FOULING MANAGEMENT AT TOTALENERGIES THROUGH USE OF HTRI SMARTPM™: CASE STUDY OF A PROJECT PROPOSAL FOR CLEANING SCHEDULE OPTIMIZATION

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ABSTRACT

Heat exchanger fouling is problematic in crude oil refining, impacting energy consumption, greenhouse gas emissions, plant capacity, and maintenance budget. As part of the digital transformation journey at TotalEnergies and with advances in research on hydrocarbon fouling, advanced fouling monitoring and prediction tool (HTRI SmartPM™) was implemented throughout TotalEnergies to better manage fouling in heat exchangers. The SmartPM software performs advanced data reconciliation, including simulation of detailed exchanger operational data using proprietary HTRI shell-and-tube heat exchanger calculation methods. After deployment and adoption of the software for fouling monitoring and reporting, the predictive functionalities have been applied to several feasibility studies concerning energy efficiency and CO_2 emissions reduction projects. The present work describes the predictive study of the cleaning schedule of a refinery. The result of this study is an industrial project proposal on the installation of new bypasses across selected exchangers, leading to an economically optimized cleaning strategy, savings in the fuel consumption of the crude preheat furnace, and the reduction in CO_2 emissions associated to its combustion.

INTRODUCTION

Heat exchanger fouling is a persistent phenomenon in crude refinery heat exchanger networks. The severity and impact of heat exchanger fouling can vary as a function of the refining unit considered, the design of the heat exchangers in the network, the presence (or absence) of fouling mitigation technologies, and the nature of the fouling (asphaltene precipitation, inorganic fouling, corrosion fouling), among others [1–3]. A variety of practical fouling solutions can be consulted in literature (e.g., [4–13]).

TotalEnergies has a clear commitment of net zero emissions by 2050 while growing and developing a strong low-carbon culture. Fouling management and industrial projects aiming to improve energy efficiency constitute levers of action into reaching this objective. Following this ambition, HTRI's SmartPM software has been deployed across TotalEnergies' refineries since 2018 for fouling management of heat exchanger networks [14].

TotalEnergies is a broad energy company that produces and markets fuels, natural gas, and electricity with a worldwide presence in over 130 countries. TotalEnergies Refining and Chemicals is a branch of TotalEnergies that focuses on operations to transform crude oil and natural gas into finished products or intermediates, which are then used to manufacture chemicals.

SmartPM is a digital twin technology that creates a digital replica of the existing heat exchanger network via direct link to the plant data historian. The digital platform allows users not only to monitor the current performance but also to optimize the operation via predictive capabilities focusing on increasing energy recovery, minimizing lost opportunity, increasing user productivity, and monitoring equipment safety. SmartPM will be referred to as the *simulator* in the rest of this manuscript.

This manuscript describes a recent case study from a crude preheat train at one of the company's refineries. A methodological approach was followed for the optimization of the heat exchanger cleaning schedule and an industrial project proposal was recommended at the end of this study, portraying the energy savings and greenhouse gas emission reduction achievable for the asset.

CASE STUDY: CRUDE PREHEAT TRAIN

Due to confidentiality, no details of the exchanger geometry, monitoring data, physical properties, or the economic parameters from the plant are presented in the paper.

A diagram of the layout of the heat exchangers present in the preheat train (post desalter section) is shown in Figure 1. In this section of the preheat train, all crudes are allocated on the tube side of the heat exchangers.

