Data-Driven Assessment of Plate Heat Exchanger Fouling in a Vegetable-Oil Deodorization Unit

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Abstract

Plate heat exchangers (PHEs) are widely used in process industries because of their high heat-transfer coefficients, compactness, and ease of cleaning [1]. However, deposition of organic and inorganic foulants on plate surfaces degrades thermal performance, increases energy consumption, and can drive unplanned shutdowns [2]. This study quantified fouling behavior in two gasketed plate heat exchangers installed in the deodorization section of a vegetable-oil refinery. Several months of historian data were extracted from the plant distributed control system, including temperature indicating transmitters (TITs) and flow indicating transmitters (FITs) on the oil and water circuits. The raw 30-s measurements were aggregated to 5-min averages, cleaned using physical consistency checks and outlier removal, and, where necessary, reconstructed using steady-state energy balances and pump curves to infer missing temperatures and flow rates.

For each exchanger and time step, the overall heat-transfer coefficient U_t and fouling thermal resistance R_f were computed from the measured heat transfer rate (Q) and log-mean temperature difference (LMTD), using a clean reference coefficient U_{clean} determined immediately after confirmed cleaning events.

Results showed that the preheater (HX-103) experienced gradual fouling with typical R_f values on the order of 10^{-3} , hr·ft²·°F/Btu, while the final coolers exhibited larger fouling resistances and more pronounced step reductions in R_f following maintenance. The methodology provides a practical framework for condition-based cleaning of PHEs using routinely collected plant data and can be extended to other units within the facility.

1. Introduction

Heat exchangers transfer thermal energy between process streams and represent critical assets in energy-intensive industries. Plate heat exchangers (PHEs) are increasingly preferred over shell-and-tube units because they offer high heat-transfer coefficients, compact footprints, and relatively simple maintenance, and because their heat-transfer area can be adjusted by adding or removing plates [3]. However, PHEs are also susceptible to fouling—the accumulation of undesired deposits on plate surfaces—which introduces additional thermal resistance, increases pressure drop, and reduces overall performance [1]. A 2014 study estimated the economic cost of fouling in heat exchangers in the US to be $14 billion dollars annually in added fuel usage, production losses, and maintenance costs worldwide [4].

In edible oil processing, PHEs are used extensively for heating and cooling vegetable oils and water streams [5]. Organic compounds, dissolved salts, and suspended solids in these streams can promote both particulate and crystallization fouling, leading to gradual deterioration in exchanger performance and the need for periodic cleaning[6]. Cleaning-in-place (CIP) and manual plate cleaning are effective but require several hours of downtime per unit, so plants benefit from data-driven cleaning schedules that trigger maintenance when fouling reaches a critical level rather than at fixed calendar intervals [7].

The objective of this study was to use plant historian data to quantify fouling behavior in selected PHEs in the deodorization area of vegetable-oil processing. Specifically, we:

1. Understand the performance of two PHEs (one oil coolers and one oil preheater) over a six-month period using TIT and FIT measurements.

2. Quantify and plot the fouling resistance over time for the PHEs over the last 6 months.

Background and Significance

A heat exchanger is a device that transfers thermal energy between two or more fluids separated by a solid surface, with the fluids having different temperatures [3]. Plate heat exchangers (PHEs) are widely used in various industries due to their advantageous characteristics over conventional shell-and-tube heat exchangers, including easy maintenance, compact size and high heat transfer coefficients. In addition to that, the possibility to add plates provides the ability to increase the heat transfer area [4]. PHEs also provide several advantages over tubular exchangers. They are generally more cost-effective, require significantly less metal during fabrication, and have a lower overall carbon footprint. In addition, PHEs are easier to clean and maintain [4].

During their operations, PHEs tend to undergo fouling, which refers to the deposition of undesired mineral deposits on the surface of heat exchangers [2]. The fouling deposition layer leads to resistance to heat flux and reduces the free space for heat flow to occur [2]. Fouling is an issue because it increases pressure drop and lowers heat transfer efficiency. It has been reported that over 90% of heat exchangers experience fouling, and that fouling related costs accounts for approximately 0.25% of the gross national product in industrialized countries [1]. Further studies have shown that fouling is responsible for 2.5% of the total CO2 emissions. The CO2 emissions primarily originate from crude oil refineries, which proves to be a serious economic and environmental problem [4]. A 2014 study estimated the economic cost of fouling in heat exchangers in the US to be $14 billion dollars annually [5]. The negative impacts of fouling have led to the development of various fouling mitigation and fouling strategies.

