THE IMPACT OF FOULING ON THE OPTIMAL DESIGN OF A HEAT EXCHANGER NETWORK: AN INDUSTRIAL CASE STUDY

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ABSTRACT

Fouling in pre-heat trains of atmospheric crude distillation units is one of the major issues hindering the efficiency of operations in oil refineries. This paper illustrates the benefits of using dynamic simulation, combined with plant measurements, to assess the impact of fouling in heat exchanger networks and to identify/evaluate heat exchanger retrofit opportunities that provide the largest savings to the refinery.

An industrial case study showing the severe fouling occurring in a heat exchanger of a crude distillation unit is presented. Once the fouling behavior of the network is well characterized and the most critical heat exchanger is identified, the performance of a given retrofit design for that unit is assessed. The comparison of the original design versus alternative ones, based on the potential reduction of fouling, provides an overall assessment of the impact on energy/economic savings for the whole network given by the proposed retrofits options.

INTRODUCTION

Fouling mitigation techniques aim to eliminate or reduce fouling and consequently increase the profitability of industrial systems. Mitigation strategies include the use of chemical inhibitors, antifouling coatings, optimal management of operations (e.g. flow-split and bypass control) and improved heat exchanger and network designs (Müller-Steinhagen *et al*. 2011; Coletti and Hewitt 2014). The choice of mitigation strategies depends on the fouling mechanism, type of heat exchanger, costs involved, and cleaning schedules. However, the benefits of mitigation strategies are difficult to quantify in advance. For this purpose, mitigation strategies benefit from fouling monitoring, accurate calculations (i.e. mathematical models) and reliable predictions capable of anticipating future fouling behavior, performance and economic savings (with respect to current practice) that can be attained if implemented in practice.

Heat exchangers are usually designed on the basis of TEMA fouling factors (TEMA 1999). This practice can lead to the oversizing of equipment that do not take full advantage of the available pressure drop and that, when installed in plant, accelerate fouling. The use of fixed fouling factors has been indeed severely criticized in the past (Epstein 1983; Rabas and Panchal 2000; Jones and Bott 2001; Bennett *et al.* 2007). New approaches to heat exchanger design include the use of model-based rating methods, optimization approaches (via genetic algorithms and mathematical programming) and Computational Fluid Dynamics. A review of relevant works is provided by Coletti *et al.* (2014). Some methodologies have been proposed to identify heat exchanger configurations that provide manageable fouling levels (Butterworth 1996; Poddar and Polley 1996; Butterworth 2002; Coletti *et al*. 2011; Yeap *et al.* 2004; Ishiyama *et al.* 2009), based on the fouling threshold concept introduced by Ebert and Panchal (1995). However, few approaches to heat exchanger design include fouling dynamics. As an example, Caputo *et al.* (2011) proposed a method to minimize the life cycle cost using a genetic algorithm in a single unit heat exchanger, with fouling dynamics described by an asymptotic rate model. Coletti and Macchietto (2009) used a dynamic heat exchanger model to test several retrofit options (number of passes, tube diameter), based on previously estimated fouling parameters using plant data.

Improved heat exchanger designs and retrofits aim to modify the operating conditions inside the unit to minimize fouling. However, a designer wishing to retrofit a heat exchanger should carefully assess all the implications of the new design, both at the heat exchanger itself and at the network level. Certain designs may successfully reduce fouling, but result in undesired side effects that may even outweigh the benefits achieved by fouling mitigation. An example of such situation was discussed in the Heat Exchanger Fouling and Cleaning XI – 2015, where Coletti *et al.* (2015) analyzed the tradeoffs between fouling mitigation, energy savings, increase in pressure drop and decrease in throughput for high shear stress design strategies. The results showed that retrofits with high shear stress (such as those displayed in Fig. 1) may result in production loss due to hydraulic interactions in the network.

In this paper, the benefits of using dynamic predictive models in combination with plant measurements to evaluate heat exchanger retrofit opportunities are demonstrated through an industrial case study. The analysis consists in the assessment and comparison of the impact of fouling on the original design against alternative ones. It provides an overall assessment of the impact on energy and economic savings for the whole network given by the proposed retrofits options.

