ADVANCED FOULING MANAGEMENT THROUGH USE OF HTRI SMARTPM: CASE STUDIES FROM TOTAL REFINERY CDU PREHEAT TRAINS

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ABSTRACT

Heat exchanger fouling is a persistent problem contributing to process economics, plant capacity, environmental concerns, and safety. Advances in research on hydrocarbon fouling have changed the impact of fouling in crude refinery operations, through the use of rigorous performance monitoring and process optimization methods, use of fouling predictive models, use of fouling mitigation technologies (e.g., use of tube inserts), etc. This work presents case studies from two TOTAL refinery preheat trains where the exchangers are subject to fouling. TOTAL has implemented a performance monitoring and predictive maintenance software (HTRI SmartPM™) throughout their refineries to improve existing fouling management practice.

The software performs advanced data reconciliation, including simulation of detailed exchanger operational data using HTRI shell-and-tube heat exchanger calculation methods and inferring fouling resistance for individual shells for shells-in-series based on dynamic fouling behavior. Dynamic fouling models are used to assess the impact of fouling on the overall network performance. Several heat exchangers in the network have tube inserts (Turbotal® and Spirelf® inserts from Petroval), and their performances are monitored and predicted.

The case studies demonstrate successful implementation of SmartPM software in TOTAL Normandy and Grandpuits refineries, enabling economically feasible, technically viable, and environmentally desirable decision-making for refinery operation.

INTRODUCTION

Crude refinery heat exchanger networks operate in a highly dynamic environment and strongly rely on practical fouling solutions. To date, a variety of practical fouling solutions are reported in literature [1, 2]; examples relevant to crude preheat train are listed in Table 1. Application of fouling mitigation options depends on a combination of decisions including the assessment of technical viability, economical feasibility, refinery philosophy, and operational strategy.

Table 1: Examples of common fouling mitigation options (not exhaustive).

Fouling mitigation options	**References**
Better heat exchanger design, retrofit, and network revamp	[3–8]
Alternative exchanger design (other than segmentally baffled exchangers)	EMbaffles®: [9, 10]; HELIXCHANGER®: [11, 12]; Compabloc®: [13–15]
Improvements in operating strategies (e.g., flow split optimization, when and which units to clean)	[16–22]
Use of mechanical vibration devices for tube/tube bundle	[23, 24]
Use of tube inserts	[25–27]
Surface coatings	[28]
Better selection of crude	[29]
Use of anti-foulants	[30–32]

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This manuscript describes case studies from two TOTAL refineries illustrating the strategic fouling management program via performance monitoring and predictive studies.

TOTAL S.A. is a multinational integrated oil and gas company with worldwide presence in over 130 countries. TOTAL Refining and Chemicals (R&C) is a part of TOTAL S.A. that focuses on downstream processing. As part of TOTAL's strategic industrial competitiveness, daily activities focus on operating assets as efficiently as possible on all the factors that can be controlled, including availability, energy efficiency, and costs. TOTAL initiated the implementation of SmartPM software as part of a project milestone and showcases TOTAL R&C's strategy.

SmartPM from HTRI is used for performance monitoring and predictive maintenance of heat exchanger networks. In this paper, SmartPM will be referred to as the simulator. The software is a digital twin technology, which mirrors operation of heat exchanger networks via connecting to the plant data historian. It can then predict the future performance of the heat exchangers and generate cleaning schedules to minimize energy use, maximize throughput, and lower CO_2 emissions. SmartPM also allows users to look at possible revamp options for minimizing the thermal and hydraulic impact of fouling, such as altering heat exchanger designs or reconfiguring network structure.

METHODOLOGY

A systematic approach for fouling management was adopted (Figure 1) from best practices reported in literature (e.g., [4]).

Heat exchanger and network model construction

Heat exchanger models used detailed exchanger geometry from exchanger specification sheets and drawings. This geometry is used in the proprietary heat transfer and pressure drop correlations developed by HTRI.

Several exchangers in the case study use two types of tube inserts (Turbotal and Spirelf). These are mechanical devices installed inside tubes to enhance heat transfer and to promote fouling mitigation. The tube insert geometries are also entered 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 [33].

Piping and instrumentation diagrams (P&IDs) 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.

Process economics

The economic details and hypothesis defined in this manuscript are for illustration and do not reflect the Normandy or Grandpuits refinery situations. The following parameters are used for the preheat train economics: cost of cleaning, 20,000 €; period when exchanger is offline for cleaning, 7 days; energy cost, 6.25 € /GJ; lost opportunity cost, 20 € /te; CO_2 emission cost, 10 € /te.

Data reconciliation

Data reconciliation performs a heat and mass balance to generate missing process parameters from available temperature, flow, and pressure measurements.

