Crystallization Fouling in Heat Exchangers: A Review

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***Abstract*—Heat exchanger fouling is a major challenge in thermal engineering, reducing heat transfer efficiency and increasing energy consumption, operating costs, and environmental impacts. This review focuses on crystallization fouling, summarizing its fundamental mechanisms, deposit formation processes, and the influence of key factors such as fluid composition, temperature, flow conditions, and surface properties. It also reviews the development of fouling models, from classical approaches to advanced computational fluid dynamics (CFD) and artificial neural network (ANN) techniques, as well as current fouling mitigation strategies, including improved heat exchanger design, online monitoring, and cleaning methods. The review identifies important research gaps, particularly in understanding the early stages of crystal formation, ageing effects, interactions between multiple fouling mechanisms, and the mechanisms underlying fouling mitigation. Addressing these challenges will impr**

***Index Terms*—heat exchanger; fouling; energy efficiency; crystallization; fouling modelling; fouling mitigation**

I. INTRODUCTION

Heat exchangers (HEs) are among the most commonly used thermal devices and are available in a variety of designs, including shell-and-tube, plate, and double-pipe heat exchangers. They are widely used in industries such as heating and cooling, power generation, transportation, chemical processing, waste heat recovery, petroleum refining, pharmaceuticals, space technology, and water or fluid treatment. Because of their broad range of applications, the global heat exchanger market is worth billions of euros and is expected to continue growing as energy demand and the world's population increase.

In many industrial and domestic applications, the fluids flowing through heat exchangers often contain dissolved minerals, suspended particles, or microorganisms. These conditions can lead to the formation of unwanted deposits on heat transfer surfaces, a phenomenon known as fouling. Fouling reduces the efficiency of heat transfer by lowering the heat transfer coefficient and altering both the surface characteristics and flow path within the exchanger.

As deposits continue to build up, they restrict fluid flow and increase friction, resulting in higher pressure drops. In severe cases, excessive scaling can make a heat exchanger unusable even before the loss in thermal performance becomes critical [1]. To minimize these effects, engineers often incorporate safety margins into heat exchanger designs, treat fluids before use, and schedule regular cleaning and maintenance. Although these measures help control fouling, they also increase operating costs and require additional downtime. According to surveys [2,3], more than 90% of heat exchangers across various industries are experiencing fouling problems.

The effect of fouling on heat transfer equipment is generally described with added thermal resistance as a result of the fouling layer. The calculation of the overall heat transfer coefficient U thus becomes:

$$\frac{1}{U} = \left(\frac{1}{h_1} + R_{f,1} \right) \frac{A_2}{A_1} + R_{\text{wall}} + \frac{1}{h_2} + R_{f,2}$$

In Equation (1), and represent the heat transfer coefficient and the heat transfer area of the heat-exchanging fluids (subscripted as 1 and 2), respectively, while denotes the thermal resistance of the wall separating the two fluid streams. Fouling resistance, , arises from deposits that accumulate on one or both sides of the separating wall, depending on the operating conditions within the heat exchanger

(Figure 1). Fouling resistance can be defined as the difference between the reciprocals of the overall heat transfer coefficients before fouling (Uc) and after fouling (Uf), expressed as:

$$\frac{1}{R_f} = \frac{1}{U_f} - \frac{1}{U_c}$$

If one assumes constant values of the overall heat transfer coefficient, , over the heat exchange area, the extra heat transfer surface area needed to achieve the same performance is obtained as:

$$A_f = A_c\left(1 + R_f \cdot U_C\right)$$

Similarly, if one assumes a constant heat exchange area, , an increase in the temperature difference between the cold and hot streams is required to achieve the same thermal performance.

$$\Delta T_f = \Delta T_c\left(1 + R_f \cdot U_C\right) = \Delta T_c \frac{U_C}{U_f}$$

Should neither of the discussed parameters be adjusted to accommodate fouling, the heat exchanger will experience a deterioration in performance.

$$Q_f = \frac{Q_C}{1 + R_f \cdot U_C}$$

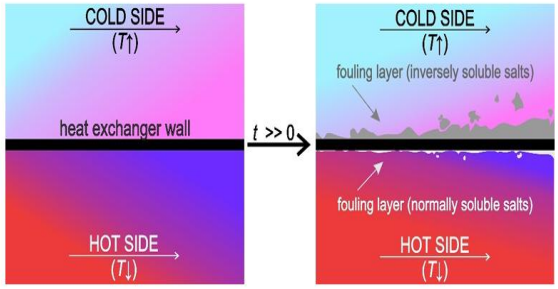

Figure1:Schematic representation of scaling in a heat exchanger.