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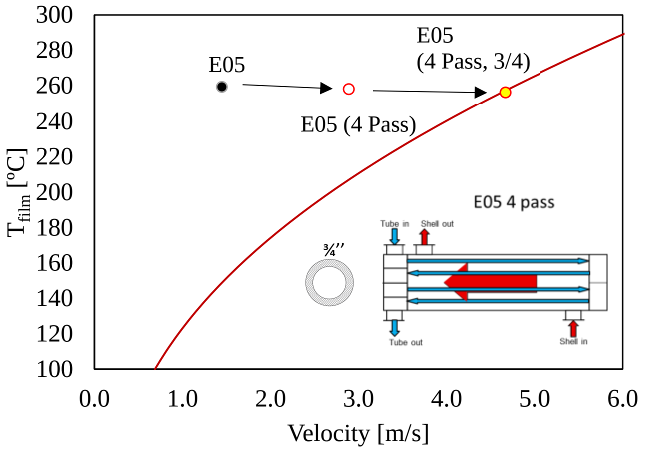


Fig. 1. Threshold plot showing the conditions of film temperature and velocity at which a system is expected to foul (above the red line) and not to foul (below the red line) on the tube-side. Effect of two retrofit options from 2 to 4 tube-side pass and from 1'' to ¾'' tube diameter on the threshold plot (Coletti *et al.* 2015).

METHOD

This paper focuses on the use of predictive dynamic simulations to test the performance of a proposed retrofit design. The overall method, called Dynamic Retrofit Test™ (Coletti, 2017) includes the following steps:

1) Characterize the fouling behaviour of the network and identify the most critical heat exchanger(s) with respect to the overall thermal and hydraulic performance.
2) Estimate necessary parameters that capture fouling and validate model predictions with primary plant data (e.g. temperature).
3) Propose an alternative retrofit design, expected to reduce fouling and improve performance.
4) Use past plant data to "re-run history" with the new design to predict and assess fouling behaviour and verify performance under the same conditions as the original design.
5) Assess the interactions between the new design and the rest of the network (i.e. "network effects"). This includes, for example, changes in the flowrate due to the different hydraulic resistance of the new geometry, variations in the driving forces for heat transfer, etc.
6) Evaluate the impact that the new design generates on the overall performance of the network energy and economic savings by comparison with the original design.

The analysis is performed using Hexxcell Studio™ (Hexxcell Ltd. 2017), a commercial software suite for the analysis, design and operation support of thermal systems undergoing fouling.

CASE STUDY

The case study presented here focuses on a preheat train in a refinery owned and operated by Repsol. The study involved the analysis of over four years of plant data for all the exchangers in the hot end section (i.e. exchangers downstream of the desalter). A simplified flow diagram of the network considered is shown in Fig. 2. Daily temperature and flowrate measurements were available for all units. The physical properties of the fluids (C_p, k, μ, ρ) were calculated over time as function of local temperature and characteristic oil parameters.

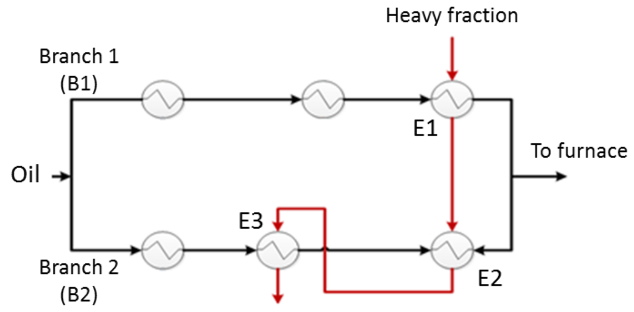


Fig 2. Simplified flow diagram of the hot end section of the preheat train.

All heat exchangers were completely clean at the beginning of the period considered. It is noted that some of the axis in the graphs have been rescaled to preserve confidentiality.

RESULTS AND DISCUSSION

1. Characterization of Fouling Behavior and Identification of Key Heat Exchangers

The first step of the analysis consisted in the assessment of the fouling behavior and operating conditions of the heat exchangers in the network. By comparing the fouling behavior in all units at the hot end, the most severe fouling build-up was observed in units E1, E2 and E3, located at the hottest extreme of the network (see Fig. 2). The severe fouling behavior is observed only after a change in trend occurring about 700 days after the start of the operating period. This is reported in Fig. 3 in terms of the overall fouling thermal resistance. Before 700 days, all the exchangers in the hot end showed similar moderate fouling build-up (only results for E1, E2, E3 shown here), indicating similar fouling mechanism related, most likely, to the only common fluid: the crude oil (tube-side fluid). After 700 days, a change in fouling behavior in E1, E2 and E3 is observed.

