

Recent Advances in Fouling Mitigation and Dynamic Modeling in Industrial Heat Exchangers: From Nanocomposite Surfaces to Full-Cycle Optimization

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Abstract

Heat exchangers are integral to nearly all industrial operations, though their thermal performance is continuously hindered by fouling, where unwanted deposits compromise efficiency. This accumulation introduces fouling thermal resistance (R_f), resulting in higher energy usage and costly maintenance. This review synthesizes key advancements (2020–2022) across two complementary domains: proactive control methods (surface engineering, flow optimization, electromagnetic fields) and advanced predictive simulations (kinetic modeling and full-cycle dynamics). We examine breakthroughs in low-adhesion materials like Ni-P-PTFE nanocomposites and the practical application of the Levenberg-Marquardt inverse method for non-intrusive parameter estimation. The paper argues for a unified approach, advocating for design guided by the Comprehensive Performance Evaluation Criteria (CPEC) and the development of integrated digital twins to optimize the entire operational life, including the Cleaning-in-Place (CIP) phase.

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I. Introduction

Heat exchangers are integral components in virtually every industrial process, from energy generation and chemical synthesis to food production. Sustaining their thermal efficiency is a persistent challenge due to fouling, the phenomenon of material accumulation (mineral scales, particulates, biofilms) on heat transfer surfaces. This deposition creates a thermal barrier, fouling thermal resistance (R_f), which severely degrades the overall heat transfer coefficient (U). The resulting inefficiencies—encompassing increased energy consumption, prolonged downtime, and frequent chemical cleaning—are responsible for significant annual economic losses [3].

The intricate nature of this issue is evident in the varying forms of deposit and the context-specific solutions required. For instance, mineral scaling from potable water, composed largely of CaCO_3 , is highly surface-dependent, with Copper (Cu) and Aluminium (Al) substrates observed to accumulate scale more readily than stainless steel [4]. Conversely, in high-temperature flue gas environments laden with particulates, geometric modifications, such as the honeycomb H-type finned tube bundle, are necessary for effective management [2]. Furthermore, temperature itself can serve as a key control factor; in corrosive marine settings, the performance of Cu-Ni 90/10 alloy is governed by a critical temperature near 60°C , where electrochemical processes governing complexation and salt dissolution shift the fouling-corrosion equilibrium [5].

Confronting this pervasive problem involves two main research avenues: proactive control methods and advanced predictive simulations. Recent breakthroughs in control include modifying surface energy via Ni-P-PTFE nanocomposite coatings to inhibit adhesion [1] and utilizing non-chemical electromagnetic fields—demonstrating peak anti-fouling efficiency (up to 91.2% at 1 kHz) by influencing crystallization kinetics [7]. In modeling, techniques such as the Levenberg-Marquardt inverse method are now being used to reliably estimate key kinetic parameters (R_f^* and τ) of the asymptotic Kern and Seaton model from online operational data [3].

Prior reviews frequently address mitigation or modeling in isolation. This paper addresses a significant gap by synthesizing these two pathways, arguing that a unified approach is essential for true system optimization. Moreover, any assessment of new anti-fouling technology must adopt the Comprehensive Performance Evaluation Criteria (CPEC), which collectively accounts for pressure drop, heat transfer, and fouling resistance [8]. This holistic framework is necessary for effective optimization across the full operational cycle, including the CIP phase [6]. Therefore, this review critically evaluates recent advances in (1) novel surface engineering and field-assisted mitigation and (2) dynamic modeling and full-cycle optimization.

II. Proactive Control and Surface Engineering for Fouling Mitigation

Proactive control methods seek to prevent or reduce the rate of deposit formation through manipulation of the heat transfer surface properties, flow conditions, or external assistance.

2.1. Material Effects and Thermal Influence

The inherent properties of the heat exchanger material fundamentally affect fouling dynamics.

- **Mineral Scaling:** Research into mineral scaling from potable water shows that the substrate material strongly influences the formation of deposits [4]. Al-Gailani et al. observed that Copper (Cu) and Aluminium (Al) surfaces fostered significantly higher scale accumulation compared to stainless steel counterparts [4].
- **Temperature Control:** In simulated marine settings, Besghaier et al. identified that a critical temperature near 60°C promoted the dissolution of salts over the formation of stable electrochemical complexes in the Cu-Ni 90/10 alloy, suggesting this temperature is conducive to deposit removal or inhibition [5].

2.2. Advanced Coatings and Surface Modification

Surface engineering involves applying or modifying materials to specifically inhibit foulant adhesion.

- **Nanocomposite Coatings:** Liu et al. developed a Ni-P-PTFE nanocomposite coating for corrugated plate heat exchangers to combat composite fouling [1]. The incorporation of Polytetrafluoroethylene (PTFE) provides low surface energy, which effectively diminishes the adhesion forces and the total mass of deposited material. While a slight clean-state heat transfer penalty was noted, the long-term fouling reduction justified the use of the low-adhesion coating [1].

2.3. Hydraulic and Geometric Optimization

Designing flow channels and geometries can enhance shear stress and facilitate deposit removal.