The fouling process can be classified into six major types: (i) crystallization fouling (scaling), (ii) particulate fouling, (iii) chemical reaction fouling, (iv) corrosion fouling, (v) biofouling, and (vi) solidification fouling. In practice, multiple fouling mechanisms may occur simultaneously, resulting in a combination of these fouling types [4]. Among them, crystallization fouling is considered the most detrimental to heat exchanger performance due to its significant impact on heat transfer efficiency. Consequently, this review places particular emphasis on crystallization fouling.

The development of fouling resistance over time depends on the heat transfer process and the dominant fouling mechanism, as illustrated in Figure 2. The evolution of fouling resistance is strongly influenced by the characteristics and mechanical strength of the deposited layer. Soft and loosely adhered deposits typically exhibit an asymptotic increase in fouling resistance, whereas hard and tenacious deposits often display a linear or even a declining-rate trend. The first three curves in Figure 2 represent idealized fouling behaviors, while the saw-tooth profile reflects periodic fluctuations caused by the break-off of aged deposits [5], a phenomenon commonly observed in experimental studies and industrial heat exchangers.

The three stages of fouling development, illustrated in Figure 2, are discussed in greater detail in the following chapter, with particular emphasis on the mechanisms governing crystallization fouling.

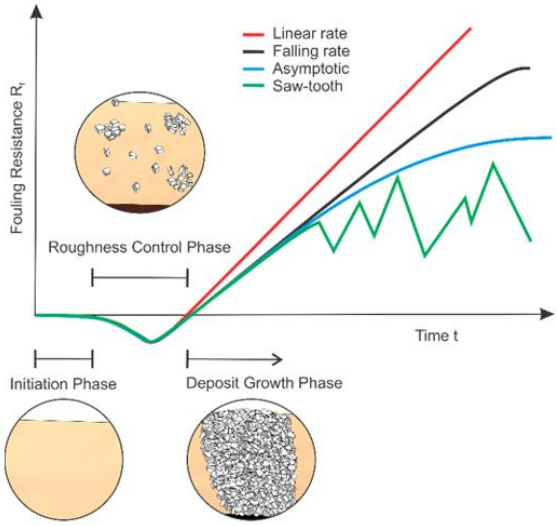

Figure 2:Typical fouling resistance curves.

II. CRYSTALLIZATION FOULING:

It is also known as scaling, occurs when dissolved salts in the heat exchange medium crystallize and deposit onto the heat transfer surface. This happens when the solution becomes supersaturated, meaning the concentration of dissolved solids exceeds the equilibrium (saturation) solubility of the solution.

Supersaturation can occur due to several reasons:

- Evaporation of the solvent, which increases the concentration of dissolved salts.
- Cooling a solution containing normal-solubility salts, whose solubility increases with increasing

temperature (e.g., NaCl and $CaCl_2$). Cooling below the solubility temperature causes these salts to precipitate.

- Heating a solution containing inverse-solubility salts, whose solubility decreases with increasing temperature (e.g., $CaSO_4$, $CaCO_3$, Na_2SO_4, and $MgSiO_3$). Heating above the solubility temperature leads to precipitation.
- Mixing solutions with different compositions, which can alter the solubility equilibrium.
- Variation in pH, which affects the solubility of many salts.

Supersaturation may also occur within the bulk fluid, resulting in the formation of crystals throughout the liquid. This phenomenon is known as bulk crystallization. The suspended crystals can act as particulate fouling agents, increasing the rate of deposition on heat transfer surfaces. In many practical situations, both bulk crystallization and surface crystallization occur simultaneously.

$$CaCl_2 \cdot 2H_2O + 2NaHCO_3 \rightarrow CaCO_3 + 2NaCl + 4H_2O + CO_2 \quad (6)$$

$$Ca(NO_3)_2 \cdot 4H_2O + Na_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O + 2NaNO_3 + 2H_2O \quad (7)$$

Calcium sulphate crystallizes from solution in three forms: gypsum ($CaSO_4 \cdot 2H_2O$), calcium sulphate hemihydrate ($CaSO_4 \cdot 0.5H_2O$), and anhydrite ($CaSO_4$). All three forms exhibit inverse solubility, meaning their solubility decreases as temperature increases. Gypsum is the predominant crystalline phase formed between 40°C and 98°C, whereas hemihydrate and anhydrite are more likely to precipitate at temperatures above 98°C.

