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HEAT EXCHANGER DESIGN WITH HIGH SHEAR STRESS: REDUCING FOULING OR THROUGHPUT?

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ABSTRACT

A common solution adopted by heat transfer engineers to mitigate fouling in shell and tube heat exchangers is to increase tube-side velocities. As a result, the wall shear stress increases and less fouling material is allowed to accumulate on the tube surfaces. Whilst this approach may indeed reduce fouling, the resulting design is typically one with higher pressure drops which, if not properly considered, may lead to unintended and costly consequences.

In refinery pre-heat trains, as an example, higher pressure drops resulting from increased flow velocity may translate directly into a reduced throughput which can greatly outweigh, from an economic point of view, the benefits of fouling mitigation. To properly assess whether it is beneficial to increase fluid velocity, it is now possible to use software tools capable of capturing the thermal and hydraulic trade-offs that exist between operating conditions (e.g. temperature, shear stress), fouling rates, pressure drops and refinery throughput over time.

In this paper it is shown that the simultaneous assessment of the interacting and non-obvious effects on fouling, pressure drops and throughput as a function of the specific thermal and hydraulic limits of the network, has significant benefits in terms of overall economics.

INTRODUCTION

Fouling mitigation is key for the profitability of many industrial processes. A key design parameter the engineer has at disposal to reduce fouling is the fluid velocity. It is widely acknowledged that increasing velocity, hence shear stress, where chemical reaction is the dominant fouling mechanism leads to reduced fouling rates (Joshi *et al.* 2009; Joshi, 2013; Coletti and Hewitt, 2015). However, higher velocities entail higher pressure drops which can translate directly into loss in throughput. As a result, a designer wishing to retrofit a heat exchanger in an existing network with higher shear stress, needs to carefully take in to account the impact of the increased pressure drops on the overall economics of the plant. Tradeoffs between increased clean pressure drops and reduced fouling need to be assessed over a long operating time horizon. The importance of capturing thermo-hydraulic effects of fouling has been highlighted by many papers in the literature (Yeap *et al.*, 2004; Ishiyama *et al.*, 2009; Coletti and Macchietto 2010).

In this paper, Hexxcell Studio™, a comprehensive software framework for the analysis, retrofit and design of heat exchangers and their networks, is used to quantitatively calculate the trade-offs between thermal and hydraulic performance of different design solutions. The software incorporates the advanced mathematical models for refinery heat exchangers undergoing crude oil fouling, based on the work by Coletti and Macchietto (2011). Simultaneous assessment of interacting and non-obvious effects on fouling, pressure drops and throughput as a function of the specific thermal and hydraulic limits of the network, has significant benefits in terms of overall economics.

CASE STUDY

A case study on the hot end of a preheat train (Fig. 1) is considered here. The network consist of 5 heat exchangers with difference geometries (Table 1) and heating fluids from the distillation column. Flow is driven by a fixed-speed pump, and controlled by back-pressure through a valve located just upstream of the furnace. Finally, the coil outlet temperature is measured and automatically controlled by manipulating the fuel feed to the furnace.

In the following sections the pros and cons of high-shear design strategies to reduce fouling for the network in Fig. 1 are assessed considering multiple scenarios with different hydraulic constraints.

In order to generate various cases with different hydraulic limitations, the hydraulic losses at units other than heat exchangers (this is valves, piping, bends, furnace, etc.) are lumped together into a single pressure drop value (ΔP_f).

Table 1.Main geometric parameters of the heat exchangers in the network.

Parameter	E01	E02	E03A	E03B	E04	E05
Nt	764	850	880	880	630	630
Np	4	4	4	4	2	2
L (m)	6.1	6.1	6.1	6.1	6.1	6.1
OD (mm)	25.4 (1in)	25.4 (1in)	25.4 (1in)	25.4 (1in)	25.4 (1in)	25.4 (1in)
BWG	12	12	12	12	12	12

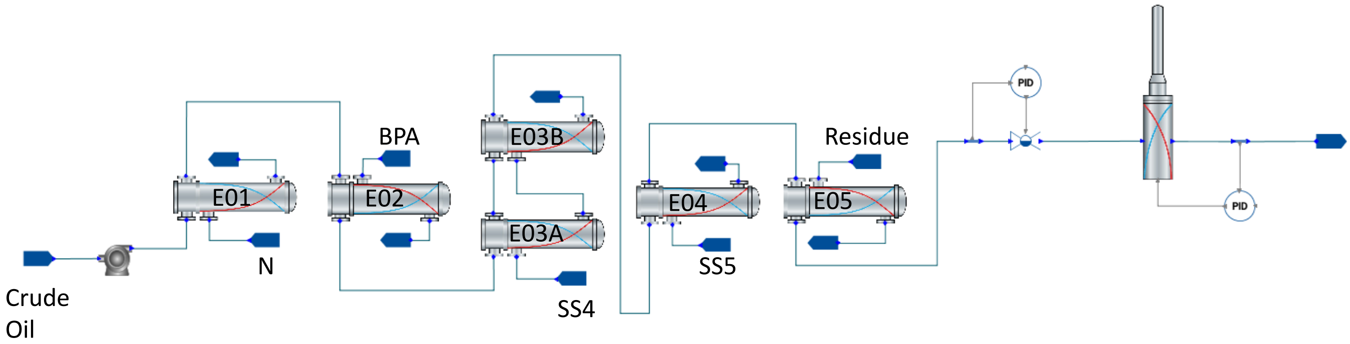


Fig. 1 Hexxcell Studio™ screenshot of the network considered.

