IMPACT OF CRUDE OIL FOULING COMPOSITION ON THE THERMO-HYDRAULIC PERFORMANCE OF REFINERY HEAT EXCHANGERS

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ABSTRACT

Crude oil fouling studies generally focus on the thermal impact of organic deposits. The hydraulic limit given by pressure drop is, however, frequent cause of shutdowns and cleaning. Inorganic matter is often found in deposit analysis, but ignored in most studies. A case study is presented based on published plant data from the Esfahan Refinery (Iran). A detailed thermo-hydraulic model of heat exchangers undergoing fouling, together with the available data and reasonable assumptions, is applied to study the exchanger most affected by fouling. Novel modifications are made to: i) capture the effect of inorganics on the deposit conductivity; and ii) use pressure drop measurements, instead of temperature, to fit key fouling parameters. Good agreement is obtained between model and plant data. This demonstrates the need and benefit of considering fouling layer composition and both temperature and pressure drop data in the fitting of model parameters and interpretation of plant data. The potential of using such a model for early detection of operative problems is highlighted.

INTRODUCTION

Fouling in the preheat train (PHT) of crude distillation units (CDUs) is a major cost in oil refineries in terms of energy losses and fuel consumption but it also impacts greenhouse gases emission and continuity of operations [1]. Estimations suggest that fouling mitigation in CDUs could lead to 15% fuel savings in the furnace downstream the PHT, equivalent to worldwide savings of about 500,000 bbl/day [2], the size of a large refinery.

Fouling monitoring and prediction is important to assess a PHT network performance and identify mitigation opportunities. Established methodologies typically focus on the thermal effects produced by the deposition of low conductivity materials on the heat transfer surfaces. Mathematical models that attempt to capture fouling as a function of process conditions and time (e.g. Ebert and Panchal [3]) are usually fitted to calculated values of fouling resistance (or rate of change in fouling resistance) [4–6] which are derived quantities, subject to a number of simplifying assumptions (e.g. lumped models, constant physical properties). More recently, Coletti and Macchietto [2] proposed a methodology to fit fouling models to primary temperature measurements as opposed to fouling resistances.

NOMENCLATURE

API	[-]	API gravity
CDU	[-]	Crude Distillation Unit
E_f	[J/mol]	Fouling deposition activation energy
HVGO	[-]	Heavy vacuum gas oil
ISO	[]	Isomax product
LVGO	[-]	Light vacuum gas oil
MeABP	[ºC]	Mean Average Boiling Point
P	[Pa]	Pressure
PHT	[-]	Pre-heat train
Pr	[-]	Prandtl Number
Re	[-]	Reynolds Number
R	[J/molK]	Ideal gas constant
T	[K]	Temperature
T_f	[K]	Tube-side film temperature
VDU	[-]	Vacuum Distillation Unit
w	[-]	Mass fraction
y	[-]	Youth variable

Special characters

α	[m^2K/J]	Deposition constant
α'	[m/s]	Modified deposition constant
γ	[$m^4K/J\ N$]	Suppression constant
γ'	[$m^3/s\ N$]	Modified suppression constant
ΔP	[Pa]	Tube-side pressure drop
δ	[m]	Fouling layer thickness
λ	[W/m K]	Thermal conductivity
$\nu_{38°C}$	[cSt]	kinematic viscosity at 38^{0}C
τ_w	[N/m^2]	Wall shear stress

Subscripts

inorg	Inorganic
L	Fouling layer
org	Organic

Superscripts

0	initial
∞	final

A severe limitation of traditional monitoring methodologies and fouling models is that the impact of fouling on the hydraulic performance is typically not considered. This relates to the gradual reduction of the cross-sectional area as fouling builds up, leading to flow restriction, increased pressure drop and, in extreme cases, to complete plugging of the exchanger's tubes. In fact, excessive pressure drop is very often the reason why operators decide to take heat exchangers out of line for cleaning [7]. The hydraulic impact of fouling is also important at network level, since it can lead to flow imbalance between parallel branches, which may reinforce fouling resulting in serious operational problems [9]. Although the use of hydraulic performance indicators based on flowrate and pressure drop has been proposed to monitor fouling build up [10,11], plant pressure drop measurements have not been used in the literature to fit fouling models. This is not only due to the lack of availability of pressure drop measurements in most industrial facilities, but also to the inability of traditional fouling rate models to capture the thermo-hydraulic interactions of deposition inside heat exchangers.