When the solution reaches the required level of supersaturation, scale formation begins through a sequence of distinct stages. Initially, the heat transfer coefficient remains nearly constant during the initiation (or delay) phase. During this period, crystal nuclei form in localized regions of supersaturation, a process that may last from a few seconds to several days depending on operating conditions. Microscopic studies, such as those conducted by Kim and Cho, have demonstrated the transition from nucleation to crystal growth, providing insight into crystal formation rates, size, and morphology.

Once stable nuclei are formed, the transport stage begins. Dissolved calcium sulphate moves from the bulk fluid to the heat transfer surface, primarily through diffusion driven by concentration gradients. As crystals deposit on the surface, a fouling layer develops. At this stage, two opposing effects influence heat transfer. The growing deposit increases thermal resistance, reducing the overall heat transfer coefficient. However, the roughness created by the initial deposits enhances local turbulence near the surface, temporarily improving heat transfer.

Because the deposited scale is initially very thin and causes negligible flow restriction, the turbulence-enhancing effect often dominates during the early stages of fouling. Consequently, the measured heat transfer coefficient may temporarily increase, resulting in an apparent negative fouling resistance. This phenomenon was quantitatively investigated by Albert et al. through $CaSO_4$ fouling experiments in a double-pipe heat exchanger, demonstrating that roughness-induced turbulence can outweigh the thermal resistance of the initial scale layer before continued deposition eventually leads to a decline in heat transfer performance. As a result, the heat transfer coefficient can temporarily increase, which is observed as negative fouling resistance and was quantitatively addressed by Albert et al. [13]. By conducting CaSO4 fouling experiments in a double pipe heat exchanger, they showed that the negative values can be attributed to increased roughness, which was detected through pressure drop measurements. Accounting for this allows the elimination of negative fouling resistances in the roughness control phase. When deposition progresses further, the constriction of the flow cross section and thermal resistance due to the fouling layer become progressively more significant [14]. The fouling resistance slowly starts increasing, first back to zero and then upwards. This time period from the beginning of the fouling process until the fouling resistance again becomes zero is termed the ‘roughness delay time’ [15] or roughness control phase and can be observed in Figure 2. After this period is complete, the process shifts into the crystal growth phase and Rf continues to change following one of the presented curves in Figure 2. Immediately after the occurrence of the first deposit (and the end of the initiation period), the layer removal or auto-retardation may begin in parallel with crystal growth and deposition. This makes the process of fouling an ever-present struggle between the opposing forces of deposit creation and removal, as first proposed by Kern and Seaton in 1959 [16]. Their model has been used as a baseline for many of the fouling models in

subsequent years and marks one of the biggest advancements in the field. The mathematical form of the model of fouling mass deposition is:

$$\frac{dm}{dt} = \dot{m}_d - \dot{m}_r = \frac{dR_f}{dt}\rho_d\lambda_d$$

position rate . md was postulated to be proportional to bulk flow velocity and solution concentration, while the removal rate . mr was based on wall shear stress and strength of the formed deposit. If all these factors, along with asymptotic fouling behaviour, are considered in Equation (8), the following form of the general asymptotic fouling model can be obtained

$$R_f(t) = R_f^*\left(1 - exp^{bt}\right)$$

The term asymptotic fouling resistance Rf∗ is obtained, which denotes a maximum value of fouling resistance where the deposition and removal mechanisms are in equilib rium. Generally, an S-shaped curve with several distinct regions can be observed, like the one presented in Figure 2 or in [17,18], once the asymptotic fouling resistance is reached. Although the model was criticised and improved over the years, the basic principle remains valid and is the foundation upon which most research is conducted. The growing deposit is also subject to aging, which can either strengthen or weaken it over time, and is one of the least understood and studied phenomena of fouling [19]. Similarly to Equation (9), several other semi-empirical equations exist, describing the fouling scenarios in Figure 2. The most simple is the general model of linear fouling Rft = dRf/dt (t − ti), followed by the falling rate model dRf/dt = K/(Rc − Rf)n [1]. The constants in such models depend on the conditions present, and as such are not readily available, meaning they need to be derived from experimental data. Any such model can be introduced into Equation (1), and if satisfactory experimental data fit is achieved, used to predict the change of overall heat transfer coefficient under fouling conditions. It is believed that, depending on the combination of influencing factors (e.g., fluid velocity, temperature, salt concentration), crystallization fouling can be mass transfer controlled, chemical reaction controlled or a combination of both [20]. Mass transfer is prevalent when the diffusion of ions from the bulk solution has a dominant effect on the process, which often occurs when a laminar boundary layer forms near the heat exchanger surface [21]. On the other hand, chemical reaction dominance is considered when the inclusion of these ions in the crystal lattice is the main process influence.

