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MANAGEMENT OF CRUDE PREHEAT TRAINS SUBJECT TO FOULING

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ABSTRACT

Crude oil refinery preheat trains are designed to reduce energy consumption but their operation can be hampered by fouling. Fouling behaviours vary from one refinery to the next. Effective management of preheat train operation requires inspection of historical plant performance data to determine fouling behaviours, and the exploitation of that knowledge in turn to predict future performance. Scenarios of interest can include performance based on current operating conditions, modifications such as heat exchanger retrofits, flow split control and scheduling of cleaning actions.

Historical plant monitoring data is frequently inconsistent and usually needs to be subject to data reconciliation. Inadequate data reconciliation results in misleading information on fouling behaviour. This paper describes an approach to crude preheat train management from data reconciliation to analysis and scenario planning based around a preheat train simulator, *smart*PM, developed at Cambridge and IHS (Ishiyama *et al*., 2009 Energy & Fuels; Kumana *et al*., 2010, AIChE J Spring meeting). The proposed methodology is illustrated through a case study which could be used as a management guideline for preheat train operations.

INTRODUCTION

Refineries are major parts of the national economy: in the UK alone, there are nine major refineries, processing over 1.8 million barrels of crude oil per day (Watson and Vandervell, 2006), consuming energy at the rate of gigawatts (~7.9 GW: Marsh-Patrick, 2006). Heat exchangers (HEXs) play a major role in energy saving on refineries. These units frequently suffer from fouling, wherein the build-up of low thermal conductivity deposits reduce the ability of units to transfer heat.

The focus of this work is the HEXs located upstream of the atmospheric distillation column on crude oil refineries. All the oil processed in a refinery passes through these units. The HEXs are connected together in a network called the preheat train (PHT) whose aim is to recover heat from the product streams (the product and also the pumparound streams) on the column to the incoming feed stream (*i.e.* crude oil), thereby reducing the energy required to heat the oil to the temperature needed for distillation. Fouling increases furnace heating costs and refinery greenhouse gas emissions.

Preheat train fouling can be caused by any combination of particulate, chemical reaction, crystallization and corrosion mechanisms, often varying between parts of the train as fluid chemistry and temperature change. The complex nature of PHT fouling behaviour is shown in Figure 1, which is a summary of refinery fouling analyses alongside pilot plant studies. This follows the approach presented by Joshi *et al*. (2009), who plotted measured plant heat exchanger fouling rates against wall shear stress. All the exchangers in the Figure were shell-and-tube units with crude on the tube-side.

The solid line on the Figure is the correlation based on plant fouling data by Joshi *et al*. (2009). This indicates that the average rate of fouling decreased with increasing tube-side wall shear stress. The influence of temperature was not significant for the observed fouling rates. Also shown on the Figure are two sets of open symbols and five of solid symbols, representing fouling rates observed in pilot plant experiment and five other refineries. Each datum represents an exchanger, often operated at different temperature (detailed in Ishiyama *et al*., 2010). There is widespread scatter in the data, indicating that shear stress is not a sufficiently controlling parameter to be used for evaluating fouling behaviours. Temperature, also, is not a sufficiently good determinant.

Given the complex behaviour of crude fouling and the complications in heat transfer introduced by the preheat train structure, it is usually impossible to write a generalized analytical solution describing the thermal and hydraulic behaviour of the preheat train. A network simulator is required.

IHS ESDU, UK has developed a novel thermo-hydraulic PHT simulator, *smart*PM, based on work at Cambridge (Ishiyama *et al*., 2008; 2009; 2010). The *smart*PM package has been developed to assist refinery operators and other key stakeholders in improving the performance of PHTs subject to fouling. The simulation technology is based on the thermo-hydraulic network aspects discussed for crude preheat trains by Ishiyama *et al*. (2009; 2010). One main feature of the simulator is the ability to take into account real plant operating constraints when analysing plant behaviour. In this paper *smart*PM is combined with sound engineering judgements for the analysis of PHT operations; its capabilities are demonstrated in a series of case studies.

