unit to operate and which, in turn, promotes the mechanism for deposit formation. Noticeably different mechanisms arise in membrane fouling, where deposition is driven by the rejection of species by the separating agent and can result in deposit forming at the surface *and* within the membrane ‘wall’ [8].

An agreed terminology is useful to describe the following aspects of fouling:

- (i) The mechanisms and processes involved in generation of fouling deposits.
- (ii) Quantifying the impact of fouling.
- (iii) Fouling dynamics and fouling behaviour.

2 Definitions

The authors have grouped the items primarily on the basis of thematic relationships. There are some terms, however, which appear more than once as they are used broadly. A detailed explanation of such a term may appear in a later section.

Readers should note that operating and design aspects are not discussed, e.g. how quantifications of fouling impacts are included in the design of a heat exchanger.

Table 1 Names for fouling layers (N.B. This is unlikely to be complete)

Name	Use, application
Fouling deposit	General term. N.B. 'deposition' is often used incorrectly to refer to the fouling deposit rather than the action by which a deposit is generated
Scale/scaling	Typically crystalline deposits generated in hard water applications, but also used with a more general meaning as continuous, adherent deposits that form because of interactions between the environment and the base material. There is also possible confusion with size scale, e.g. from lab to industrial scale.
Precipitate	Insoluble, crystalline materials that have formed a continuous adherent layer on the base substrate. Typically found in water systems.
Sludge	Insoluble materials that are loosely bonded or unbonded to the supporting surfaces. Can be combinations of organic and inorganic material and are typically found in towers, boilers, and tanks.
Soil layer	Mainly used for foodstuff based deposits and in the context of cleaning.
Contamination	Mainly used for microbiological deposits (e.g. spores or biofilms) and in the context of cleaning.
Biofilm	Slime layer on surfaces formed by microorganisms that are themselves embedded in the layer.
Wax layer	Crystallisation of waxes from hydrocarbon mixtures
Slagging	Gas side fouling in the radiant section of fired heaters
Coke formation	Furnace deposits in crude oil processing
Wall build-up	Spray driers

2.1 Quantifying fouling

Heat exchangers are widely used in the chemical, processing, power generation and other industries. They serve as preheaters, condensers, evaporators or as heat integration devices. In a heat exchanger, thermal energy is transferred from a hot process stream on one side of a heat transfer surface to a cold stream on the other (see Fig. 1). The rate of heat transfer, or duty, Q , is usually modelled as

$$Q = UAF\Delta T_{LM} \quad (1)$$

where ΔT_{LM} is the log-mean temperature driving force, F is the configuration factor and A is the area of thermal contact between the two streams: U is the overall heat transfer coefficient and quantifies the ability of the device to transfer heat per unit time. It is an overall (integrated) measure because it is usually not possible to measure local duties and temperatures in different parts of an industrial heat exchanger. When layers of unwanted material start to accumulate on either or both sides of the heat transfer surface, its ability to transfer heat, expressed via U , decreases.

Consider a deposit layer forming on one side of the heat transfer surface. The layer is often assumed to have uniform thickness, of value δ_f , as it is difficult to measure any variation in situ. The amount of foulant per unit area, m_f , is related to the density of the layer, ρ_f .

Fouling in heat exchangers is normally quantified by its impact on the overall heat transfer rate, as local variations in deposit coverage and thickness, heat flux and pressure drop cannot be determined reliably, see Table 2.

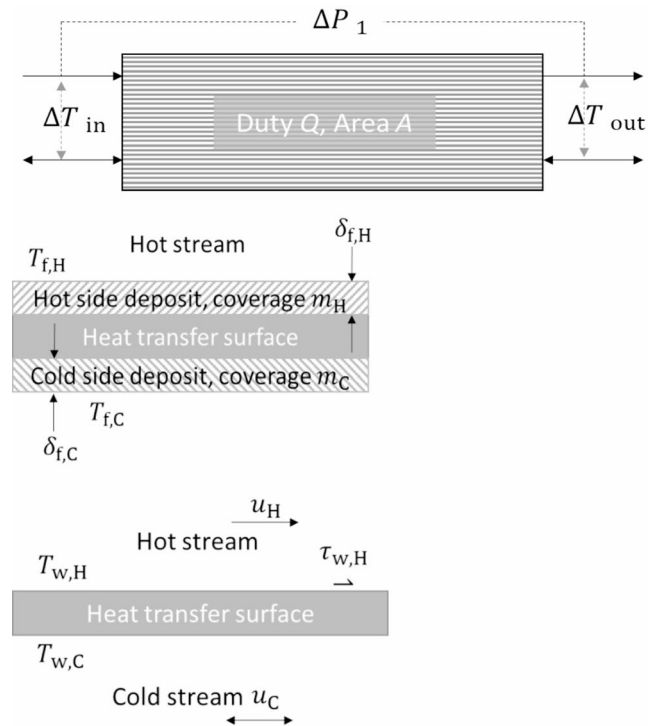


Fig. 1 Schematics of heat transfer in the presence of fouling. The temperature at the heat transfer surface is labelled the *wall temperature*, T_w , while the temperature at the interface between a deposit and the stream is labelled the *interface temperature*, T_f