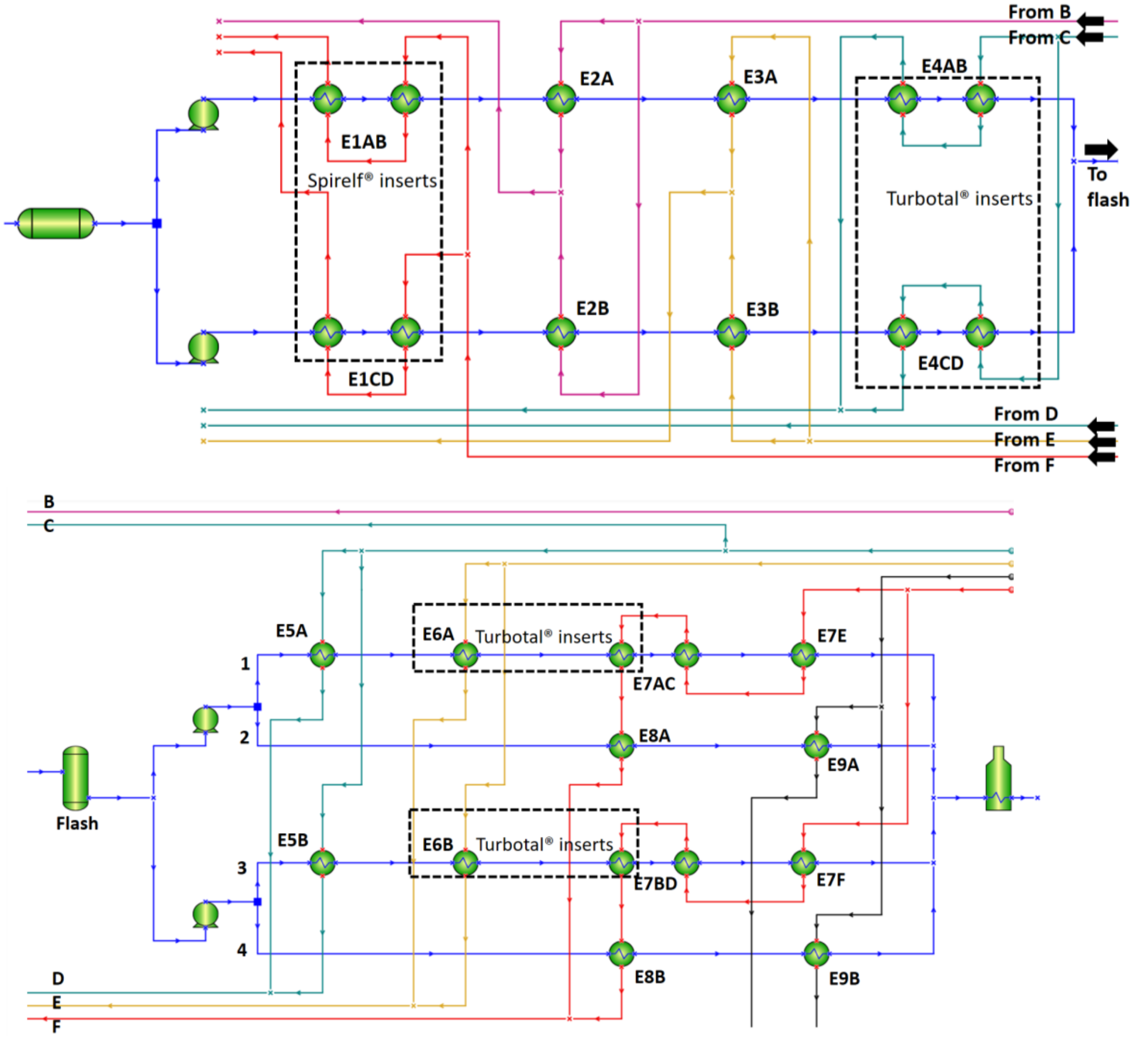

Fig. 1. Post desalter schematic of the case study refinery crude preheat train. Starting from the crude desalter (top left). Symbols with labels starting with 'E' denote shell-and-tube heat exchangers.

The post desalter section of the preheat includes 12 shells divided in two parallel branches followed by a crude preflash column, where a part of the feedstock is fractionated. Downstream of the preflash column, crude is distributed to four parallel branches and passes through a total of 14 heat exchangers before remixing and reaching the crude preheat furnace.

The following sections synthesize the steps followed to implement advanced monitoring with using the simulator for this preheat train and the methodology followed to improve the current cleaning practice.

METHODOLOGY FOR MODEL CONSTRUCTION

A systematic approach for fouling management was adopted based on industrial best practices (e.g., Fig. 2 [15]). Detailed heat exchanger geometry, flow diagrams, P&ID diagrams, and information of the associated streams are used to construct the digital version of the existing heat exchanger network model. Heat exchanger models used detailed exchanger geometry from exchanger specification sheets and drawings. The detailed geometries are used in the proprietary heat transfer and pressure drop correlations developed by HTRI. P&ID diagrams are used to construct the connection between the streams and the heat exchangers and also to identify the locations of isolation valves, monitoring data tags, and control structure.