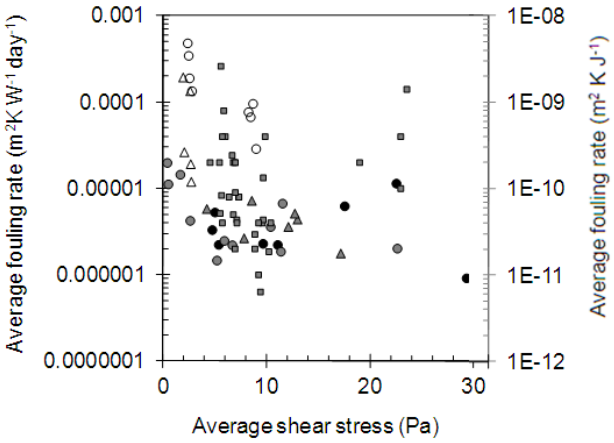


Figure 1: Plot of average fouling rate in refinery shell-and-tube units against estimated wall shear stress. Solid locus: correlation reported by Joshi *et al*. (2009). Solid symbols are the fouling rates obtained from 5 refineries; open triangles and open squares denote pilot plant fouling data obtained from Wood River tube flow and Exxon tube flow, respectively, both reported by Knudsen *et al*., (1999). Black circles in dashed ellipse indicate HEXs where shell-side fouling was thought to be significant. Reproduced from Ishiyama *et al*., (2010).

Using *smart*PM software to manage operation of PHTs

*smart*PM is a computer simulation. The accuracy of its calculations reflects the accuracy of the information supplied by the user. To reduce the possibility of poor performance, a data reconciliation stage is introduced as the initial step. Figure 2 summarises the work flow and the major steps are described below.

1. *Monitoring and data reconciliation*

Preheat train performance is evaluated through plant monitoring (temperature and flow measurements); here the reliability of data reconciliation plays a significant role. Most PHT operators do not monitor all stream temperatures (or flow rates) and frequently estimate the missing data using ‘short-cut' methods. An incorrect choice of ‘short-cut' method, such as the use of linear interpolation, is shown here to result in misleading conclusions.

In *smart*PM, monitoring data are linked to the network simulator model though the graphical attachment of ‘indicators' to appropriate streams. These indicators can store time-dependent flow rate, temperature and/or pressure measurement data. The indicators are currently populated from an automatically-generated spreadsheet which is itself either populated by manual copy-and-paste or direct linking to an external data source such as a distributed control system. Direct linking of *smart*PM to a data historian is also possible.

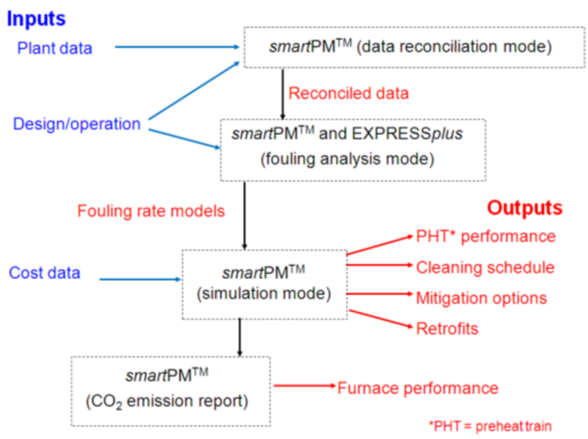


Figure 2: Schematic of *smart*PM calculation flow. Text in blue indicates major input to each processes, text in red indicates major output from preceding processes. EXPRESSplus is an IHS ESDU HEX design package.

The *smart*PM data reconciliation approach is based on three steps:

(*i*) Generation of missing data through simulation using full heat exchanger modelling.
(*ii*) Filtering unreliable data through a ‘trusted' heat balance.
(*iii*) Grouping heat exchanger monitoring data into different time sections to identify trends under different operating periods.

The reconciled data are then utilized to make key operational decisions to improve preheat train performance. The data reconciliation mode also generates historical fouling resistance (R_f) profiles for each exchanger with time.

When the plant parameter set is incomplete, any missing values are generated through a constructed simulator, which could be used for a single heat exchanger or a heat exchanger network of any structure. The steps are divided into four stages.

I. An initial mass balance is performed to generate any missing stream mass flow rates.
II. Initial guesses for missing temperatures are made.
III. The above values are used to calculate estimates of R_f
IV. These R_f values are then used as initial values and the temperatures of the streams generated through the simulation. The steps are summarized in Figure 3.

The initial temperature guess employs linear interpolation of the known temperatures associated with the exchanger group.

2. *Fouling analysis mode*

This step is performed following data reconciliation. The fouling behaviour of a crude slate can be quantified by fitting dynamic fouling models to the fluctuating values of metal wall temperature, crude temperature and wall shear stress occurring in each heat exchanger.