III. MODELLING CRYSTALLIZATION FOULING

The history of fouling research and modelling up to 1979 was comprehensively reviewed by Somerscales [72]. This review highlights the transition from the early observational studies of fouling phenomena to a more scientific and systematic approach, which was initiated by the pioneering work of Kern and Seaton. The subsequent developments and emerging research interests in fouling studies were later summarized in a review by Müller-Steinhagen [73]. Through his investigations of $CaCO_3$ precipitation, Hasson [74] was the first researcher to treat crystallization fouling as a mass-transfer-controlled process. Based on this approach, he proposed a fouling growth rate model describing the deposition of crystalline material under mass transfer limitations.

$$\dot{m}_g = \frac{\{[Ca(HCO_3)_2 - K_s']\}}{(1/K_m) + (1/K_R)}$$

where (K_m) represents the mass transfer coefficient at the fluid–deposit interface, (K_R) is the reaction rate constant associated with crystal formation on the surface, and (K_s) denotes the solubility product of the deposit. The solubility product, which can be obtained from literature data, together with (K_m), which can be estimated from empirical correlations based on the system geometry, enabled Hasson to determine the reaction rate from the experimentally measured fouling growth rate. He further refined the model and proposed that $CaCO_3$ deposition is primarily controlled by the forward diffusion of Ca^{2+} and HCO_3^- ions toward the surface, where the crystallization reaction takes place [75].

Crystallization fouling has often been described using the “classical” deposition rate law, in which the deposition rate is expressed as a function of the concentration driving force and a temperature-dependent rate constant. However, this approach does not account for the effects of nucleation or the availability of crystal growth sites:

$$\dot{m}_d = K_R^*\left(C_{fl} - C_{sat}\right)^n$$

Although numerous models have been developed for crystallization fouling, most of them involve one or more of the following simplifications [80]:

- The effects of surface roughness and changes in surface area are neglected;
- Only a single fouling mechanism is assumed to occur;
- Fluid properties are considered constant;
- The fouling layer is assumed to be homogeneous;
- Changes in flow cross-sectional area are neglected;
- The morphology and shape of deposits are not considered;
- The induction period and roughness delay period are ignored;
- Equipment design and material properties are not incorporated;
- Steady-state operation is assumed.

In many cases, these models do not attempt to describe the fundamental mechanisms governing fouling. Instead, they focus on quantifying the influence of selected operating parameters within specific experimental setups, most commonly including flow velocity, bulk and/or surface temperature, concentration, and exposure time. Briançon et al. [81] investigated fouling in industrial crystallizers and developed a simplified empirical model to characterize the process. Arsenyeva et al. [82] developed a model for predicting precipitation and particulate fouling at different flow velocities and surface temperatures in plate heat exchangers, both with and without enhanced heat-transfer surfaces.

However, the model is unable to account for salt concentration or the concentration and size distribution of suspended solid particles. Babuška et al. [83] developed a $CaCO_3$ fouling model that incorporates both deposit aging and temperature distribution within the fouling layer. In their approach, aging was included in the deposit removal term, enabling the model to reproduce the characteristic sawtooth behaviour observed experimentally. Esawy and Malayeri [84] proposed a model for $CaSO_4$ scaling on finned tubes during nucleate pool boiling. The model predicted microlayer supersaturation beneath bubbles as a function of surface geometry and demonstrated good agreement with experimental results within a heat flux range of 100–300 kW m^{-2}.

Kapustenko et al. [85] presented a mathematical model for the practical evaluation of water fouling in plate heat exchangers; however, its application requires the determination of several dimensionless constants. Jamialahmadi and Müller-Steinhagen [86] investigated fouling during the dihydrate process for phosphoric acid production and proposed a mechanistic model that can be applied to optimize cleaning procedures. Their model considered the effects of concentration, surface temperature, and fluid velocity. Souza and Costa [87] developed a model of a cooling water system consisting of a cooling tower, water pump, interconnected pipe sections, and multiple shell-and-tube heat exchangers. Their analysis demonstrated that fouling in a single heat exchanger could significantly reduce the performance of the entire system.