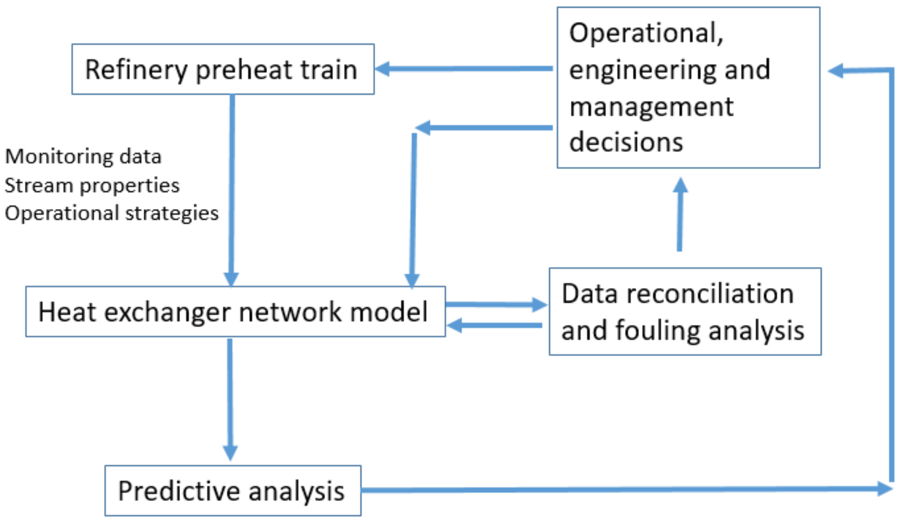

Fig 1. Flow chart of fouling management program.

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Fouling analysis

A combination of different fouling deposits are observed throughout the preheat train [34, 35]. For exchangers located downstream of the desalter, even though some presence of salt/iron in the deposits may be observed [36, 37], the impact of fouling on the crude-side is proven to be dominated by chemical reaction fouling [36, 38, 39]. The case studies presented in this paper offer further confirmation.

From Normandy plant experience, both the crude stream and heavy product streams are subject to fouling. A 'dynamic fouling model' 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) is modeled via the asphaltene precipitation model:

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

Here, dR_f/dt is the rate of change in thermal resistance, h is the film transfer coefficient, a is the fouling propensity factor which depends on the crude chemistry and the fouling surface, R is the gas constant, E is the activation energy of the conversion of maltenes to asphaltene cores [40], and τ is the shear stress.

Heavy hydrocarbon stream fouling is modeled via the particulate fouling model [41]:

$$\frac{dR_f}{dt} = C_1 \frac{\tau^{-C_2}}{\mu^{C3}} \quad (2)$$

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

Hydraulic model

Fouling results in increased hydraulic resistance (and increased pressure drop for the same flow rate), and therefore a potential throughput limitation may occur when a hydraulic limit is met. When a heat exchanger network is hydraulically limited via the centrifugal pump capacity, its operation is modeled through incorporating the pump characteristic curve and tracking the relationship between the throughput and the network pressure drop with the pump operating curve [18, 42].

Prediction and scheduling cleaning

The simulator is used for the prediction and scheduling of exchanger cleaning which uses a modified version of a heuristic scheduling algorithm reported in literature [18, 43, 44]. The cleaning schedule provides information on when and which units to clean while maximizing the 'Net benefit'. 'Net benefit' is the difference between the sum of the overall energy and throughput benefit compared to a no-cleaning state and the total cost of cleaning.

Case studies

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

Case study 1: TOTAL Normandy refinery preheat train

A schematic of the preheat train model (post desalter section) is shown in Figure 2. In this section, all crudes are on the tube side. The crude is split into two parallel branches following the desalter, mixed to a single stream, and then split into four parallel branches before entering the furnace. There are 12 shells with tube inserts installed, and their type and location are marked in the figure.

Fouling analysis

Fouling on the crude side is modeled via Equation (1). The fouling propensity factor is fitted for the crude stream by selecting exchangers where only the crude side is known to dominate fouling (e.g., exchangers excluding heavy product streams). The historical fouling performance and predicted fouling profile for E5A is shown in Figure 3(a). Figure 3(a) is a combination plot of the tubeside film transfer coefficient, pressure drop, and fouling resistance. The effect of occlusion of the tubeside flow area due to fouling is observed via the gradual increase in the tubeside pressure drop and the film transfer coefficient.

During exchanger cleaning at the plant, visual observation revealed significant fouling of the heavy hydrocarbon stream on the shell side (Figure 4). Fouling of this stream is modeled via Equation (2). The constant C_1 was fitted to model the additional fouling via fixing C_2 and C_3 as recommended in literature [41]. Figure 3(b) shows historical performance and prediction of fouling for E1A. The tubeside pressure drop in prediction remains almost constant as the fouling model for the crude in Equation (1) calculated negligible fouling compared to the shellside fouling calculated by Equation (2). This aligns with the field observations.

Cleaning analysis

There are no bypasses to isolate the exchanger during cleaning at the last section of the exchanger network. Hence, when an exchanger is taken offline for cleaning during operation, the branch has to be shut down and the flow diverted to the other branches. The operational strategy is combined with the scheduling algorithm described in literature [18, 45], and an optimized cleaning schedule was generated [Figure 5 (a)]. The generated cleaning schedule is for illustration only and does not reflect

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the cleaning strategy of the Normandy refinery preheat trains. In the generated cleaning schedule, the exchangers with tube inserts are selected. It has been considered that the refinery has a series of cleaning options, including chemical and mechanical cleaning. The tube inserts are not required to be replaced during cleaning due to the selection of the cleaning method. As a consequence, in this generated cleaning schedule, units with tube inserts can be cleaned effectively via chemical cleaning on the tube side. The net cleaning benefit increases from years 1 to 3 [Figure 5(b)] even with the reduction in cleaning events from years 1 to 3 [Figures 5(c) and (f)]. This shows that the benefit of cleaning actions of the current year is recovered in the subsequent years [Figures 5(c) and (e)].