Fouling in plate heat exchangers (PHEs) is not a single event, but a progressive process that can be described in four stages: induction, growth, steady state, and aging [2]. Understanding these stages is crucial for predicting performance decay and establishing effective cleaning strategies.

Initiation

The initiation stage is when the exchanger surface becomes conditioned and the first deposits or biofilms begin to form. In this phase, the thermal resistance is negligible, but the foundation for later growth is established [2]. In edible oil and water services, initiation may occur quickly because organic compounds and dissolved salts readily create nucleation sites.

Growth.

Once initiated, deposits accumulate at a faster rate, as foulants are continuously transported from the bulk fluid to the plate surface [2]. This stage is marked by a steady decline in the overall heat transfer coefficient and a corresponding rise in fouling resistance. For particulate-rich flows, a parallel increase in pressure drop may also appear, signaling partial blockage.

Steady State.

Eventually, deposition and removal processes balance. Shear forces and turbulence in the narrow-corrugated channels of the PHE help to detach deposits as fast as they form, leading to an apparent plateau in fouling resistance [2]. At this point, the exchanger continues to operate with reduced efficiency but without further rapid deterioration.

Aging.

In some cases, deposits undergo chemical or physical changes—such as polymerization, crystallization, or dehydration—that make them more complicated and more adherent [2]. Aging layers are more resistant to chemical cleaning-in-place (CIP), and repeated CIPs may result in reduced recovery of the heat transfer coefficient.

According to Perry's Chemical Engineers' Handbook, six primary fouling mechanisms are recognized in heat exchangers: corrosion, biological growth, chemical reaction fouling, freezing, particulate deposition, and crystallization (or precipitation) [4]. While this classification provides a comprehensive framework, not all mechanisms are equally relevant in plate heat exchangers (PHEs) used in food and process industries.

In PHEs, corrosion fouling is typically less significant, since plates are fabricated from corrosion-resistant alloys (e.g., stainless steels, titanium). When corrosion occurs upstream in piping, its effect is indirect—introducing particulates that then accumulate within exchanger channels. Biological fouling is also limited in closed industrial cooling loops or municipal water systems when proper water treatment programs are applied [4]. Freezing fouling is considered exceptional and is not treated as a primary fouling class under TEMA standards.

For water-based heating and cooling services, which are prevalent in many industrial processes, including power generation, desalination, and communal hot water systems, the predominant mechanisms are particulate and crystallization fouling [4]. Suspended solids, corrosion products, and fibers can accumulate in narrow channels, leading to plugging and increased pressure drop. Meanwhile, dissolved salts can precipitate under supersaturated or high-temperature conditions, forming crystalline scale on the plate surfaces and directly reducing the overall heat transfer coefficient. These two mechanisms—particulate and crystallization—represent the most significant operational challenges for the exchangers in this project, since they directly degrade thermal performance, increase energy consumption, and dictate the effectiveness of cleaning strategies [4].

Managing fouling helps reduce downtime which affects production and incurs maintenance expenses. Cleaning a PHE requires several hours of downtime, typically 4 to 6 hours per cycle—

which places a heavy burden on both productivity and operating costs [6]. The economic impact of fouling and cleaning arises in multiple ways. First, fouling reduces the exchange rate's effective operating period, cutting into the amount of product that can be processed within a given day [6]. Second, to sustain production levels while one unit is offline, plants often need additional exchangers or standby capacity, which increases capital and maintenance costs.

Managing fouling can be done by developing a regular cleaning interval which adapts to the real-time fouling of the PHE. Having regular cleaning interval can serve three purposes, condition-based preventive maintenance can be adopted to reduce process downtime [7]. Secondly, having a predicted end-of-useful-life for the PHE can be used as an input to adjust operation parameters and extend the life between successive shutdowns. Lastly, with the progression of fouling the likelihood of other defects such as corrosion, fatigue-cracking and leakage increases with the plates being most susceptible. Having a preventive maintenance schedule lowers the possibility of critical failure which may render a heat exchanger unsuitable for further use leading to more process shutdown [7].

Maintaining heat exchanger performance requires periodic removal of deposits that accumulate on the plates. The Heat Exchange Institute (HEI) identifies three primary cleaning methods suitable for gasketed plate heat exchangers: backflushing, cleaning-in-place (CIP), and manual cleaning [8].