Bobičić et al. [88] modelled the dynamic response of a counterflow plate heat exchanger subjected to external flow and temperature fluctuations. Although the model does not include fouling effects, it provides valuable insight into the development of future control strategies for intelligent and energy-efficient district heating and cooling systems. Accurate fouling prediction would enable such control algorithms to respond immediately to undesirable internal changes, such as fouling exceeding a predefined threshold, and implement appropriate corrective actions.

Despite the availability of numerous practical models and experimental measurements, several fundamental aspects of fouling remain insufficiently understood. This indicates significant potential for further investigation into fouling mechanisms. Ideally, such research would lead to a universal model capable of describing crystallization fouling and its underlying mechanisms; however, this remains highly challenging due to the complexity and multi-factorial nature of the process. Nevertheless, improving the understanding of fundamental fouling phenomena is essential for enhancing model accuracy and extending their applicability to a wider range of operating conditions and influencing parameters.

In recent years, fouling modelling has shifted from the analysis of individual heat exchangers toward the modelling of entire plants and thermal networks. This approach enables significant industrial energy savings and encourages collaboration between

industry and academia [73]. Guelpa et al. [89] developed a fouling detection methodology and validated it in six distribution networks within the Turin district heating system. The developed software can predict the need for cleaning of individual heat exchangers based on primary-side mass flow rate and temperatures measured on both sides of the exchanger, which are commonly available parameters in district heating applications. The method does not require information regarding pressure losses, heat exchanger type, geometry, or dimensions. The authors estimated that up to 1.6% of the total annual primary energy consumption of the network could be saved through regular cleaning of heat exchangers.

Artificial neural networks (ANNs) have also demonstrated promising potential for improving the accuracy of industrial fouling models. Aguel et al. [90] investigated the thermal performance of a cross-flow heat exchanger in a phosphoric acid concentration plant and developed a mathematical model enhanced with an ANN using backpropagation. The model was applied to predict optimal heat exchanger cleaning schedules. Alsadaie et al. [91] studied the dynamic modelling of $CaCO_3$ and $Mg(OH)_2$ fouling in multistage flash desalination systems. Their results indicated that operating temperatures between 90 and 100 °C can effectively reduce rapid fouling development in the investigated desalination plant. Using deep learning techniques, Sundar et al. [92] developed a generalized and scalable statistical model for predicting fouling resistance based on commonly measured industrial heat exchanger parameters. The model achieved an (R^2) value exceeding 99%, indicating excellent agreement between predicted and experimental data. Although ANNs have shown highly promising initial results, their application to fouling prediction remains a relatively new research area, with limited published studies currently available.

Computational fluid dynamics (CFD) software has also advanced significantly in recent years, enabling its increasing application in fouling process modelling. The numerical approach allows the calculation of local temperature, concentration, and flow velocity gradients in both time and space, all of which strongly influence fouling development. Brahim et al. [93,94] applied CFD to simulate $CaSO_4$ crystallization fouling on a flat heated surface. Although the initiation period and deposit aging were not considered, the model provided satisfactory predictions of fouling layer growth and temperature distribution within the deposit.

Walker and Sheikholeslami [95] used CFD to investigate the influence of flow velocity and flow regime on bulk crystallization. Under laminar flow conditions, the model predicted radial concentration gradients caused by the radial distribution of flow velocity, resulting in a diffusive flux in the radial direction. Under turbulent flow conditions, crystallization was predicted to occur predominantly within the viscous sublayer rather than in the bulk fluid, due to the increased residence time of particles in regions characterized by lower flow velocities.

Xiao et al. [96] investigated the induction period of fouling in a microscale channel, focusing on the growth of crystals with different sizes, densities, distributions, shapes, and orientations, as well as their influence on flow dynamics and heat transfer. The study showed that tall and slender crystals provided greater enhancement of heat transfer during the induction period compared with shorter and wider crystal structures. Yang [97] examined the induction period of crude oil fouling in a tube heat exchanger using CFD modelling. The simulation incorporated fouling deposition, removal, and aging mechanisms while evaluating the effects of surface temperature and flow velocity.

