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Smart Predictive Maintenance of Heat Exchangers Using AI and Near-Infrared (NIR) Spectroscopy

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***Abstract* -** Calcification in heat exchangers, primarily composed of calcium carbonate, significantly reduces efficiency and increases maintenance costs. Traditional detection methods are often time-consuming and ineffective. This proposal outlines the integration of Near-Infrared (NIR) spectroscopy with Artificial Intelligence (AI) to enable automated predictive maintenance for heat exchangers. NIR spectroscopy provides non-invasive, rapid, and accurate detection of calcification, while AI algorithms analyse spectral data to predict failure risks. We propose an AI-driven system that leverages NIR Spectral data to optimize operating conditions, detect anomalies, and mitigate issues before they escalate. The system will be validated through laboratory-scale experiments, to demonstrate the improvements in efficiency, energy savings, and operational reliability compared to traditional methods. This study seeks industrial partnership to implement the platform in real-world industrial applications.

***Keywords*:** Calcification, Heat Exchanger, NIR, Predictive Maintenance

1. Introduction

Heat exchangers are indispensable components in a wide range of industrial applications, including power generation, chemical processing, and HVAC systems, due to their role in efficient thermal energy transfer [1, 2]. However, their performance is often compromised by fouling, a phenomenon where unwanted deposits accumulate on heat transfer surfaces. Among the various types of fouling, calcification the deposition of calcium-based salts such as calcium carbonate ($CaCO_3$) is particularly problematic due to its prevalence in systems utilizing water for cooling [3, 4].

Calcification reduces heat transfer efficiency, increases energy consumption, and leads to operational downtime, resulting in significant economic losses. The global industrial sector incurs an estimated $10 billion annually in additional energy costs and maintenance due to fouling-related inefficiencies, with calcification accounting for a portion of these losses [4].

Despite extensive research on fouling mechanisms, the specific processes driving calcification in heat exchangers are incompletely understood. The current literature highlights the influence of factors such as water chemistry, flow velocity, and surface temperature on the nucleation and growth of calcium deposits [5]. However, gaps remain in understanding the interaction between these factors under dynamic operating conditions, as well as the long-term evolution of the calcification layers and their impact on thermal performance.

In recent years, advancements in AI and spectroscopic techniques such as Near-Infrared (NIR) spectroscopy have opened new doors for addressing fouling challenges. NIR spectroscopy provide non-invasive, real-time insights into the chemical composition of deposits, while AI algorithms can analyse this data alongside operational parameters to predict fouling behaviour and optimize maintenance schedules and trigger intervention procedures [6]. This integration of technologies holds the potential to revolutionize fouling management by enabling proactive and data-driven decision-making.

1.1. Paper contributions

The mitigation of calcification in heat exchangers has long been a persistent challenge, addressed through a range of traditional methods and, more recently, advanced techniques involving AI and machine learning technologies. Building upon these advancements, this research proposes an innovative AI-based platform that integrates cutting-edge technologies into a cohesive, real-time, and interactive solution. The platform will not only enhance the detection and mitigation of calcification but also provides actionable insights and predictive maintenance capabilities.

Additionally, the proposed solution aims to improve the thermal efficiency of heat exchangers, reduce energy losses caused by calcification, and extend their operational lifespan. By leveraging predictive maintenance features, the platform offers valuable feedback to both operators and manufacturers, ensuring a comprehensive and adaptive approach to optimizing heat exchanger performance. This holistic system represents a significant step forward in addressing the challenges posed by calcification, delivering both immediate and long-term benefits for industrial applications.

1.2. Hypothesis and research proposal scope

The proposal targets *Shell-and-Tube* heat exchanger types [7], under specific operating conditions and assumptions. First, it focuses on a heat exchanger configuration where a hot liquid flows inside the tubes, while coolants circulate outside the tubes. Second, the coolants covered in this proposal are limited to hard water, soft water, seawater, and river water, providing a range of conditions to assess the effectiveness of the proposed solution. By examining these parameters, the proposal seeks to advance the understanding of calcification dynamics and improve the accuracy of detection and mitigation strategies in industrial heat exchangers.

1.3. Paper structure

The paper is structured as follows: Section 2 reviews the existing literature on fouling and calcification phenomena, and the state-of-the-art solutions to detect and mitigate calcification in heat exchangers. Section 3 explores how cutting-edge technologies in NIR and AI have been applied to detect the calcification cases. Section 4 details the proposed solution to enhance calcification detection and mitigation using ML and NIR, while Section 5 concludes the paper and gives insights on the future work.

