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SIMULTANEOUS CONSIDERATION OF FLOW AND THERMAL EFFECTS OF FOULING IN CRUDE OIL PREHEAT TRAINS

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ABSTRACT

Given models linking flow resistance and fouling resistance it becomes possible to simulate the effects of fouling on the hydraulic performance of a refinery pre-heat train. Such a simulation has been used here to identify when plant throughput will be limited by pressure drop; how throughput can be improved through the cleaning of individual exchangers and groups of exchangers; and how much production can be maintained when individual exchangers are taken off-line.

Determination of better operating strategy requires a simulation of both hydraulic and thermal performance. In this paper we implement a pragmatic linked model and consider the results from a set of simulations.

INTRODUCTION

Oil companies worldwide are currently under pressure to maximise refinery throughput. The first processing step undertaken in a refinery is the separation of the crude oil into various petroleum fractions via fractional distillation. The economics of this process are dictated almost completely by energy considerations, so that heat recovery from the products via a train of heat exchangers pre-heating the crude oil prior to final vaporisation in a furnace is critical. Unfortunately, heat exchangers handling crude oil are subject to high fouling levels and consequently the performance of these units deteriorates over time.

Pre-heating of the crude oil is often undertaken in three distinct stages. The oil is first heated to a temperature of between 125 and 145^{o}C (dependant upon on its specific gravity) before being treated in a desalter in order to remove dissolved inorganic salts. The desalted crude is then heated further to around 170^{o}C before entering a flash column where ‘light’ components are removed. The removal of these ‘lights’ is necessary in order to reduce the vapour pressure generated within the system as the crude is heated to a final temperature of around 370^{o}C in the furnace prior to distillation.

The exchangers positioned upstream of the desalter can foul quite severely. The mechanisms involved are varied and include salt and wax deposition and combinations thereof. If the desalter is operating properly, the fouling rates in exchangers positioned between the desalter and the flash column are usually quite low. The exchangers at the hot end of the train can also foul severely. Here chemical reaction fouling tends to be the dominant mechanism (Watkinson and Wilson, 1997). The rate at which this type of fouling occurs normally increases with exchanger wall temperature and reduces with surface shear. Reliable, predictive models of chemical reaction fouling rates are not yet available owing to the complexity of the chemistry and physics: Yeap *et al*. (2004) discuss quantitative models which encapsulate trends exhibited in experimental and field trials.

Fouling has two major effects, which can be classified as (*a*) thermal and (*b*) hydraulic. The thermal effect is reduced heat transfer within the train. This reduction in heat recovery, in turn, results in higher loading on the fired heater at the end of the train and sometimes difficulties in maintaining the temperature at which the desalter positioned within the train operates. Since the efficiency of the desalting operation reduces as its operating temperature falls, a reduction in the heat recovery prior to the desalter can result in increased fouling rates downstream. Difficulty in maintaining desalter temperature or firing limitations on the furnace can ultimately force a reduction in plant throughput.

Fouling results in the formation of roughened deposits adhering to the surface of the exchanger tubes. The crude is often passed through the tubes and the flow area available reduces as these deposits grow, increasing the flow resistance encountered within the exchanger and ultimately the network. There are occasions when the flow resistance becomes so high that the operators have to reduce throughput.

Much work has been done on identifying operating strategies and cleaning cycles solely on the basis of the thermal effects of fouling (Pretty & Polley, 1996; Joshi et al, 2007). However, the hydraulic effects of fouling appear to have been largely ignored. Unfortunately, changes in temperatures within the pre-heat train do not provide a direct indication of the hydraulic effect. Indeed, they can be misleading.

The thermal impact of fouling depends upon the 'effectiveness', *e*, of the exchanger involved. The effectiveness is a function of the number of transfer units, NTU, associated with the exchanger. The NTU, in turn, is dependant upon the product of the exchanger area and its overall heat transfer coefficient. The relationship between *e* and NTU is a non-linear function including exponential terms. Where the number of transfer units is high, the sensitivity of *e* to changes in NTU is low. Thus, in a large exchanger a quite significant reduction in overall heat transfer coefficient due to fouling may not result in a particularly large change in outlet temperature. The thermal benefits of cleaning such a unit would be small. An oversized heat exchanger (large NTU due to large area) can therefore be relatively robust towards fouling in terms of heat transfer: the *hydraulic* effects of fouling, however, increase strongly with exchanger size. Whilst the effect on outlet temperature may appear low in a large exchanger, the effect of fouling on pressure drop is high.