Operating conditions such as temperature, flow, and pressure are directly monitored ('A' in Fig. 2) and recorded in the plant data historian (e.g., OSIsoft® PI System®). The SmartPM digital platform is directly linked to the data historian ('B' in Fig. 2) enabling performance analysis, prediction, and reporting of the heat exchanger network, creating a digital twin model. Different workgroups in the organization are able to interact with the digital platform ('C' and 'E' in Fig. 2) to make operational decisions, *what if* analyses, etc. which feed back to the heat exchanger network (either as operational expenditure or capital expenditure decisions; 'D' in Fig. 2).

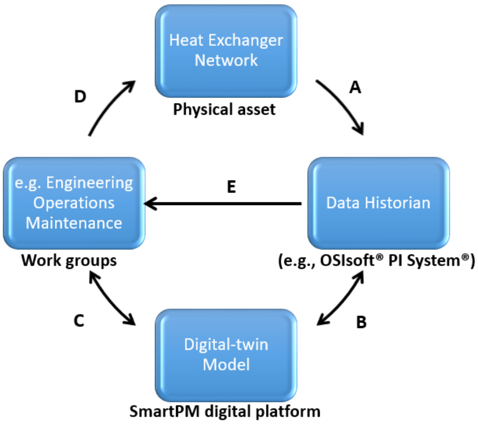

Fig. 2. Key steps involved in the fouling management program.

Several exchangers in this case study are comprised of two types of tube inserts (Turbotal® and Spirelf®). These mechanical devices installed inside tubes enhance heat transfer and promote fouling mitigation. The proprietary thermal and hydraulic equations to model these inserts are also available in the simulator; hence, the tube-insert geometries are included in the model. Turbotal® inserts are rotating devices hooked on a fixed head set on the tubesheet on the inlet side. This system converts the energy of the fluid flow in the tubes into rotation. Spirelf® inserts are vibrating devices secured on both tube ends by a fixing wire. This system converts the energy of the fluid flow in the tubes into vibration [16].

Heat exchanger network model

Fig. 1 includes all of the heat exchangers in which there is crude flow after the desalter. The locations of the monitoring instruments can be specified to the model so that the operating data (flow rates, temperatures, and pressures) can be imported to the software. Each of the flowing crude and product streams of the model are characterized by sets of thermophysical properties related to the thermal and hydraulic calculations.

The model includes an operating constraint based on the furnace firing capacity to adequately consider potential throughput limitations when the preheat train is fouled. To do so, the enthalpy curves of the feed are provided within the model, and the furnace operating constraints (maximum furnace firing capacity) are included as a part of the calculations [17]. If heat exchanger fouling increases and no cleaning operation is carried out, furnace maximum duty may be exceeded, therefore limiting the throughput of the unit.

Data reconciliation

Data reconciliation is done through performing a heat and mass balance throughout the network and also by simulating the detailed exchanger operating conditions based on available temperature, flow, and pressure measurements. The data reconciliation generates all exchanger operating conditions, including the fouling resistance. The fouling resistance of the operating shell and tube unit can be represented as:

$$\frac{1}{U_o} = \frac{1}{h_o} + R_{f,o} + \frac{d_o \ln\left|\frac{d_o}{d_i}\right|}{2k_w} + \frac{d_o}{d_i} \times R_{f,i} + \frac{d_o}{d_i} \times \frac{1}{h_i} \qquad (1)$$

$$R_f = R_{f,o}\frac{d_o}{d_i} + R_{f,i} \qquad (2)$$

Here, U_o is the overall coefficient based on outside area, h_o is the shell-side fluid film coefficient, h_i is the tube-side fluid film coefficient, k_w is the thermal conductivity of the tube material, d_i is the tube internal diameter, d_o is the tube external diameter, $R_{f,i}$ is the tube-side fouling resistance, $R_{f,o}$ is the shell-side fouling resistance. Segregating shell- and tube-side fouling resistance contributions was previously discussed by Ishiyama *et al.* [14] and not repeated here.