It is important to identify whether the fouling parameter is based on a *local* or an *overall* (integrated) method. Estimates of fouling behaviour based on heat exchanger performance are an example of the latter. Experimental studies of fouling can provide local estimates of heat fluxes and/or overall rates of

Table 2 Measures of amount of deposit formed. All equations are written for flat walls

Item	Definition	Symbol/Unit	Equation
Fouling (verb participle)	The <i>process</i> of accumulating unwanted material on (heat transfer) surfaces.		
Fouling resistance	Additional thermal resistance to the flow of heat arising from the presence of the fouling layer on the hot flow side (H) and/or the cold flow side (C)	R_f [$\text{m}^2 \text{K W}^{-1}$]	$\frac{1}{U} = \frac{1}{h_H} + R_{f,\text{th},H} + \frac{x_w}{\lambda_w} + \frac{1}{h_C} + R_{f,\text{th},C}$ (2)
Thermal fouling resistance	Change in overall heat transfer coefficient due to the presence of fouling layer(s), defined as the difference between the reciprocal of the overall heat transfer coefficients for a fouled (U_f) and a clean (U_0) heat transfer surface.	$R_{f,\text{th}}$ [$\text{m}^2 \text{K W}^{-1}$]	$R_{f,\text{th}} = \frac{1}{U_f} - \frac{1}{U_0}$ (3)
Deposit resistance	An alternative form of writing $R_{f,\text{th}}$ presented by <i>Smith and Hitimana</i> [9] for fouling in a fouling test cell, where R_d quantifies the conductive resistance of the deposit layer and ΔR_h the change in film heat transfer coefficients.	R_d [$\text{m}^2 \text{K W}^{-1}$]	$R_{f,\text{th}} = R_d + \Delta R_h$ (4)
Fouling factor	Another name in common use for ‘fouling resistance’: mathematically, it is not a factor but an additional term.	R_f, R_d [$\text{m}^2 \text{K W}^{-1}$]	
Asymptotic fouling resistance	Steady, non-zero value of the fouling resistance achieved after some time when the fouling rate approaches zero. Also referred to as final value of the fouling resistance.	R_f^∞ [$\text{m}^2 \text{K W}^{-1}$]	
Mass based fouling resistance	Estimate of the thermal fouling resistance based on the deposit mass. Calculated from the ratio of fouling layer thickness δ_f and thermal conductivity λ_f , assuming the fouling layer is uniformly distributed over the heat transfer surface	$R_{f,m}$ [$\text{m}^2 \text{K W}^{-1}$]	$R_{f,m} = \frac{\delta_f}{\lambda_f} = \frac{m_f}{\rho_f \lambda_f}$ (5)
Specific fouling mass	Mass of foulant per unit area	m_f [$\text{kg}\cdot\text{m}^{-2}$]	$m_f = \rho_f \delta_f$ (6)
Mean fouling layer thickness	Average value assuming an even distribution of the deposit over the whole surface area. This can be estimated from the mass deposited mass or the fouling resistance, if the deposit density or thermal conductivity, respectively, is known.	δ_f [m]	
Surface coverage	Fraction of the heat transfer area A_{HT} covered by fouling deposit.	A_f [$\text{m}^2\cdot\text{m}^{-2}$] or [%]	$a_f = \frac{A_f}{A_{\text{HT}}}$ (7)

heat transfer, depending on the configuration and measurement technique(s) employed. Detailed mathematical models usually generate estimates of local fouling behaviour which are then combined with a simulation of the system, which computes variation in temperatures and flow rates across the unit, to give an overall measure.

2.2 Fouling rates

The fouling rate, see Table 3, quantifies the change in thermal resistance with respect to time. From the definition in Eq. (3) it follows

$$\frac{dR_{f,\text{th}}}{dt} = \frac{d}{dt} \left(\frac{1}{U_f} - \frac{1}{U_0} \right) = \frac{d}{dt} \left(\frac{1}{U_f} \right) - \frac{d}{dt} \left(\frac{1}{U_0} \right) \approx \frac{d}{dt} \left(\frac{1}{U_f} \right) \quad (8)$$

with the final equality applying if the conditions do not change such that U_0 is constant.