Both thermal and hydraulic effects need to be considered when evaluating operating strategies and considering cleaning schedules.

HYDRAULIC SIMULATION

The prediction of flow through branched systems such as arise in refinery preheat trains is not difficult; there are a number of commercial packages available. However, these packages generally employ standard equations which are restricted to `clean` systems.

This shortfall can be countered by assuming that the fouling results in the formation of a uniform rough deposit within the tube. It is then possible to relate the pressure drop of the fouled unit to its clean state. Of course, the approach ignores the fact that the thickness of the deposit may well varies over the length of the exchanger. This simple model is in many ways the only practical option, as any distributed parameter model would require 'tuning' data that are inaccessible in most real cases. Nevertheless, this *uniform roughened core model* provide a starting point for the development of techniques for undertaking flow analysis for fouled systems. Different formulations are discussed by Yeap *et al.* (2004): the influence of variation in deposit thickness is the subject of ongoing research (and models for predicting this effect are under development (Polley *et al.*, 2007)).

Mathematically, the heat transfer fouling resistance, R_f, is related to the deposit thickness, δ, and the thermal conductivity of the deposit, λ_f, via the thin slab approximation:

$$R_f \approx \frac{\delta}{\lambda_f} \qquad [1]$$

One difficulty that is encountered in undertaking these simulations is determining the thermal conductivity of the deposit. This can be resolved by considering two limiting conditions. The first is that the deposit consists primarily of asphaltene and occluded crude oil: in this case λ_f is assumed to be similar to that of the oil being processed. The second condition is that the deposit consists of 'asphaltene' (which has $\lambda_f \sim 0.2$ W/m.K). In reality the overall thermal conductivity will lie between these limiting values as the deposit undergoes decomposition to form coke (as described in Nelson's model (1934)).

NETWORK PERFORMANCE

The *uniform roughened core model* has been incorporated into an analysis of flow through branched systems.

The uniform core model relates clean and fouled pressure drops through the relationship:

$$\frac{\Delta P_{fouled}}{\Delta P_{clean}} = \frac{f_{fouled}}{f_{clean}} \left(\frac{d_i}{d_i - 2\delta} \right)^5 \qquad [2]$$

Where a smooth surface can be assumed, both friction factors follow a Blasius type equation and the ratio can be dropped if the exponent is adjusted by the power on the Reynolds Number used in the Blasius equation.

With a roughened model, individual friction factor equations are used for clean and fouled conditions. For the clean tube a Blasius equation is used. For the rough deposit an equation that incorporates a consideration of surface roughness is used (Coulson & Richardson, 1996).

The analysis has been undertaken using spreadsheets developed for individual cases. Such a spreadsheet has been developed for the pre-heat train shown in Figure 1 which shows several units operating in parallel. The fouling rates in individual exchangers are summarised in Table 1.

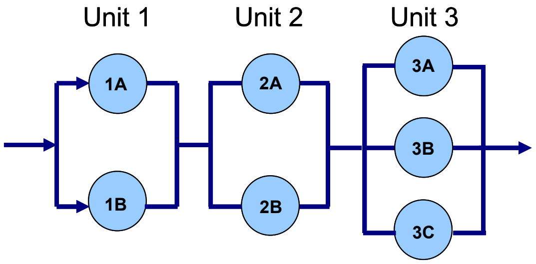

Figure 1. Pre-heat train structure for case study simulations. Hot streams not shown, for simplicity.

The throughput target is 100 kg/s. The exchangers are returned to service after all have been cleaned, with a small fouling resistance following cleaning of 0.0001 m^2 K/W.

The simulation is first used to predict the effect of fouling on possible throughput. It is assumed that the available pressure drop is 300 kPa. (The incorporation of pump characteristics into the simulation is straight-forward but has been omitted for brevity). The results of this simulation are given in Figure 2 and the response is approximately linear.