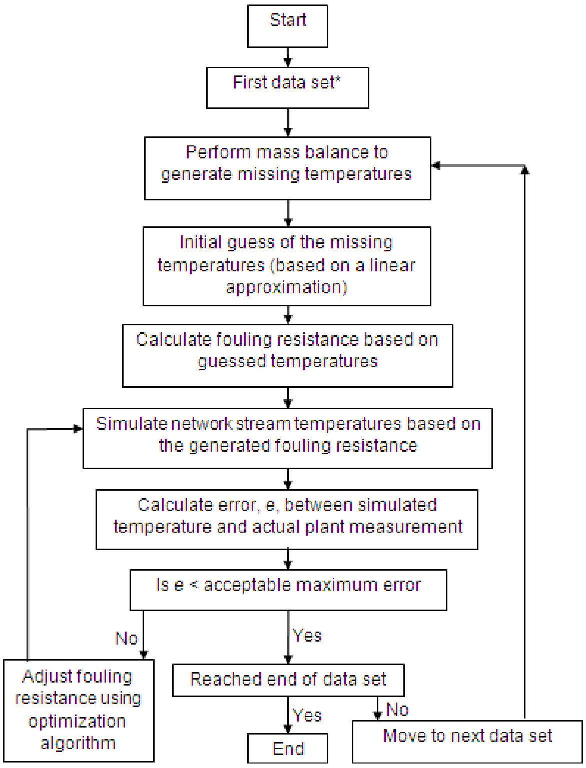


Figure 3: Data reconciliation steps with missing intermediate flow/temperature measurements.

In this mode, the user can specify time intervals for fouling analysis – there can be one or more for a particular exchanger, *e.g.* between each cleaning operation. The time intervals are selected through visual inspection of the R_f-time profiles. If the user does not specify a time interval the whole R_f –time data is selected automatically.

Once the time intervals are selected, the fouling rates are generated for each time period with the corresponding operating condition; this then is used to obtain parameters for the fouling rate model(s). The three dynamic fouling models in Table 1 are currently incorporated for selection and use in simulation. These dynamic models are used in their integrated forms (*e.g.* integrated form of equation (1) is described in Ishiyama *et al.*, 2008).

In the table, $\dot{R}_f$ is the rate of fouling; Re and Pr are the Reynolds number and Prandtl number respectively; E_i is the activation energy, τ_s is the surface shear stress, T_{film} is the tube-side film temperature; A_i and γ_i are dimensional constants, respectively. h is the film heat transfer coefficient either on the tube- or shell-side of an shell-and-tube heat exchanger. The derivation of these models is explained elsewhere (Yeap *et al.*, 2004; Polley 2010).

A 'network fouling map' is then generated, where the rate of fouling (predicted/simulated) is plotted against the crude film temperature and equivalent shear stress for each exchanger in the network.

Practically, crude oil fouling could be a combination of chemical reaction, particulate, corrosion and salt crystallization fouling. The use of chemical reaction fouling models are practically valid for heat exchangers located at the hot end of the preheat train.

Table 1: Summary of fouling models used in *smart*PM

Fouling model	Description
(1)	$\dot{R}_f = A_1 Re^{-0.66} Pr^{-0.33} \exp\left(\frac{-E_1}{RT_{film}}\right) - \gamma_1 \tau_s$ Ebert-Panchal model for tube-side fouling (Yeap *et al*., 2004)
(2)	$\dot{R}_f = \frac{A_2}{h} \exp\left(\frac{-E_2}{RT_{film}}\right) - \gamma_2 \tau_s$ Generalized Ebert-Panchal model for both crude on the tube- and shell-side (for shell-and-tube heat exchanger) (Polley, 2010)
(3)	$\dot{R}_f = \frac{A_3}{h} \exp\left(\frac{-E_3}{RT_{film}}\right) P$ Ashphaltene precipitation model for different heat exchanger types (Polley, 2010)

3. *Network simulation, scheduling cleaning and assessing retrofits*

Simple simulation

In any simulation mode, the user defines, for example, inlet temperature, flow rates and branch flow splits. This mode simulates the performance of the network over a selected time period assuming that exchanger fouling is either static or varies due to a user-defined linear rate in one or more heat exchangers.

Crude fouling simulation

This mode simulates the performance of the network over a selected time period assuming that exchanger fouling in individual heat exchangers is either dynamic in nature, static or varies due to a user-defined linear rate. Three dynamic fouling models are currently incorporated for selection in simulation. Again, the user has control over, for example, inlet temperature, flow rates and branch flow splits.

Optimum cleaning schedule

In this mode, the user can specify which heat exchangers can be taken offline for cleaning, the duration and cost of any individual cleaning event and the economic return from any cleaning event. The program will then automatically generate the most cost effective cleaning schedule where fouling is either static (does not change over time), varies due to a user-defined linear rate in one or more heat exchangers, and/or increases following any one of the three dynamic fouling models.