When there is fouling on one side of the heat transfer surface, as arises when one stream is precursor free or when the surface is electrically heated, the thermal impact of the deposit is often modelled as arising from a layer with thermal conductivity λ_f and density ρ_f . The change in thermal resistance can be related to the amount of deposited solids mass per unit area m_f , via

$$\begin{aligned} \frac{dR_{f,m}}{dt} &= \frac{d}{dt} \frac{m_f}{\rho_f \lambda_f} = \frac{1}{\rho_f \lambda_f} \frac{dm_f}{dt} \\ \frac{m_f}{\rho_f^2 \lambda_f} \frac{d\rho_f}{dt} - \frac{m_f}{\rho_f \lambda_f^2} \frac{d\lambda_f}{dt} &\approx \frac{1}{\rho_f \lambda_f} \frac{dm_f}{dt} \end{aligned} \quad (9)$$

Table 3 Fouling rates

Item	Definition	Symbol/Unit	Equation
Deposition rate	Rate of deposition of foulant material per unit area per unit time	\dot{m}_d [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$]	
Removal rate	Rate of removal of deposit material per unit area per unit time.	\dot{m}_r [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$]	
Net deposition rate	Mass-related deposition rate. Resultant of deposition and removal rate according to the <i>Kern & Seaton</i> model.	\dot{m}_f [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$]	$\dot{m}_f = dm_f/dt = \dot{m}_d - \dot{m}_r$ (11)
Fouling rate	Change in overall thermal resistance with time	\dot{R}_f [$\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}\cdot\text{s}^{-1}$]	$\dot{R}_f = dR_f/dt$ (12)

with the final equality again applying when the layer properties are uniform and constant. Following *Kern* and *Seaton* [9], mass deposition is often described as a superposition of the simultaneous processes of layer growth and layer removal, giving the net deposit formation rate as:

$$\dot{m}_f = \dot{m}_d - \dot{m}_r \quad (10)$$

It should be noted that Eq. (10) predicts that $R_{f,m}$ will decrease over time if deposition stops but the density or the thermal conductivity increase. This is an example of *ageing*, and illustrates how fouling behaviour, as quantified from the available process data, can be the result of different processes. Understanding the processes which are likely to arise in a given case is therefore important for determining which parameters are expected to be uniform and/or constant.

Smith and *Hitimana* [10] provide a detailed discussion of characterising fouling in a fouling test cell, where fouling only occurs on one side of the heat transfer surface. They used Eq. (8), as in this case the deposit resistance R_d can be uniquely identified.

2.3 Fouling mechanisms and process

The formation of a fouling layer causes additional thermal resistance. In general, five types of fouling can be distinguished, based on the deposition mechanism: corrosion fouling, crystallization fouling, particulate fouling, biofouling, and reaction fouling [11]. The fouling mechanism is normally determined by the nature of the *fouling precursor*, the component in the process stream that eventually forms the deposit. More than one fouling mechanism can be active at the same time. For example, metabolites of microorganisms generated during biofouling can initiate corrosion fouling [12].

Epstein [13] described the sequence of possible events involved in fouling as: induction; transport; deposition; removal; and aging. He summarised the state of knowledge of the processes involved for each fouling type in a 5×5 matrix. The classification of *Epstein's* 5×5 matrix is often used and in many cases is still valid. It is the authors' opinion that this classification should be extended, to incorporate developments in the field in the last four decades. Possible approaches could be, for example:

- Clearer demarcation of the fouling *mechanisms* by differentiation between primary and secondary effects, as visualised in Fig. 2(a).
- Extension of *events* to include categories such as attachment; internal growth; and blockage, see Fig. 2(b). Internal growth is driven by external effects whereas ageing refers to changes in material after it has been incorporated into the deposit.

These and other relevant definitions are specified in Table 4.