Fouling analysis

With the operating conditions generated during the data reconciliation process, fouling throughout the heat exchangers of the preheat train can be modelled by considering the type of deposit potentially present in the exchanger. Different fouling deposits can be observed through a preheat train [1]. If fouling downstream of the desalter is dominated by chemical reaction fouling, it can be satisfactorily modelled using the exchanger operating conditions [14].

For the example network discussed in Fig. 1, both the crude stream and heavy product streams are subject to fouling based on plant operational experience. A 'dynamic fouling model' is used to model fouling which relates the rate of fouling of the dominant fouling mechanism to the operating conditions of the exchanger. The use of the model requires pragmatic understanding of the fouling behavior throughout the heat exchanger network. Crude stream fouling (downstream of the desalter) was modelled via the asphaltene precipitation model [14]:

$$\frac{dR_f}{dt} = \frac{\alpha}{h} exp\left(-\frac{E}{RT}\right) f(\tau) \qquad (1)$$

Here, dR_f/dt is the rate of change in thermal resistance, h is the film transfer coefficient, α is the fouling propensity factor which depends on the crude chemistry and the fouling surface, R is the gas constant, E is the fouling activation energy, and τ is the shear stress.

Heavy hydrocarbon stream fouling is modelled via a particulate fouling model [18]:

$$\frac{dR_f}{dt} = C_1 \frac{\tau^{-C_2}}{\mu^{C_3}} \tag{2}$$

Here μ is the dynamic viscosity; C_1, C_2, and C_3 are dimensional constants defined for the stream.

Prediction and scheduling cleaning

Optimization of cleaning scheduling is a popular research area (e.g., [19–23]). In this work the cleaning scheduling algorithms proprietary to HTRI were used via the simulator.

Fouling models [e.g., Equations (1) and (2)] are fitted to the reconciled data which can then be used for predictive studies including *what if* analysis. Predictions can be performed to identify the impact of fouling over a prolonged period in the absence of any cleaning actions. This enables evaluation of fouling mitigation technologies (such as tube inserts) prediction of cycle length without furnace constraints, and impact of design modifications on an exchanger, among others.

The cleaning schedule can be used to obtain information on *when* and *which* heat exchanger(s) to clean by comparing the difference between the overall energy and throughput benefits of the cleaning, the no cleaning state, and the total cost of cleaning the unit(s). The simulator is also used to perform an economic quantification of a previously implemented cleaning strategy and compare the net benefit against a different schedule proposed by the user or the simulator. In the case study presented, the cleaning schedule was used to assess the best candidate for cleaning heat exchangers by taking into account the current cleaning strategy of the refinery. The simulator was used to configure several cleaning schedules to obtain a quantitative comparison.

CURRENT HEAT EXCHANGER CLEANING STRATEGY

There are no bypasses to isolate exchanger during cleaning at the last section of the exchanger network (post flash section). Hence, when an exchanger is taken offline for cleaning during operation, the entire branch has to be shut down and the flow diverted to the other branches (e.g., in Fig. 1, if exchanger E-5A is cleaned, branch ‘1’ has to be shut and the crude flow diverted to branches 2, 3, and 4). This constraint limits the throughput of the unit during the cleaning operations.

The original cleaning strategy (before using the simulator) consists in implementing cleaning campaigns during which a total of 18 shells are cleaned. Figure 3 shows a typical distribution of the cleaning timeline. Cleaning events are represented by blue bars on the figure.

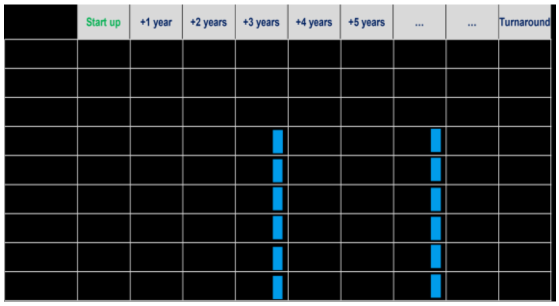

Fig. 3. Cleaning strategy for the preheat train’s exchangers.