Zhang et al. [98] applied CFD to model $CaSO_4$ fouling and investigate the influence of key operating parameters, including inlet temperature, flow velocity, foulant concentration, and deposit porosity. Haghshenasfard et al. [99] developed a CFD model for subcooled flow boiling to predict $CaSO_4$ deposition on heated surfaces. The model considered the effects of fluid temperature, surface temperature, flow velocity, and surface roughness; however, it did not account for the increasing thermal resistance caused by the growth of the fouling layer.

The accuracy of CFD-based fouling models is highly dependent on the quality and completeness of the input parameters. Furthermore, incorporating additional fouling mechanisms significantly increases computational requirements. Nevertheless, the continuous advancement of computational power and numerical methods is expected to overcome these limitations, creating substantial opportunities for future fouling simulations at increasingly smaller scales, including micro- and nanoscale systems.

IV. FOULING INHIBITION AND CLEANING

Since fouling, particularly crystallization fouling, can severely impair the performance of heat transfer equipment, effective mitigation and cleaning strategies are essential to maintain satisfactory equipment operation throughout its service life. Figure 8 presents various approaches for addressing fouling in heat exchangers, ranging from considerations during the initial design stage to offline cleaning procedures. The selection of one or more strategies generally depends on the equipment type and material, fouling severity, dominant fouling mechanisms, operating conditions, associated costs, and desired performance outcomes [100].

Whenever possible, fouling considerations should be incorporated during the design phase, with additional mitigation and cleaning measures implemented to maximize long-term performance. The Engineering Sciences Data Unit (ESDU), in collaboration with experts in the field, has published design guidelines to support manufacturers in this process, as described in [101,102]. These publications focus on cooling water fouling in freshwater and seawater systems, respectively, and provide information on common fouling mechanisms, influencing factors, and recommended operating conditions. They also address material selection, fouling mitigation approaches, and cleaning procedures.

General design recommendations include minimizing regions with low flow velocity within heat exchangers and selecting materials with suitable fouling resistance. Freshwater systems are commonly constructed using carbon steel and cast iron; however, these materials require significant maintenance over their operational lifetime. Therefore, the use of corrosion-resistant alloys, such as stainless steels, is recommended to improve long-term performance. In seawater applications, copper alloys have traditionally been widely used due to their favourable properties; however, the application of titanium has increased because of its superior corrosion resistance and other performance advantages.

For systems with a high susceptibility to fouling, liquid–solid fluidized bed heat exchangers have recently emerged as a promising alternative. In these systems, suspended particles are continuously fluidized and impact the heat transfer surfaces, thereby mechanically removing deposited material and reducing fouling accumulation.

Heat transfer coefficients were significantly enhanced in this type of heat exchanger, while fouling was considerably reduced due to continuous particle–wall collisions. The same research group also proposed a mathematical model and validated it using experimentally obtained data [104]. Similar heat exchanger configurations have also been investigated for eutectic freeze crystallization applications [105,106].

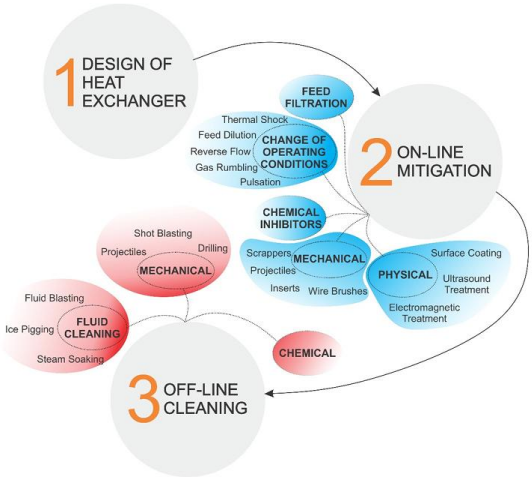

Figure 3: Various preventive and curative measures to counteract fouling of heat exchangers.

Since modifying the design or replacing the type of heat exchanger can result in significant expenses, online and offline fouling mitigation strategies are often employed to maintain satisfactory operation. In addition to modifying operating conditions and applying filtration techniques, several mechanical, chemical, and physical methods have been developed over the years for fouling control.

Among these approaches, chemical agents and inhibitors are the most widely used because they are applicable to various equipment geometries and are commercially available for a broad range of operating conditions. These additives can be classified into several groups according to their operating principles, including ion exchangers, pH controllers, scale inhibitors, adsorption agents, crystal growth modifiers, surfactants or dispersants, antioxidants, and metal deactivators [100].