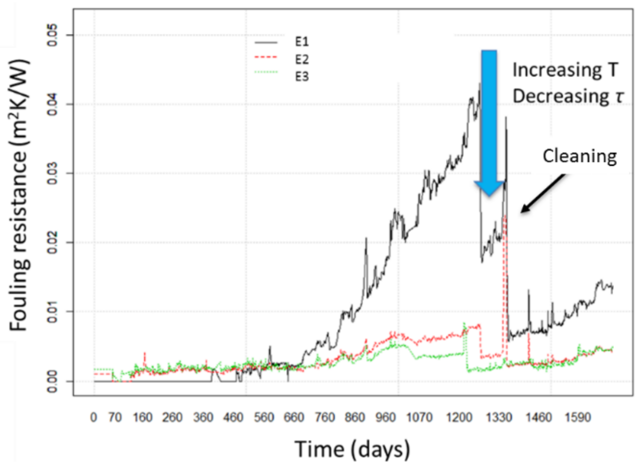


Fig. 3. Overall thermal resistance in the three units at the hottest end of the preheat train.

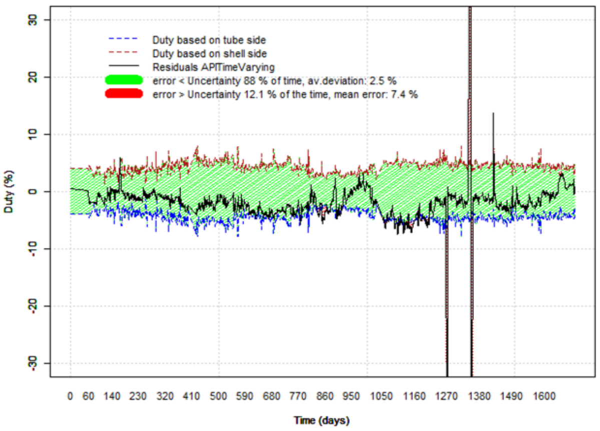


Fig. 4. Model fitting and predictions for one of the exchangers in the network. The blue line indicates heat duties calculated with tube-side measurements, the red line duty calculated with the shell-side measurements. The difference between these two lines (green band) is considered to be the measurement error. Model simulations (black line) are within the uncertainly of the measurement (±5% of the heat duty) for the entire 4.5-year period.

As shown in Fig. 2, the three exchangers share the same shell-side fluid (a heavy oil fraction). Furthermore, a clear correlation was observed between the extent of fouling (after the change in behavior) and the operating conditions on the shell-side:

- Fouling rate: E1 > E2 > E3.
- Shell-side fluid temperature: E1 > E2 > E3.
- Shell-side shear stress: E1 << E2 < E3.

The conclusion of this analysis was that moderate tube-side fouling builds up in all units for the initial 700 days. After this initial period, a marked drop in performance in E1 (and, to a lesser extent, in E2, E3) was associated to severe shell-side fouling, which becomes the dominant resistance to heat transfer. This conclusion is also supported by the analysis of the tube-side pressure drop information available for each branch of the train. No significant change in overall tube-side pressure drop was observed when the sharp increase in fouling resistance is detected. The causes of this sharp increase are unknown, but they appear to be related to operational changes in the distillation unit. Overall, E1 was the unit most adversely affected. The greater fouling rates in this unit could be due to the very low shell-side velocities (thus shear stress), to the higher temperature on the shell-side fluid, or to the greater concentration of foulant, as depletion of foulant due to severe deposition in E1 would explain the lower fouling rate in downstream units E2 and E3. The lower velocities are due to the different design of these units. E1 is a four 16-pass shells in parallel, whilst E2 and E3 are heat exchangers with 2-parallel-2-series and 2-parallel 8-pass shells, respectively. Therefore, E1 was identified as the key heat exchanger in the network and selected for retrofit, with the objective of increasing the shell-side velocity.