User defined cleaning schedule

This mode simulates the performance of the network given a user-defined cleaning schedule. This would either estimate optimal performance where cleaning scheduling information was available, and has therefore been defined, or where an optimum cleaning schedule has been modified to re-schedule some or all events to coincide with the onsite availability of maintenance crew.

For each of the simulation modes, both performance and economic data are presented graphically and in tabular form. This allows, for example, energy and maintenance costs to be compared between operating scenarios.

4. *CO_2 emissions and economic reporting*

Greenhouse gas emission is reported in terms of mass to be consistent with predominant regulatory reporting and carbon trading schemes. Hence CO_2 emission in this report is not directly converted into monetary terms as these economics generally fall outside our scope (in contrast to the raw data). The economics are complicated due to the current volatility in carbon markets with many unpredictable factors that affect the future price of carbon.

There are two main methods to convert furnace fuel usage to CO_2 emissions. The *first method* is by using the stoichiometric combustion equations with fuel gas composition and combustion efficiency of the burners. This method is discussed at length by Gadalla *et al*., (2005).

The *second method* employs simple emission factors. Typical emission factors are available from Australian National Greenhouse and Energy Reporting (NGERS) guidelines (in units of mass of CO_2/volume gas combusted) and API Compendium (in units of mass of CO_2/energy generated by the fuel) (Shires, 2009).

The former method is used to perform CO_2 emission analysis in *smart*PM.

CASE STUDIES

The use of the *smart*PM software is illustrated using three case studies. Each case study highlights different aspects of the package, as summarized in Table 2.

Case Study 1: Data Reconciliation

Figure 4 shows a section of the preheat train of a well-instrumented refinery processing heavy crude oil. All temperatures are measured. In the first case study the stream temperatures labelled T_1 to T_8 are assumed to be missing and in the second case study temperatures T_1 to T_{10} are assumed to be missing. The data reconciliation calculations were carried out in two ways.

(i) Calculation is based on linear approximation of temperature and local heat balances.

(ii) Calculation is performed using the *smart*PM methodology. This data reconciliation case study was presented at the 2011 AIChE spring meeting (Ishiyama *et al*., 2011).

The fouling resistances were evaluated and Figure 5 presents a snapshot of values across the PHT at a given time instance. The values estimated with the above data missing are compared with those calculated with the actual values available, the 'actual' fouling resistance. The assumption of T_1 to T_{10} being missing is for illustration, and is not uncommon.

The data set labelled 'I' shows an over-prediction of the fouling resistance, which would cause the operator to consider cleaning an exchanger earlier than necessary. Data sets marked 'II' are those where fouling is under-predicted, thereby masking the true extent of fouling in the unit. This gives false information about a unit's tendency to foul, and delay cleaning.

The case study emphasises the need to instrument PHTs properly and to maintain the data collection system. Not all units need to be instrumented, and tools like *smart*PM can be used to identify the number of devices required to give sufficient accuracy in data reconciliation calculations, including the effect of sensor malfunction.

Table 2: Case studies demonstrating the use of *smart*PM

Case study	Aim
1	Demonstrate the importance of data reconciliation. Due to confidentiality reasons, only the network structure and a snap shot of R_f values are presented.
2	Demonstrates the importance of fouling analysis (based on Ishiyama *et al*., 2010).
3	An example network, demonstrating the capability of fouling simulation, retrofit and cleaning scheduling analysis.

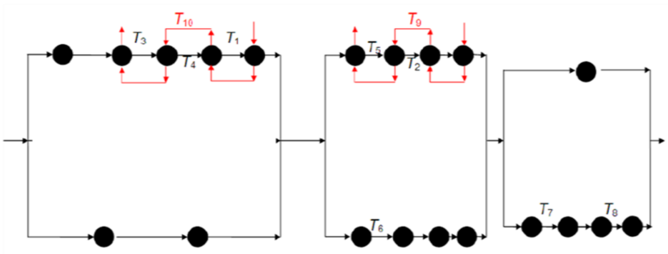


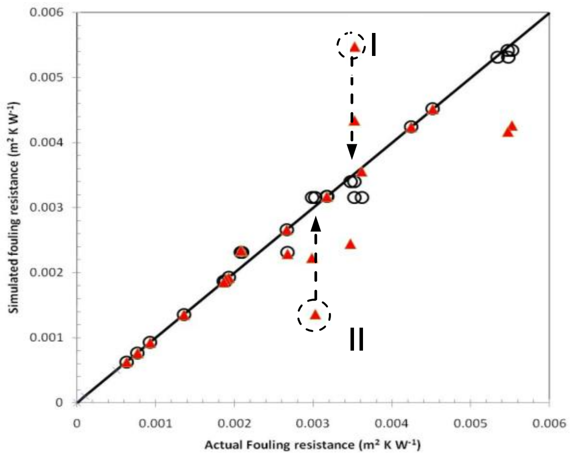
Figure 4: Case study 1 preheat train. The refinery is well instrumented. Stream temperatures T_1 to T_{10} are the measurements considered to be missing in this study: all other stream temperatures and flow rates are known.