It is also useful for the plant to have a list of exchanger candidates to clean (or not to clean) on a specific date. An illustration is provided in Figure 6, where the benefit of cleaning an exchanger is listed in the order of descending 'net benefit', which is calculated for a period of 1 year. In Figure 6(a), a negative 'net benefit' for some exchangers implies that the plant will lose money by cleaning these units. The chart also shows that the units with the highest 'net benefit' are not necessarily the units with the higher furnace inlet temperature increase, as the rate of the drop in the furnace inlet temperature would differ for different cleaning actions due to the dynamic fouling behavior. The benefit of cleaning groups of exchangers based on Figure 6(a) is given in Figure 6(b). The analysis shows that the impact of cleaning an exchanger/group is less for the overall network compared to the individual unit itself. That is, cleaning exchangers 7CD gives a heat duty increase of 7.86 MW (16.7 – 8.84 MW) compared to the total network duty increase of 4.13 MW. The net benefit of cleaning initially increases with the increased number of cleanings but could decrease if the cost of cleaning dominates the actual benefit of cleaning [Net benefit column in Figure 6(b)].

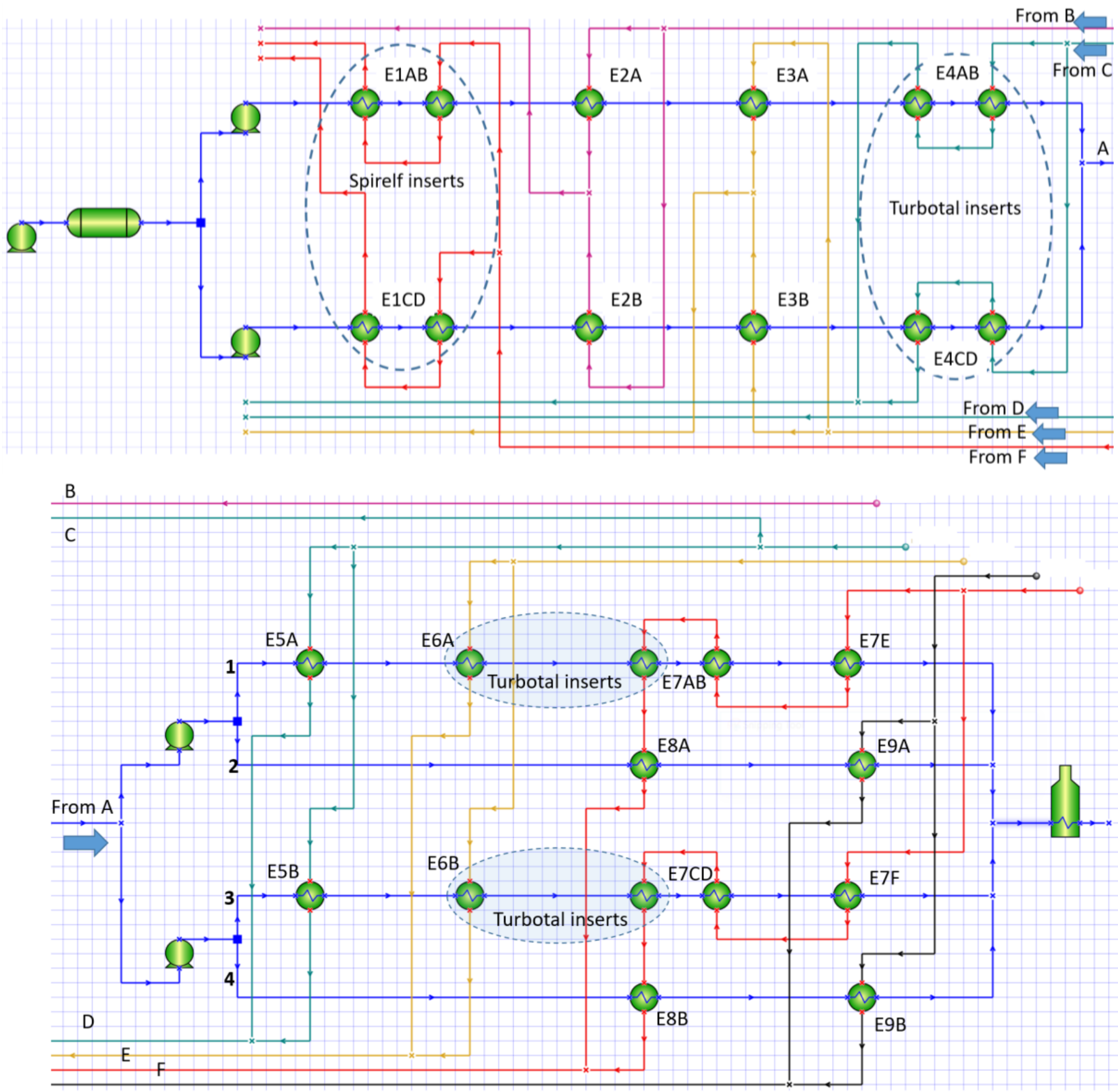

Fig. 2. Post desalter section of Normandy crude preheat train.