Backflushing.

Backflushing is a relatively simple approach where the flow direction is periodically reversed to dislodge particles, scales, or deposits that may be trapped in the channels [8]. By forcing the process fluid in the opposite direction to regular operation, backflushing can flush out suspended solids or light fouling layers before they harden. This method is most effective as a preventive measure rather than as a corrective one once significant fouling has developed.

Cleaning-in-Place (CIP).

CIP avoids disassembly by circulating an appropriate chemical cleaning solution through the heat exchanger [8]. While circulation in the reverse direction often improves results, effective cleaning can also be achieved in the normal flow direction if velocity is increased above operating levels [8]. Because CIP relies on the chemical dissolution of deposits, careful selection of the cleaning agent is essential to prevent damage to the plates or gaskets. Alkaline solutions are often used for organic deposits, while acidic solutions address mineral scaling [8]. CIP is particularly valuable for operations where downtime must be minimized, and it is most effective against early-stage or soft deposits.

Manual Cleaning.

Manual cleaning remains the most common and reliable method for restoring performance. This process involves shutting down the exchanger, opening the frame, and removing the plates for direct cleaning [8]. High-pressure water jets or soft non-metallic brushes are typically used to clean the plate surfaces. Manual cleaning is more labor-intensive and requires downtime. However, it is effective for removing hardened or aged deposits that resist chemical removal. It also allows direct inspection of the plates and gaskets, which is critical for identifying corrosion or mechanical damage that cannot be detected externally.

Heat Exchanger	**Function**
HX – 101	First oil cooler
HX – 102	Final oil cooler
HX – 103	Oil preheater

HX – 104	Water heater
HX – 105	Water cooler

2. Methods

2.1 Process description and equipment

The study focused on three gasketed PHEs located in the deodorization circuit of a vegetable-oil refinery:

- HX-101 – First oil cooler
- HX-102 – Final oil cooler
- HX-103 – Oil preheater

In the deodorizer, hot refined oil is contacted with stripping steam under vacuum to remove odor-forming volatiles. Upstream, the preheater (HX-103) raises the oil temperature using recovered heat from downstream streams; downstream, HX-101 and HX-102 cool the deodorized oil to storage or subsequent processing conditions.

All three exchangers were gasketed plate units with nominal heat-transfer areas of approximately 269–377 ft^2, depending on model and plate count. Because the preheater had plates removed during a previous maintenance event, its effective area was adjusted based on the current plate count recorded in the maintenance logs.

2.2 Instrumentation and data sources

Each PHE was instrumented with temperature indicating transmitters (TITs) on the hot and cold inlets and outlets, as well as flow indicating transmitters (FITs) on at least one side. In practice, three of the four temperatures were available per exchanger: HX-101 and HX-102 lacked cold-side outlet TITs, while HX-103 lacked a hot-side outlet TIT. One or both flow rates were available from FITs; for HX-101 the oil flow rate was inferred from pump curves rather than direct measurement.

All signals were recorded by the plant programmable logic controller (PLC) and archived in the plant process historian. Historian tags were exported as comma-separated value (CSV) files for the period 1st May 2025 to 31st October 2025 at a base sampling interval of 30s.

The primary monitoring window spanned 1st May to 31st October 2025. To establish the clean reference coefficient U_{clean} for the preheater, a short segment of data immediately following the confirmed 7 November 2025 cleaning was additionally used, as this period provided the most reliable near-clean baseline

2.3 Data aggregation and cleaning

Raw 30-s data were first aggregated to 5-min intervals to reduce file size and suppress very short-term noise. For each variable and 5-min window, we computed the arithmetic mean, provided that at least 50 % of the underlying 30-s samples were present.

Data cleaning proceeded in several steps:

1. Removal of non-numeric artefacts and spacing issues.

   CSV files were inspected for stray spaces or non-breaking spaces in TIT and FIT columns; these were removed programmatically.

2. Physical range checks.

Temperatures outside the plausible operating range for oil and water in this unit (e.g., below ambient or above 300 °F) and flows below the minimum measurable flow were flagged and set to blank.

3. Outlier removal.

For the temperature and flow-rate values, we computed the 5-min mean and standard deviation over the whole period. Points more than 3σ from the mean were treated as outliers and replaced with blanks. This step removed spikes caused by sensor dropouts or brief upset conditions without clipping genuine long-term trends.