Case Study 2: Fouling Analysis

This case study is based on the analysis of a REPSOL refinery preheat train in Argentina consisting of 18 HEX in the PHT reported by Ishiyama *et al*. (2010). Figure 6 shows the PHT structure which includes a desalter and a flash tower. The HEX design parameters and the thermo-physical properties are given in Ishiyama *et al*. (2010). Heat exchangers sharing a common numeric value have the same hot stream fluid, *e.g.* the heavy gas oil (HVGO) goes through the four HEXs numbered 8A-D.

Chemical reaction fouling is expected to be the dominant mechanism for fouling in heat exchangers located downstream of the desalter. Following data reconciliation, the fouling rates obtained for these units are compared with the maximum film temperature in the unit and the average tube-side velocity in Figure 7. HEXs 7 and 9A-E show an increase in fouling rate with increasing film temperature and decreasing velocity, as described by the Ebert-Panchal model [Eq. (1)]. This equation was fitted to the data sets and the result is plotted as a plane in Figure 7: reasonably good agreement is evident.

(*a*)



(*b*)

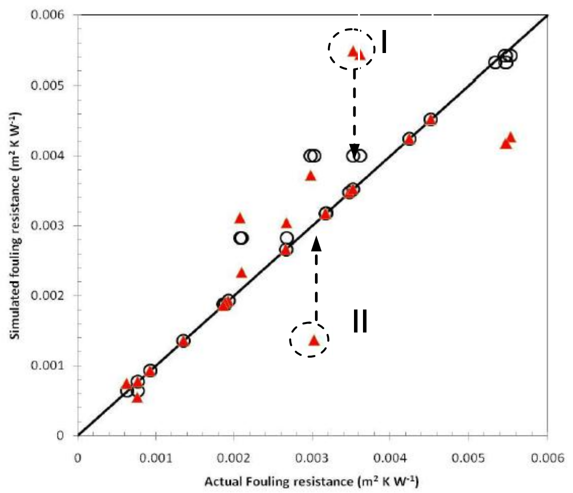


Figure 5: Snapshot of R_f values in Case Study 1. Solid triangles denote results based on simple linear temperature approximation, open circles denote values calculated using smartPM. Scenario (*a*) assumes data for T_1-T_8 are missing and (*b*) T_1-T_{10} are missing.

Irregular behaviour is evident in HEXs 8B-D. These start from the second unit downstream of the desalter (Figure 6). This fouling behaviour is thought to arise from poor operation of the desalter. There is likely to be water carry-over from the desalter and inspection of the operating temperature and gauge pressure indicates that the water would vaporise in unit 8A, causing crystallisation fouling. Shell-side fouling could also be present: dismantling the units would be required to confirm the source of the anomalous fouling behaviour.

The above comments illustrate how data reconciliation studies can be used to probe the operation of the PHT and identify malfunctioning units.

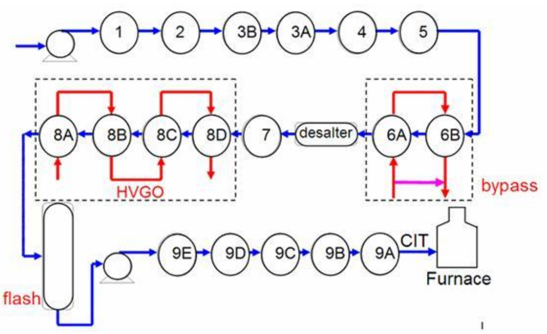


Figure 6: Case study 2 network consisting of 18 HEXs. CIT is the coil inlet temperature. The HVGO hot stream passes through HEXs 8A-8D on the shell-side, counter-current to the crude. HEXs 6A and 6B are used to control the desalter inlet temperature.