Current cleaning strategy includes cleaning the last group of heat exchangers upstream of the preflash column (E4ABCD) and all of the units between the preflash column and the furnace. Two cleaning campaigns are considered as the current heat exchanger cleaning strategy. The tube inserts of the heat exchangers equipped with this technology are replaced during each cleaning campaign.

METHODOLOGY FOR CLEANING STRATEGY IMPROVEMENT

The procedure described below allows evaluation of the potential benefits of different cleaning schedule configurations. The different scenarios were built using the results of the cleaning algorithm of the simulator, the operational strategy of the refinery, and the hardware constraints (exchanger cannot be individually isolated).

Initialization of the prediction studies

The initialization of the cleaning schedule simulations require inputs for

- flow rates, inlet temperatures, and pressures for crude oil and for other streams present in the preheat train
- fouling state of the heat exchangers of the preheat
- information on cleaning (duration, cost, method/degree of cleaning)
- energy, lost opportunity, and emission cost parameters
- duration of operating campaign and any other operational constraints

The configurations studied consider cleaning schedules that are implemented during an entire cycle of the unit, from a ‘clean startup’ following a turnaround (for general maintenance and cleaning of heat exchangers) until end of the operating cycle.

The efficiency of a heat exchanger cleaning operation may vary as a function of the cleaning method employed, the aging of the fouling deposit, the efficiency of application of the cleaning method, cleaning vendor, etc. (e.g., [24–26]).

Figure 4 shows the evolution of the fouling resistance on one of the heat exchangers of the preheat train. These results are used to calculate an average efficiency of a cleaning operation carried out during a cleaning campaign. This average efficiency is represented by the fouling resistance value of the heat exchanger after cleaning (for a specific cleaning method / cleaning vendor). The assessment is done for all heat exchangers of the preheat train to complete the inputs required to initialize the cleaning schedule simulation.

Cleaning scenarios without hardware modifications (in the absence of bypasses)

In the absence of bypasses across shells in the current setup, it is not possible to isolate a single heat exchanger for a cleaning operation. The current strategy focuses on cleaning a total of 18 shells in two steps. The first step includes cleaning of nine shells associated with one branch (e.g., E4AB, E5A, E6A, E7AC, E7E, E8A, and E9A); once these units are cleaned and back online, nine shells associated with the other branch (E4CD, E5B, E6B, E7BD, E7F, E8B, and E9B) are cleaned and brought back online.

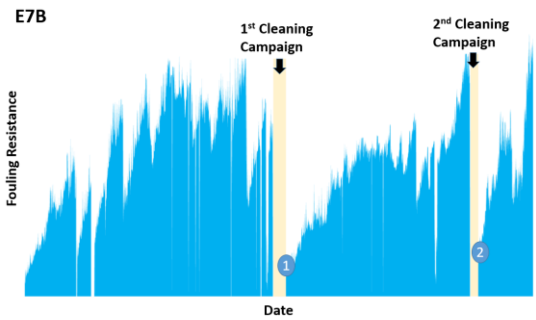

Fig. 4. Assessment of fouling resistance after cleaning for the heat exchangers of the preheat train. Labels 1 and 2 (immediately after the 1st and 2nd cleaning campaigns) denote the minimum resistance after cleaning.

Figure 5 presents a cleaning scenario in which a single cleaning campaign is done during an entire cycle. This scenario is used to assess the impact of lost opportunity (because of throughput reduction during cleaning campaigns) between the current cleaning strategy (Fig. 3) and the single cleaning campaign scenario (Fig. 5).

Figure 6 presents a cleaning scenario in which three cleaning campaigns are done during an entire cycle. This scenario is used to assess the impact of an additional cleaning campaign (without any further hardware modification) compared to the current cleaning strategy (Fig. 3).

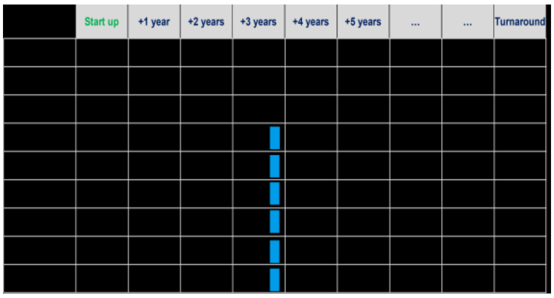

Fig. 5. Single cleaning campaign for the preheat train. The bars represent cleaning events.