A second limitation of traditional monitoring methodologies is that they do not account for the composition of the fouling layer when using plant data to assess the heat exchanger performance. The relative thermal and hydraulic impact of fouling depends on the thermal conductivity of the deposit layer which is a function of its composition. The same thermal performance detected using plant data can be explained by a variety of combinations of fouling thickness and thermal conductivities of the fouling layer. As a result, it is paramount to estimate correctly the deposit thermal conductivity. However, this is not an easy task. As previously noted by different authors [12,13], ageing plays a very important role in the case of crude oil fouling by gradually increasing the thermal conductivity of the organic deposits in the fouling layer. Things complicate even further when the fouling layer deposit is not entirely organic but it is made of a mixture of both organic and inorganic material. A significant proportion of inorganic material (15-80%) has been found in various field [14,15] and laboratory studies [16–18]. Notably, the inorganic material typically found in deposits collected from refinery PHTs (such as SiO_2, $CaSO_4$, Fe_2O_3, FeS) have higher thermal conductivity than organic matter (1-5 W/mK, compared to 0.2-1 W/mK for organic matter) [19–21]. It is therefore clear that ignoring the presence of inorganic material may lead to significant errors in assessing the thermo-hydraulic performance of heat exchangers. Unfortunately, this information is not readily available and can be obtained only via analytical characterization of the deposits after shutting down a heat exchanger for sampling.

In this paper, the detailed dynamic, distributed model for heat exchangers undergoing fouling previously developed by Coletti and Macchietto [2], and implemented in Hexxcell Studio^{TM} [22] for organic fouling, is extended to account for the presence of inorganic material. A case study based on field data reported by Mozdianfard and Behranvand [15] is used to illustrate the importance of using pressure drops and deposit composition when assessing the performance of refinery heat exchangers.

CASE STUDY BACKGROUND – ESFAHAN REFINERY

A recent field study published using data from the Esfahan refinery (Iran) [15] provides a rare and comprehensive set of data of both plant measurements and deposit characterization. The authors gathered data for over 4 years of operation including pressure drop, temperature and flowrate measurements in a number of heat exchangers in the pre-heat train. The network is composed of 12 shell-and-tube heat exchangers, comprising a total of 24 shells. Taking advantage of a major shutdown and cleaning, during which an overhaul of the network structure was carried out, the authors were able to analyse the composition of samples collected in different heat exchangers along the network (9 deposits were collected on shell-side and 1 on the tube-side). Three main types of fouling deposits were observed: i) Corrosion products, at the cold end (before desalter), with leakage problems reported in previous cycles; ii) Inorganic salts, in units close to the desalter (upstream and downstream); iii) Organic material, especially severe at the hot end.

The composition of the fouling deposits is observed to evolve along the pre-heat train, which indicates a gradual change of the predominant fouling mechanism.

The key heat exchanger in the network, i.e. the most affected by fouling and focus of the retrofit (E155AB), is studied in detail in this paper by using the data reported in Mozdianfard and Behranvand [15]. Severe fouling in this unit, located between desalter and flash drum (Figure 1), led to an unacceptable increase in pressure drops (up to 3.5bar), which, in turn, led to the decision of shutting it down for cleaning and overhaul the network structure. This is a clear example where hydraulic performance limitations, as opposed to thermal ones, are the driving factor. The analysis of the deposit inside the tubes revealed a composition of 80wt% inorganic matter (including SiO_2, $CaSO_4$, and iron oxides) and only 20wt% organic. According to the authors, this large content of inorganic salts indicated operational issues with the desalter. The temperature of the desalter was indeed found to be outside the optimal operating range, a likely consequence of fouling in other parts of the network, causing malfunctioning of the unit.

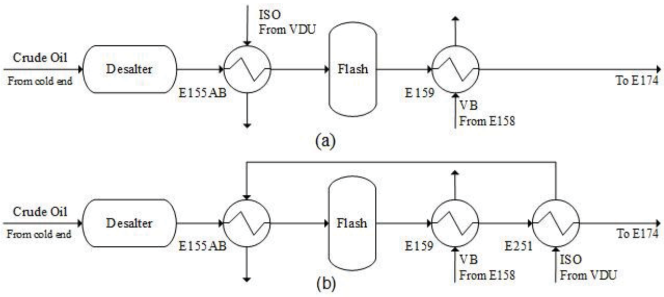

Figure 1 Network structure before (a) and after overhaul (adapted from Mozdianfard and Behranvand [15]).