By varying this value, the effects of fouling on energy efficiency and hydraulic performance can be assessed and the trade-offs of a potential high-shear retrofit can be captured.

Organic fouling is described following the classic Ebert-Panchal (1997) model, written in terms of fouling layer thickness:

$$\frac{d\delta}{dt} = \lambda_0 \alpha \,\mathrm{Re}^{-0.66}\,\mathrm{Pr}^{-0.33} \exp\left(-\frac{E_f}{RT_{film}}\right) - \lambda_0 \gamma \tau \qquad (1)$$

Equation 1 captures the dependence of the fouling rate as a function of temperature and flow conditions. In the literature, this is typically used in a lumped way. However, here the fouling rate, calculated with Eq. 1, is locally applied along the length of each pass in the heat exchanger. This allows calculating the local thickness of the fouling layer, the related progressive reduction in cross-sectional area and the variations in heat flux along the length of the heat exchanger. As a result, the thermo-hydraulic interactions between fouling growth, heat exchange and pressure drops can be captured accurately and the economical tradeoffs between various cost items (furnace energy, throughput reduction, CO_2 emissions) can be assessed. Due to the short operation window, cleaning and associated cost were not considered here.

NON-HYDRAULICALLY VS. HYDRAULICALLY LIMITED NETWORK

In the network in Fig. 1 the flowrate of crude oil depends on the total pressure drop and the opening of the valve. As the pressure drop increases due to fouling, the PID controller instructs the valve to open in order to maintain the flowrate to the desired set-point. If the valve position during operations does not reach the fully opened position, the system is not hydraulically limited and the mass flowrate can be maintain at the set point. On the other hand, if the valve reaches the maximum opening at any point during operations, the mass flowrate cannot be controlled and production decreases. In this case the system is hydraulically limited. Examples for valve opening and pressure drop over time for a non-hydraulically limited (A) and a hydraulically limited network (D) are shown in Fig. 2.

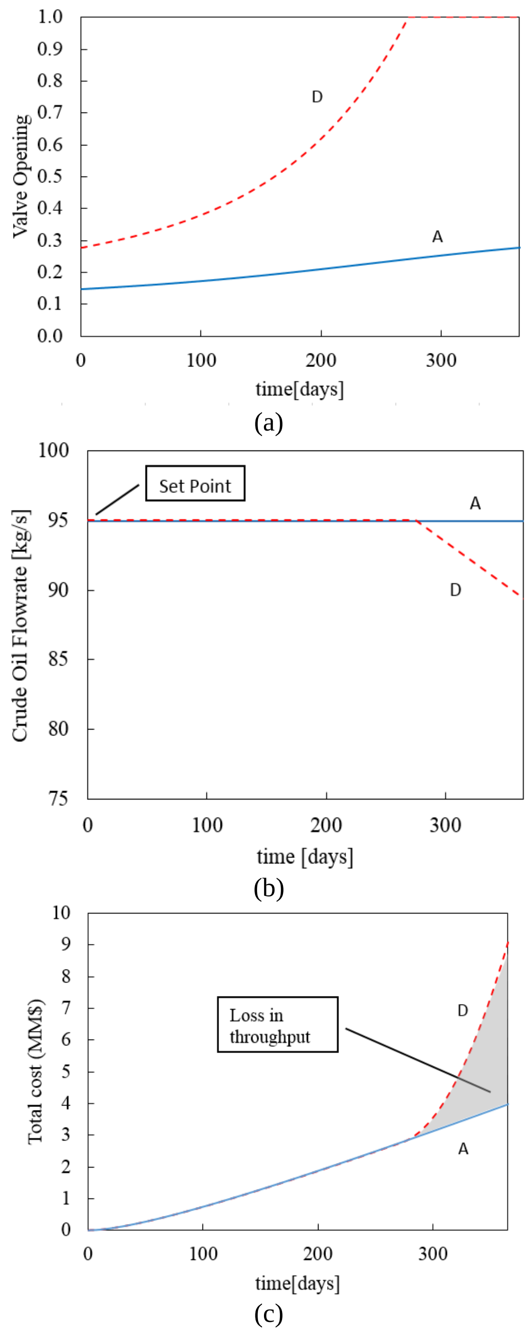


Fig. 2 Valve opening (a), crude oil flowrate (b) and cost (in in USD) due to fouling (c) for the network in Fig. 1, considering a low (A, ΔP_n = 17.5 bar) and large hydraulic resistance (D, ΔP_n = 20.5 bar).