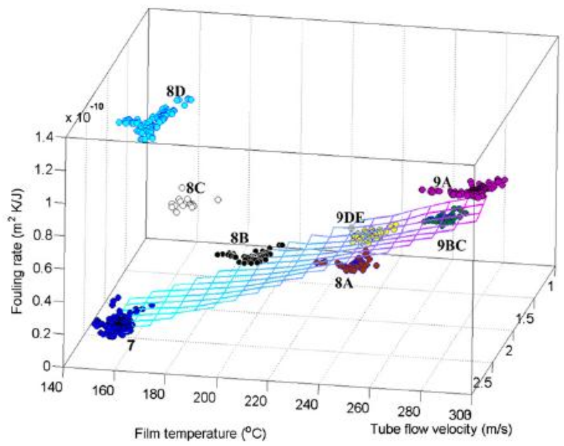


Figure 7: Comparison of fouling rates in exchangers located downstream of the desalter. Data labels indicate the exchanger (Figure 6). The surface indicates the best fit given by the Ebert-Panchal model [Fouling model (1)] for the data in HEXs 7, 9A-E.

Case Study 3: Network Simulation/Retrofit & Scheduling

Figure 8 is a schematic of a typical PHT hot end. The design specifications of the units are given in Table 3 (at the end of the paper). The stream inlet conditions and the physical properties are reported in Table 4 and 5. This section of the PHT has a clean heat duty of 28 MW. The operating scenarios considered are summarized in Table 6 and the performance, gauged by CIT and other measures, presented in Figure 9. The fouling rate model presented by fouling model 2 is used (generalized Ebert-Panchal model), with model parameters (A_2 = 0.986 h^{-1}, E_2 = 36,000 J mol^{-1} K^{-1}, γ_2 = 4.8 × 10^{-8} m^2 K W^{-1} h^{-1}). A cleaning cost of 10,000 US$/unit was used in the simulations.

Table 4: Stream inlet conditions for Case Study 3

Stream name	Inlet temperature (°C)	Inlet flow (kg s^{-1})
I	190	256
II	320	60
III	280	60
IV	300	60

Table 5: Thermo-physical properties of streams

Specific heat capacity, J kg^{-1} K^{-1}, C_p = 2273 + 0.005 T
Dynamic viscosity, Pa s, μ = a exp (b/(T + 273))
Stream 1 a = 1.95 × 10^{-3}, b = 0
Stream 2 a = 1.1 × 10^{-14}, b = 1.405 × 10^{4}
Stream 3 a = 6 × 10^{-14}, b = 1.302 × 10^{4}
Stream 4 a = 5.4 × 10^{-14}, b = 1.302× 10^{4}
Thermal conductivity, W m^{-1} K^{-1}, λ = 0.116
Density, kg m^{-3}, ρ = 800 – 0.002T

*streams 1, 2, 3 and 4 is assumed to have the same specific heat capacity, thermal conductivity and density (in this study). T is in °C

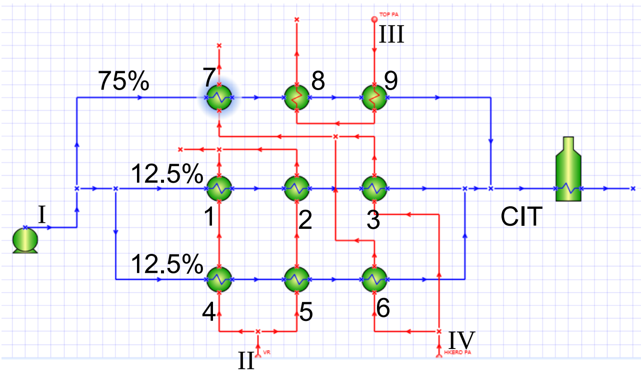


Figure 8: Case Study 3 network (preheat train hot end before furnace), consisting of 9 HEX on three parallel cold streams. Percentage values indicate flow splits.

Table 6: Operating scenarios for Case Study 3 network

Scenario	Description
1	Original network without any modification
2	Targeted cleaning. *i.e.* the network is simulated based on a predefined cleaning schedule. In this example unit 9 is cleaned every 6 months.
3	Optimized cleaning (numerical optimization without considering limits on the frequency of cleaning)
4	Retrofitted network – arrangements considered to reduce rate of fouling

(*a*)

(*b*)

(*c*)