2. Parameter Estimation and Model Predictions

The next step of the analysis consisted in the estimation and validation of fouling parameters to enable the prediction of deposition on both tube-side and shell-side fouling. This is an essential step as it provides confidence in the accuracy of the model that will be used to test alternative designs.

The parameter estimation procedure used is detailed elsewhere (Coletti and Macchietto 2011; Diaz-Bejarano *et al.* 2017; Chunangad *et al.* 2016). Tube-side fouling parameters were estimated over the first 700 days where the preliminary analysis indicated that no shell-side fouling occurred. Shell-side parameters alone were estimated after day 700. An example of the fitting performed in this study is provided in Fig. 4 where data for 3.5 years of operations were used to fit the fouling model parameters, and the remaining year of operation was predicted well within the measurement errors which were, in this case, very accurate (±5% of the heat duty).

It is noted that the predictive models fitted and verified with plant data take into account the full history of events, including the change in fouling behavior and cleaning actions.

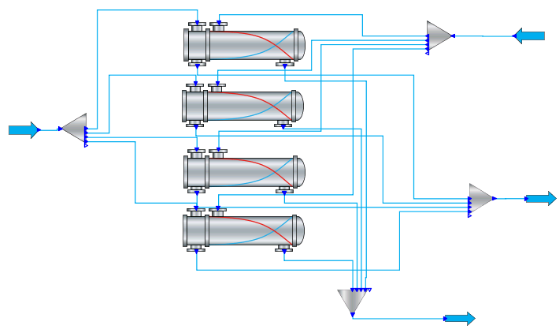
3. Alternative Design for E1

E1 was selected as the heat exchanger to retrofit. Repsol proposed a new design consisting in a rearrangement of the existing shells and number of pass per shell. The original and proposed designs are shown in Fig. 5. The objective of the retrofit was to double the shell-side design velocity to reduce fouling. For this purpose, the original design consisting of four 16-pass shells in parallel was proposed to be modified to 8-pass shells, rearranged to 2-parallel-2-series.

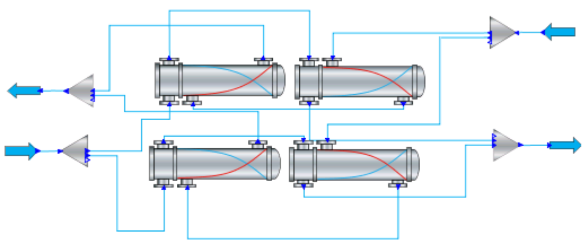
Once the alternative design was selected, historical plant data were used as described in the next sections to test its performance against the existing configuration for heat exchanger E1 in isolation and in the network.

4. History-based Evaluation of the Proposed Retrofit

The proposed retrofit was assessed by performing a



(a)



(b)

Fig. 5. Configuration of the original design (a) and the proposed retrofit (b).