As highlithed by Coletti and Macchietto (2010), a reduction in throughput is the most severe cost associated with fouling. Using the same performance indicators and cost values as in that reference (Coletti and Macchietto, 2010), the cost associated to fouling due to additional fuel consumption at the furnace, additional CO_2 emissions and production loss can be estimated for the two previous cases.

HIGH SHEAR STRESS DESIGN IN A NETWORK WITH LOW HYDRAULIC RESISTANCE

In this section we consider Network A (low overall hydraulic resistance) and evaluate the advantages of a high shear design retrofit. Given the low hydraulic resistance, and as previously shown, there is tolerance for the increase in ΔP produced by fouling deposition in the heat exchangers without reaching the hydraulic limit. The initial heat duty and pressure drops are summarized in Table 2.

Table 2. Summary of clean heat duties and pressure drops in the network A.

	Q_0 [MW]	ΔP_0 [bar]
E01	3.8	0.6
E02	3.5	0.5
E03AB	4.8	0.9
E04	6.3	0.1
E05	9.3	0.1

The first question to be addressed is which the best candidate in the network to be retrofitted using a high shear stress design is. This is the heat exchanger that offers the highest benefits. These can be quantified in a number of ways (highest return on capital investment, overall NPV etc.). In this work, several graphical/evaluation options are used to identify the most problematic exchanger with respect to fouling. One such graph is the threshold fouling plot (Butterworth, 1996; Poddar, 1996), where each heat exchanger in the network is placed depending on its initial operating conditions. This allows assessing the location of each heat exchanger with respect to the threshold between fouling and no fouling conditions (Fig. 3).

However, the dynamics of the system is also of interest and should be considered, since the network conditions, and thus the interaction between the different units, change because of fouling over time. For this purpose, two representations are used i) Fouling resistance over time (traditional approach, Fig. 4) and ii) a TH plot (Diaz-Bejarano et al., 2015) of heat duty and pressure drop relative to clean (Fig. 5).

Based on the above analysis, it can be concluded that the heat exchangers E04 and E05 are those more severely affected by fouling. Given that E05 has greater potential for heat recovery (initial heat duty of 9.3MW compared to 6.3MW of E04), it is decided to target this heat exchanger in the retrofit. It is to be noted that, this heat exchanger has only 2 tube passes, which explains the low pressure drop compared to the other units. As a result, it is reasonable to assume, in first instance, that a high-shear stress retrofit will be sucessful. The question now becomes, which is the best retrofit to conider and what it is its impact on fouling, pressulre drops and flowrate.

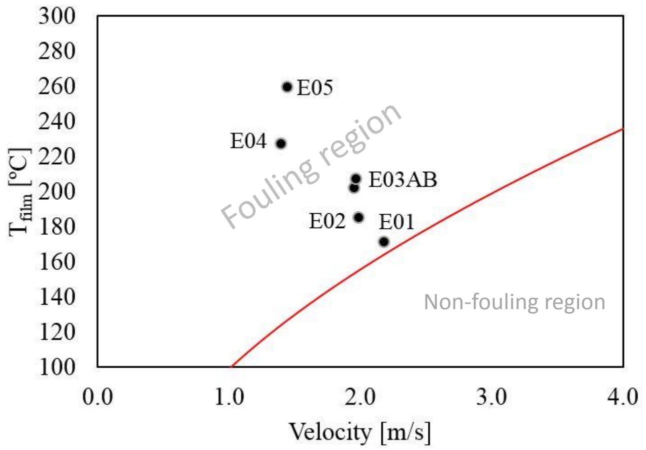


Fig. 3. Operating conditions (average) and their location w.r.t. the threshold (calculated with Eq. 1) for the heat exchangers in the network.

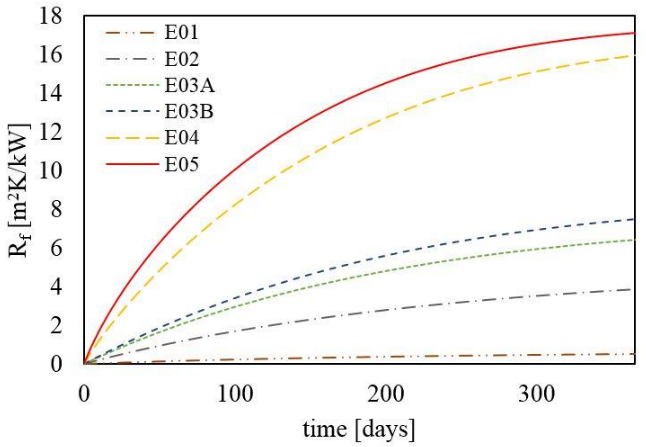


Fig. 4. Variation of lumped fouling resistance over time for the heat exchangers in the network.