Time steps with very small heat duties Q or log-mean temperature differences ΔT_{lm} produced unrealistically large or sign-flipped U_t. Rows with Q or ΔT_{lm} below small thresholds were therefore discarded.

4. Selection of valid operating windows.

- Only time steps with all three available temperatures and at least one flow measurement were retained for further analysis or the other flow rate could be inferred from pump curves were retained. The first oil cooler was dropped from the fouling analysis even though the oil flow could be inferred from the pump curve because the water flow was unknown. To avoid interpreting uncertain data, quantitative results are reported only for the preheater and final cooler.

2.3.1 Unit selection and exclusions

To preserve data fidelity and ensure defensible modeling, we restricted the quantitative analysis to plate heat exchangers with ≥3 of 4 temperature measurements and at least one reliable flow measurement (or a verifiable pump-curve estimate). Units with two missing temperature tags or indirect/mixed measurements (e.g., temperatures only available downstream in a storage/mixing vessel) were excluded because the inferred outlet temperatures would introduce uncontrolled bias into Q, LMTD, and U reconstruction. This prioritization yields cleaner fouling trajectories $R_f(t)$ and tighter uncertainty bounds for the optimization.

Water–water exchangers (HX -104 and HX -105) on closed, chemically treated loops typically exhibit low fouling propensity under steady operation (limited particulates, stable chemistry, minimal organics), so their incremental performance decay over a semester-scale study is often within instrument noise. Accordingly, they were deprioritized for the primary analysis remaining with HX – 101, HX – 102 and HX – 103.

2.4 Reconstruction of missing temperatures

Because one outlet temperature was missing on each exchanger, we reconstructed that quantity using a steady-state energy balance. Assuming negligible heat loss to the surroundings and equal heat duties on the hot and cold sides, we wrote [8]:

$$\dot{m}_h c_{p,h}\left(T_{h,i} - T_{h,o}\right) = \dot{m}_c c_{p,c}\left(T_{c,o} - T_{c,i}\right)$$

For HX-102, the cold-side outlet temperature $T_{c,o}$ was unknown and was solved from the equation above using the measured hot-side duty using this equation[8].

$$T_{c,o} = T_{c,i} + \frac{Q_h}{\dot{m}_c c_{p,c}}$$

For HX-103, the hot-side outlet temperature $T_{h,o}$ was reconstructed using the measured cold-side duty as shown below.

$$T_{h,o} = T_{h,i} - \frac{\dot{m}_c c_{p,c}}{\dot{m}_h c_{p,h}} (T_{c,o} - T_{c,i})$$

Time-varying specific heat capacities for vegetable oil and water were obtained from literature sources literature as functions of temperature; between tabulated points [9]. 90% of the oil type being run is palm so the specific heat capacities of palm oil were utilized.

2.5 Flow-rate estimation from pump curves

For the final oil cooler (HX-102), no flow meter was available on the water side. Instead, water mass flow rate was therefore estimated from the manufacturer's pump performance curve for the installed feed-water pump (appendix 1). The rated operating point on the curve corresponds to a capacity of approximately 153 GPM at the specified head. The nominal design flow was used as a constant value in all heat-balance calculations.

One of the preheater cooling-water flow meter read 0 throughout the study period, indicating instrument failure. Instead, water mass flow rate was therefore estimated from the manufacturer's pump performance curve for the installed feed-water pump (appendix 2) indicating a rated operating point of about 145 GPM. The line supplying water to the preheater is 3 in however there is a 1½ in line that branches to a boiler. Assuming flow splits proportional to pipe cross-sectional area, about 80 % of the flow (≈116 GPM, ≈ 58,000 lb/hr) is available to the preheater.

2.5.1 Reading flow from the pump curve

Flow rates were derived by correlating the calculated operational head with the manufacturer's performance curve. For variable frequency drive (VFD) pumps, the rated curve was scaled to the measured operating speed using standard affinity laws prior to correlation.

2.6 Thermal calculations

For each 5-min time step and exchanger, we computed:

1. Heat transfer rate.

$$Q_h = \dot{m}_h c_{p,h} \left(T_{h,i} - T_{h,o} \right)$$

$$Q_c = \dot{m}_c c_{p,c} \left(T_{c,o} - T_{c,i} \right)$$

Where both flows were known, agreement between Q_h and Q_c was used as a consistency check; otherwise, the measured side was taken as the reference duty.