Cleaning scenarios with hardware modifications

The simulator was used to evaluate a hypothetical scenario assuming all exchangers can be bypassed and isolated for cleaning while the production continues. Based on this, it was possible to identify the heat exchanger yielding the best net benefit when a cleaning operation is carried out.

The outcome of this study is a quantitative benefit assessment and project proposal for a hardware modification (installation of bypasses) which combined plant layout knowledge, operational constraints for heat exchanger cleaning, and the results of the cleaning schedule algorithm.

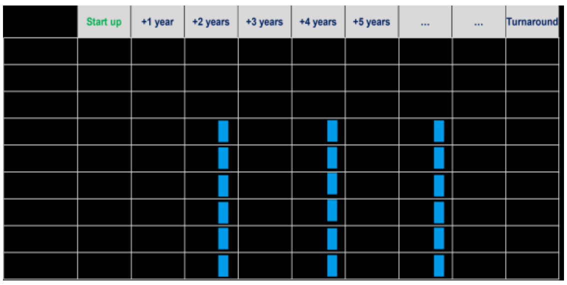

Fig. 6. Three cleaning campaigns for the preheat train.

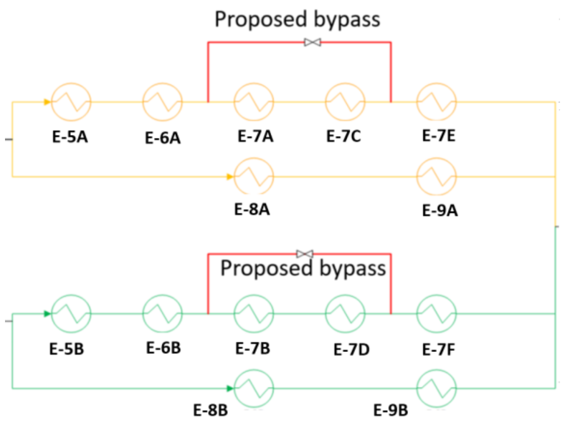

Fig. 7. Hardware modification on preheat train for online cleaning of heat exchangers E-7ABCD.

The modification consists of installing bypass lines at the boundaries of the heat exchangers identified as key for energy consumption by using the cleaning schedule algorithm. This hardware modification opens the possibility of isolating this single group of heat exchangers (E7AB and E7CD in Figure 7) for cleaning while the rest of the units remain online.

Given the possibility for cleanings without throughput reduction, the general cleaning campaigns can be maintained (as in current cleaning strategy), and specific cleaning operations of the exchangers that can be isolated can be added to the cleaning strategy. Figure 8 shows the intended cleaning schedule if the exchangers equipped with a bypass are cleaned on an annual basis based on the availability of the cleaning contractors. General cleaning campaigns are represented by blue bars on the figure whereas specific cleaning operations of the bypassed exchangers are represented by red bars on the figure.

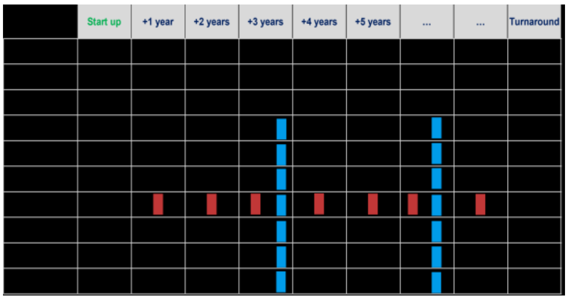

Fig. 8. Two cleaning campaigns and yearly specific cleaning operations for the preheat train.

The evolution of the furnace inlet temperature (FIT) is followed up during the simulation, and the impact of the cleaning operations is assessed by comparing the FIT of the different scenarios.