2. Fouling and Calcification in Heat Exchangers

Fouling and calcification in heat exchangers are significant challenges that adversely affect thermal efficiency and operational performance [3, 4, 8, 9]. Fouling refers to the accumulation of unwanted deposits on heat transfer surfaces, while calcification specifically involves the formation of hard, insoluble calcium-based scales. These deposits act as insulating layers, reducing heat transfer rates, increasing energy consumption, and leading to higher maintenance costs [10, 11]. The mechanisms of calcification, its impact on heat exchanger performance, and the latest advancements in detection and mitigation strategies are explored in detail in the next subsections.

2.1. Understanding calcification contamination

Calcification refers to the process of calcium-based scale formation on the surfaces of heat exchangers, primarily due to the precipitation of calcium carbonate ($CaCO_3$) and other calcium salts from water or coolant fluids [8, 12]. This occurs when water containing dissolved calcium and bicarbonate ions is subjected to elevated temperatures or changes in pH, leading to the deposition of hard, insoluble mineral layers [10].

Figure 1 depicts a cross-sectional view of a heat exchanger tube affected by calcification. The insulating effect of calcification not only diminishes the thermal performance of heat exchangers but also necessitates frequent cleaning and downtime, and economic losses.

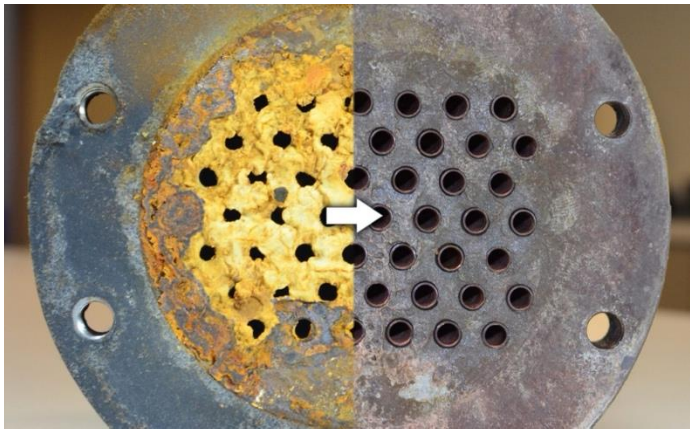

Fig.1: A bundle of heat exchanger tubes in calcification state and clean state.
Photo credit: https://www.apexengineeringproducts.com [accessed 22 Jan 2025].

2.2. Calcification mitigation approaches

Several strategies have been developed to mitigate calcification in heat exchangers, including chemical treatment, electrochemical cleaning, ultrasound wave cleaning and coating surface modification. Table 1 provides an overview of the state-of-the-art approaches addressing calcification in heat exchangers. Each method has its strengths and limitations, making them suitable for specific scenarios. For instance, chemical cleaning is highly effective for severe scaling but poses environmental and equipment safety risks [13]. Ultrasonic treatment and magnetic water treatment offer environmentally friendly alternatives but are limited in their effectiveness for certain types of scaling [14, 15]. Electrochemical methods and surface coatings provide long-term solutions but come with high costs and maintenance requirements [16].

Authors in [17, 18] developed an anti-fouling surface coating approach by modifying SUS304 with micro/nanoscale holes and applying polymethyl methacrylate (PMMA) and hexagonal boron nitride (BN) coatings, with the PMMA-coated heat exchanger showing the best performance by minimizing $CaCO_3$ deposition and maintaining the lowest fouling factor due to reduced contact angle hysteresis. Overall, optimized heat exchanger design is a sustainable approach but is often constrained by high upfront investments and limited applicability to existing systems [19, 20].

The mentioned solutions address the calcification problem to some extent, but they often react too late, as they have evolved over time without fully tackling the core issue: how to detect calcification at an early stage without causing prolonged downtime and how to optimize the intervention procedures. The next section summarizes how emerging technologies like AI and NIR have been engaged to answer these questions.

3. NIR and AI for Advanced Calcification Detection

3.1. NIR Spectroscopy overview

Near-Infrared (NIR) spectroscopy is a non-destructive analytical technique that uses near-infrared light, typically in the wavelength range of 780 nm to 2500 nm, to analyse the chemical composition of materials. When NIR light interacts with a surface, it is absorbed, reflected, or scattered based on the molecular bonds present in the material. By analysing the resulting spectral data, NIR spectroscopy can identify specific compounds, such as calcium carbonate, and provide quantitative information on their concentration and distribution.