Fouling mitigation in E155AB was expected after the overhaul which introduced the extra heat exchanger (E251AB in Figure 1b). Unfortunately, this was not the case and the pressure drop raised quickly reaching values of 3 bars after 1 year of operation. However, an improved thermal performance of the network was achieved as the furnace inlet temperature increased by more than 5ºC on average.

This study aims to (i) apply the advanced heat exchanger model by Coletti and Macchietto [2] to capture the thermo-hydraulic behaviour of E155 (ΔP and T) and (ii) evaluate the effect of inorganic material on performance. The available data in the reference paper is used together with realistic assumptions to provide a full specification of the heat exchanger model. Parameter estimation is carried out in order to fit the plant data and capture the dynamics of fouling and its impact on the performance of the exchanger. The main objective is to assess whether the main trends in the observed measurements are captured, even in the presence of the limited available data and number of assumptions. A second objective is to evaluate various scenarios for fouling compositions and check whether the presence of inorganic has a significant impact.

MODELLING APPROACH

A detailed dynamic, distributed model for shell-and-tube heat exchanger undergoing fouling [2] has been extended to account for pressure drops in headers and nozzles [23] and for the effect of different composition of the fouling layer as detailed below.

Effect of Composition on Layer Heat Transfer Properties

The deposition rate is governed by a modified version of the threshold model introduced by Panchal *et al.* [24]:

$$\frac{d\delta}{dt} = \alpha' \mathrm{Re}^{-0.66} \mathrm{Pr}^{-0.33} e^{-E_f/RT_f} - \gamma' \tau_w \quad (1)$$

This equation is solved locally for each tube pass along the heat exchanger. The deposition and suppression constants, α' and γ', are related to those in the original model [24], α and γ, as follows: $\alpha' = \lambda_L^0 \alpha$; and $\gamma' = \lambda_L^0 \gamma$.

Previous studies taking into account ageing consider organic matter as the only component of the fouling layer [2, 12,13]. Fouling is considered to be initially formed as a gel-like material, with a typical conductivity of 0.2 W/mK (considered similar to that of crude oil). This substance gradually ages at high temperature forming coke, with a typical conductivity of 1 W/mK. The local conductivity of the deposit (in axial and radial coordinates) is calculated as follows:

$$\lambda_L = \lambda_L^\infty + \left(\lambda_L^0 - \lambda_L^\infty\right) y \quad (4)$$

where λ_L^∞ is the conductivity of the aged deposit, λ_L^0 is the conductivity of the fresh deposit, and y is the "youth" variable which varies from 1 to 0 following the kinetics proposed in [12].

In this study, the deposit is considered as a mixture of inorganic and organic material. Inorganics are reported to have higher thermal conductivity than organic deposits. Therefore, deposits formed by a mixture of inorganic and organic material are expected to have better heat transfer properties than deposits constituted only by organic matter. The conductivity of the inorganic/organic layer is here considered equal to the weighted average based on mass fraction of each pseudo-component. As a result, the conductivities of the fresh and aged deposit are:

$$\lambda_L^0 = w_{org} \lambda_{org}^0 + w_{inorg} \lambda_{inorg} \quad (5)$$

$$\lambda_L^\infty = w_{org} \lambda_{org}^\infty + w_{inorg} \lambda_{inorg} \quad (6)$$

Where w_j is the mass fraction of material j in the deposit, which can be inorganic (*inorg*) or organic (*org*). This model assumes perfect mixture of organic and inorganic materials in the deposit and no ageing of the inorganic part. More sophisticated conductivity models for heterogeneous solid materials are available for different internal structures [25]. Here this model is assumed adequate since no information on the internal structure is available.

Solution Method

The model, which comprises a system of partial, differential and algebraic equations (PDAE), was implemented in Hexxcell Studio™, and solved using a commercial solution platform [26]. The partial differentials on space domains are solved using a Centred Finite Discretization method, as explained in the reference work [2].

INPUTS AND MODEL SPECIFICATION FOR E155AB

Heat Exchanger Geometry

The heat exchanger considered, E155AB, comprises two AET type shells, each with two tube passes. Crude oil (cold fluid) flows through the tube-side and Isomax (hot fluid) through shell side. Not all required geometrical parameters are available in the reference paper [15] thus the missing ones (e.g. clearances and inlet/outlet baffle spacing) were determined using typical design values and rules of thumb [23,27–29].