Given that the scenarios were simulated considering the same throughput conditions for the streams involved in the network, the comparison of the FIT is used to calculate the difference of energy to be provided by the crude preheat furnace between a proposed scenario and the current cleaning strategy (cf. Figure 3).

RESULTS

Figure 10 show the difference between FIT throughout the operating cycle between a scenario in which heat exchangers identified as key for energy by the cleaning schedule algorithm are cleaned on a half-yearly basis and the current cleaning strategy implemented for this preheat train. Table 1 presents the cleaning strategies for which potential benefits and greenhouse gas emissions reduction were estimated by comparison of FIT values.

The daily difference in FIT between a given cleaning strategy and the current one is used to estimate the daily energy savings on furnace preheat and the potential greenhouse gas reduction associated with the improved preheat performance. The economic benefit of the energy savings and the greenhouse gas emissions reduction is compared to the additional expenditure necessary to carry out the intended cleanings. An economic parameter 'Savings / Extra budget' is introduced to perform a comparison between the different cleaning scenarios. 'Savings represents the gross energy and greenhouse gas savings compared to the current cleaning campaign. 'Extra budget' represents the additional operational expenditure associated with each cleaning scenario (cost of cleaning and installation of tube inserts).

A variant of this scenario implies increasing the number of specific cleaning operations carried out for the heat exchangers that can be bypassed. Figure 9 shows the intended cleaning schedule if the exchangers equipped with a bypass are cleaned on a half-yearly basis. General cleaning campaigns are represented by blue bars on the figure whereas specific cleaning operations of the bypassed exchangers are represented by red bars on the figure.

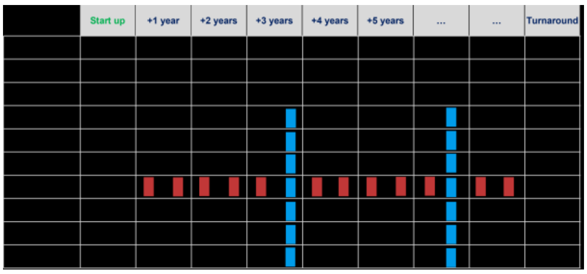

Fig. 9. Two cleaning campaigns and half-yearly specific cleaning operations for the preheat train.

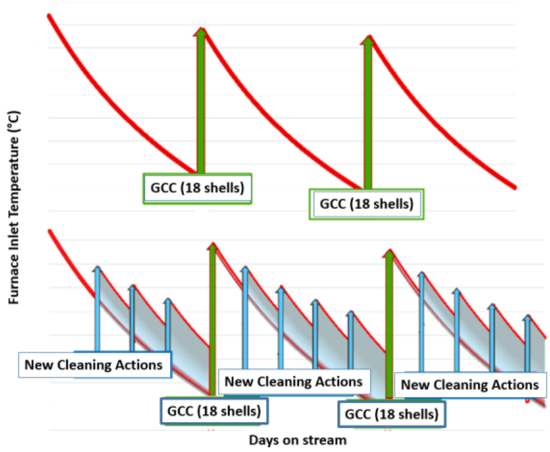

Fig. 10. Two cleaning campaigns and yearly specific cleaning operations for the preheat train. GCC indicates Global Cleaning Campaign (cleaning 18 shells) and 'New Cleaning Actions' indicate cleaning of E-7ABCD.

Several additional configurations including installation of multiple bypass lines for other heat exchangers identified as key for energy consumption by using the cleaning schedule algorithm were tested during this study. This manuscript presents the scenario yielding the highest energy savings and greenhouse gases reduction potential.

Figure 11 presents the ratio between the energy and greenhouse gas savings and additional expenditure for cleaning during an entire cycle. This figure represents the variation on the ratio and the greenhouse gas emissions reduction between a studied scenario (A, B, C, or D) and the baseline. The results were estimated at two different CO_2 prices.