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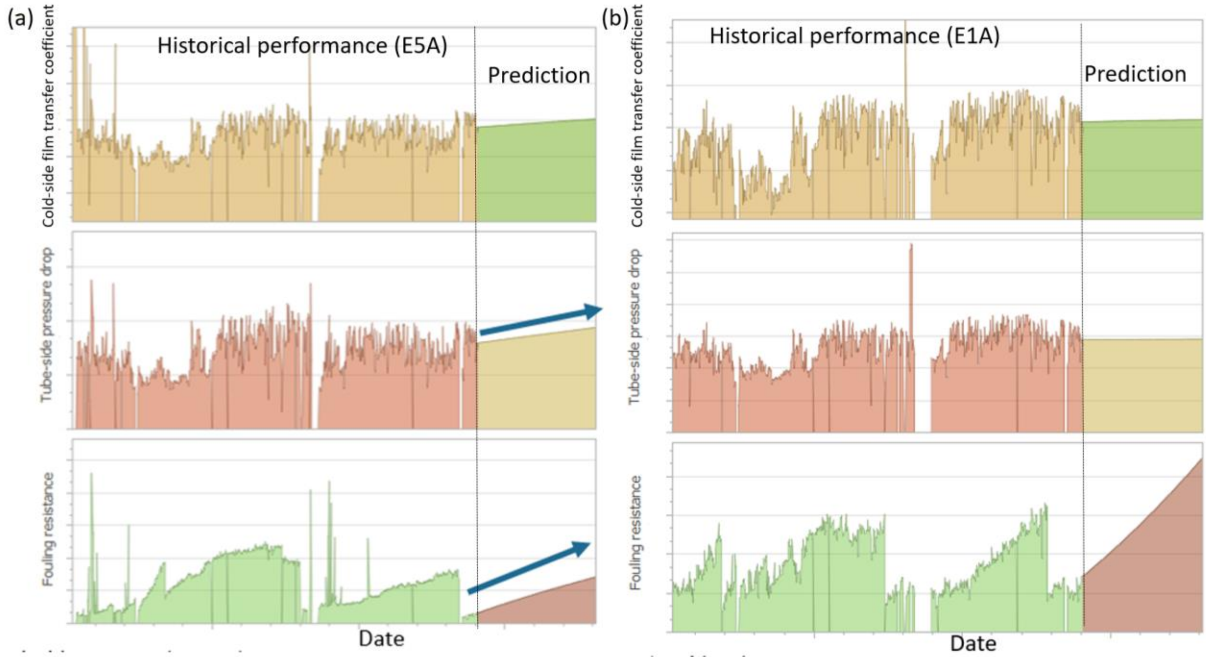

Fig. 3: Combination plot of cold-side film transfer coefficient, tubeside pressure drop, and fouling resistance for (a) E5A (exchanger with dominant fouling on the tube side) and (b) E1A exchanger with dominant fouling on the shell side (heavy hydrocarbon stream).