NIR spectroscopy operates on the principle of molecular overtone and combination vibrations. When NIR light interacts with a material, certain wavelengths are absorbed by the molecular bonds (e.g., C-H, O-H, N-H), causing transitions in their vibrational states. The resulting absorption spectrum is unique to the chemical composition of the material, allowing for the identification and quantification of specific compounds [21].

Table 1: Traditional approaches to mitigate calcification in heat exchangers

Approach	Description	Reference
Chemical Cleaning	Use of acids (e.g., HCl, citric acid) or alkalis to dissolve calcium deposits.	[13]
Ultrasonic Treatment	Application of ultrasonic waves to disrupt and remove calcium deposits.	[14, 15]
Electrochemical Methods	Electrolysis to precipitate calcium ions before they form scale.	[16]
Surface Coatings	Application of anti-fouling coatings (e.g., hydrophobic or nano-coatings) to prevent scaling.	[17, 18]
Optimized Heat Exchanger Design	Designing heat exchangers with materials or geometries that minimize scaling	[19, 20]

3.2. Applications of NIR spectroscopy in industrial settings

NIR spectroscopy has emerged as a vital tool for real-time, non-destructive monitoring across various industries. In the food and beverage industry, NIR spectroscopy has proven to be a promising technique for food safety inspection and control. Its advantages include speed, non-invasive measurement, ease of use, and minimal sample preparation requirements, making it an ideal solution for quality assurance [22]. In water treatment, NIR spectroscopy has become a valuable tool for rapidly analysing and detecting water quality parameters. It has demonstrated effectiveness in both qualitative and quantitative assessments of pollutants, including COD (Chemical Oxygen Demand), organic matter, microbial contamination, metal ions, and emerging contaminants [23].

Similarly, in chemical manufacturing, NIR spectroscopy plays a critical role in real-time process monitoring and quality control. For example, in polymer extrusion processes, NIR is used to measure critical parameters such as composition, moisture content, reaction status, and rheological properties (e.g., viscosity and melt flow index). These in-line measurements enhance process control, optimize production, and improve product quality, even in demanding industrial environments [24].

We believe that NIR spectroscopy, particularly when integrated with AI, represents a transformative technology for industrial process optimization. Its applications span multiple industries, offering significant improvements in efficiency, sustainability, and profitability.

3.3. Artificial Intelligence (AI) and Machine Learning (ML) techniques

First, it's important to clarify the distinction between AI and ML. ML is a subset of AI that focuses on enabling machines to learn from data without being explicitly programmed. While AI encompasses a broad range of technologies designed to mimic human intelligence, ML specifically uses algorithms that improve their performance on a task as they are exposed to more data over time. This distinction highlights ML's role as a data-driven approach within the broader field of AI.

ML has demonstrated significant benefits in industrial applications, including energy conservation, reduced environmental impact, and improved production efficiency. Its ability to optimize processes and analyse data has made it a valuable tool for driving sustainability and operational excellence in various industries [25, 26].

Table 2 provides selected ML approaches for detecting calcification and fouling in heat exchangers with high level of accuracy. Long Short-Term Memory (LSTM) method achieves 99.43% accuracy in real-time fouling prediction, enabling early detection and reducing downtime [27]. Also, the authors in [28] applied the eXtreme Gradient Boosting (XGBoost) algorithm to develop an intelligent fault diagnosis for heat exchangers with 99.79% accuracy, which outperforms the traditional methods.

Table 2: ML techniques for calcification detection in heat exchangers

Method	Performance Metrics	Citation
LSTM	Accuracy: 99.43%	[27]
XGBoost	Accuracy: 99.79%	[28]

To conclude, recent ML models can effectively identify patterns, classify data, and diagnose faults in heat exchangers. However, current applications of these methods are to be typically offline and rely on specialized detection equipment, which limits their ability to perform real-time monitoring and fault detection. Accordingly, to fill the gap, this paper proposes integrating NIR technology with ML approaches to enable real-time and dynamic monitoring of calcification formation and provide predictive maintenance solution for heat exchangers.

4. NIR and ML-based Platform for Heat Exchanger Interactive Maintenance

Hereby, we explore the integration of NIR spectroscopy with ML technique to monitor and maintain heat exchangers efficiently. The platform leverages NIR sensors to collect real-time data on coolant inlet and outlet water, while a ML model analyses the data to predict potential faults and optimize intervention procedures.

4.1. Platform modules and functions

The proposed platform integrates several advanced technologies, each playing a critical role in ensuring efficient and predictive maintenance. Figure 2 depicts the platform's modules.

Data Collection: collects periodically data from the NIR spectroscopy, temperature and pressure sensors. The collected data provides detailed insights on the chemical composition, temperature and pressure of the inlet and outlet flows.