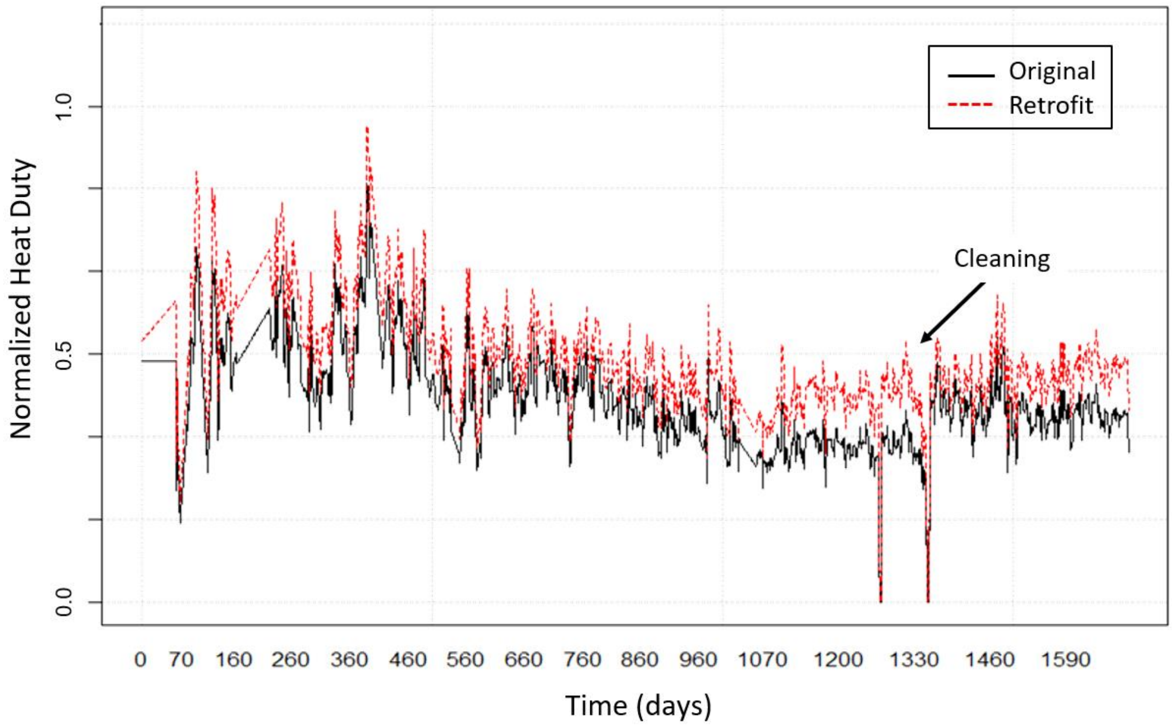


Fig. 6. Heat duty with original (continuous line) and proposed design (dashed line). The y-axis is normalized to protect confidentiality.

dynamic simulation considering:

a) Historical inlet conditions of temperature and flowrate (corresponding to operating period shown in Fig. 3).
b) Predictive fouling models for the tube-side and shell-side with the parameters estimated in Stage 2.

The results of the dynamic simulation allow assessing fouling build-up, operating conditions and overall heat exchanger performance that the new design would have had, had it been operating in place of the original design for the operating period considered. This information, compared with that for the original design, allows evaluating the benefits of the proposed retrofit.

Fig. 6 shows the comparison between the heat duty with the original design and with the proposed new one over the 1600 days of operation considered. The proposed retrofit provides greater heat recovery throughout the period. The heat duty is on average 2.5 MW higher. Over the first part of the operation period, the increase in duty is due to the improved thermal design of the proposed retrofit. After the change in fouling behavior, shell-side fouling is expected to be partly mitigated by the improved design, contributing to the increase in duty. Therefore, the proposed design is expected to improve the performance of the unit and, consequently, of the entire pre-heat train.

However, the thermal aspects are only part of the picture and it is important to consider the hydraulic effects that the new design has on performance. Fig. 7 shows the tube-side pressure drop with the original and new design. The values shown take into account the reduction in cross-sectional area of the tubes as a result of fouling deposition. The new design shows only a 10% increase in pressure drops when compared to the original one and it is thus not expected to significantly impact the hydraulics of the network. This provides a good indication that throughput will not be affected by implanting this change in the refinery even after an extended period of operations. The increase in pressure drop observed after 700 days is due to an increase of throughput.

Fig. 8 and Fig. 9 provide insights on the evolution over time of the tube-side and shell-side deposit thickness, respectively, as predicted by the model for each of the alternative exchanger designs. It is noted that these profiles are averages, calculated from the spatial distribution of the deposit in both tube and shell-sides. The actual deposition rate is captured as a function of local conditions and results in deposit thickness profiles that vary along the heat

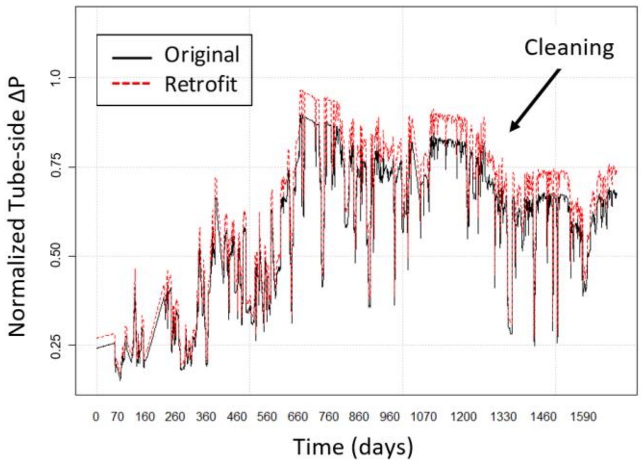


Fig. 7. Tube-side pressure drop in fouled conditions with original (continuous line) and proposed design (dashed line). The y-axis is normalized to protect confidentiality.