2. Log-mean temperature difference (LMTD) [9].

For counter-current operation:

$$\Delta T_1 = T_{h,i} - T_{c,o}$$

$$\Delta T_2 = T_{h,o} - T_{c,i}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})}$$

3. Overall heat-transfer coefficient [9].

$$U_t = \frac{Q}{A \Delta T_{lm}}$$

where A was the effective plate area based on the current plate count for each exchanger.

2.7 Determination of clean reference coefficient

Since cleaning events in an operating facility are dictated by production and maintenance schedules rather than by the study, the analysis relied on the confirmed cleaning and plate-replacement events available in the plant record. For each exchanger, we identified the window immediately following confirmed cleaning and used the first stable operating period after it to define the clean reference coefficient — 8 November 2025 for the preheater (HX-103) and 8 July 2025 for the final cooler (HX-102). For the preheater, this confirmed clean state fell just after the primary monitoring window, so a short post-cleaning segment was used to establish its baseline.

The corresponding U_t values during stable operation were averaged to define the clean reference U_{clean} for that unit. For HX-103, this average was approximately 1382 Btu/ (hr·ft^2·°F); the final cooler exhibited a daily average of 109.37 Btu/ (hr·ft^2·°F).

2.8 Fouling resistance calculation

The instantaneous fouling thermal resistance R_f was defined as[10] :

$$R_f = \frac{1}{U_t} - \frac{1}{U_{clean}}$$

Only time steps with positive, physically reasonable $U_t$values were retained for this calculation. Very small negative R_f values—which typically resulted from measurement noise when the exchanger was effectively clean—were set to zero for plotting and summary statistics.

To reduce visual clutter and emphasize long-term trends, weekly averages of $R_f$were computed for each exchanger and used in the trend plots discussed below.