Table 1. Fouling rates for units in case study (Fig. 1)

Unit	Fouling Rate [m^2K/W.h]
1A,B	1.4×10^{-6}
2A,B	1.5×10^{-6}
3A,B,C	2.1×10^{-6}

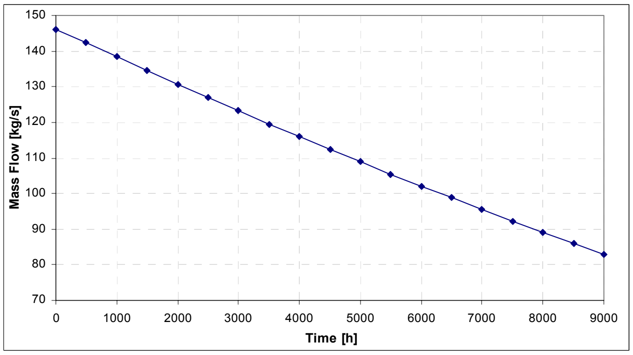

Figure 2. Case study 1: effect of fouling on throughput.

On start-up the resistance presented by the train is low and the flow will have to be throttled. Over time the resistance builds until after 6000 hours operation the throttling valve is fully open. From this point onwards the plant throughput is affected by the fouling and production falls quite rapidly. The operator would now consider if throughput could be restored by the cleaning of individual units.

In Figure 3 we show the improvement in production that can be achieved by cleaning one of the exchangers (1A, 2A or 3A) at specified points in time. At 6000 hours, throughput could be increased by 4 kg/s if 1A or 1B is cleaned, by 5.4 kg/s if 3A,B or C is cleaned or by 6.8 kg/s if either 2A or 2B is cleaned. If the cleaning operation is undertaken after 7000 hours the benefit arising from cleaning one of the unit 3 exchangers has risen to 6.4 kg/s whilst the benefit resulting from cleaning either 2A or 2B has risen to 7.3 kg/s.

Generally, it can be expected that the plant operator will become 'interested' in cleaning an exchanger when the plant has difficulty in achieving its desired throughput. If the decision was made to clean a single exchanger as soon as throughput is restricted by pressure drop, the simulation results show that the better option would be to clean one of the exchangers in unit 2. In reality, the operator would probably choose to embark on a cleaning campaign and clean a number of exchangers in sequence. The simulation could be used to identify the cost benefit of such a campaign.

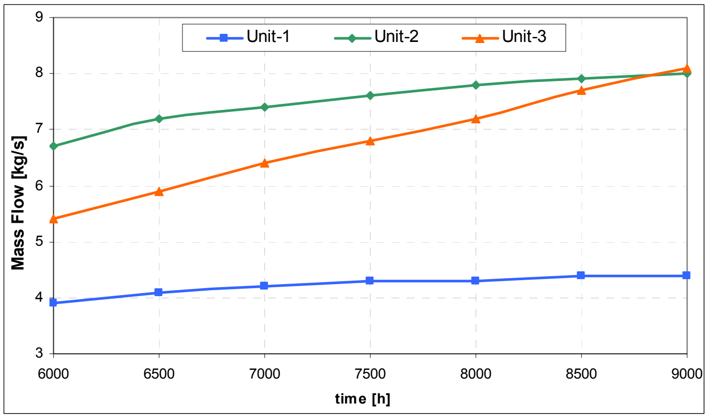

Figure 3. Case study 1: immediate increase in throughput achieved from cleaning one individual exchanger in given unit.

The operator is not only interested in determining the immediate gain in throughput but how that change is maintained during subsequent operation. The simulation can be used to generate this information, for instance Figure 4 shows the performance improvement that would result from cleaning a single exchanger in unit 3. The step change is followed by a deterioration that is approximately linear - a property that can be exploited for cost analysis purposes.

The major cost associated with the cleaning of an exchanger is generally the production lost during the period of removing, cleaning and re-installing the device. The simulation can be used to establish the impact of cleaning of individual exchangers on throughput. For instance, the simulation can be executed with one unit (1A, 2A or 3A) absent at a given point in time with the other units operating under fouled conditions (at that time point, the flow resistance is time dependant). The simulation then calculates the production rate that can be achieved during the period that the unit is out of operation (see Figure 5). The difference between this value and the production rate when all exchangers present is the loss in production occurring during the cleaning operation: this can be compared with the increase in production following cleaning (Figure 4).

The simulation of hydraulic performance during the maintenance period in Figure 5 shows that if cleaning is left until the required throughput is difficult to achieve then production has to be reduced by 32% during the cleaning operation. This raises the question "Would the operator benefit by cleaning any of the exchangers before throughput restrictions actually occur?" The simulation provides the answer: the design of the network is such that even in a clean condition the flow restriction resulting from taking one of the unit 2 exchangers out of service would require the throughput to be reduced. The production gains for earlier cleaning are shown in Figure 6, while restrictions on throughput are shown in Figure 7. Plant operators can use this type of analysis alongside production targets and constraints to determine the better cleaning strategy.