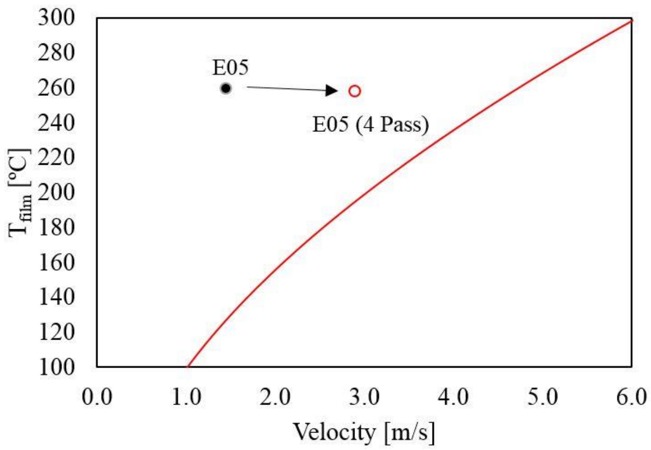


Fig. 6. Effect of retrofit from 2 to 4 tube-side pass on the position of E05 on the threshold plot.

To illustrate the main point of this paper wo options are for retrofit are consideded here:

a) Increased number of tube-side passes;

b) Reduced diameters of the tube.

First, option a) for the retrofit of unit E05 is analysed by increasing the number of passes from 2 to 4.

As shown in Fig. 6, the initial operating conditions are closer to the threshold and, therefore, less severe fouling rate is expected. With the new configuration, the threshold condition is reached and the thermal performance of the heat exchanger does not go below 43%, compared to the 14.5% after a year of the original design. The total cummulative cost (in USD) due to fouling is shown in Figure 7. The new design, as a result of the partial mitigation of fouling, leads to total savings of 15.8% after one year.

Examining the pressure drop in absolute terms (Fig. 8), it is clear that the high shear stress design introduces a substantial hydraulic impact in the system. For the same fouling thickness, the increase in pressure drop is faster in a heat exchanger designed with high-shear stress, as a result of the non-linear dependence of pressure drop on flow area. However, given the low value of the total hydraulic resistance in the network, the flowrate can be controlled at the set-point by opening the valve. The comparison is shown in Fig. 9. The maximum valve opening reached is about 30%, indicating that there is still flexibility to operate even with greater pressure drops. As a result, the option of increasing furher the shear stress in this heat exchanger is investigated by reducing the tube size from 1 inch to ¾ inch.

In order to maintain the same heat exchange area, the number of tubes is recalculated, increasing from 630 to 840. The flow area is thus reduced by 25%, leading to higher velocities. The location of the new operating conditions with respect to the threshold is shown in Fig. 10.

Regarding the hydraulics, the high shear design introduces a substantial offset on pressure drop (Fig. 11(a)). In this case, the opening of the valve plays a more important role, reaching values of about 80% valve opening (Fig. 11(b)).

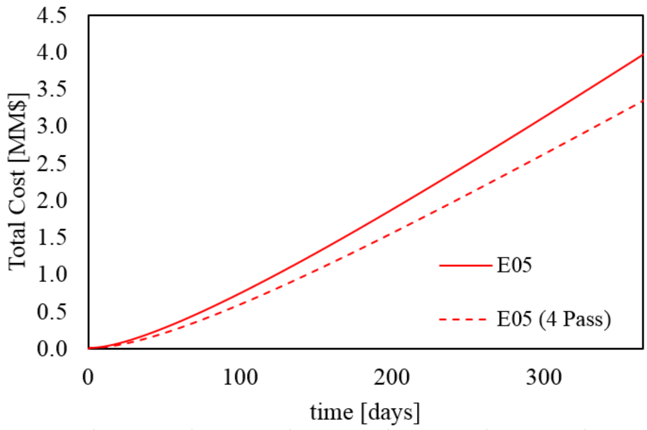


Fig. 7. Effect of E05 retrofit from 2 to 4 tube-side pass on total costs in USD.

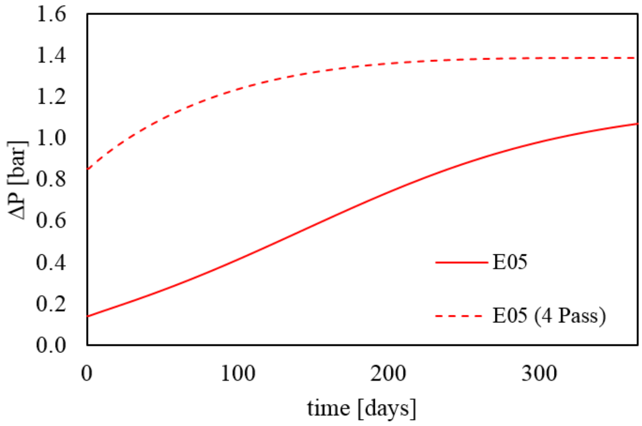


Fig. 8. Effect of retrofit from 2 to 4 4 tube-side pass on the pressure drops across E05.

