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# A New Diagram for Long-Term Heat Exchanger Network Cleaning and Retrofit Planning

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With the long-term operation of Heat Exchanger Networks (HENs), fouling is a frequent problem. This is related to decreasing long-term heat transfer performance. Fouling decrease the heat transfer coefficient and reduce the efficiency of heat exchange. Different fluid types have different characteristics in corrosiveness and contribute to different results for fouling. The current graphical tools cannot fully tackle the HEN cleaning and retrofit design in the long-term operation.
This paper proposes a new graphical tool called Time vs Temperature Diagram (TTD) for HEN long-term management, taking fouling into consideration. It visualises the long-term temperatures change of each heat exchanger on hot and cold streams. The effect of heat exchanger cleaning can be shown visually in this diagram. This diagram can help to determine the cleaning and retrofit plan over a long period. An example is illustrated to show how to apply this diagram.

## 1. Introduction

Heat exchanger fouling is a common problem in different kinds of heat exchangers. During fouling, the surface of a heat exchanger wall develops another layer of solid material. This can happen for a variety of reasons, such as accumulation of solid particles suspended in fluid on heat exchange surface, deposit formed by the crystallisation of inorganic salts dissolved in the fluid on the heat exchange surface, fouling formed by solidification of fluid on the surface of a subcooled heat exchanger, and fouling caused by chemical reaction on heat transfer surface.
Fouling restricts heat transfer, leading to problems of losing heat transfer efficiency, which increases the cost of heat exchanger operation and may also increase the risk for safety production. The evolution of fouling resistance is shown in Figure 1. It grows up with the prolonged time of use. After cleaning operation, the fouling resistance reduces according to the cleaning intensity. The progress of researches for heat exchanger maintenance and fouling mitigation can be found in a review contributed by (Klemeš et al., 2020).
Heat exchanger cleaning is a routinely used way to mitigate the fouling effect. Regular cleaning of a heat exchanger can reduce the consumption of raw materials and energy, improve production efficiency, and greatly reduce the production cost. The cleaning schedule has been studied to determine the optimal cleaning period. Al Ismaili et al. (2019) studied the cleaning scheduling of Heat Exchanger Networks (HENs). They proposed a multiple scenario feasible path mixed-integer optimal control problem approach. They found out that the cost of fuel and the clean overall heat transfer coefficient are two important factors that influence the overall cost of HEN maintenance. Tian et al. (2016) proposed an approach by simultaneously considering optimising operation condition and cleaning schedule to mitigate fouling in HEN. Velocity was redistributed to improve the operation condition, and a simulated annealing algorithm was applied for the cleaning schedule. Diaby et al. (2016) proposed a specialised Genetic Algorithm for the problem of the cleaning schedule of the preheat train in a crude oil refinery. Santamaria and Macchietto (2019) proposed a mixed-integer nonlinear

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problem and reformulated it as a mathematical program with complementarity constraints to solve the plan for optimal cleaning scheduling. Trafczynski et al. (2021) developed a least-squares based method for monitoring fouling growth. The developed method was compared with two simple existing methods and proved its effectiveness and advantage. Their research can help to determine the cleaning schedule.