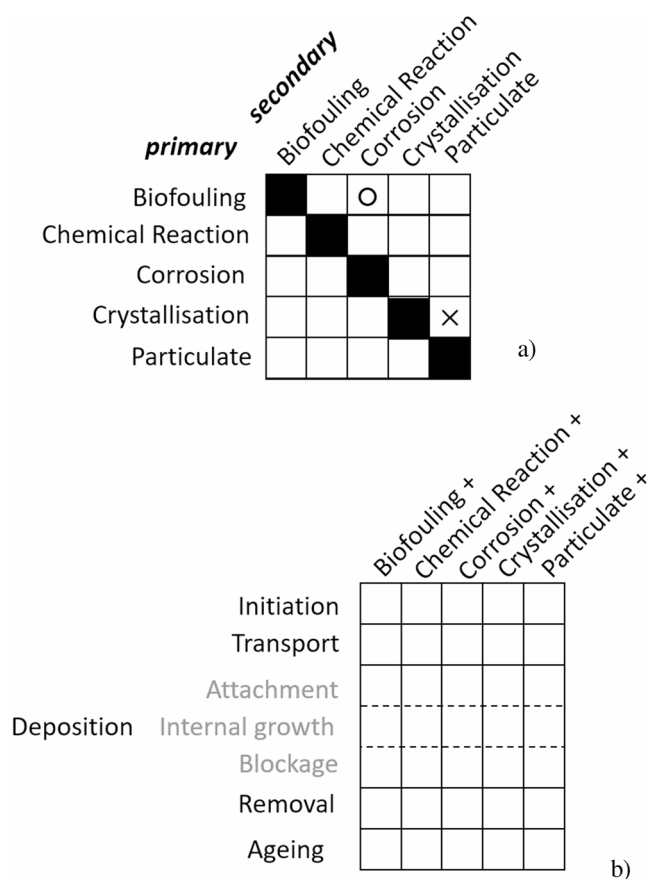


Fig. 2 Modified Epstein matrix: (a) Demarcation between primary and secondary deposition mechanisms. Examples indicated: crystallisation in the bulk causing particulate fouling downstream (x), or a biofilm promoting corrosion fouling (o); (b) Extension of the deposition stage

Table 4 Fouling mechanisms and processes

Item	Definition
<i>Epstein's 5 × 5</i> matrix	Fouling phenomena in macro-scale devices were divided into 5 different categories according to the cause of fouling and the form of the fouling precursor that attaches to the surface (initially the heat transfer surface, later the fouling layer).
Crystallisation fouling	Crystallisation of dissolved solutes or freezing of pure liquid or liquid mixtures on surfaces. The underlying process is related to solidification from some of the components on a surface and is caused by heterogeneous crystallisation. Homogenous crystallisation, by contrast, results in solid forming in solution, e.g. in the bulk of a fluid flow. This can give rise to particulate fouling.
Particulate fouling	Deposition of fine particles already present in the process stream, occurring when a stream is a suspension or a particle-laden fluid flow. This includes sedimentation.
Chemical reaction fouling	Attachment of materials that form when precursors, i.e. the parent materials, react in the wall region, promoted by the temperature there (e.g. polymerisation, decomposition) with possibly a catalytical effect of the surface material.
Biofouling	Attachment of micro- or macro-organisms to the surface. In addition to direct contamination from the organism, its metabolic products and extra cellular polymeric substances can cause fouling issues in many applications.
Corrosion fouling	Fouling layers composed of corrosion products, formed by reaction of the heat transfer surface itself.
Initiation	Delay period before significant fouling is recorded.
Transport	Fouling precursor is transported from the bulk fluid flow to the surface. Driving forces include diffusion, inertia, thermophoresis and sedimentation.
Suppression	Processes limiting the deposition of precursors, i.e. preventing attachment. Not to be mistaken for removal.
Deposition	Accumulation of foulant material on the heat transfer surface. In fouling the general term for attachment, internal growth, blockage.
Attachment	Contact with, and adhesion of, the precursor to the surface.
Internal growth	In biofouling, nutrients and other molecules are transported from the bulk fluid into the deposit layer and are metabolized by the biofilm to form new microbial cells (which also produce more extra-cellular polymers), thereby increasing the volume, mass and thermal resistance. Similarly, a porous crystalline (mineral or wax) layer can harden over time as a result of continued crystallisation within pores.
Blockage	Total obstruction of the flow cross-sectional area, e.g. due to bridging of particles or immense crystal growth. For micro-channels, gas bubble diameters are in the range of the characteristic dimension and are capable of blocking the whole cross section, requiring high pressure gradients to move the bubbles. Partial blockage can occur in multi-channel designs such as shell and tube heat exchangers resulting in some channels with no flow and others with enhanced velocity, depending on the control concept.
Removal	Detachment of material already in the fouling later by fluid forces, e.g. quasi-steady erosion of a deposit.
Dissolution	Physicochemical process leading to material loss, driven by differences in concentration or chemical potential.
Sloughing	A removal process in which regions of the deposit are shedded regularly owing to internal weaknesses. An example is in biofouling, when the layer becomes too thick and the microorganisms activate molecular triggers to release part of the attached layer, thereby allowing nutrients to reach the deposit in the wall region.
Ageing	The spatial or chemical structure of the deposited material changes over time so that the deposit's thermal, mechanical and chemical properties differ from the fresh deposit or fouling precursor. This affects the thermal resistance and strength of the layer. Internal growth can also change the deposit properties.

2.4 Fouling development

Figure 3 shows a plot of the evolution of the thermal fouling resistance, often termed a 'fouling curve'. The fouling behaviour can be divided into three phases, see also Table 5.

The first phase, *initiation*, is characterized by a fouling resistance of $R_{f,th} \simeq 0 \text{ m}^2 \text{ K W}^{-1}$, i.e. there is no significant change in the thermal performance of the unit. In this phase the main development is associated with conditioning of the surface from its initial state to a form where fouling precursors will attach to it or be generated there.