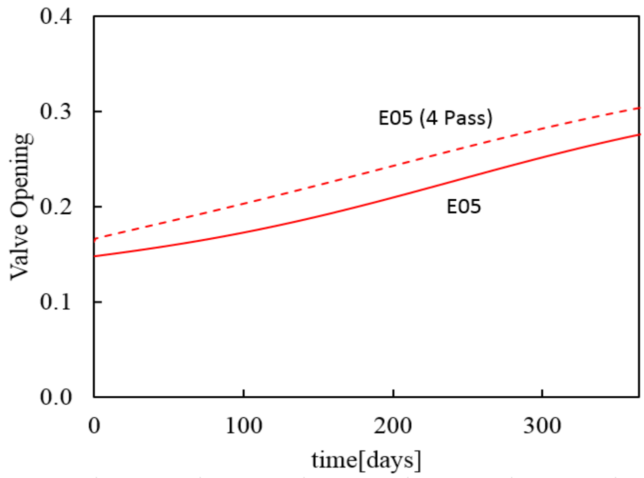


Fig. 9. Effect of E05 retrofit from 2 to 4 tube-side passes on valve opening.

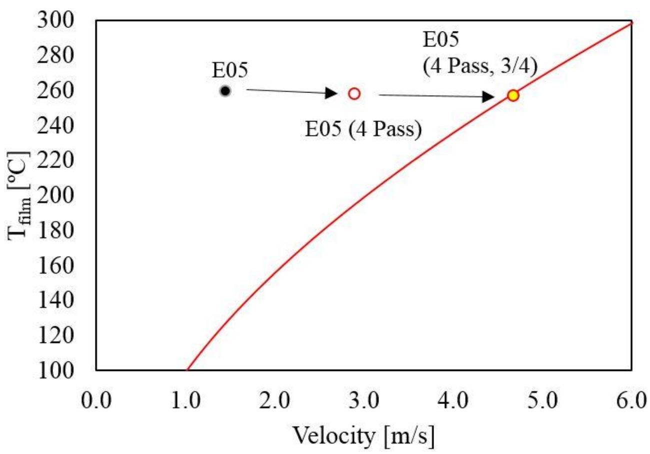
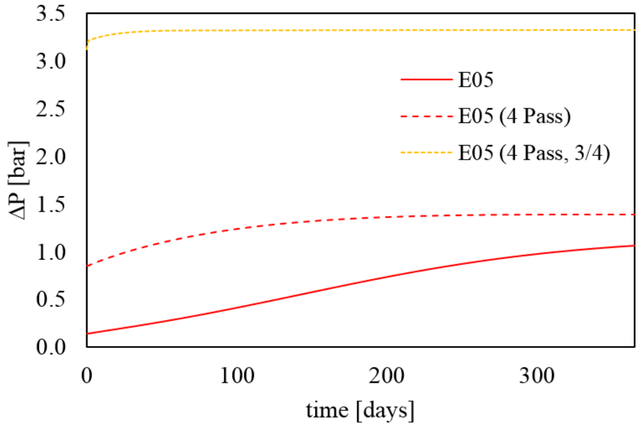
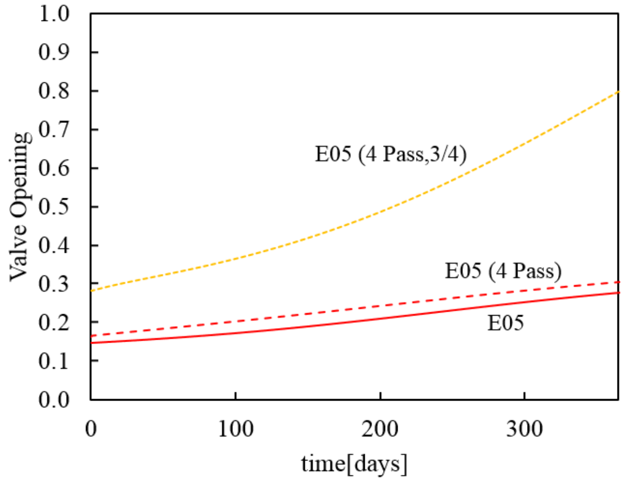


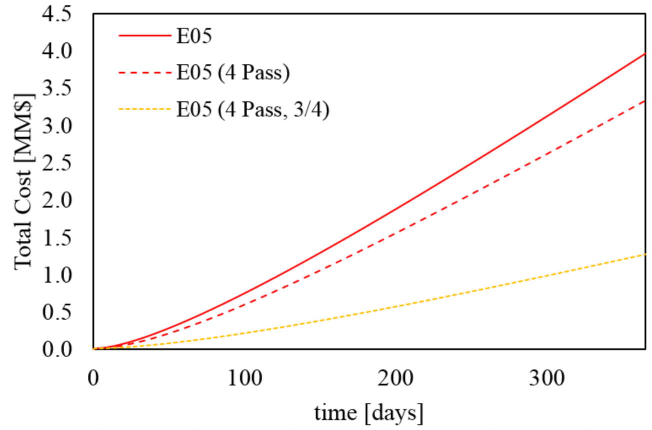
Fig. 10. Effect of the additional retrofit from 1'' to ¾'' tube diameter on the position of E05 on the threshold plot.