Physical Properties

The crude oil processed is reported to have an average API of 33.9. Starting from this information, the physical parameters for the oil were extracted from the assay of a typical Iranian Light oil [30]. Isomax (ISO) is usually Vacuum Heavy Gas Oil (VHGO) obtained in the Vacuum Distillation unit (VDU) [31] where the atmospheric residuum from the CDU is distilled at low pressure. ISO physical properties are considered those of a VHGO cut of a typical light oil [30]. The key characterization factors for each fluid are shown in Table 1.

Process conditions

Two time periods are considered: Period 1 (before the overhaul) and Period 2 (after the overhaul). Crude oil inlet temperature over time is reported in [15] for both periods but crude oil flowrate is missing. In this paper, it has been assumed to be constant and equal to the reported working plant capacity, 370,000 bbl/d (working at 85% overcapacity) divided between the two identical lines in the refinery.

Information on the heating fluid (ISO) are also missing and assumptions regarding both inlet temperature and flowrate have been made to fully specify the model. Using an overall mass balance around the atmospheric and vacuum distillation columns, and based on the Iranian crude oil assay used as reference [30], the flowrate of the ISO stream has been estimated to be 16.4v% of the total crude oil.

Table 1. Key physical properties and input stream data.

	Crude oil	Isomax (ISO)
Fluid	Cold	Hot
Side	Tubes	Shell
Physical Prop.	Iranian light oil	VHGO
API	33.5	29.5
MeABP (ºC)	316	446
$\nu_{38\,^\circ C}$ (cSt)	6.41	13
Inlet T (ºC)	Plant data	Period 1: 440 (const.) Period 2: 400 (const.)
Flowrate (m^3/h)	1225.5 (const.)	201.3 (const.)

The inlet temperature of the ISO stream was calculated using the measured temperatures at the beginning of the each period, for which the exchanger is assumed to be clean. By applying a heat balance for the oil inlet/outlet temperature, the assumed flowrates, and the heat exchanger geometry in clean conditions, the resulting inlet ISO temperature is 440ºC for the first period and 400 ºC for the second period. This temperature is reasonable if the stream is considered to come directly from the VDU, where temperatures up to 538ºC are reached (this is the "cut" temperature reported for the Vacuum Residuum of the light Iranian oil). In period 2, a slight cooling of the stream occurs as it passes through the new exchanger (E251) before reaching E155 [15], which justifies the drop in inlet temperature of 40ºC after the overhaul.

Other assumptions

Other assumptions used in this case study are:

a) Shell-side fouling has a negligible effect on thermal performance thus it is not included in the analysis. However, some fouling on the shell-side was observed [15].
b) Both organic and inorganic fouling deposition follows the Ebert-Panchal model (Eqn. 1). Ideally, different fouling mechanisms should be modelled for each type of foulant, since they are likely to have different dependence on operating conditions.
c) Intermediate ageing rate is assumed [13].

MODEL FITTING AND EVALUATION PROCEDURE

Once the model has been fully specified, key fouling parameters are fitted to plant data in order to capture the dynamics of the deposition and its impact on the heat exchanger performance. The procedure used in this case study is as follows:

1) Several deposit compositions are considered. These values determine the conductivities for the ageing model and the local thermal conductivity of the deposit.
2) Key fouling parameters are fitted to pressure drop measurements for Period 2. Deposition (α) and suppression (γ) constants in Eqn. (1) are estimated, but the activation energy (E_f) is fixed to a typical value of 30kJ/mol.
3) Results are assessed for the deposit compositions considered by comparing thermal performance against outlet temperature measurements in Period 2.
4) Simulation results, obtained with the parameters estimated in Period 2, are compared to plant data for Period 1, assuming same deposit composition before and after overhaul.

RESULTS

Three deposit concentration scenarios were considered (Table 2). Case (a) corresponds to the crude oil fouling case with deposit exclusively formed by organic matter. Cases (b) and (c) consider two possible scenarios according to the analysis of tube-side deposits during the overhaul. In each case, the inorganic portion is represented by a model inorganic foulant that determines the contribution of this pseudo-component to the total conductivity.

Pressure drop measurements, rather than temperature, are used here to fit fouling parameters. Given the assumption of constant flowrate, points that cannot be explained unless flow variation is considered (i.e. measurement noise or temperature change are not sufficient to explain unexpected variation in the measure data), are excluded from the parameter estimation (marked in black in Figure 2). These include the first point in the data series which has a very low value (0.5bar) compared to the predicted one for nominal flowrate (1.30bar), 5 data points between days 150 and 400 when an unexpected peak is observed, and one outlier at 495 days. The estimation was carried out by using a maximum likelihood approach to find the best estimates of the parameters. A constant variance model with standard deviation of 0.3bar was used. Pressure drop in Period 1 was used to estimate α and γ for each of the three cases considered. The results are shown in the Table 3. The overlay plot for pressure drops is shown in Figure 2.