The second phase represents a transition, which is also called the *roughness-controlled* phase. First deposits, e.g. individual particles, clumps of crystals or micro-organisms attach to the surface and have an increasingly positive influence on heat transfer at the heat transfer surface by penetrating the momentum boundary layer and augmenting

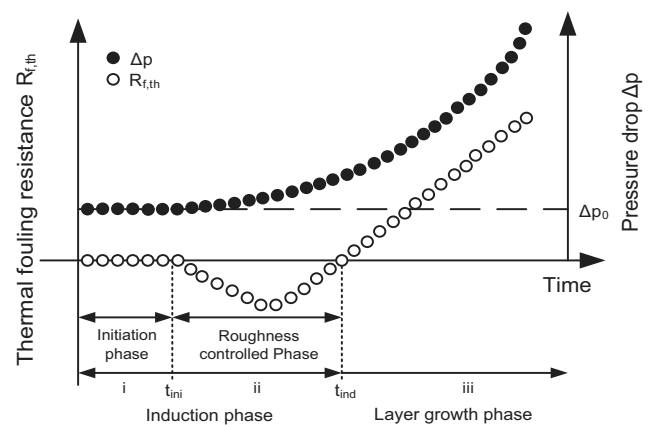


Fig. 3 A 'fouling curve': a graphical record of the thermal fouling resistance and, in this case, the pressure drop over process time. Labels indicate phases in fouling behaviour.

Adapted from [14]

Table 5 Fouling development

Item	Definition	Symbol/Unit
Fouling curve	Record of the thermal fouling resistance over time (Figs. 3 and 4).	
Initiation phase	Characterised by a thermal fouling resistance of zero (Fig. 3). This can be due to a conditioning of the surface prior to deposit attachment.	
Initiation time	Time at the end of the initiation phase (Fig. 3).	t_{ini} [s]
Roughness controlled phase	Characterised by a negative value of the thermal fouling resistance, i.e. enhanced heat transfer over the initial state, due to an increased surface roughness by first matter attaching (Fig. 3).	
Induction phase	Combination of any initiation and roughness controlled phases (Fig. 3). Depending on the fouling mechanism and process conditions the induction phase can be absent, short or long.	
Induction time	Time at the end of the induction phase (Figs. 3 and 4).	t_{ind} [s]
Layer growth phase	Increase in deposit mass, resulting in an increase of surface coverage and layer thickness (Fig. 3). The fouling curve can show different progressions (Fig. 4), depending on the balance between internal structure and external removal mechanisms acting on the deposit.	

convection. At high flow velocities this surface roughness increases turbulence in the wall region [15]. This enhancement of the film heat transfer coefficient over the clean case results in the calculated thermal fouling resistance being negative, despite the presence of foulant species. As deposition progresses, the formation of deposits increases and the new attached mass represents an additional thermal resistance. This initially compensates for the positive influences of roughness on heat transfer. After some time the two effects cancel each other out and the fouling resistance reaches $R_{f,\text{th}} = 0 \text{ m}^2 \text{ K W}^{-1}$, marking the end of the transition phase. The first two phases combined are also referred to as the *induction* phase.

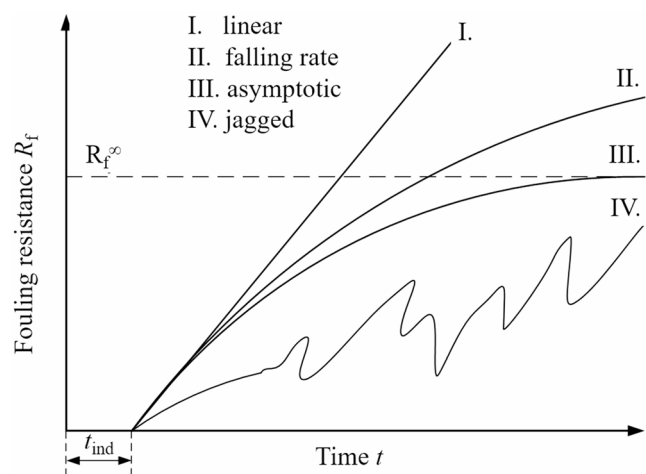
The authors acknowledge that the term ‘negative fouling resistance’ is a controversial one in the fouling community. If a fouling resistance is associated with a fouling layer of finite thickness, the quantity can only take positive values, see Eq. (5). The origin of the apparently negative effect lies in the enhancement of film heat transfer which is usually omitted from calculations such as Eq. (3). The authors recommend that this behaviour be referred to as ‘negative apparent fouling resistance’: the discrepancy is avoided when thermal resistances are calculated rigorously, e.g. using Eq. (4).