- **Particulate Flow:** For heat recovery from flue gas containing significant fly ash, Tang et al. determined that the honeycomb H-type finned tube bundle was superior among tested configurations, offering the best performance in terms of low fouling thermal resistance and ease of cleaning [2].
- **Performance Evaluation:** Gao et al. studied eight different enhanced tubes in a cooling tower water system [8]. They argued that the non-linear relationship between velocity and asymptotic fouling resistance (R_f^*) necessitates a holistic metric. They proposed the Comprehensive Performance Evaluation Criteria (CPEC), which balances heat transfer (Nu) against hydraulic losses (friction factor, f) and residual fouling (R_f^*) for true system assessment [8].

2.4. Field-Assisted Control

Non-chemical methods using external fields are gaining traction for mineral scale inhibition.

- **Electromagnetic Treatment:** Yan et al. experimentally confirmed that electromagnetic anti-fouling technology can significantly reduce scaling in cooling water systems [7]. The magnetic field modifies the crystallization process to decrease surface adhesion. Crucially, they identified a maximum anti-fouling efficiency of 91.2% achievable at an optimal frequency of 1 kHz [7].

III. Dynamic Modeling and Optimization of the Operational Cycle

The shift to predictive maintenance requires robust modeling that captures the kinetics of fouling and its interaction with cleaning cycles.

3.1. Kinetic Modeling and Non-Intrusive Parameter Estimation

Fouling accumulation in many contexts follows the asymptotic trend defined by the Kern and Seaton model:

$$R_f(t) = R_f^* \left(1 - e^{-\frac{t}{\tau}} \right)$$

- **Inverse Problem Solution:** Fguiri et al. successfully implemented the Levenberg-Marquardt (LM) technique to estimate the asymptotic resistance (R_f^*) and characteristic time (τ) simultaneously in a phosphoric acid/steam heat exchanger [3]. By using routine operational data, this inverse method facilitates continuous, non-intrusive thermal monitoring, eliminating the need for internal measurement [3].

3.2. Integrated Full-Cycle Dynamic Modeling

Advanced modeling now encompasses the entire equipment lifecycle, integrating the periods of fouling and cleaning.

- **Dynamic 2D Simulation:** Sharma and Macchietto developed a dynamic 2D distributed model for plate heat exchangers used in dairy processing, seamlessly linking the production (fouling growth) phase with the Cleaning-in-Place (CIP) phase [6]. The model tracks the net change in deposit mass (m) over time:

$$\frac{dm}{dt} = \dot{m}_{deposition} - \dot{m}_{removal}$$

- **Optimization Criteria:** The core advantage of this dynamic framework is its ability to calculate the cost-optimal operating period. The model determines the point where the cost incurred by thermal energy loss due to fouling is balanced by the cost of the subsequent CIP cycle, defining a critical deposited mass (m_{crit}) as the optimal shutdown threshold [6].

3.3. Performance Criteria for Optimization

Optimization must account for all performance variables, not just fouling resistance. Since fluid velocity has a complex, non-linear influence on Rf^* [8], the objective function for any optimization model must be broadened to include pumping costs, justifying the use of the holistic CPEC metric defined in Section 2.

IV. Conclusion and Outlook

This analysis confirms that substantial progress in heat exchanger management stems from parallel developments in material science for deposit prevention and predictive simulation frameworks. The primary conclusion is that effective long-term optimization requires integrating these two domains.

Domain	Key Technical Achievement	Impact	Citation
Surface Control	Ni-P-PTFE nanocomposite [1]	Low-energy coating significantly reduces composite fouling mass.	[1]
Optimization	Dynamic 2D Model with m_{crit} [6]	Allows for calculation of the cost-optimal run length by integrating fouling and CIP dynamics.	[6]
Modeling	Levenberg-Marquardt estimation [3]	Enables non-intrusive, real-time determination of fouling kinetic parameters (Rf^* , τ).	[3]
Evaluation	CPEC metric [8]	Mandates holistic assessment, accounting for Nu , f , and Rf^* simultaneously.	[8]

The most important conceptual shift is the imperative to move beyond Rf minimization toward comprehensive system evaluation. The CPEC framework is essential for guiding future anti-fouling design toward true economic optimality.

4.2. Recommended Future Research Trajectories

1. **Creation of Integrated Digital Twins:** The foremost challenge is to integrate existing technologies into unified predictive tools. This involves developing robust digital twins by linking the dynamic, full-cycle models [6] with online data streams and real-time parameter updates provided by inverse methods [3].
2. **CPEC-Directed Technology Development:** All new mitigation strategies, including novel materials and geometric enhancements, must be validated and optimized using the CPEC metric [8]. Future design efforts should focus on maximizing the CPEC value, rather than merely reducing Rf , to guarantee practical value.
3. **Exploration of Combined Effects:** Research should investigate the synergistic benefits of applying multiple mitigation techniques. For instance, testing geometric solutions (honeycomb fins [2]) in conjunction with field-assisted methods (electromagnetic at 1 kHz [7]) on low-energy surfaces [1] could yield breakthroughs in anti-fouling performance far exceeding individual strategies.

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