(a)



(b)



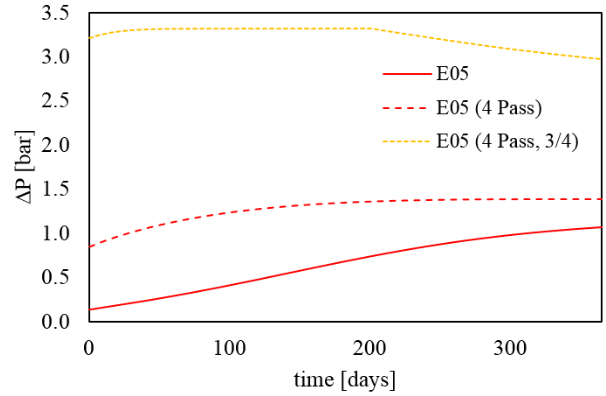
(c)

Fig. 11. Effect of the additional E05 retrofit from 1'' to ¾'' tube diameter on pressure drops (a), valve opening (b) and total costs in USD (c).

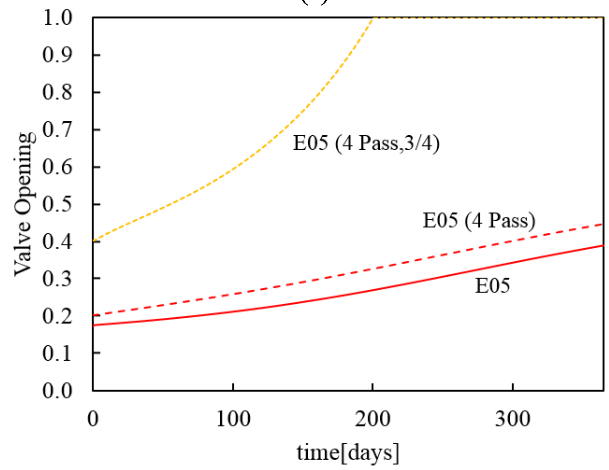
With the new design, the operating conditions are right on the threshold. As a result, the amount of fouling deposited is negligible, leading to very substantial improvement in energy efficiency and consequently cost savings, as shown in Fig. 11(c). After 1 year, the cumulative cost is reduced by 67.8% w.r.t the original design.

HIGH SHEAR STRESS DESIGN UNDER MORE RESTRICTIVE HYDRAULIC LIMITATIONS

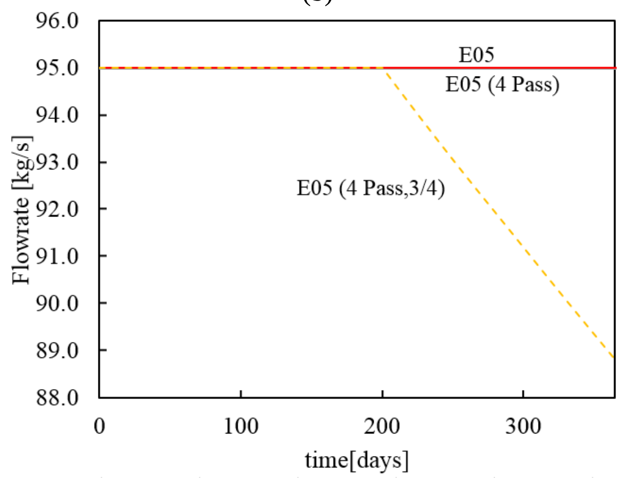
In this section, the impact of a high shear design retrofit is evaluated when the system is subject to more restrictive hydraulic limits. The various cases are quantified using ΔP_n, the network pressure drop excluding heat exchangers. Higher ΔP_n produces higher hydraulic resistance hence a different dynamic response to fouling build-up in the heat exchangers. The same retrofit options for E05 are assessed under scenarios B, C and D with increasing hydraulic resistance from A to D.



(a)



(b)



(c)

Fig. 12 Pressure drop (a), valve opening (b) and flowrate (c) for base case and retrofit scenarios for Network B.

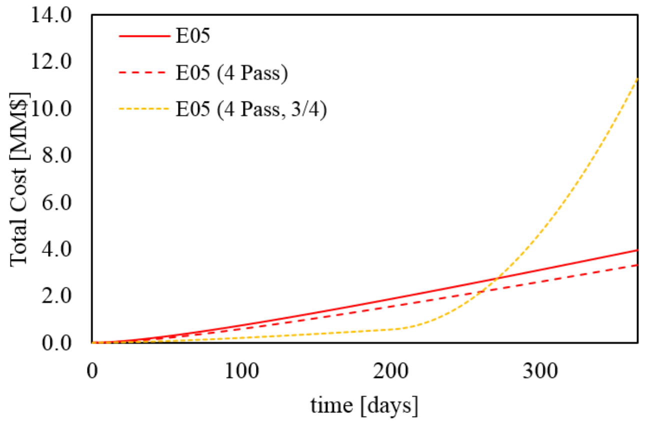


Fig. 13 Total costs in USD for base case and retrofit scenarios for Network B.