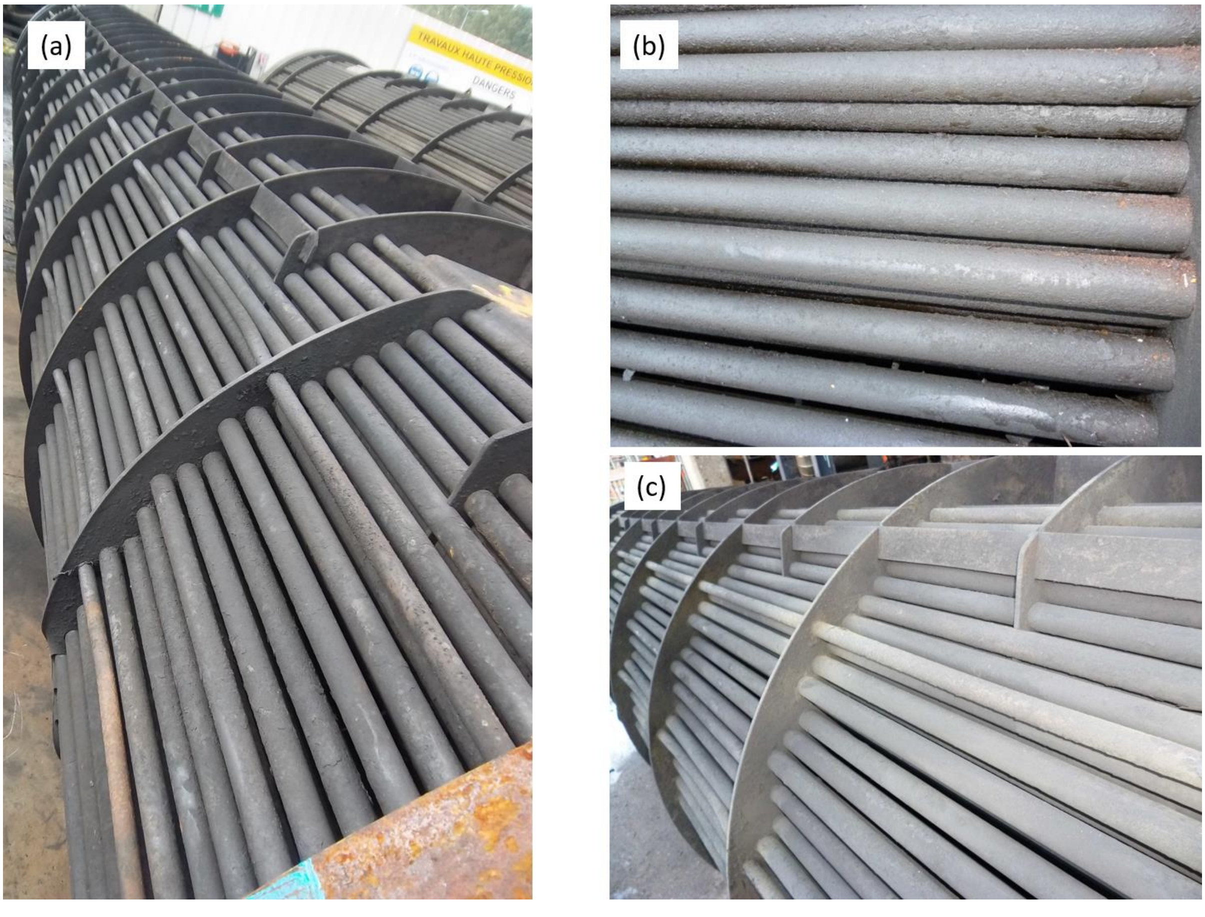

Fig. 4: Fouling on shell side (heavy hydrocarbon stream) of exchangers E1ABCD; (a) tube bundle and sections of baffles of E1D; (b) and (c) tube-bundle and sections of baffles of E1B.

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(a)

	2018		2018 Total	2019				2019 Total	2020				2020 Total	2021	2021 Total	Grand ...
	August	Nove...		February	May	August	Nove...		February	May	August	Nove...		February		
E5AB Total														20K	20K	20K
E5A														20K	20K	20K
E7AB Total				40K				40K								40K
E7A				20K				20K								20K
E7B				20K				20K								20K
E7CD Total	40K		40K		40K		40K	80K				40K	40K			160K
E7C	20K		20K		20K		20K	40K				20K	20K			80K
E7D	20K		20K		20K		20K	40K				20K	20K			80K
E7E Total						20K		20K			20K		20K			40K
E7E						20K		20K			20K		20K			40K
E7F Total		20K	20K							20K			20K			40K
E7F		20K	20K							20K			20K			40K
E9B									20K				20K			20K
Grand Total	40K	20K	60K	40K	40K	20K	40K	140K	20K	20K	20K	40K	100K	20K	20K	320K

Fig. 5: (a) Gantt chart of when and which units to clean, with figures representing the cost of cleaning; (b) total net saving; (c) average furnace duty saving; (d) annual cleaning budget; (e) annual CO2 saving; and (f) number of cleans.

(a)

Top Exchangers to Clean on 17 August 2018

Name	Unit	Shell Side	Tube Side	Net Benefit (EUR)	Network Duty Increase (MW)	Initial FIT Increase (°C)	Cost of Cleaning (EUR)
E7CD	E7CD	Product 4	Cold	502K	4.14	4.74	103K
E7F	E7F	Product 4	Cold	261K	2.47	2.81	83.4K
E8B	E8AB	Product 4	Cold	152K	1.21	1.52	33.2K
E9B	E9B	Product 3	Cold	119K	0.861	0.89	33.2K
E3B	E3AB	Product 2	Cold	71.7K	0.524	0.35	26.6K
E3A	E3AB	Product 2	Cold	48.7K	0.438	0.3	28.8K
E1CD	E1CD	Product 4	Cold	42.7K	0.623	0.43	66.4K
E1AB	E1AB	Product 4	Cold	42.4K	0.626	0.43	66.9K
E7E	E7E	Product 4	Cold	8.8K	0.872	0.98	98.7K
E7AB	E7AB	Product 4	Cold	-5.8K	1.05	1.19	119K
E2A	E2AB	Product 5	Cold	-14.7K	0.056	0.04	23.9K
E2B	E2AB	Product 5	Cold	-20K	0.038	0.03	26.2K
E4AB	E4AB	Product 1	Cold	-20K	0.22	0.16	84.5K
E4CD	E4CD	Product 1	Cold	-20K	0.257	0.19	83.5K
E5B	E5AB	Product 1	Cold	-20K	0.572	0.56	83.5K
E5A	E5AB	Product 1	Cold	-20K	-0.139	-0.12	98.8K
E6B	E6AB	Product 2	Cold	-20K	0.456	0.54	83.4K
E6A	E6AB	Product 2	Cold	-20K	0.239	0.27	98.7K
E8A	E8AB	Product 4	Cold	-20K	0.154	0.19	37.3K
E9A	E9A	Product 3	Cold	-20K	0.047	0.05	37.3K