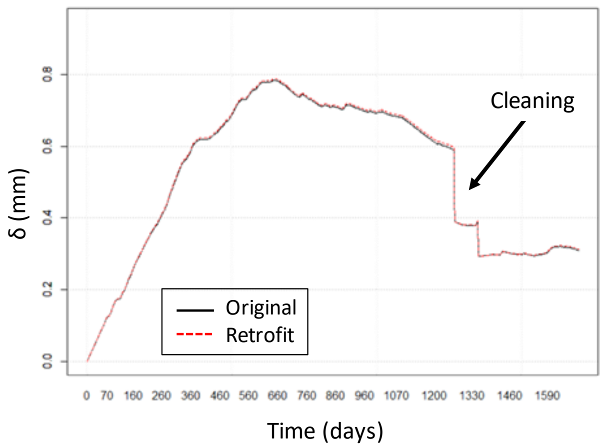


Fig. 8. Tube-side average deposit thickness with original (continuous line) and proposed design (dashed line).

exchanger and for each pass (not shown here for simplicity). The simulations include partial cleanings and the change in fouling behavior to severe shell-side fouling detected after 700 days of operations.

The tube-side velocity in the two alternative designs is very similar since, in the new arrangement, the tube-side flow in each shell has doubled while the number of pass per shell is halved. As a result, the tube-side deposit thickness (Fig. 8) in the two cases is almost identical. In fact, the proposed retrofit leads to very similar tube-side shear stress (not shown here) and the small difference detected in the tube-side pressure drop (Fig. 7) is only due to the longer distance travelled inside the exchanger for the tube-side fluid.

The shell-side deposit (Fig. 9) starts building up significantly after the change in fouling behavior, becoming the dominant resistance to heat transfer. In this case, the difference between the two design options is noticeable. The proposed retrofit leads to about 50% reduction in the shell-side deposit thickness thus it is expected to be successful in mitigating fouling in E1. The difference in fouling build-up is ultimately a consequence of the increase in shear stress introduced by the proposed retrofit (Fig. 10).

It is concluded that the proposed retrofit would have led to lesser fouling build-up and enhanced heat recovery compared to the original design. The new configuration, together with higher shell-side heat transfer coefficient,

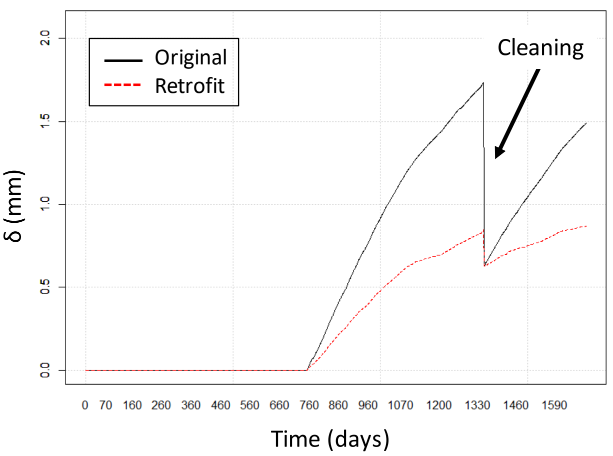


Fig. 9. Shell-side average deposit thickness with original (continuous line) and proposed design (dashed line).

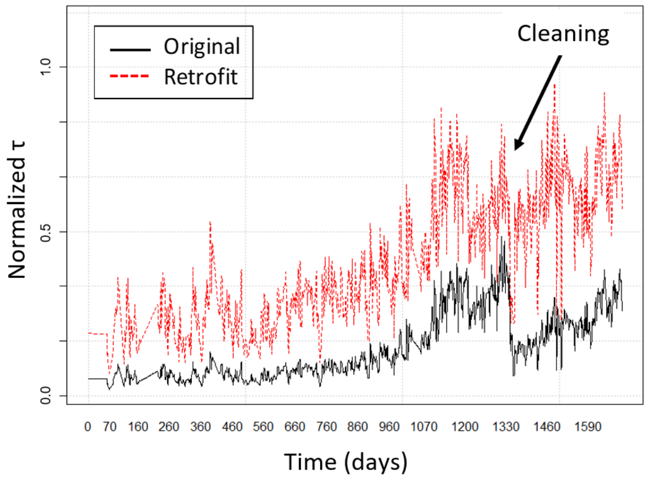


Fig. 10. Shell-side average shear stress in fouled conditions with original (continuous line) and proposed design (dashed line). The y-axis is normalized to protect confidentiality.

explain the higher heat duty with the proposed design over the initial 700 days, during which shell-side fouling is negligible. The partial mitigation of shell-side fouling explains the higher heat duty with the proposed design in the second part of the operating period.