Data Analysis: analyses the collected data using ML model, which will be trained to identify calcification patterns, and predict potential calcification risks. Algorithm 1 details the steps of analysing the received data to detect in real-time based calcification formation.

Decision-Making: receives input from the *Data Analysis* to interact accordingly. As shown in Algorithm 1 (steps 15-23), the module will generate actionable recommendations for predictive maintenance. These recommendations include optimized cleaning schedules, operational adjustments, or targeted interventions to prevent the scaling.

System Optimization: translates the recommendations to orders that adapt the heat exchanger operation conditions. For example, increase or decrease the coolant fluid flow rate inside the exchanger. This dynamic control ensures that the system operates at peak performance while minimizing maintenance costs.

Validation and Feedback: continuously validate actions and recommendations through laboratory experiments and real-world data. Also, it will be used to refine the ML model and improve the accuracy of NIR detection, ensuring the system evolves and adapts to new challenges.

Together, these components will form a robust and intelligent platform that not only detects and predicts calcification but also optimizes heat exchanger performance, reduces downtime, and lowers operational costs.

4.2. Platform integration with cooling system

The integration of NIR technology for monitoring and controlling calcification rates in heat exchangers involves a systematic approach. The process is designed to enhance operational efficiency, reduce maintenance costs, and enable predictive maintenance. Below are the detailed steps:

4.2.1. Installation of NIR technology

NIR sensors will be installed at two critical points within the cooling system: at the inlet, before the cooling fluid enters the heat exchanger, and at the outlet, after the cooling fluid exits the heat exchanger. This dual-point installation enables continuous monitoring of the fluid's mineral composition, providing real-time insights into changes that could indicate scaling, fouling, or other inefficiencies.

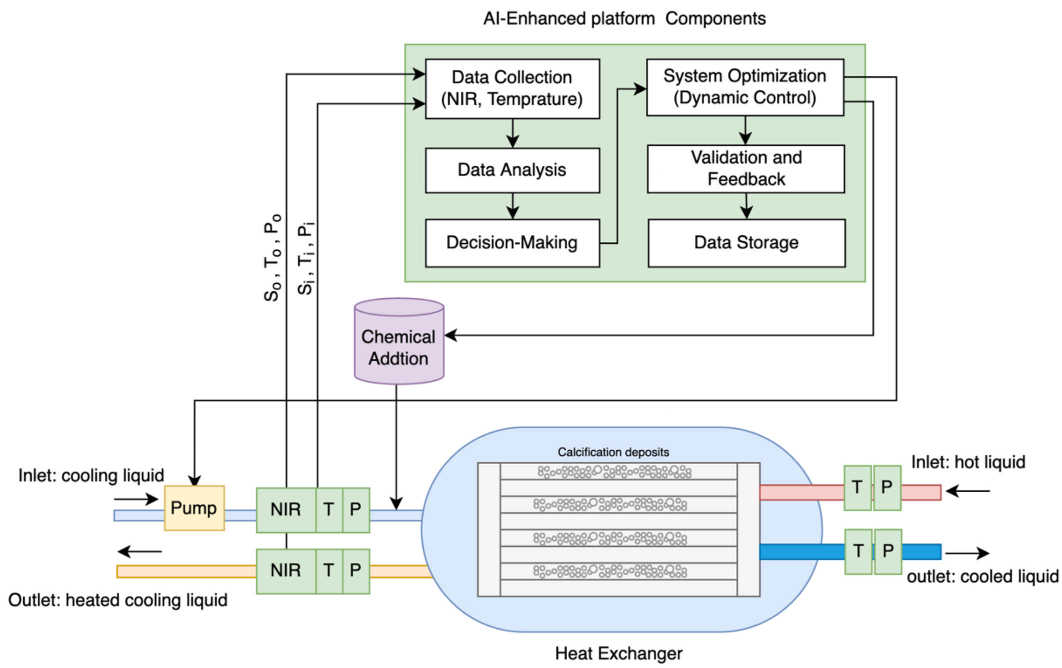

Fig. 2: AI-Enhanced platform for heat exchanger interactive maintenance.

4.2.2. Monitoring mineral composition of cooling fluid

Via the NIR technology the platform will be able to measures the concentration of mineral components, such as calcium carbonate, in the cooling fluid. When water is used as the cooling fluid, the system operates as follows:

- If the fluid is free of calcification components: The system sends a signal to allow the fluid to enter the heat exchanger.
- If the fluid contains calcification components: The system triggers an alert to replace the fluid or inject fresh cooling water. A notification is sent to the heat exchanger operator for corrective action.