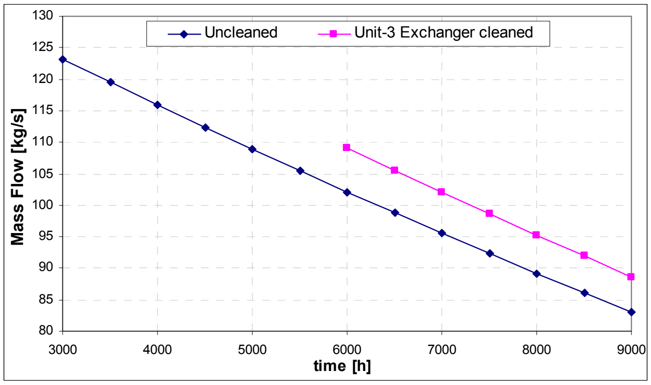

Figure 4. Case study 1: increased throughput resulting from cleaning one of the Unit 3 exchangers after 6000 h

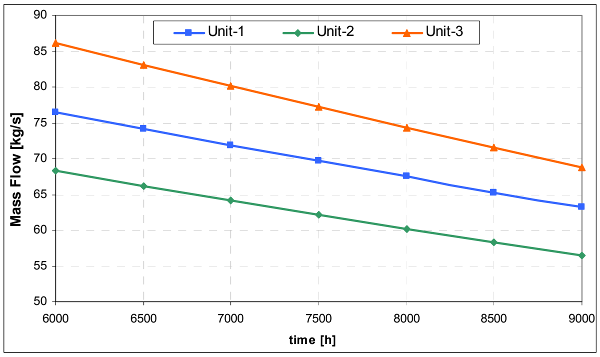

Figure 5. Case study 1: throughput during maintenance conducted at specific times

Bypassing

One means of maintaining production while an exchanger is off-line is the manipulation of a bypass about its position. For example if unit 1A is removed for cleaning and there is a bypass pipe around the unit, full production could be obtained by manipulation of the bypass flow. The impact of cleaning is then thermal rather than hydraulic. A combination of thermal and hydraulic simulation (see below) can then be used to determine the effects of operating the bypass on both production and heat recovery. If cleaning occrus when the throughput is limited by hydraulics then the bypass flow required to maintain production rate is 50% if the unit contains two parallel exchangers and one is removed for cleaning, and 33% if it contains three parallel exchangers.

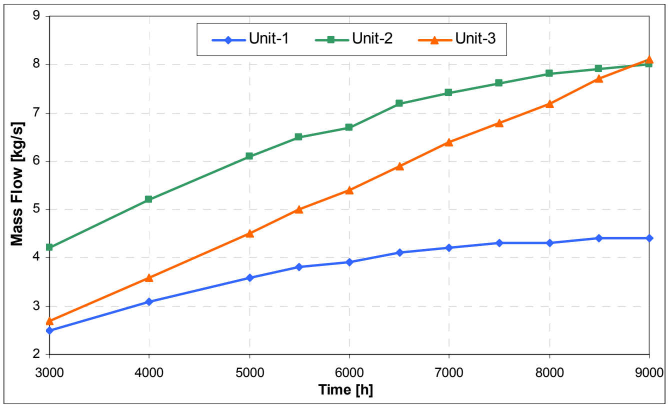

Figure 6. Case study 1: immediate gain in throughput through cleaning (extended to cover earlier period)

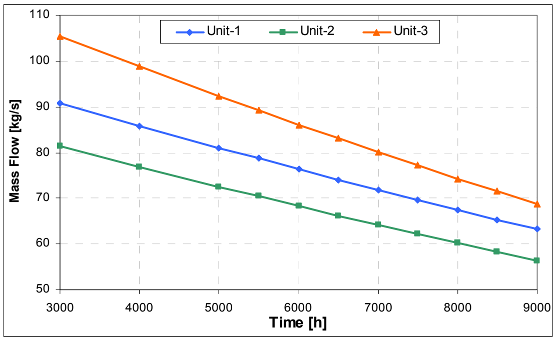

Figure 7. Case study 1: reduced production when exchanger from given unit is off-line

Use of Simultaneous Thermal and Hydraulic Simulation in Pre-Heat Train Design

The cleaning strategy that provides the best economics in operating a preheat train will clearly be a function of the network design. Yet, cleaning analysis is rarely considered as an integral part of design. This does not need to be the case. The development of pre-heat train structure, the specification and design of individual heat exchangers and the identification of operating strategies can be combined using simultaneous thermal and hydraulic simulation.