Whenever possible, fouling-related considerations should be incorporated during the initial design stage, with additional mitigation and cleaning strategies

implemented to maximize equipment performance. The Engineering Sciences Data Unit (ESDU), together with specialists in the field, has published design guidelines to assist manufacturers in this process [101,102]. These guidelines address cooling water fouling in freshwater and seawater systems and describe common fouling mechanisms, influencing parameters, recommended operating ranges, material selection, mitigation techniques, and cleaning procedures. General recommendations include minimizing low-velocity regions within heat exchangers and selecting construction materials with appropriate resistance to fouling and corrosion.

Freshwater cooling systems are commonly constructed using carbon steel and cast iron; however, these materials require considerable maintenance throughout their service life. Therefore, the adoption of corrosion-resistant alloys, such as stainless steels, is recommended to improve operational performance. In seawater systems, copper alloys have traditionally been preferred; however, the application of titanium has increased due to its superior corrosion resistance and other advantageous properties.

For applications with severe fouling tendencies, liquid–solid fluidized bed heat exchangers have recently emerged as a promising solution. In these systems, fluidized particles continuously impact the heat transfer surfaces, mechanically removing deposited material and reducing fouling accumulation. Maddahi et al. [103] investigated $CaSO_4$ fouling in such a heat exchanger and compared its performance with that of a conventional forced-convection heat exchanger. The fluidized bed configuration resulted in a significant increase in heat transfer coefficient and a noticeable reduction in fouling due to particle–wall collisions. The authors also developed a mathematical model and validated it using experimental data [104]. Similar heat exchanger concepts have been investigated for eutectic freeze crystallization applications [105,106].

Shih et al. [107] compared five commercially available antiscalants using turbidity measurements and calcium potential analysis. Their results demonstrated significant differences in induction time depending on the type and dosage of antiscalant applied. Sousa and Bertran [108] evaluated four fouling inhibitors, including phosphonates and polymeric inhibitors, by continuously monitoring particle size distribution using laser diffraction combined with simultaneous pH measurements. Phosphonates, which primarily inhibit crystal growth, showed lower fouling prevention efficiency compared with polymeric inhibitors, which influence both nucleation and crystal growth mechanisms.

Despite their effectiveness, chemical fouling inhibitors also present several disadvantages. Many commercially available additives may contain environmentally harmful compounds or interact unfavourably with equipment materials, potentially causing corrosion, degradation, or cracking of the heat transfer surfaces [109].

However, in recent years, research focus has shifted toward the development of advanced coatings and surface modification techniques, with their primary applications being the mitigation of biological and crystallization fouling. Al-Janabi et al. [116] investigated the contribution of intermolecular interaction energies to $CaSO_4$ fouling by modifying surface energy through four different types of coatings. Within their study, they developed and validated a simplified surface energy-based fouling criterion.

Experiments conducted by the same research group using Ni-P-BN coatings demonstrated significant reductions in adhesion forces between the heat transfer surface and deposited foulants. However, these coatings exhibited considerable aging effects, resulting in reduced abrasion resistance [117]. Yang et al. [118] investigated low-surface-energy Cu-DSA and Ni-P-PTFE coatings and observed reduced fouling compared with uncoated copper surfaces. In subsequent work, they experimentally demonstrated that fouling reduction through weakened adhesion forces could only be achieved during the induction period of fouling development [119].

Cheng et al. [120] studied amorphous and nanocrystalline Ni-P coatings and found that both coatings exhibited scaling inhibition properties during tap water fouling. The authors suggested that an increased proportion of the nanocrystalline phase reduces the anti-fouling performance of the coatings. In a later study, the same research group investigated Ni-Cu-P-PTFE coatings with different PTFE concentrations under flow boiling conditions [121]. These coatings demonstrated anti-fouling characteristics, and the researchers proposed that an

increase in surface free energy promotes fouling formation.

He et al. [122] investigated the anti-fouling performance of hierarchical micro/nanostructured (HMNS) surfaces fabricated using electrical discharge machining (EDM). The results showed that this surface treatment improved hydrophobicity, corrosion resistance, and surface roughness. Compared with polished surfaces, the modified surfaces significantly extended the fouling induction period, particularly at lower heat flux conditions.