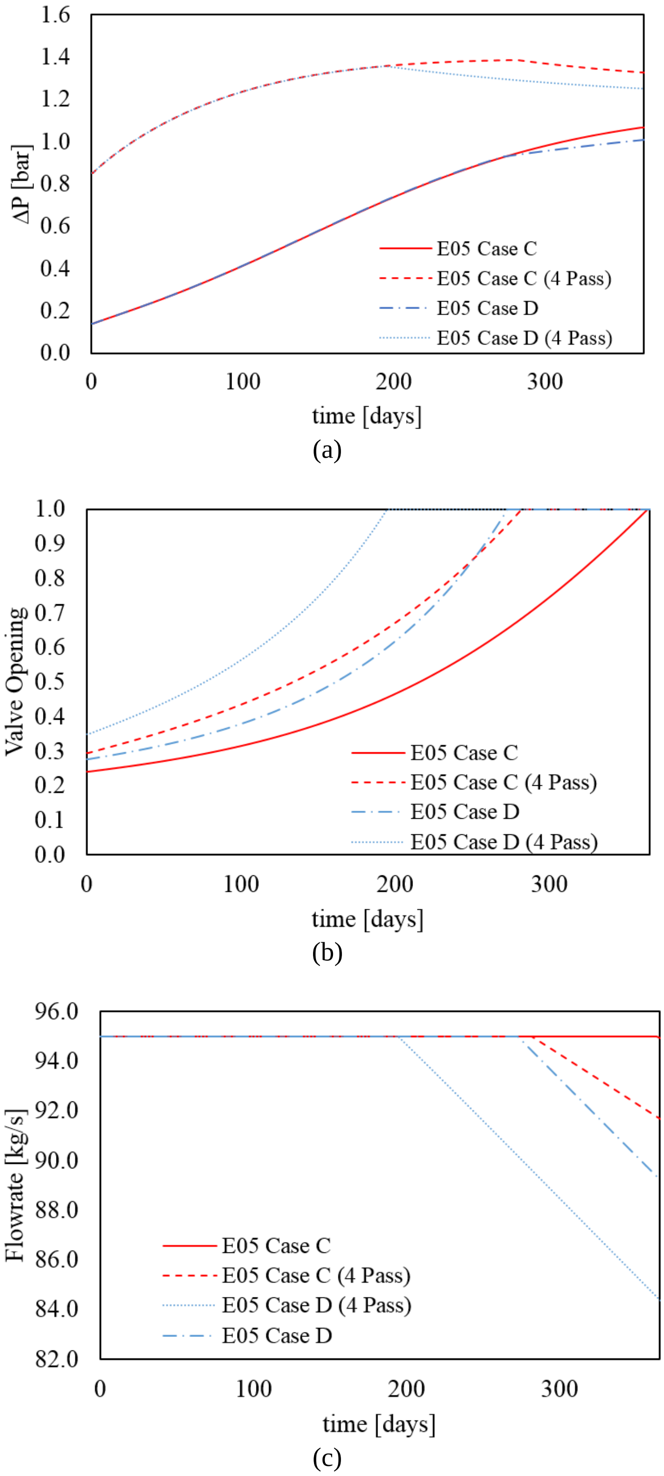


Fig. 14 Pressure drop (a), valve opening (b) and flowrate (c) for base case and retrofit scenarios for case C and D.

Fig. 12 shows the pressure drop, valve opening and flowrate for network B (ΔP_n = 18.5 bar). The results show that a first stage of retrofit does not lead to a hydraulic limit. However, if a second stage of retrofit (tubes of 3/4in) is introduced, a hydraulic limit is reached at around 200 days: the valve reaches saturation and the throughput decreases. The associated costs in USD (Figure 13) show that a second retrofit is economically advantageous as long as the hydraulic limit is not reached; once this happens, the costs increase dramatically as a result of the loss in production. The cost reaches the same level as those for the original design after 272 days; this implies that a heat exchanger with two levels of retrofit would only be advantageous if the operating cycle is less than 272 days. High shear stress design leads to savings during the non-hydraulically limited period but produces losses during the hydraulically limited period.

These results highlight the importance of having reliable predictions of fouling to find a suitable retrofit option. Apparently sensible design decisions, such as reducing tube diameters while increasing the number of tube-side passes, may not only fail to produce the expected operational improvements and economic savings, but even make the original situation worse.

If the value of ΔP_f is higher, the situation in which even the first retrofit becomes ineffective may happen. In Fig. 14, results are presented for scenario C (ΔP_n = 20) and D (ΔP_n = 20.5 bar). The valve opening shows that for 20 bar the valve reaches the fully open postion approximately after a year with the original design. If E05 is retrofitted by increasing the number of passes, a hydraulic limit is reached after 280 days, and the cost of fouling with the new design reahces that of the original design after 315 days.

Due to the large overall hydraulic resistance, a high shear design retrofit increases the pressure drops across the network bringing it closer to its hydraulic limit thus producing a decrease in flowrate. Crucially, the decrease in flowrate not only leads to production loss but it also generates lower velocities defeating the original purpose of increasing redesigning the heat exchanger for high shear stress.