Let us consider the design of a heat recovery system for heating crude oil up to the desalter temperature. The minimum operating temperature of the desalter is to be 125°C. If the desalter temperature falls below this value its efficiency falls and fouling will be promoted downstream.
It is recognised that fouling will occur and that desalter temperature will ultimately be controlled by manipulating the temperature at which a hot stream enters the heat recovery unit immediately upstream of the desalter. This is, in turn, achieved by adjusting the amount of bypass around a heat recovery unit positioned downstream and results in reduced recovery and an energy penalty. The fouling that occurs in the downstream unit affects the amount of bypassing that needs to be employed (In some plants the desalter temperature is controlled naturally by this downstream fouling).

The structure to be explored is that shown in Figure 1. The initial sizes for exchangers and exchanger fouling rates are given in Table 2 (and are lower than those used in the previous example). The heat recovery matches involve the hot streams summarised in Table 3.

Table 2. Case study 2: exchanger sizes and fouling rates

Unit	Preliminary size	Fouling rate
	m^2	m^2K/W.hour
1	2×585	0.8×10^{-6}
2	2×510	0.5×10^{-6}
3	3×330	1.0×10^{-6}

Table 3. Case study 2: hot streams

Unit	Mass flow-Flow rate kg/s	Heat Capacity kJ/kg K	Inlet Temperature ºC
1	90	2.2	180
2	65	2.3	190
3	70	2.3	200

The crude oil flow-rate is 151 kg/s (100,000 barrels/day) and its density is assumed to be constant at 820 kg/m^3, thermal conductivity ~ 0.1 W/m K and heat capacity ~ 2.4 kJ/kg K. The viscosity does vary noticeably with temperature and can be considered to be 6 cps in the first unit, 2 cps in the second unit and 0.9 cps in the third unit. (These properties are used for demonstration purposes. They should not be taken as being representative of any particular crude oil.)

The objective is to identify the combination of exchanger geometry and maintenance schedule that yields the best overall economic performance. As demonstrated in the example described above and in that undertaken below, simultaneous thermo-hydraulic simulation provides the economic information required for such optimisation.

The first step in our analysis is the determination of the response of the system to fouling. Figure 8 shows the pressure drop across the section, desalter temperature and temperature of the hot stream entering unit 3 necessary to maintain desalter temperature over an operating period of one year.

On start-up a de-alter temperature of 140ºC is achieved with a hot stream inlet temperature of 200ºC. It can be maintained above 125°C for a period of 2500 hours without any need to increase the hot stream inlet temperature. However, after this point the temperature has to be progressively increased (by reducing the amount of heat extracted in the heat recovery unit positioned at the hot end of the train) in order to maintain good de-salting conditions. The pressure drop through the train increases from a value of 170 kPa on start-up to 260 kPa after one year's operation.

The provision of increased hot stream inlet temperature results is achieved through reduced heat recovery downstream. It therefore results in reduced energy efficiency and increased operating costs. The increased energy consumption is shown in Figure 9. It can be seen that the energy costs resulting from fouling are very high. These could be reduced by cleaning some of the exchangers.

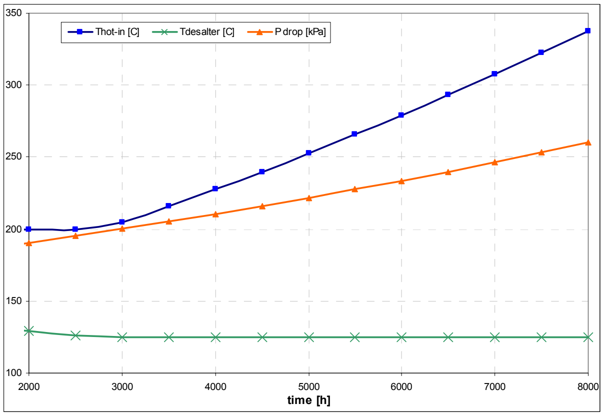

Figure 8. Case study 2: Response of initial design to fouling

As already noted above, the increase in the temperature at which the hot stream enters unit 3 can be controlled by the level of fouling encountered in the exchanger at the hotter end of the train rather than through the manipulation of a bypass around that unit. In this situation the identified energy saving can only be met by cleaning both unit 3 and the hotter unit. Simulation of the full train will provide the required information on cleaning benefit and cost.