(b)

Top Exchanger Sets to Clean Together on 17 August 2018

Name	Net Benefit ...	Cost of Cleanin...	HX / Unit Duty - Before ...	HX / Unit Duty - After Cl...	Network Duty Gained After Clea...	Initial FIT Increas...
E7CD	502K	103K	8.84	16.7	4.13	4.73
E7CD + E7F	720K	124K	13.3	26.3	5.1	5.78
E7CD + E7F + E8B	853K	136K	16.1	29.1	5.69	6.56
E7CD + E7F + E8B + E9B	990K	156K	18.3	32.2	6.54	7.45
E7CD + E7F + E8B + E9B + E3B	1.06M	182K	21.3	36.6	7.07	7.79
E7CD + E7F + E8B + E9B + E3B + E3A	1.11M	210K	25.4	41.8	7.51	8.08
E7CD + E7F + E8B + E9B + E3B + E3A + E1CD	1.09M	293K	40.1	54.5	7.97	8.38
E7CD + E7F + E8B + E9B + E3B + E3A + E1CD + E1AB	1.08M	376K	55.2	67.5	8.43	8.69
E7CD + E7F + E8B + E9B + E3B + E3A + E1CD + E1AB + E7E	989K	521K	62.6	78.6	9.29	9.66

Figure 6: The list of exchangers to clean (or not to clean) on a specific date: (a) list of individual exchanger benefits; (b) list of group exchanger benefits.

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Case study 2: TOTAL Grandpuits refinery preheat train

A schematic of the Grandpuits refinery crude preheat train is shown in Figure 7. The network starts with a crude stream from the feed pump mixing with a side stream. The network consists of two crude booster pumps. Only the crude-side of the network was observed to have the dominant fouling impacting the network performance.

The network also has tube inserts on several exchangers to mitigate fouling on the crude stream. Effectiveness of the use of tube inserts can be observed via comparing the fouling profiles of units 31AB (plain tube units) and 31CD (tube-insert units), as shown in Figure 8. E31AB and E31CD have similar exchanger geometries and flow rates, but E31CD has the hotter surface temperature due to the location in the network. The rate in increase in fouling is negligible for E31CD compared to E31AB.

During operation the network can be hydraulically limited (via the pumping capacity) with fouling in heat exchangers. The hydraulic performance of the network was modeled via the extension of pump hydraulic simulation described in literature [18, 42, 46]. A minimum allowed furnace inlet pressure (FIP) is defined during operation. FIP is calculated via accounting for the pump heads provided by the feed pump and the booster pumps and deducting the pressure drops incurred in the network via the exchangers under fouled condition. If the FIP cannot be maintained above the minimum allowed FIP, throughput reduction is inevitable due to the pump hydraulic limit. The FIP profiles measured and predicted are plotted in Figure 9.

The curve A-B-C (in Figure 9) was obtained from prediction via defining the minimum allowed FIP (B-C). The FIP drops from A to B in prediction is due to the fouling in the network at constant throughput. This trend is matched closely with the historical drop in FIP.

The hydraulic simulation in the TOTAL Grandpuits refinery is a preliminary study; at the time of writing this document, detailed results are still under validation with the refinery. However, this case study illustrates the potential of SmartPM for hydraulic simulation.