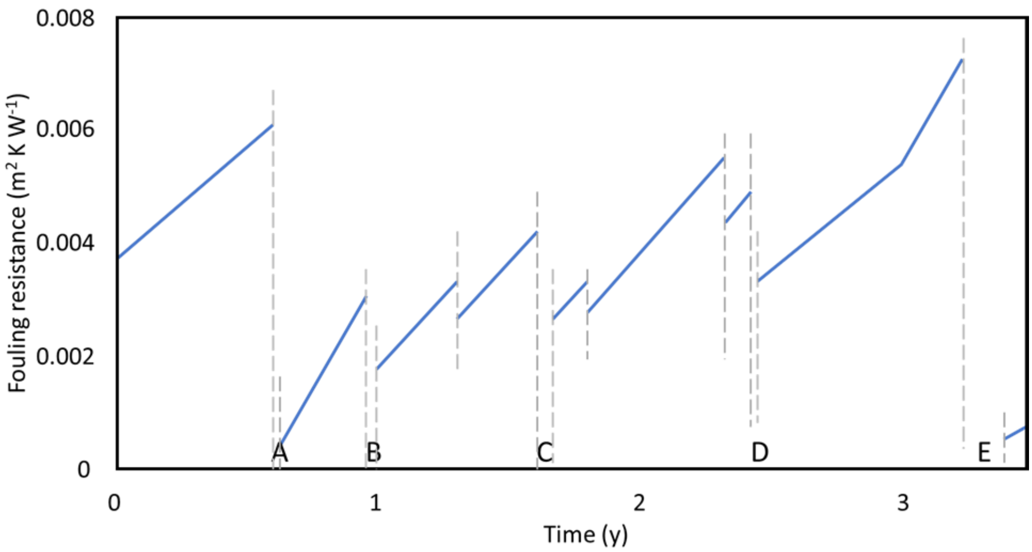


*Figure 1: Linear fitting of fouling resistance changing in a heat exchanger for a 40-month period. During period A and E, rigorous cleaning was performed; During period B, C, and D, less intensive cleaning was performed. Developed from (Al Ismaili et al., 2019)*

Pinch Analysis-based methods are intensively used for Heat Integration, extending the traditional use of mathematical programming. The state-of-the-art innovations of Pinch Analysis can be found in work done by Wang et al. (2021). One useful tool is Advanced Grid Diagram originated from Lakshmanan and Bañares-Alcántara (1996). Yong et al. (2014) further developed Retrofit Thermodynamic Diagram to Shifted Retrofit Thermodynamic Diagram (SRTD), which can illustrate the thermodynamic feasibility of the HEN design plan. Yong et al. (2015) improved their previous version of the SRTD and proposed a Shifted Retrofit Thermodynamic Grid Diagram (SRTGD), which has the parameters such as temperatures and heat capacity flowrates for better visualisation and decision-making of HEN retrofit. Wang et al. (2020a) developed an SRTGD with the temperature range of heat exchangers (SRTGD-TR) to minimise the total cost in the HEN retrofit design process. Several heat exchanger types, including shell-and-tube, double-pipe, spiral plate, and spiral tube, were selected if a new heat exchanger is implemented in the retrofit plan. Wang et al. (2020b) further improved their proposed grid diagram for heat exchanger selection in the retrofit process by introducing shifted temperature range and developed an SRTGD with the shifted temperature range of heat exchangers (SRTGD-STR). Temperature ranges of six heat exchangers are coupled in the grid diagram for heat exchanger selection in the HEN retrofit design.

However, these previous researches on Advanced Grid Diagram or even on Pinch Analysis have some limitations in the HEN retrofit problems. They are mostly used for a single period rather than long-term retrofit. With the continuous operation of HEN, fouling is an inevitable problem. This is related to long-term heat transfer performance. Fouling will decrease the heat transfer coefficient and reduce the efficiency of heat exchange. Different fluid types have different characteristics in corrosiveness and contribute to different results for fouling. Fouling characteristics of different heat exchanger types can also influence the results of the cleaning and retrofit design plan. However, the current graphical tools cannot tackle the HEN cleaning and retrofit planning in the long term.

A novel graphical tool for long-term HEN cleaning and retrofit planning is developed for solving the previously analysed issues. It has the following features.

(i) It can show the information of the HEN. The supply and target temperatures of streams, the inlet and outlet temperatures of heat exchangers, and the connection of streams through heat exchangers can be illustrated on a diagram.

(ii) It can show the temperature changing of heat exchangers during a time period.

## 2. A new graphical method for utility targets

There are two parts of this newly developed Time vs Temperature Diagram (TTD). Figure 2 shows an example of TTD, and the diagram is generated according to the stream data shown in Table 1. The notation of the heat transfer used in this work is the following:

- S[number]: hot or cold stream
- E[number]: recovery heat exchanger
- H[number]: utility heater
- C[number]: utility cooler