3. Results

3.1 Preheater (HX-103)

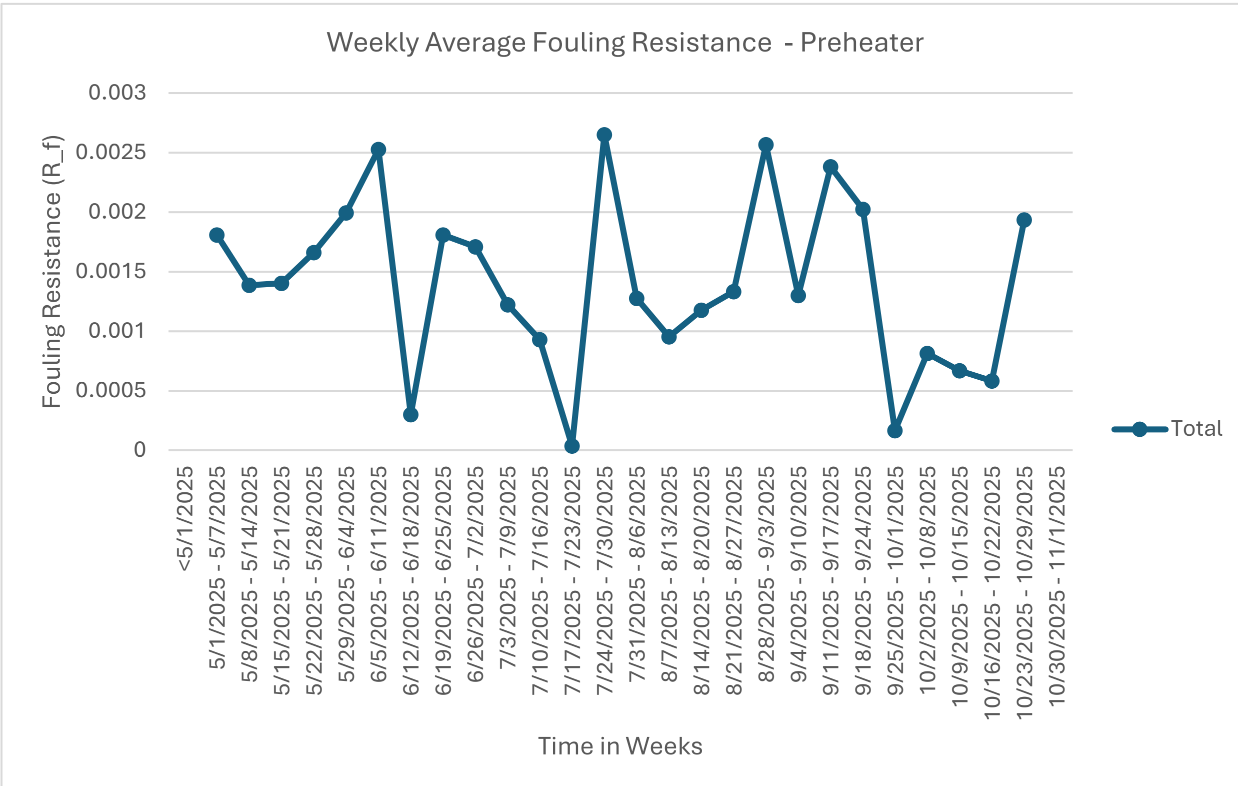
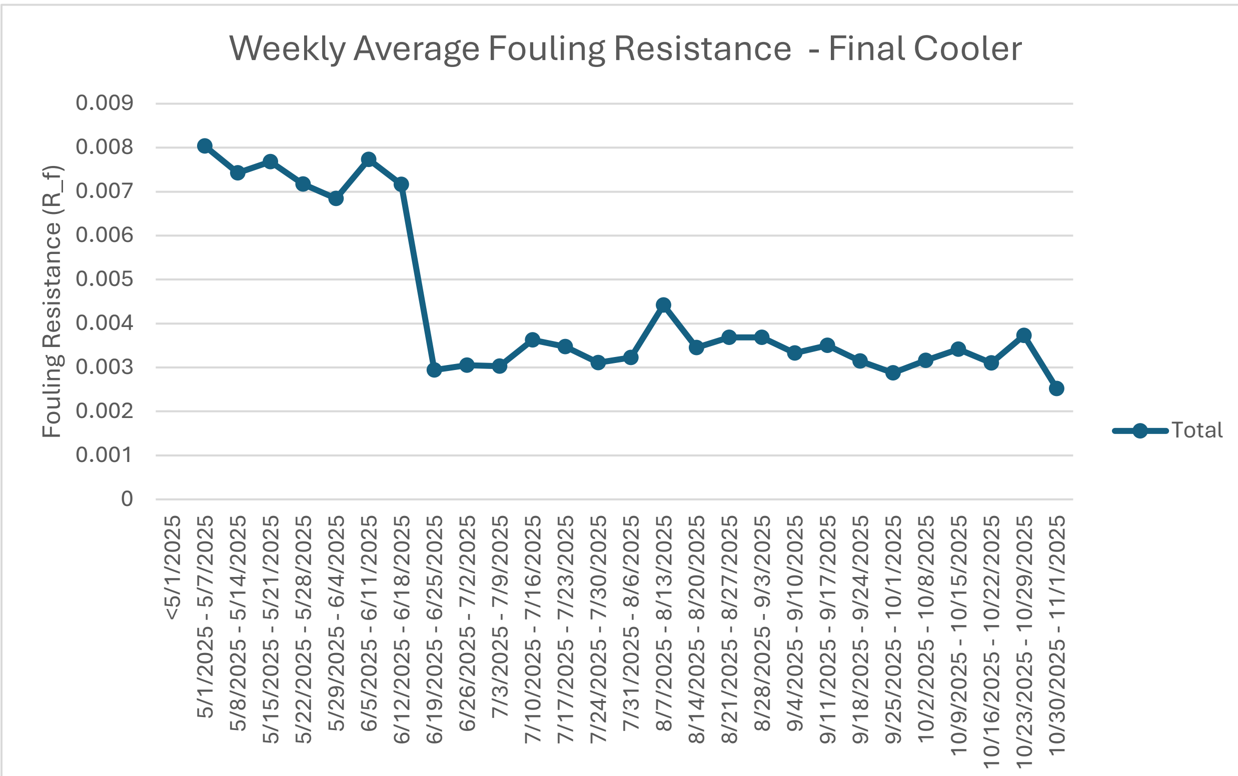


Figure 1 shows that the preheater operated with relatively modest fouling throughout the monitoring period. Weekly average R_f values generally lay between about 1.0×10^{-3} and 2.5×10^{-3} hr·ft²·°F/Btu, with some week-to-week variability but no evidence of runaway growth. A small number of weeks exhibited very low apparent R_f, approaching zero; these coincided with periods of reduced load and sparse valid data and are interpreted as near-clean operation rather than true negative fouling.

The scheduled chemical cleaning of the preheater occurred on 7 November 2025. Only a short window of data was available after this event, so the post-clean behavior could not be fully characterized. The available post-clean points do, however, indicate a reduction in R_f toward the clean baseline, consistent with removal of deposits. Overall, the preheater appears to foul relatively slowly, with moderate fluctuations driven by operating conditions.