In the final third phase, the *layer growth* phase, the effect of roughness on the fouling resistance no longer changes. As the thickness of the fouling layer increases and the rate of heat transfer decreases, the fouling resistance continues to increase. In devices where the fluid flows through a confined channel (e.g. tube or gap between plates) growth of the layer will change the available flow cross-section. For a device operating at constant volumetric flow rate, this will increase the film heat transfer coefficient (h_C or h_H in Eq. (2)) and the overall rate of heat transfer. This contribution is not explicitly identifiable by an integral thermal fouling quantification according to Fig. 3 and is often neglected as it is often dwarfed by the change in resistance associated with conduction through the layer.

Deposition also affects the pressure drop, ΔP , across a heat exchanger through roughness and constriction effects. Unlike the thermal fouling resistance, ΔP starts at a finite value, which increases as the surface roughness develops, see Fig. 3: for fixed flow rates ΔP cannot decrease unless the viscosity of the fluid changes significantly as a result of large changes in bulk temperature [16]. Flow constriction will also increase ΔP . While it is possible to calculate the influence of roughness and constriction effects on heat transfer in fouling quantification, it remains a challenge to separate the measured pressure drop reliably into roughness and acceleration contributions [17, 18].

Depending on the type of fouling and the material-, apparatus- and process-specific conditions, the paths shown in Fig. 4 can result:

- (i) Linear increase in the fouling resistance– ‘linear fouling’. This behaviour is typically observed when (a) the rate of deposition is constant and (b) there is no deposit removal and (c) the properties of the fouling layer do not change significantly.

**Fig. 4** Examples of four characteristic fouling curves

- (ii) Slowing down of the rate of deposition as the fouling progresses, without reaching a steady level of deposition or layer thickness— ‘falling rate fouling’. This trend can arise because either the deposition or removal fluxes change as the fouling layer grows. One example is when the overall temperature driving force is constant and the rate of deposition depends on the temperature at the stream-deposit interface, T_f . The latter will change as the layer grows, normally to cause the deposition flux to decrease.
- (iii) ‘Asymptotic fouling’: deposit growth reaches a plateau where the thermal fouling resistance does not change noticeably over time ($\rightarrow R_f^\infty$). This occurs when the deposition and removal fluxes balance (e.g. $\dot{m}_d - \dot{m}_r = 0$, no ageing), or the driving force for deposition becomes very small and removal fluxes are zero. This phenomenon is often observed in process conditions with a constant wall temperature or a constant inlet temperature of the heating medium.
- (iv) ‘Sawtooth fouling’ occurs when there is an irregular ablation rate, which can lead to significant dips in the fouling curve. Once cause of this is the lower adhesive force between the coating and the heat transfer surface [13]; sawtooth behaviour can also arise in biofouling (see above).

2.5 Fluid/surface (layer) interactions

In the standard evaluation of fouling by means of an overall heat balance, yielding the thermal fouling resistance according to Eq. (2), a constant film heat transfer coefficient is often assumed on the fouling side. Growing fouling

layers reduce the free flow cross-section and the surface roughness, resulting in an increase of flow velocity and turbulence. This affects the local wall shear stress imposed by the flow on the deposit-process stream interface, τ_w , and thus the overall pressure drop, ΔP , as well as the propensity for heat transfer from the interface into the flow, characterized by the film heat transfer coefficient h (denoted α in some disciplines). Studies show that assuming a constant heat transfer coefficient can result in the deposit layer thickness being underestimated by up to $2.5\times$ [17]. The relevant terms are specified in Table 6.

2.6 Surface/layer interactions

One strategy for fouling mitigation is the reduction of adhesive forces at the heat transfer surface/layer interface. Careful choice of materials as well as modification of an existing surface can be used to reduce fouling in the early stages of the deposition process [19] and promote removal. The adhesion mechanisms at the interface can be characterized as (i) molecular and (ii) mechanical interactions, see Table 7. One approach for (i) is to change the molecular interactions through energetic processes. Those in (ii) are determined by the surface topography, which can be altered by mechanical or electrochemical processes. Surface coatings can affect both mechanisms. Micro-nano topographic modifications can also affect adhesion and growth (examples of such modifications are the imitation of shark skin or lotus plant surfaces).

Another way to influence the physical interactions at the interface is the use of additives. A wide range of additives employing anti-foulant chemistries is available on the market for various process applications.