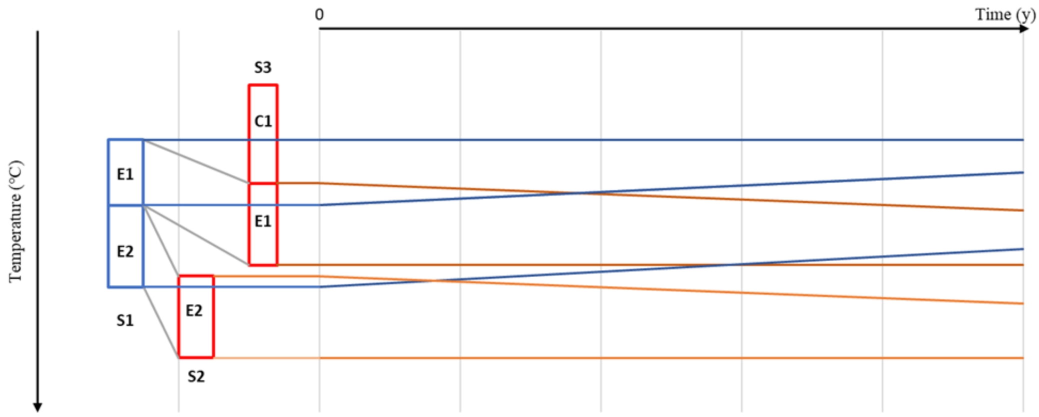


*Figure 2: TTD for the example HEN when no cleaning schedule is set*

*Table 1: Stream data for example*

| Stream | $T_S$ (°C) | $T_T$ (°C) | $CP$ (kW/°C) |
|---|---|---|---|
| 1 | 200 | 470 | 5 |
| 2 | 600 | 450 | 5 |
| 3 | 430 | 100 | 4 |

$T_S$ is the supply temperature, (°C); $T_T$ is the target temperature, (°C); $CP$ is the heat-capacity flow rate, (kW/°C)

The left part is a 90 ° left rotated SRTGD, and it presents the structure of HEN and how heat is transferred by heat exchangers. The right part is a diagram with the year as x-axis and temperature as y-axis; it shows 1) inlet and outlet temperature changes of each heat exchanger in its operating time, 2) the fouling characteristic of each heat exchanger, and 3) strategies for the cleaning operation.

### 2.1 Step 1 Structure the SRTGD

The SRTGD is a useful tool for Heat Integration. The horizontal axis tracks the temperature span. The width represents the heat-capacity flow rate (CP) of each stream. The area of the rectangle represents the workload of a heat exchanger. And dashed lines should have a positive slope to indicate that the plan is feasible. These features are modified for the development of the TTD.

On the left side of the TTD, it is in the form of a rotated SRTGD. The y-axis represents the temperature span. The upper side has a lower temperature, while the lower side has a higher temperature. The length of each rectangle represents the temperature span of a stream, and the width represents the heat-capacity flow rate. Cold streams are on the left, and hot streams are on the right. The slope should be positive when the figure rotates left 90 ° to ensure thermodynamic feasibility.

The retrofit plan in the first period of the HEN can be determined based on this left part of the diagram. The method for retrofit plan making is similar to the rules introduced in Yong et al. (2015).

### 2.2 Step 2 Convert to the Time vs Temperature Diagram

The important feature of the proposed TTD is that it considers the operating time of a HEN. The left part of the TTD is a modified SRTGD, and the right part of the TTD uses "year" as the x-axis. The right part is started from the first year the design is implemented, and it tracks the temperature changing in a long-term HEN operating period.

Several features of the right side of the TTD are listed.

- The inlet and outlet temperatures of each heat exchanger are tracked in this diagram.
- The slope of each line on the right side represents the temperature change due to the fouling characteristic.

### 2.3 Step 3 Fluid types and fouling characteristic

During operation with liquids and gases, a dirt film may build up on the heat exchanger surfaces, which causes fouling. Two issues that would affect the efficiency of the heat transfer should be considered in the long-term HEN operating management. One is the fluid type, and the other is the heat exchanger type. For the heat exchanger types, as different heat exchanger types have different fouling characteristics, the heat transfer coefficient and fouling resistance can also have different changing rates in the operating period. The fouling characteristics for each type of heat exchanger depending on the fouling mechanism and flow-passage geometry (Panchal and Rabas, 1999). For the fluid type, certain fluids are more corrosive or contribute to fouling more. These two issues, in turn, reduce the overall heat transfer rate through the surface of heat exchangers and then reduce heat recovery and increase used utility.