4.2.3. Fluid control based on solid particle concentration

Relaying on a well-crafted ML models the platform will be able to monitor the inlet and outlet cooling fluid, so if solid particles, such as calcification components are detected, the platform directs the pump to adjust the fluid flow based on the particle concentration. For instance, in the case of low solid particles concentrations, the pump increases the flow rate of the cooling fluid, utilizing high-pressure pulses to prevent particle deposition and maintain system efficiency. While in cases of high concentrations, the pump mixes the cooling fluid with chemical additives to dissolve the particles, followed by high-pressure pulsed flow to thoroughly flush the system and remove any residual deposits.

4.2.4. Delta temperature-based monitoring

The platform continuously monitors the delta temperature ΔT of the cooling fluid. Thus, if ΔT decreases below the designed threshold, it indicates reduced heat transfer efficiency, likely caused by calcification deposits insulating the heat transfer surfaces. In such cases, the platform alerts operators to schedule cleaning or maintenance to restore optimal efficiency. While if ΔT remains within the designed range, the heat exchanger is operating efficiently, and no immediate action is required.

Algorithm 1 Calcification detection and intervention algorithm

Input:
S_i: NIR Spectral data of Inlet cooling water.
T_i: Temperature of Inlet cooling water.
P_i: Pressure of Inlet cooling water.
S_o: NIR Spectral data of Outlet cooling water.
T_o: Temperature of Outlet cooling water.
P_o: Pressure of Outlet cooling water.
ΔT: $T_o - T_i$.
ΔP: $P_i - P_o$.
Th_c : $CaCO_3$ concentration threshold.
Ex_r : Exchanger heat transfer ratio.
procedure CalcificationDetection($S_i, T_i, P_i, S_o, T_o, P_o$)
  $C_i \leftarrow$ CalciumCarbonateDetection(S_i) ▷ Predict $CaCO_3$ concentration in inlet cooling water via ML
  $C_o \leftarrow$ CalciumCarbonateDetection(S_o) ▷ Predict $CaCO_3$ concentration in outlet cooling water via ML
  if $C_i > \mathrm{Th}_C$ **then**
    Action: *Send Alarm to Change the cooling water*
  else if $C_o == C_i$ & $\Delta P == 0$ & $\Delta T == Ex_r$ **then**
    Action: *normal case, no action required*
  else if $C_o > C_i$ & $\Delta P == 0$ & $\Delta T == Ex_r$ **then** ▷ Low $CaCO_3$ concentration case
    Action: *Pump injects high pressure or pulsed cooling water*
  else if $C_o >> C_i$ & $\Delta P > 0$ & $\Delta T < Ex_r$ **then** ▷ High $CaCO_3$ concentration case
    Action: *Add and mix chemical additive to the cooling water*
    Action: *pump injects the mixed cooling water with high pressure*
  end if
end procedure

4.2.5. Pressure drop-based monitoring

The system regularly checks the inlet and outlet cooling fluid pressure so if ΔP increases above the baseline threshold, it indicates the buildup of calcification deposits, which narrow the flow passages and increase resistance. In such cases, the system alerts operators to schedule cleaning or maintenance to restore efficiency. Conversely, if ΔP remains within the baseline range, the heat exchanger is operating normally, and no immediate action is required.

4.2.6. Real-Time data aggregation and predictive maintenance

The real-time logging of calcification rates and thermal conductivity data enables the creation of an operational database. This database provides the *Decision-Making* component with robust insights for predictive maintenance (i.e., identifying potential failures before they occur), and proactive interventions for scheduling maintenance and corrective actions to avoid heat exchanger downtime.

5. Conclusion and Future Work

Calcification, primarily caused by calcium carbonate deposition, poses a significant challenge to the efficiency and longevity of heat exchangers, leading to reduced thermal performance, increased energy consumption, and higher maintenance costs. Traditional detection and mitigation methods are often inefficient, time-consuming, and unable to address the problem proactively. To overcome these limitations, this research proposes an innovative, smart platform that integrates Near-Infrared spectroscopy and machine learning technologies for real-time detection, analysis, and mitigation of calcification.

As future work, this research will focus on the development and implementation of the proposed platform. This will involve developing a robust system capable of real-time detection, analysis, and mitigation of calcification in heat exchangers. Following platform development, laboratory-scale validation will be conducted to evaluate its accuracy, reliability, and effectiveness under controlled conditions. The outcomes of this phase will lay the foundation for scaling up the technology and deploying it in operational environments.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this research proposal the author(s) used DeepSeek (www.deepseek.com) service to improve the readability and language of the manuscript. After using the service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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