Table 6 Fluid/surface (layer) interactions

Item	Definition	Symbol/Unit	Equation
Mass transfer	Physical processes (e.g. diffusion, convection) causing transport of species.		
Mass transfer coefficient	The rate of mass transfer is conventionally expressed as a mass flux (rate per unit area), where the flux is directly proportional to the difference in concentrations in the bulk fluid and at the fluid boundary. The mass transfer coefficient is the proportionality constant.	β [m s^{-1}]	
Shear stress	Stress that causes a force F_s tangentially acting on an area (as opposed to normal stress). Shear stress is of the same physical magnitude as pressure, namely force per area.	τ [Pa]	$\tau = \frac{F_s}{A}$ (13)
Wall/layer shear stress	Shear force per unit area exerted by the flowing fluid on the fluid-deposit or fluid-surface boundary, along the boundary.	τ_w [Pa]	
Layer roughness	If it is assumed that the temporal change of the film heat transfer coefficient h is solely due to the change in surface roughness arising from deposition, then h can be described by the change in flow resistance quantified via the change in friction coefficient ξ from clean to fouled state.	ξ_f [-]	$h(t) \propto \frac{\xi_f(t)}{\xi_0} h_0$ (14)
Constriction	Partial obstruction of the channel due to growth of a fouling layer on the walls, causing either higher pressure drop or lower flow rate. If the flow rate is constant the film convective heat transfer coefficient h will increase.		

Table 7 Surface/layer interactions

Item	Definition	Symbol/Unit
Adhesion	Describes the attractive forces at the points(s) of contact between two different or identical substances by molecular forces, primarily van-der-Waals and electrostatic forces.	
Surface energy	Measure of the energy required to break the intermolecular bonds when a new surface of a liquid or solid is created. It is defined as the energy that must be expended to generate unit area of new surface.	γ [$\text{J}\cdot\text{m}^{-2}$]
Contact angle	Angle formed by a liquid droplet with the smooth surface of a solid. Advancing contact angles are an important parameter for quantifying the wettability of solid surfaces: the smaller the contact angle between the wetting liquid and the wetted solid surface, the higher the wettability of the wetted solid surface in relation to the wetting liquid. Wetting behaviour is also affected by surface morphology at fine length scales, surface heterogeneity, and whether the liquid is advancing or retreating across the solid.	θ [$^\circ$]
Hamaker constant	Parameter quantifying van-der-Waals attractions. The Hamaker constant depends on both the substances that make up the two bodies and the separating medium: $A_H \propto \rho_1 \rho_2$ for 1 and 2 separated by vacuum.	\tilde{A}_H [J]
Zeta potential	Electrical potential at the shear layer of a moving particle in a suspension or emulsion, which describes the ability of an electrical field caused by a charge to exert force on other charges.	ζ [V]
Surface roughness	Unevenness of a solid surface. The roughness has an influence on the wettability of a solid. Often quantified by the average roughness element height Ra or mean waviness height Rz .	Ra, Rz [m]

2.7 Layer properties

The properties of the fouling layer, as listed in Table 8, will depend on its structure, which may evolve locally over time at a rate determined by the local temperature T , time t and, in the case of biofouling, by the availability of nutrients and oxygen. The temperature in the deposit will vary between that at the heat transfer surface-deposit interface, T_s , and the deposit-process stream.

The local concentrations of nutrients and oxygen in biofilms depend on the diffusional limitations and on the metabolic activity (nutrient/oxygen uptake rate) of the microorganisms inside the deposit. This may lead also to different compactness and composition of the extracellular polymeric matrix produced by the microbial species.

2.8 Dimensionless groups

A dimensionless number is a parameter in a dimensionless mathematical model of a physical state or process. In chemical engineering several dimensionless numbers are

used which are relevant to, but not specific for, fouling, viz. Nusselt, Reynolds, Sherwood, Schmidt. They will not be discussed here. There are, however, some dimensionless groups or ratios which have specific relevance to fouling, see Table 9.

2.9 A note on cleaning

Cleaning is a separate processing step performed to reduce the amount of fouling deposit present. Some fouling mitigation technologies (such as the circulation of abrasive balls in shell-and-tube heat exchangers; fluidized bed heat exchangers; and back-pulsing in membranes) employ removal in situ during regular operation and are not classed as cleaning.

Cleaning methods are classified as either cleaning-in-place (CIP), which do not require disassembly of the exchanger to allow cleaning agents to contact the deposit, and mechanical techniques. Cleaning methods are particular to the nature and age of the deposit (see reviews [20, 21]). In mechanical methods, the forces imposed by the cleaning device or cleaning fluid need to be larger than the adhesive

Table 8 Layer properties

Item	Definition	Symbol/Unit
Cohesion	Attractive forces between atoms as well as between molecules within a substance, which determines its internal strength and resistance to shear and penetration. This differs from adhesion, which is between foulant species and the heat transfer surface.	
Shear strength	Force or stress at which the layer starts to deform, break, or fracture.	τ_f [$\text{N}\cdot\text{m}^{-2}$]
Thermal conductivity	Material property that determines the rate of heat flow through a material by thermal conduction. Thermal conductivity is a measure of how well a material conducts heat.	λ_f [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]
Deposit microstructure	The spatial distribution of material in the fouling layer. For example, in biofouling, different microbial species can develop in different locations of the deposit according to the profiles of nutrient concentration and to their role in biofilm growth and stability. Crystalline deposits of calcium sulphate (needles) differ from carbonate (rhomboheda). Milk deposits at high temperature (milk scale) are very different to pasteuriser (protein 'broccoli').	