The fouling characteristic is considered in the right part of the proposed TTD. The orange/blue lines represent the inlet and outlet temperatures of heat exchangers on hot/cold streams. The supply temperatures of hot and cold streams are assumed to be fixed, while with the use of heat exchangers, the fouling resistances of heat exchangers are increasing, which leads to the reduction of heat transfer coefficients. Temperature spans of heat exchangers are reducing, and more utility should be used. The slopes of these lines indicate the characteristic of the fouling effect. If the fluid tends to cause fouling, then the slope would be steeper, which means it would reduce more heat transfer and may require more expenditures on cleaning and maintenance. This requires further detailed calculations to determine the shape of the line. Figure 2 shows only an example by using straight lines to track temperatures. The right side of the diagram can also show if the heat exchanger is cleaned, how much heat can be recovered. This also requires a further calculation to determine the amount of heat duty saved. For cold streams, the outlet temperature of the cleaned heat exchanger would increase as well as the heat transfer. In this way, the utility cost could be saved.

### 2.4 Step 4 Cleaning and retrofit planning

Fouling formation had happened in the operation of a heat exchanger, which increases the fouling resistance. The relationship of fouling resistance and overall heat transfer coefficient can be calculated by Eq(1).

$$\frac{1}{U} = \frac{1}{ht} + \frac{1}{hs} + Rf \tag{1}$$

where U is the overall heat transfer coefficient, kW/(m$^2$ °C), ht is the tube side convective heat transfer coefficient in a heat exchanger kW/(m$^2$ °C), hs is the shell side convective heat transfer coefficient in a heat exchanger, kW/(m$^2$ °C), Rf is the fouling resistance, (m$^2$ °C)/kW.

The increase of Rf will decrease the overall heat transfer coefficient and subsequently change the outlet temperatures of the hot stream and cold stream of the heat exchanger.

Figure 2 is a sketch map that shows the changing of temperatures of heat exchangers with the increasing working time. However, in the real heat exchanger application, the changing of temperatures is not in a straight line. This study is just an example that illustrates how to use this new proposed TTD for heat exchanger cleaning and retrofit planning.

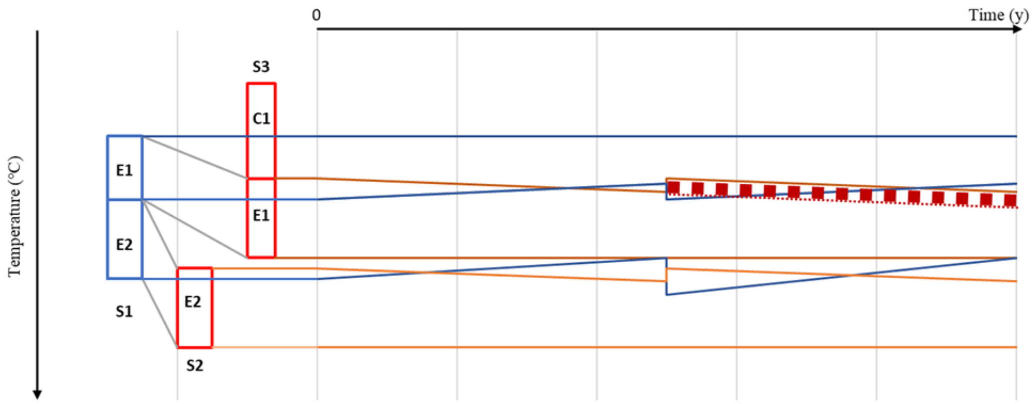


*Figure 3: Heat exchangers are cleaned once in the studied period*

Figure 3 shows that if heat exchangers are cleaned once in the studied period. For heat exchanger E1, when compared the schedule of Figure 3 with the one in Figure 2, it shows that the heat in the dashed line period can be recovered due to the cleaning. Using Eq(2), it can calculate how much duty is recovered.

$$Q = W_h Cp_h (T^{h,in} - T^{h,out}) \tag{2}$$

In Eq(2), $W_h Cp_h$ represents heat capacity flow rate of hot streams, $T^{h,in}$ is the inlet temperature of hot streams, and $T^{h,out}$ is the outlet temperature of hot streams.