3.2 Final oil cooler (HX-102)



The final oil cooler (Figure 2) exhibited the most pronounced fouling of the two exchangers. Before the cleaning on 7 July 2025, weekly average R_f values were consistently high, typically around 7×10^{-3}–8×10^{-3} hr·ft²·°F/Btu. This level of fouling represents a substantial additional thermal resistance compared with the preheater.

Immediately after the 7 July cleaning, the weekly average R_f dropped sharply to approximately 2.5×10^{-3}–4.0×10^{-3} hr·ft²·°F/Btu. For the remainder of the observation period, R_f remained in this lower band, with a mild upward drift but no return to the pre-clean level. This behavior clearly demonstrates that the cleaning was effective in restoring a significant fraction of the original heat-transfer performance and that fouling in HX-102 rebuilds over a timescale of weeks to months.

4. Discussion

The data-driven methodology successfully translated routinely collected historian measurements into quantitative fouling trajectories for two critical PHEs in the deodorization circuit. Several key observations emerge from the weekly R_f trends.

4.1 Relative magnitude of fouling

Across the two exchangers, typical fouling resistances fell within the range expected for plate units handling relatively clean water and refined vegetable oil. The preheater consistently showed the lowest fouling, with weekly R_f values on the order of 10^{-3}hr·ft²·°F/Btu. The final cooler developed the largest fouling resistances and showed a more noticeable upward drift over time, reaching up to roughly 8×10^{-3}hr·ft²·°F/Btu before cleaning.

This ranking is consistent with the thermal duties and operating roles of the units: HX-102 cools the hottest product stream and is therefore more prone to crystallization and deposition, while HX-103 recovers heat at more moderate temperatures.

4.2 Cleaning effectiveness

Where clear maintenance events could be identified from work orders and purchase records, the fouling trends showed sharp reductions in R_f immediately after cleaning. The final cooler provided the clearest example: R_f decreased by roughly a factor of two to three right after the 7 July cleaning and remained low for the remainder of the period.R_f

For the preheater, only limited data were available after the 7 November cleaning, but the available points suggest a move back toward the clean baseline. Overall, these observations confirm that the existing cleaning-in-place and manual plate-washing procedures are effective at removing deposits and restoring near-design performance.

4.3 Suitability for condition-based maintenance

The fouling trajectories evolve on the timescale of weeks rather than days, indicating that there is sufficient lead time to schedule cleaning based on measured performance instead of fixed calendar intervals. For example, a condition-based strategy could trigger cleaning of HX-102 when R_f exceeds a threshold in the range of 5×10^{-3}hr·ft^2·°F/Btu. Applying similar relative thresholds to HX-103 would have captured the major fouling episodes observed in this dataset while avoiding unnecessary early cleanings.

Implementing such thresholds in the plant control system would allow operators to monitor "fouling health" continuously using historian data and plan maintenance during convenient production windows.

4.4 Uncertainty and limitations

The analysis relied on inferred quantities where instrumentation was incomplete—notably, reconstructed outlet temperatures and oil flow rates derived from pump curves. Errors in these reconstructions propagate into Q, U_t, and R_f. In addition, some of the large spikes in calculated fouling resistance are likely attributable to brief sensor glitches, low LMTDs, or imperfect data cleaning rather than true physical fouling.

The weekly averaging approach mitigates much of this noise but does not eliminate it entirely. Future work could incorporate more rigorous filtering (e.g., Kalman filtering or Bayesian regression) and exploit additional plant data such as pressure drop across the plate pack to better separate fouling effects from measurement uncertainty.

5. Conclusions

This study demonstrated that existing historian data from a vegetable-oil refinery can be used to monitor fouling in plate heat exchangers without installing additional instrumentation. By aggregating and cleaning 5-min temperature and flow data, reconstructing missing variables via energy balances and pump curves, and computing the overall heat-transfer coefficient and fouling resistance, we obtained time-resolved fouling trajectories for two critical exchangers.

The approach captured both gradual performance degradation and step changes associated with cleaning events. The resulting fouling resistances fall within ranges reported in the literature for similar services and provide a quantitative basis for defining condition-based cleaning thresholds. Implementing such thresholds could reduce unnecessary cleaning, avoid severe fouling events, and improve energy efficiency in the deodorization circuit. The same framework is readily extendable to other exchangers within the plant and to similar facilities where PHE fouling is a concern.