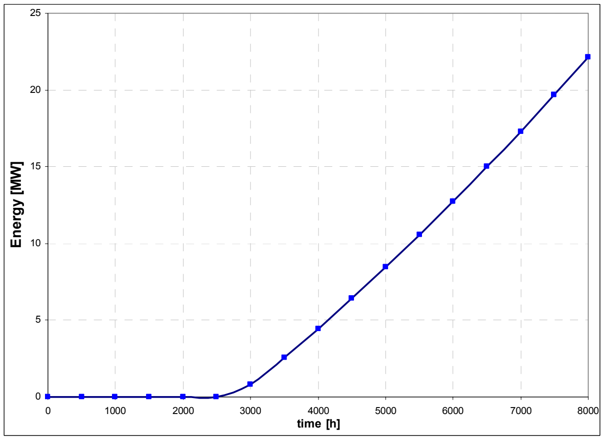

Figure 9. Case study 2: energy costs associated with maintaining de-salter temperature

Cleaning of refinery exchangers is an expensive operation. It requires much pre-planning and can require the introduction of cranes onto site. If the units are to be cleaned off-site, the operation can take several days to undertake. (As shown above, reduced throughput during the cleaning period can be established using the simulation). Rather than clean a single exchanger it can be advisable to undertake a "campaign" in which a number of units are cleaned (in quick succession).

The effects of cleaning a single exchanger in unit 3, two exchangers in unit 3 and single exchangers in units 2 and 3 are shown in Figure 10.

The cleaning of exchanger 2A has an immediate energy saving of 1.6 MW which remains fairly constant over subsequent operation. The original response and the response subsequent to cleaning both approximate straight lines. The horizontal distance between the curves provides an indication of how soon the energy conditions that existed prior to cleaning can be re-established. This could be the "operating time benefit". For this case it is seen to be just 500 h.

The cleaning of exchanger 3A yields a higher saving (of 2.6 MW) and the operating time benefit is extended to 1000 h.

A campaign involving cleaning exchangers 3A and 3B results in an immediate saving of 2.6 MW. However, the temperature of the stream entering the unit remains at its lower limit of 200°C for around 500 hours. By the end of this period the saving has increased to 4.5 MW. The operating time benefit is 1200 h.

Finally, a campaign involving the cleaning of 2A and 3A results in higher savings: the immediate saving of 2.6 MW extends to 5.3 MW after 500 h and the operating time benefit is 1500 h.

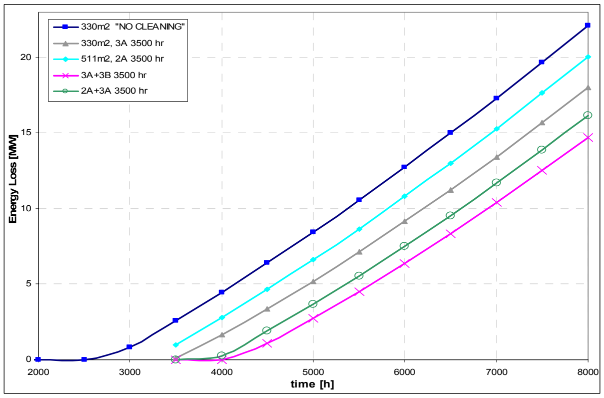

Figure 10. Case study 2: energy saving associated with several exchanger cleaning actions

Exchanger Sizing in System Context

As indicated above, exchanger sizing can now be undertaken in the context of its effect upon the behaviour of the pre-heat train. In Figure 11 we show the effects of increasing the size of the exchangers in unit 3 from 330 m^2 to 440 and then 550 m^2.

Increasing size to 440 m^2 would yield an energy saving benefit equivalent to cleaning the smaller unit after 4000 h of operation.

Increasing the size further, to 550 m^2, would provide a pre-heat train that would not need an increase in the inlet temperature of the hot stream until after 4000 hours operation and would provide significant energy saving benefit.