5. Evaluation of network effects

The previous analysis provides useful, quantitative information on the impact of the retrofit proposed on the heat exchanger performance and its fouling behavior. However, heat exchanger networks are highly interactive systems. The end question is how the new retrofit will affect the performance of the network as a whole and how mitigation of fouling in the unit under study will translate into energy savings at the furnace.

For this purpose, network simulations were set up for the entire hot end of the Repsol pre-heat train considering both the original and proposed design for E1. The simulations consider a nominal operating point for the inlet streams to the network and initial clean conditions in all units. The flow-split between parallel branches was controlled to reflect actual refinery operations. Other situations, such as free flow split could also be considered. The fouling behavior is predicted with the fouling models fitted in the previous stages, considering both tube and shell-side fouling throughout the entire network simulation. The objective of the simulation is to predict how the network would perform after a hypothetical major shutdown. The simulations were run for a period of four years.

The network simulation takes into account fouling dynamics in all the exchangers and how these, in turn, impact the operating conditions downstream. The hot end in this study (Fig. 2) consisted in two parallel branches, with some of the heat exchangers connected by the product streams (hot fluids). The most relevant network effect arises from the interactions between exchangers E1, E2 and E3 which are interconnected. The hot fluid enters first the shell-side in E1, which is in Branch 1. After that, the hot fluid enters E2 and, finally, E3. Both E2 and E3 are in Branch 2.

Fig. 11 shows the outlet temperature from Branch 1 (B1) and Branch 2 (B2) after start-up in clean conditions. With the original design, the outlet temperature from B1 is initially higher than from B2. At this stage, E1 is clean and recovers a significant amount of heat, cooling down the hot stream significantly and, consequently, reducing the potential for heat recovery in E2 and E3. As fouling builds-up, E1 recovers less heat, the heavy oil fraction enters E2 at a higher temperature and the performance of B2 increases (despite the build-up of fouling in E2 and E3). The two lines (B1 and B2 original in Fig. 11) cross each other at approx. 300 days. After that, the outlet temperature from B2 stays at higher values than that from B1.

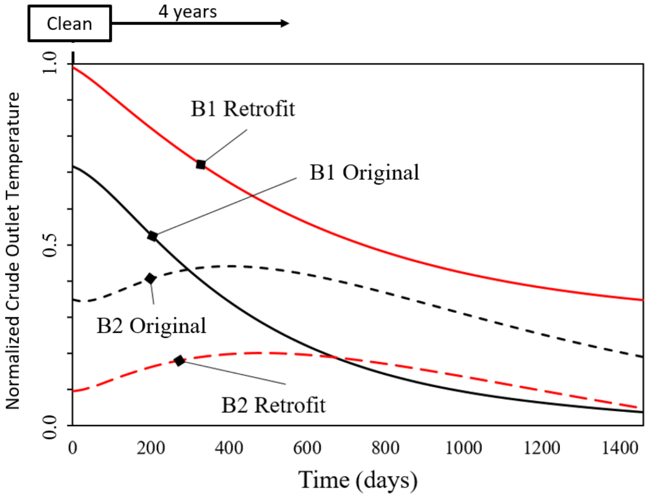


Fig. 11. Outlet temperature from parallel branches (B1 and B2) with original and proposed design, after start-up in clean conditions. The y-axis is normalized to protect confidentiality.

With the proposed retrofit, the outlet temperature profile for B1 (B1 Retrofit in Fig. 11) is shifted to higher values, due to the improved thermal design of E1 (important at the initial stages) and the partial mitigation of shell-side fouling (important over the long term). On the other hand, the heat recovery in B2 is reduced, as the heavy oil fraction enters E2 at systematically lower temperature, and the outlet temperature (B1 Retrofit in Fig. 11) is shifted to lower values. The two lines (B1 and B2 Retrofit in Fig. 11) do not cross each other over the simulated time horizon. Consequently, the retrofit of E1 is expected to increase heat recovery in B1 but to reduce it in B2.