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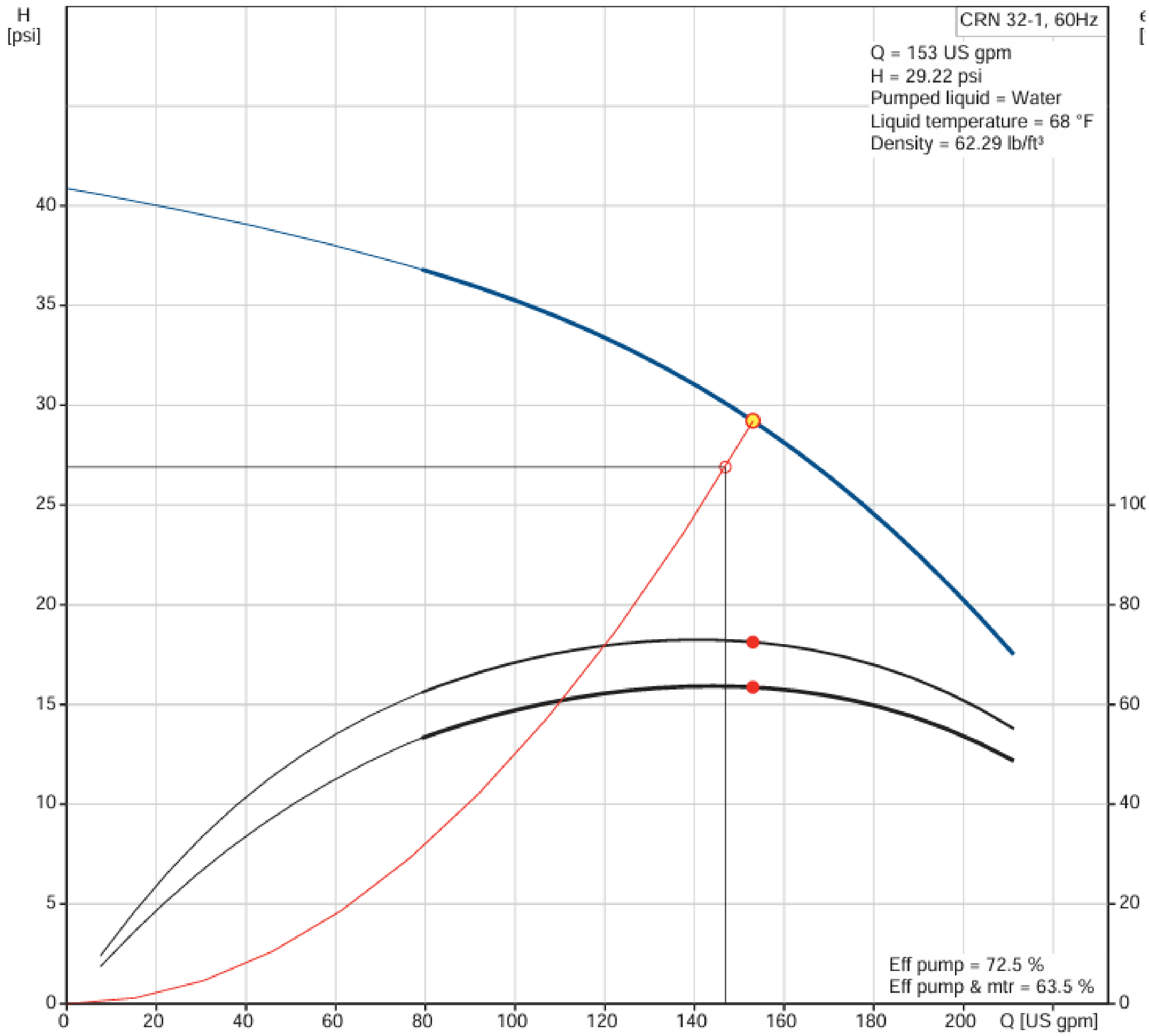
Appendix 1: Pump Curve for Final Cooler Feed Water Pump

Company name:
Created by:
Phone:

Date: 1/30/2017

96419591 CRN 32-1 60 Hz 27P59



Appendix 2: Pump Curve for Preheater Feed Water Pump

GRUNDFOS

Company name:
Created by:
Phone:

Date: 1/30/2017

On request CRN 32-3-2 60 Hz 27P31