Table 9 Dimensionless numbers

Item	Definition	Symbol/Unit	Equation
Fouling Biot number	Product of the overall heat transfer coefficient at the clean state U_0 and the thermal fouling resistance R_f . The Biot number compares the thermal resistance of a conductive layer to the convective resistance associated with heat flow to the layer. When Bi is large, layer conduction dominates the rate of heat transfer.	$Bi_f [-]$	$Bi_f = U_0 \bullet R_f$ (15) $\frac{U}{U_0} = \frac{1}{1+Bi_f}$ (16)
Degree of fouling increase	Relative impairment of fluid dynamics versus thermal performance due to fouling.	$DFI [-]$	$DFI = \left \frac{\Delta P^*}{Bi_f} \right $ (17) with $\Delta P^* = \frac{\Delta P_f - \Delta P_0}{\Delta P_0}$ (18)
Thermohydraulic efficiency	Ratio of heat transfer and flow resistances	$THE [-]$	$THE = \frac{Nu/Nu_0}{(C_f/C_{f,0})^{1/3}}$ (19)
Stokes number	Quantifies the significance of the inertia of a particle for its motion in a moving fluid. It is defined as the ratio of the characteristic time t_p , with which friction adjusts the speed of the particle to the velocity of the surrounding fluid, to the characteristic time t_F , in which the fluid itself changes its velocity due to external influences. For $St \ll 1$, the particle follows the local flow. This is relevant for particulate fouling.	$St [-]$ N.B. St is also used for the Stanton number	$St = t_p/t_F$ (20)

or cohesive strength of the fouling layer. Chemical cleaning includes the use of detergents, biocides and other substances (acids, bases) that change the internal structure of the deposit so that it can be removed by fluid flow, or solvents that promote dissolution of the deposit into the cleaning fluid.

The definition of clean will depend on the application, and can range from returning a heat exchanger operating performance to its initial level to restoring the heat transfer surface to a condition free from all deposits or foreign species (decontamination).

The topic of cleaning (and decontamination) is a rich field in its own right and requires its own taxonomy [20].

2.10 Standardisation in reporting

In many publications, important information is not provided which would be useful to understand the experiments and the results. Standardization of reporting would be helpful and allow the data collected to be studied later by machine learning techniques. Table 10 presents a suggested reporting

Table 10 Reporting schedule (provide details if known and appropriate)

Category	Information
Application	Background
Fouling mechanism	Mechanism(s) active Identity of precursor(s)
Fluids	Gas, liquid, suspension, etc. Key chemical conditions (e.g. pH, concentration, particle size, scaling index)
Device	Flow configuration Geometry and configuration Dimensions Operating mode (batch, semi-batch, continuous, loop)
Surface	Surface material and preparation procedure Surface morphology, e.g. roughness
Mode	Experimental, modelling, simulation, data reconciliation
Measurement method	How is fouling being quantified Local or integral measure Real time or post-test measure Characterisation of fluid and surface before, during and/or after the fouling test
Operating parameters	Key temperatures Flow rates and velocities Relevant dimensionless groups (e.g. Reynolds number) Wall shear stresses
Deposit	Can deposit be inspected (in real time or post-test)? Physical form (e.g. topographic and internal structural properties) Chemical composition Distribution
Reporting format	Are data available online?

scheme and researchers are encouraged to provide this information within their reports or papers, or provide it as supplementary information.

3 Conclusions and outlook

The authors have reviewed the terminology used in fouling research. This internal discussion has resulted in the recommendation for the extension of *Epstein's 5 × 5 matrix*. A further finding is the inconsistent handling of the definition of the thermal fouling resistance. This is where care is needed, to avoid misinterpretation of findings or miscalculation of the extent of fouling.

The authors did not find any recent surveys or calculations on the economic importance of fouling or its effects on the environment and health. There is a pressing need for such reviews given the current emphasis on sustainability.

The importance of fouling is growing as climate change drives the widespread installation of devices such as heat pumps and air coolers. These applications may require new or adapted definitions of the terminology presented here.

The taxonomy presented here does not claim to be complete and should be reviewed regularly. Extending it to include additional fields of application, such as membranes or separating devices in process engineering, should be considered as this would allow the common scientific themes to be highlighted.

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