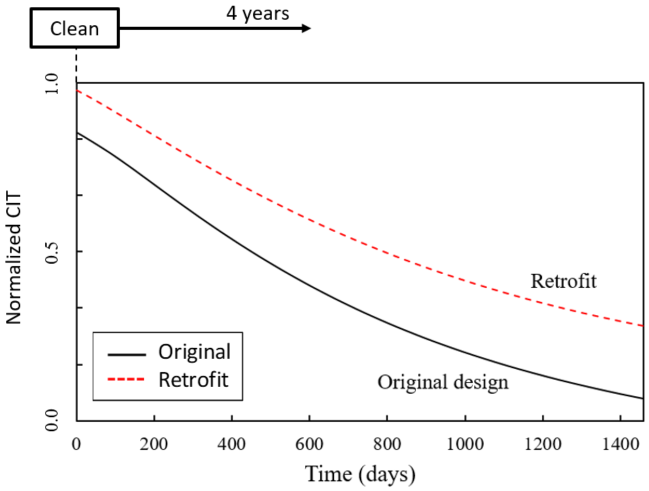


Fig. 12. CIT time profiles with original (continuous line) and proposed design (dashed line), after start-up in clean conditions. The y-axis is normalized to protect confidentiality.

The end objective of the retrofit is to increase the inlet temperature to the furnace (CIT), thus reducing fuel costs, without compromising refinery production. The CIT time profiles are shown in Fig. 12. The network with the retrofit design is expected to lead to systematically higher CIT. The difference in the CIT between the proposed retrofit and the original design increases as fouling builds up, reaching 6.5ºC after 1400 days. This improvement occurs despite the network compensation effects previously discussed.

6. Impact on energy and economic savings

Based on the network simulations, the heat duty in E1 is estimated to improve, on average, 4.5 MW with the new design. However, only 60% of the 4.5MW improvement achieved in E1 is translated into sensible heat savings at the furnace as a result of the limitation introduced by the network interactions. That is, the overall heat duty in the network is estimated to increase, on average, 2.7 MW.

Nevertheless, the fuel savings in the furnace are significant. The overall performance of the network is expected to result in estimated fuel savings larger than $1.2 MM after 2 years and over $2.8 MM after 4 years (considering an energy price of 20 $/MWh and taking into account the furnace efficiency).

CONCLUSIONS

A methodology to evaluate alternative heat exchanger design by using advanced predictive dynamic simulations and historical plant data has been presented and demonstrated in an industrial case study. It provides a quantitative assessment of benefits (e.g. increase in CIT, estimated energy savings at the furnace and overall economics) and possible drawbacks (e.g. loss in production) of various retrofit options. The analysis considers heat exchanger performance over time, impact on fouling rates, hydraulic effects and network interaction.

The main conclusions of the case study considered here are:

1. The proposed retrofit is expected to increase heat recovery in the heat exchanger compared to the original design by 2.5-4.5 MW.
2. The increase in heat recovery is due to a combination of better use of available heat transfer area, improved heat transfer coefficient and shell-side fouling mitigation.
3. Network interactions are expected to reduce the benefits of the retrofit.
4. The overall increase in heat recovery at the network is expected to increase by 2.7 MW with the proposed retrofit.
5. Significant estimated savings in fuel cost of 1.2 MM$ after 2 years.

It should be noted that whilst in this case study a relatively simple and low-cost retrofit has been considered, the same methodology can be used to evaluate other mitigation technologies (e.g. tube inserts, helical baffle heat exchangers) and assess the expected return on investments that they provide in a specific service.

NOMENCLATURE

B1, B2 Branch 1, Branch 2
CIT Coil Inlet Temperature, ºC
C_p Specific heat capacity, J/kg K
k Fluid thermal-conductivity, W/m K
T Temperature, ºC
δ Deposit thickness, mm
ΔP Pressure drop, bar
μ Fluid dynamic viscosity, Pa s
ρ Fluid density, kg/m^3
τ Shear stress, Pa

Subscript

film Film temperature

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