According to these results, the higher the savings/extra budget ratio, the better the profitability of the proposed strategy. The greenhouse gas emissions reduction varies as a function of the chosen cleaning strategy which is a key input on deciding which cleaning strategy to implement. Scenario A results in a degradation of the performance of the preheat train and additional greenhouse gas emissions. The savings/extra budget ratio is not presented for Scenario A in Figure 12, given the worsened energy savings results when compared to the baseline. Scenarios B, C, and D provide a prospect of improving the performance of the preheat train, thereby reducing the energy consumption of the crude preheat furnace. The scenario implying hardware modification for bypass line installation provides the best results in terms of greenhouse gas emissions reduction potential. Scenario B offers a lower saving/extra budget ratio than Scenario C despite a comparable number of cleaning operations carried out during the cycle. This implies better energy savings and greenhouse gas emissions reduction potential for Scenario C, in which there is less time between two cleaning operations. Scenario C offers a better saving/extra budget ratio than Scenario D, even though greenhouse gas emissions reduction potential is higher for the latter. Given the higher cost of carrying out cleaning operations on a half-yearly basis, the saving/extra budget ratio is lower for Scenario D as the number of cleaning operations increases cleaning cost and operational safety. Based on the compromise, expected savings account for 4.5% of the total furnace Fuel Gas consumption.

CONCLUSION

A study was conducted within one TotalEnergies refinery for optimization of the cleaning strategy of a crude distillation unit preheat train. This study led to a project proposal for installation of new bypass lines on heat exchangers identified as key for cleaning via using the SmartPM software.

Important greenhouse gas emissions reduction savings can be achieved by optimizing preheat train cleaning strategy. The optimum cleaning strategy results from an acceptable savings/extra budget ratio associated to relevant gas emissions reduction potential.

Table 1. Summary of scenarios studied for preheat cleaning strategy optimization.

Scenario	Base	A	B	C	D
Global cleaning campaigns per cycle	2	1	3	2	2
Hardware modification	No	No	No	Yes	Yes
Additional cleanings of bypassed exchangers	-	-	-	1/year	2/year

NOMENCLATURE

C_1 m^2 K W day^{-1} $(Pa)^{C2}$ $(Pa\ s)^{-C3}$
C_2 Constant in Equation (2), dimensionless
C_3 Constant in Equation (2), dimensionless

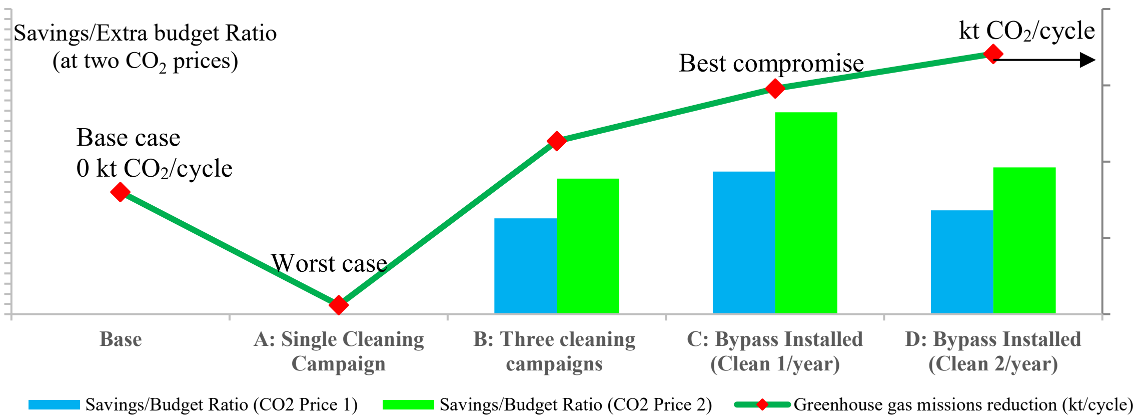

Fig. 11. Economic ratio between potential savings assessment and additional budget to be provided for implementation of the cleaning strategies identified.

d diameter of the tube, m
E Activation energy, J mol^{-1}
h Film transfer coefficient, W m^{-2} K^{-1}
R Universal constant, J mol^{-1} K^{-1}
R_f Fouling resistance, m^{2}K W^{-1}
T Film temperature, °C
t time, s
U overall heat transfer coefficient, W m^{-2} K^{-1}

α Fouling propensity factor, s^{-1}
μ Dynamic viscosity, Pa s
τ Shear stress, Pa

Subscripts
i inner surface / tube-side
o outer surface / shell-side

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