Oon et al. [123] examined titanium-coated stainless steel surfaces, where titanium was selected due to its high corrosion resistance and favourable surface adhesion properties. The coated surfaces demonstrated reduced $CaCO_3$ deposition compared with uncoated materials. Mayer et al. [124] measured the adhesion forces of individual $CaCO_3$ crystals on untreated and modified stainless steel surfaces, providing valuable data for the development of detailed scaling models. Reed et al. [125] reported successful disruption of biological fouling on copper and aluminium surfaces through the application of nanostructured surface modifications.

Even when heat exchangers are designed with fouling considerations and effective online mitigation methods are implemented, some degree of offline cleaning remains necessary. This is typically performed using fluid-based cleaning methods, chemical treatments, or mechanical approaches, as described in [100]. Since offline cleaning often requires process shutdown, minimizing its frequency is highly desirable. Therefore, the planning of cleaning cycles requires an optimal balance between process reliability, equipment performance, and cleaning-related costs.

Numerous studies have investigated cleaning cycle optimization; however, many focus on a specific cleaning strategy while assuming that fouling layer properties remain unchanged throughout the heat exchanger's operational lifetime. In reality, the physical and chemical characteristics of deposits evolve over time due to aging effects, and these changes must be considered when developing cleaning strategies and determining optimal cleaning intervals.

The time interval between successive cleaning operations was initially investigated by Ma and Epstein [131] and was later extended by Pogiatzis et al. [132] to incorporate deposit aging effects. In their approach, aging was represented as an increase in deposit resistance to chemical cleaning, resulting in an earlier transition toward mechanical cleaning as the preferred strategy. Similar optimization approaches have also been applied beyond individual heat exchangers, with cleaning strategies for entire heat exchanger networks being optimized as demonstrated in [133].

The optimization process resulted in significant economic savings, particularly when deposit aging effects were pronounced. An important consideration when evaluating cleaning strategies, and fouling phenomena in general, is the variation of input parameters, namely the uncertainty associated with operating conditions. Many proposed cleaning strategies assume steady-state operation of the heat exchanger or heat exchanger network; however, in practical applications, operating parameters can vary considerably, which may significantly affect the optimization results.

A commonly applied two-layer fouling model, in which the growing deposit is represented by two layers with distinct properties and different resistance to cleaning methods, was extended by Di Pretoro et al. [134] to incorporate uncertainty in the inlet hot-stream temperature. Gaussian and Beta probability density functions were used to describe the temperature distribution. The results demonstrated that the choice of probability distribution has a significant impact on both the cleaning cost and the optimal cleaning cycle duration, highlighting the importance of accurately characterizing and controlling system input parameters during cleaning optimization.

Similar conclusions were reported by Al Ismaili et al. [135], who investigated different Gaussian distributions to represent operational uncertainties. Their results revealed substantial differences between cleaning schedules optimized while considering uncertainty and those obtained under deterministic assumptions, demonstrating the necessity of incorporating parameter variability into heat exchanger network cleaning strategies.

V. CONCLUSIONS

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n recent years, environmentally sustainable production and transportation technologies have

gained increasing attention across all industrial sectors as the world moves toward a carbon-neutral society. Despite its significant environmental impact, fouling has received comparatively limited attention in this context. Fouling in crude oil refineries alone has been estimated to contribute approximately 88 million tonnes of CO_2 emissions annually, corresponding to around 2.5% of total anthropogenic CO_2 emissions from these facilities [109]. Furthermore, the economic impact of fouling is substantial, with associated costs estimated at approximately 0.25% of the gross national product in highly industrialized countries [102]. These considerations, among others, emphasize the need for greater research efforts toward a deeper understanding of fouling mechanisms and the development of effective mitigation strategies.

Several important aspects of fouling remain insufficiently understood, including deposit aging, the initial stages of fouling development, and the interactions between different fouling mechanisms. In particular, improved understanding of fundamental fouling processes could significantly influence the design and operation of future heat transfer equipment. Emerging technologies, such as artificial neural networks and computational fluid dynamics (CFD) simulations, are expected to play an increasingly important role once the underlying mechanisms are better characterized, enabling more accurate prediction of process behaviour.

Advances in fundamental fouling knowledge may also lead to the development of more efficient and environmentally sustainable fouling mitigation methods. Many existing mitigation techniques have been developed primarily through empirical trial-and-error approaches, highlighting the need for further investigation into their fundamental operating principles. Although fouling can currently be reduced through various preventive and corrective measures, complete elimination remains unrealistic. Therefore, the demand for improved and innovative fouling mitigation strategies is expected to continue in the future.

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