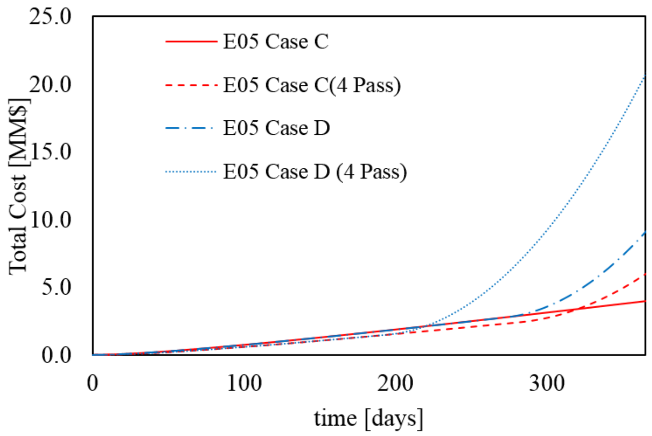


Fig. 15 Total costs in USD for base case and retrofit scenarios for case C and D.

CONCLUSIONS

Simulation results in this paper show that whilst a high shear stress design is beneficial to reduce fouling in a specific heat exchanger, it introduces higher pressure drops in the network. If key thermal and hydraulic network interactions are not taken into account, production loss costs can significantly outweigh the benefits in energy savings achieved by fouling mitigation.

Tradeoffs between fouling mitigation, energy savings, increase in pressure drop and decrease in throughput need to be captured, quantified and assessed on a case by case basis to ensure an effective heat exchanger retrofit.

NOMENCLATURE

A_a Ageing activation energy, 1/s
C_p Specific heat capacity, J/kg
E_a Ageing activation energy, J/mol
E_f Fouling activation energy, J/mol
h Heat transfer coefficient, W/m^2
K Proportionality constant, dimensionless
L Tube length
Np Number of Passes
Nt Number of tubes
Pr Prandtl number, $C_p\mu/\lambda$, dimensionless
R Radius, m
R_{flow} Radius at the fouling layer-fluid interfase, m
R_g Ideal gas constant, 8.314 J/molK
r Radial coordinate, m
$\tilde{r}$ Dimensionless radial coordinate, dimensionless
Re Reynolds number, $\rho u d_o/\mu$, dimensionless
t Time, s
T Temperature, K
T_{film} FilmTemperature, K
y Deposit youth, -
z Axial coordinate, m
α Deposition constant, m^2 K J^{-1}
γ Suppression constant, m^4 K J^{-1} N^{-1}
δ Deposit thickness, m
ΔP Pressure drop, Pa
ΔP_n Network pressure drop excluding heat exchangers, Pa
λ Thermal-conductivity, W/mK
ρ Density, kg/m^2
τ Shear stress, N/m^2

Subscript
0 initial
i inner
L layer
o outer
s shell
t tube
w wall

REFERENCES

Butterworth, D. (1996). Visualize your design of shell–and–tube heat exchangers. Chem. Tech. Eur., 3(4), 20–24.

Coletti, F. and S. Macchietto (2010). Refinery pre–heat train network simulation: assessment of energy efficiency and carbon emissions. Heat Transfer Eng. 32 (3&4): 228-236.

Coletti, F. and S. Macchietto (2011). A dynamic, distributed model of shell–and–tube heat exchangers undergoing crude oil fouling. Ind. Eng. Chem. Res. 50 (8): 4515–4533.

Coletti, F. and Hewitt, G.F. (2015). Crude Oil Fouling, Deposit Characterization, Measurements, and Modeling. Gulf Professional Publishing. ISBN: 9780128012567.

Diaz-Bejarano, E., Coletti, F. and Macchietto, S., 2015. Detection of changes in fouling behaviour by simultaneous monitoring of thermal and hydraulic performance of refinery heat exchangers. *Comp Aided Chem Eng*, 37, pp.1649 – 1654.

Ishiyama, E. M., Paterson, W. R., and Wilson, D. I. (2009a). The effect of fouling on heat transfer, pressure drop, and throughput in refinery preheat trains: Optimization of cleaning schedules. Heat Transfer Eng., 30(10), 805–814.

Joshi, H.M., Shilpi, N. B. and Agarwal, A. (2009). Relate crude oil fouling research to field fouling observations. In: H. Müller–Steinhagen, M.R. Malayeri and P. Watkinson, (Eds.), Int. Conf. Heat Exchangers Fouling and Cleaning; Schladming, Austria, Jun. 14-19, pp: 1-14.

Joshi, H.M. (2013). Crude oil fouling field data and a model for pilot-plant scale data. In: H. Müller–Steinhagen, M.R. Malayeri and P. Watkinson, (Eds.), Int. Conf. Heat Exchangers Fouling and Cleaning; Budapest, Hungary, Jun. 09-14.

Poddar, T. K. and Polley, G. T. (1996). Heat exchanger design through parameter plotting. Chem. Eng. Res. Des., 74(8), 849–852.

Yeap, B. L., Wilson, D. I., Polley, G. T., and Pugh, S. J. (2004). Mitigation of crude oil refinery heat exchanger fouling through retrofits based on thermo–hydraulic fouling models. Chem. Eng. Res. Des., 82(A1), 53–71.