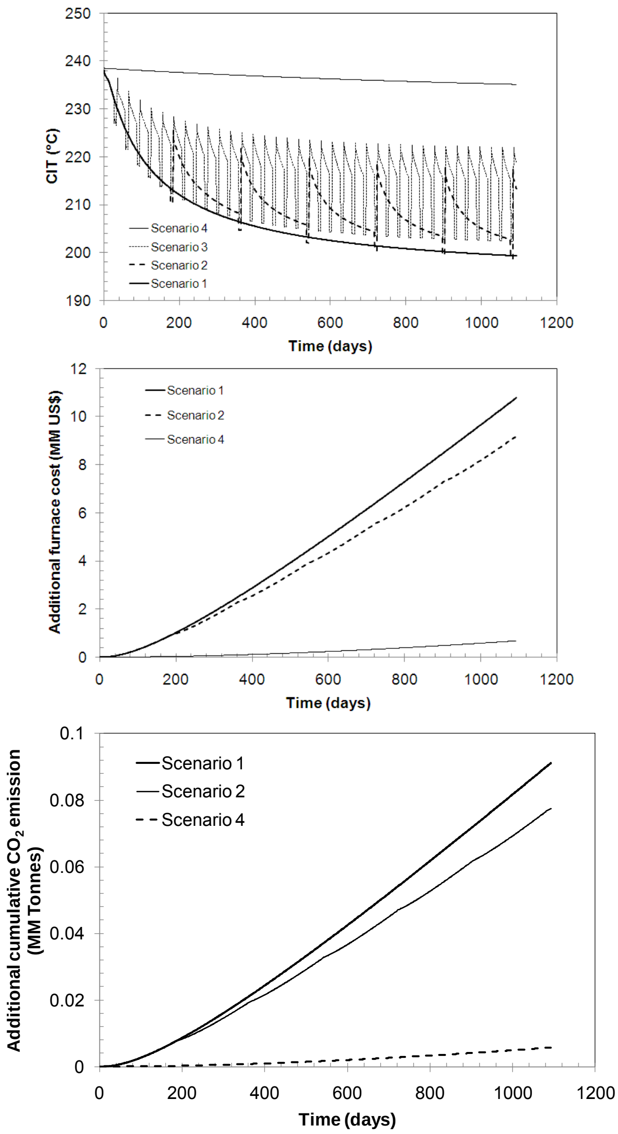


Figure 9: Network performance summary. Profiles for (*a*) CIT (coil inlet temperature), (*b*) furnace cost (MM stands for millions), and (*c*) additional CO_2 emission.

The performance of the original network is presented by the solid bold line in Figure 9. There is a drop in CIT (coil inlet temperature) of around 40 K over a 3 year operating period. The economic penalty is paid through additional furnace costs and increased CO_2 emission penalties, adding up to US$12M over 4 years. All calculations are based on energy cost of 0.54 US$/kW day.

The heat duty of each unit at the start of the operating campaign and after 3 years are presented in Figure 10. This presentation is important as it serves to identify *key heat exchangers* on the preheat train duty and to identify the impact of fouling, for a system undergoing no cleaning. It is immediately evident that unit 9 has the highest initial heat duty and the fastest fouling rate.

Scenario 2 considers the result of a refinery fouling mitigation plan involving cleaning unit 9 every 6 months. The performance is plotted as a bold dashed line on Figure

9. Comparison of scenarios 1 and 2 indicates that this targeted cleaning strategy would save around US$2M over the 3 year operating period. More frequent cleaning, represented by Scenario 3, results in an unrealistic CIT profile (Figure 9 (*a*)), even though costs are minimized.

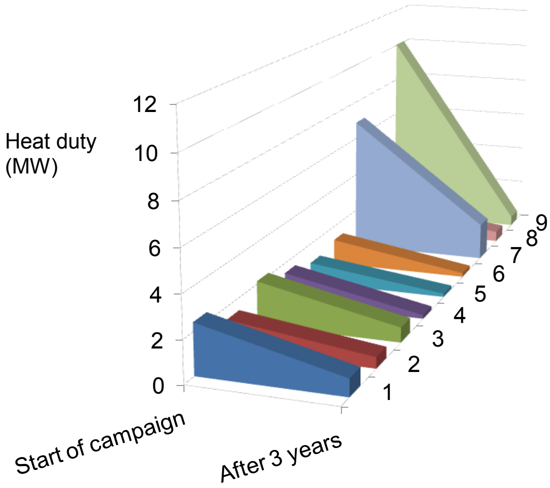


Figure 10: Snapshot of HEX duties. Units labels given on Figure 8.

A prime consideration in developing the *smart*PM tool is that different refineries have different approaches to PHT design and operating philosophies. One may choose to design a network with low heat exchanger flow velocities in order to focus on heat integration. Others may employ high flow velocities, at the expense larger pumps and pumping costs in order to reduce fouling. The *smart*PM tool can be used to investigate the change from one operating philosophy to another.

Scenario 4 investigates a possible retrofit option to improve the network performance. Noting that exchangers 8 and 9 both feature the crude passing through the shell-side, and exchanger 9 exhibits the highest rate of fouling, one possible response would be to change the configuration to put the crude on the tube-side. Direct swapping from shell- to tube-side would result in a very high tube-side flow velocity (>5 m s^{-1}) as 75% of the crude flow passes through this leg of the train. A feasible operating condition in exchangers 8-9 can be obtained by splitting the crude into parallel streams, giving tube-side velocities of ~ 3 m s^{-1}. Analysis of the expected fouling behaviour (not reported here) predicted by equation (2) indicated that this flow velocity would located the tube-side condition near the fouling threshold and give negligible fouling. The modified network is presented in Figure 11 and the performance given by the grey line on Figure 9.