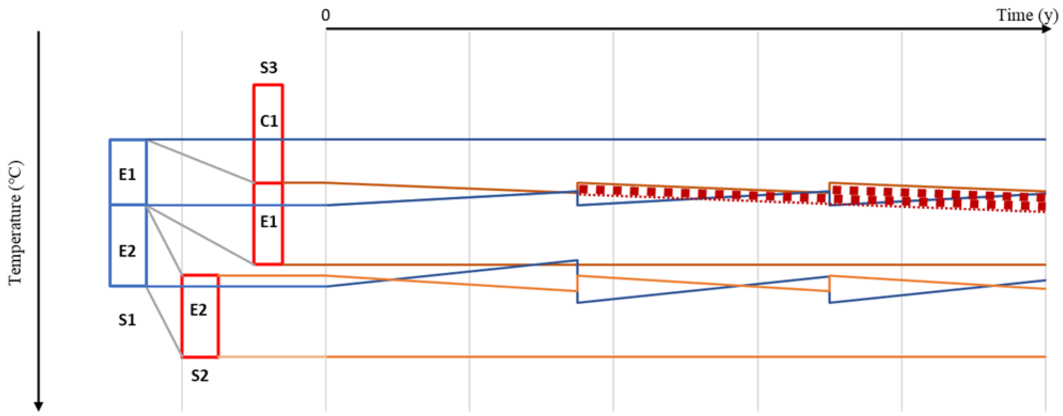


*Figure 4: Heat exchangers are cleaned twice during the studied period*

Figure 4 shows if heat exchangers are clean twice in a certain period. When compared this plan with no cleaning and cleaning once in the same studied period, it can be observed that more heat which is represented by the dashed line, can be recovered. The amount of heat recovery can still be calculated by Eq(2).

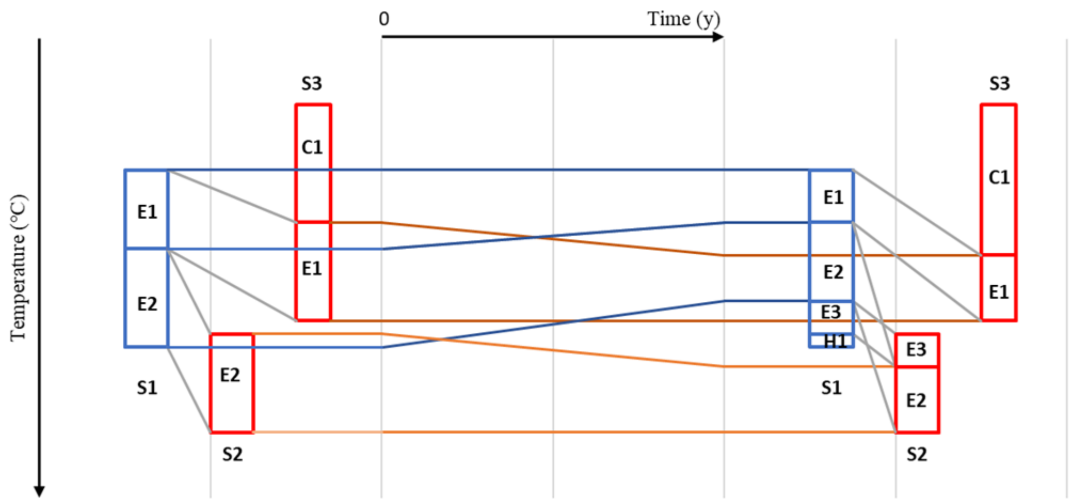


*Figure 5: Retrofit plan for the example after a period*

By using this TTD, it can detect whether to clean heat exchangers or retrofit the current HEN. For this case, there are also existing chances to retrofit the current HEN by adding one more spare heat exchanger rather than doing the cleaning. The plan is shown in Figure 5. With the decreasing temperature difference, target temperatures of streams are not able to be achieved through currently used heat exchangers. A similar amount of heat can be recovered by adding heat exchanger E3. This should be compared economically to see whether to clean existing heat exchangers immediately to withstand some losses or continuing using them and adding one more spare heat exchanger until a more proper time for cleaning is arriving.

## 3. Conclusions

In this study, a newly developed Time vs Temperature Diagram (TTD) for HEN long-term management has been introduced. This tool can help to determine the cleaning and retrofit planning for a long period visually. This tool has information such as HEN structure, inlet and outlet temperatures of each heat exchanger, the heat capacity of heat exchangers, and it tracks the temperature changes of heat exchangers over a long period. An example is illustrated to show the basic idea of this TTD.
However, besides the advantages of this diagram, it is still an initial idea generated in this study. The temperature change caused by the fouling has not been fully precisely calculated. Only a straight line is used to represent the changing trend. Consequently, the economic benefit brought by the cleaning or retrofit should be further studied and calculated in detail. This can help the engineers determine the final plan of cleaning and retrofit application.

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