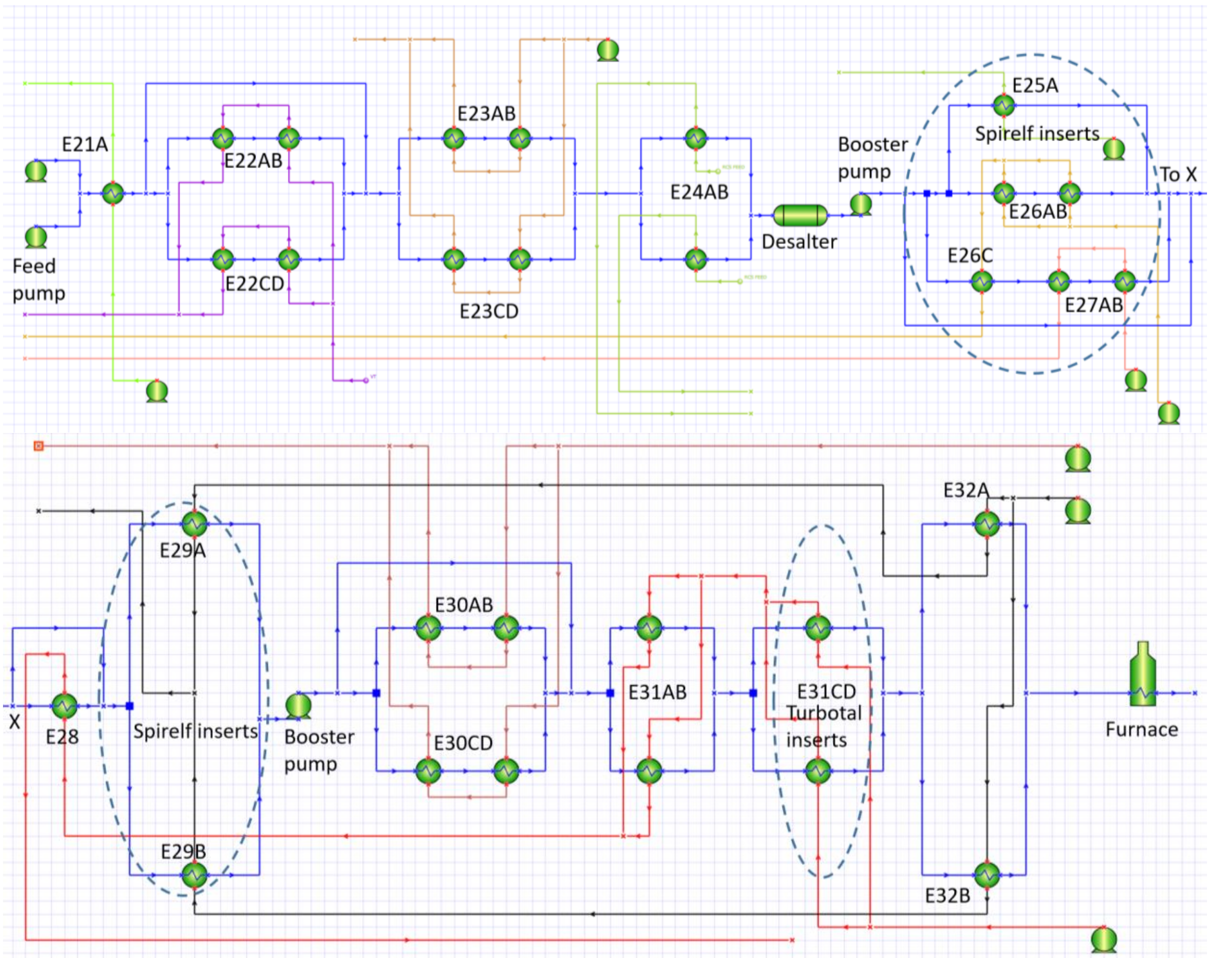

Figure 7: Grandpuits refinery crude preheat train.

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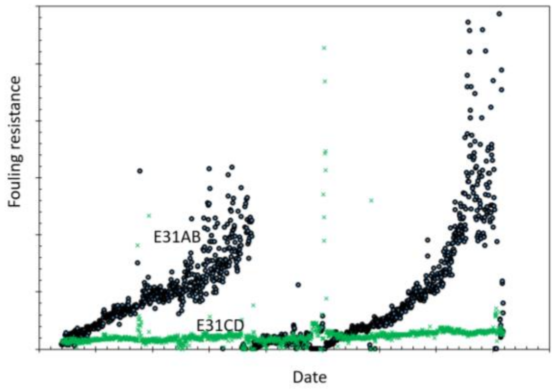

Figure 8: Comparison of thermal resistance performance of plain tube and unit with tube insert at Grandpuits network.

As with the network described in the first case study, this network also consists of exchangers without bypasses which prevent individual isolation and bypassing of shells during online cleaning. When any of the units in the parallel branches of E32AB, E31CD, and E29AB are cleaned, the branch consisting of the exchanger to be cleaned has to be shut down and the flow diverted to the other branch. When the exchanger is back online after cleaning, the flow spontaneously adjusts to minimize pressure drop across the network. Also, units 29A-32A and 29B-32B have to be cleaned together based on the product-side piping arrangements. These constraints were incorporated in generating an optimized cleaning schedule (Figure 10). The cleaning action in Figure 10 is reflected in the furnace inlet temperature and furnace inlet pressure in Figure 11. Apart from two periods (A and C marked on Figure 11) when the exchangers were offline for cleaning, the throughput remains constant throughout operation due to the planned cleaning actions. Both operations, with and without cleaning, maintain the throughput in the first year of operation, implying that the net benefit achieved via cleaning is reflected in terms of the energy gain only. However, in the second year, as the throughput gain dominates, the benefit of cleaning is an order of magnitude higher than in the first year (Figure 12).