Incorporation of Fouling Models into the Simulation

At the hot end of a pre-heat train the fouling is usually dominated by chemical reaction fouling. This type of fouling has been the subject of much study and several models have been developed for the prediction of fouling rates from knowledge of wall temperature, exchanger velocity and physico-chemical activation energy (1). Techniques for the prediction of apparent physico-chemical activation energies from plant measurements are under development (Polley *et al*. 2007a, b).
The velocity distributions and local heat transfer coefficients are determined by the thermo-hydraulic simulation. Consequently, the incorporation of fouling models into the above procedures will be straight-forward.

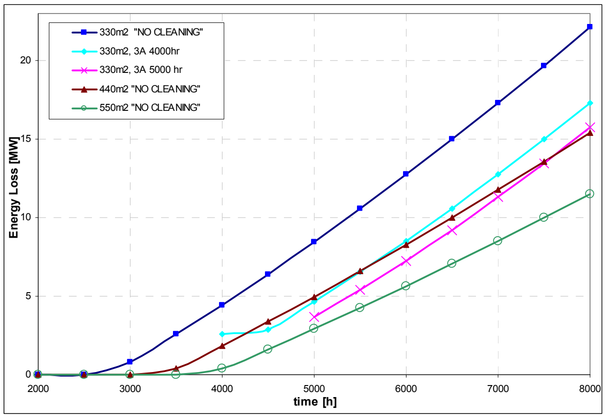

Figure 11. Case study 2: Influence of exchanger size on network performance

Concluding Comments

A means of simultaneously simulating the effects of fouling on overall pressure drop, flow distribution and thermal performance of pre-heat trains has been developed. Using such a simulation it is possible to:

1. Identify whether throughput will be restricted by the hydraulic effects of fouling or by difficulties in maintaining process operating temperatures (desalter temperature, pre-flash column temperature or furnace inlet temperature).
2. The plant throughput that can be achieved when one or more exchangers are isolated for cleaning.
3. The cost benefits of cleaning in terms of energy saving or improved throughput.

Heat exchangers for use in pre-heat trains are usually designed as individual units. The simulation provides the means of designing exchangers as part of a full operating system. The interaction between exchanger design and maintenance schedule can be established.

The approach can be extended to include a consideration of how the individual heat recovery matches are configured. Where fouling is severe and is likely to result is throughput problems the choice of which hot stream should be used at the coldest end of the process could be a significant factor. In this case the crude oil temperature rise per unit pressure drop could provide a guide to match selection.

For the hot end of the train, fouling models relating velocity, wall temperature and fouling rate can be incorporated into the simulation.

Many of the identified responses appear quite linear. Such a property will aid the development of numerical procedures for the identification of optimal configurations.

References

Coulson J.M., Richardson J.f, Backhurst J.R. & Harker J.H., *Chemical Engineering Vol. 1,* 5th.edition, Butterworth Heinemann, (1996)

Joshi H., Hoeve F. & Van der Zijden E. Applying technology advancements to improve heat exchanger economics and environmental performnace in refinery crude pre-heat trains, *Heat Exchanger Fouling & Cleaning VII,* Engineering Foundation Conference, Tomar, July 2007
Nelson, W.L., Fouling of heat exchangers (1934) Refinery & Nat Gasol Manufacture, vol 13 p271

Pretty B. & Polley G.T. Modelling heat exchanger networks in spreadsheets using Ntu method, *National Petroleum*

Refiners Association Computer Conference, Atlanta, Novemebr 1996

Polley G.T., Wilson D.I., Pugh S.J. & Petitjean E. 'Extraction of crude oil fouling data parameters from plant monitoring', Heat Transfer Engineering, 2007, 28(3), 1-8.

Polley G.T. & Gonzales Garcia G. "Recent developments relating to the analysis of exchanger monitoring data", *Heat Exchanger Fouling & Cleaning VII,* Engineering Foundation Conference, Tomar, July 2007

Watkinson, A.P. and Wilson, D.I. 'Chemical reaction fouling - A review, 1997, Engng and Thermal Sciences, 14, 361-374.

Yeap B.L., Wilson D.I., Polley G.T. & Pugh S.J. 'Mitigation of crude oil refinery heat exchanger fouling through retrofits based on thermo-hydraulic models', Chem. Eng. Res. Des. 2004, 82A,53-71.

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