The decrease in CIT is reduced to less than 5 K over the 3 year operating period. This scenario is predicted to decrease the additional costs due to fouling (furnace cost and CO_2 tax) by around $US3M per year, which represents a marked improvement.

Table 7 summarizes the techno-economic performance of the different Scenarios. Scenario 4 is evidently highly attractive and would justify detailed investigation.

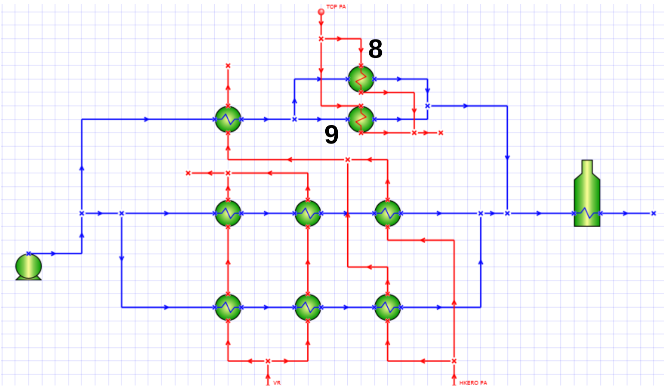


Figure 11: Modified network for Case Study 3, with units 8 and 9 changed to operate in parallel with crude passing on the tube-side.

Table 7: Summary of operating scenarios (MM stands for millions)

Scenario	Cumulative additional fuel cost MM US$ (for 3 years)	Cumulative additional CO_2 emission (for 3 years) MM tonnes	Average heat duty over 3 years (MW)
1	10.8	0.09	9.575
2	9.2	0.08	12.32
3	6.9	0.06	16.24
4	0.7	0.01	27.06

CONCLUSIONS

1. A novel crude preheat train simulator has been developed through IHS ESDU based on research performed by the group at Cambridge.
2. The software tool provides a useful guide to the refiners on performing data reconciliation, simulating network performances, assessing retrofits and economic evaluation of cleaning scheduling.
3. Three case studies illustrated different applications of this software tool.

NOMENCLATURE

Romans

A_1 pre-exponential factor in equation (1), m^{2}K J^{-1}
A_2 pre-exponential factor in equation (2), s^{-1}
A_3 pre-exponential factor in equation (1), h^{-1}

CIT coil inlet temperature, °C
C_p specific heat capacity, J kg^{-1} K^{-1}
P attachment probability, -
Pr Prandtl number, -
E_1 activation energy in equation (1), J mol^{-1}
E_2 activation energy in equation (2), J mol^{-1}
E_3 activation energy in equation (3), J mol^{-1}
h film heat transfer coefficient, W m^{-2} K^{-1}
P attachment probability factor, -
R gas constant, J K^{-1} mol^{-1}
R_f fouling resistance, m^{2}K W^{-1}
$\dot{R}_f$ fouling rate, m^{2}K J^{-1}
Re Reynolds number, -
T_{film} film temperature, K

Greek

γ suppression constant, m^2 K W^{-1} Pa^{-1}
λ thermal conductivity, W m^{-1} K^{-1}
μ dynamic viscosity, Pas
ρ density, kg m^{-3}
τ_s surface shear stress, Pa

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Table 3: Heat exchanger geometry for Case Study 3

	Tube length (m)	Tube i.d. (m)	Tube o.d. (m)	Total number of tubes	No. of tube side passes	Shell diameter (m)	Baffle spacing (m)	Baffle cut	Initial resistance (m^{2}K W^{-1})
1	6.1	0.015	0.019	1600	4	1.32	0.39	0.2	0.00014
2	6.1	0.020	0.025	1000	4	1.24	0.38	0.225	0.0005
3	6.1	0.020	0.025	1018	6	1.31	0.39	0.275	0.0006
4	6.1	0.020	0.025	300	1	0.71	0.39	0.2	0.0007
5	6.1	0.020	0.025	300	1	0.71	0.39	0.2	0.0018
6	6.1	0.020	0.025	300	1	0.71	0.39	0.2	0.0009
7	6.1	0.020	0.025	980	2	1.24	0.38	0.225	0.00001
8	6.1	0.021	0.025	840	4	1.14	0.39	0.225	0.0002
9	6.1	0.021	0.025	840	4	1.14	0.39	0.225	0.0003