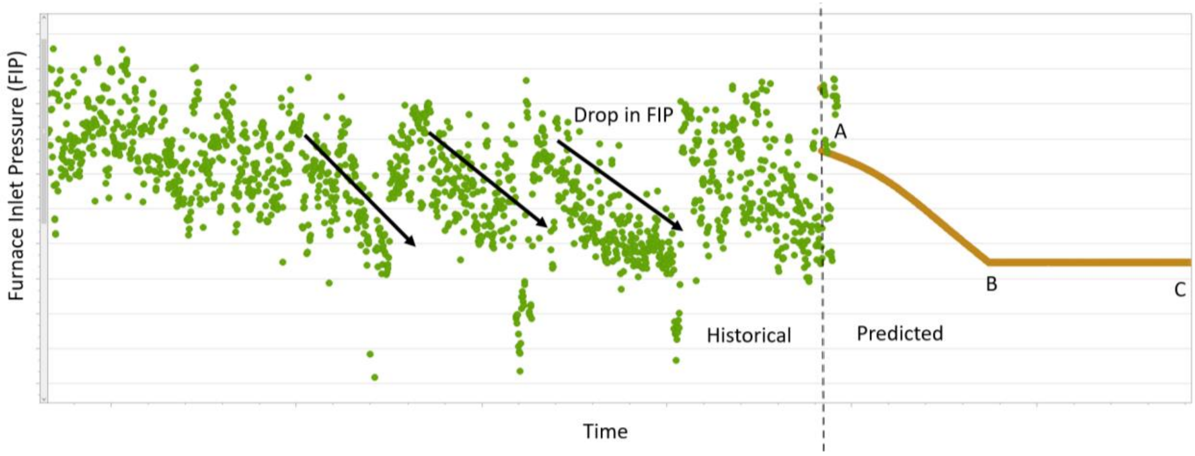

Figure 9: Historical and predicted furnace inlet pressure profile. Prediction study shows a no-cleaning scenario. A, start point of predictive study; B to C, minimum allowed furnace inlet pressure.

Date

E30ABCD			40K		40K	40K
E30A			20K			20K
E30B			20K			20K
E30C					20K	
E30D					20K	
E32AB	20K			20K		
E32A				20K		
E32B	20K					
E31AB		40K				
E31A		20K				
E31B		20K				
E29AB	20K			20K		
E29A				20K		
E29B	20K					
Grand Total	40K	40K	40K	40K	40K	40K

Figure 10: Gantt chart on when and which units to clean.

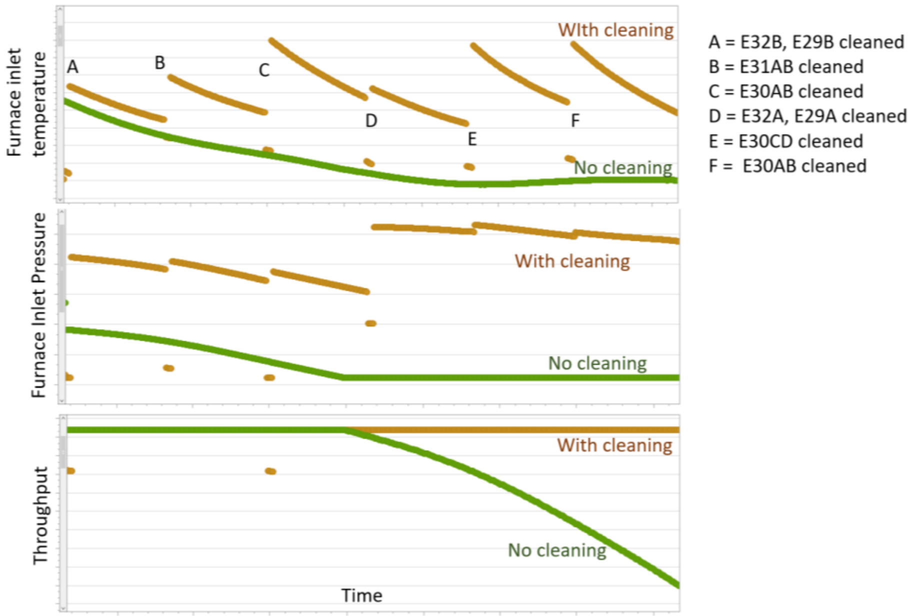

Figure 11: Grandpuits network performance profiles: (a) furnace inlet temperature, (b) furnace inlet pressure, and (c) throughout.

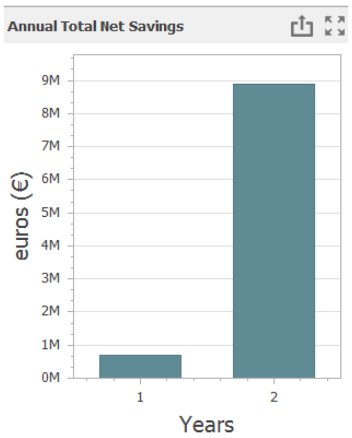

Figure 12: Annual total net saving.

The use of the simulator is currently being extended to other TOTAL refineries for fouling monitoring and cleaning budget allocation. Potential additional practical applications of hydraulic simulation are under consideration. The central technical support team and research and development team also plan the usage of dynamic fouling prediction methods in the assessment of the impact of network retrofit and revamp on fouling.

CONCLUSIONS

- TOTAL, working with HTRI, is implementing a fouling management program across its refineries for heat exchanger network management.
- Successful implementation of SmartPM software at TOTAL Normandy and Grandpuits refinery CDU trains is demonstrated, including the following:
  - Monitoring of exchanger performance with/without tube-inserts
  - Use of dynamic fouling models to predict fouling of both crude and product side fouling
  - Techno-economic analysis of optimizing cleaning schedules
  - Potential of modeling network hydraulics and quantifying opportunity cost

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
E Activation energy, J mol^{-1}
h Film transfer coefficient, W m^{-2} K^{-1}
R_f Fouling resistance, m^{2}K W^{-1}
T Film temperature, °C
α Fouling propensity factor, s^{-1}
μ Dynamic viscosity, Pa s
τ Shear stress, Pa

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