Table 2. Deposit concentrations considered in fitting procedure.

Case	w_{org} (%)	w_{inorg} (%)	λ_{inorg} (W/mK)	λ_L^0 (W/mK)	λ_L^∞ (W/mK)
a	100	0	-	0.20	1.00
b	20	80	1.0 (SiO_2)	0.84	1.00
c	20	80	2.3 ($CaSO_4$)	1.88	2.04

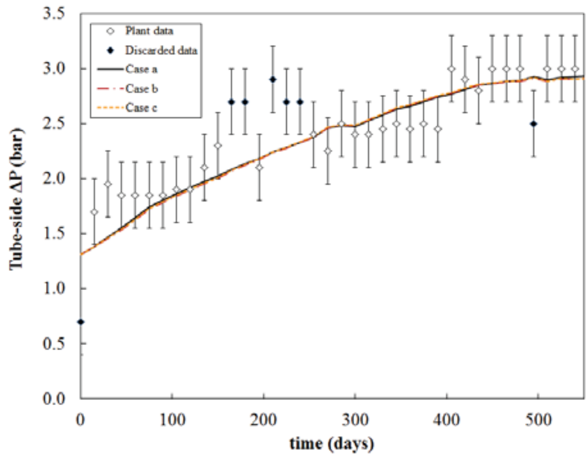

Figure 2. Model simulations vs. plant measurements for E155AB tube-side pressure drop over Period 2.

Table 3. Estimated parameter values and statistical significance.

Case	α ($10^3 m^2 K J^{-1}$) Value	$t_{(95\%)}$	γ ($10^{12} m^4 K J^{-1} N^{-1}$) Value	$t_{(95\%)}$	χ^2	α' ($10^3 m s^{-1}$)	γ' ($10^{12} m^3 N^{-1} s^{-1}$)
a	11.5	2.27	17.7	1.70	8.25	2.30	3.5
b	2.7	2.37	4.77	1.82	9.07	2.27	4.0
c	1.3	2.35	2.24	1.83	8.98	2.39	4.2
Ref.		1.7*		1.70*	40**		

*t-value > t-ref indicates parameter accurately estimated (standard deviation and the confidence interval are small compared to the estimated parameter).
**χ^2-value < χ^2-ref indicates good fit of the model to the experimental data.

Statistical test for accuracy of parameter values (t-test) and model fit (χ^2-test) to plant data were passed for all cases (Table 3). On the other hand, the parameters resulted to be highly correlated which is likely the consequence of having assumed a constant flowrate. For a more appropriate comparison of the estimated values, the overall deposition and suppression constants (Eqn. 1) are shown in Table 3. Once the model was fitted, simulations were run in order to generate outlet temperature data for comparison with the experimentally measured points. The results are shown in Figure 3.

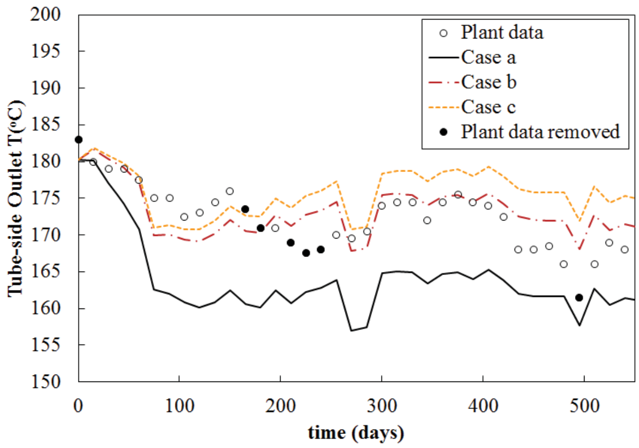

Figure 3. Model simulations vs. plant measurements for E155AB tube-side outlet temperature over Period 2.

In Case (a) (organic only deposit) model predictions do not match the outlet temperature measurements which are underestimated by approximately 10ºC over the entire period. This indicates that the resistance to heat transfer through the deposit layer should be smaller than the simulated one, and consequently the deposit conductivity of Case (a) is too low. The results greatly improve when considering heterogeneous deposits composed of 80% of inorganic and 20% of organic, as revealed by the experimental analysis. Inclusion of inorganic deposits such as $CaSO_4$ (Case c) leads to a slight overestimation of the outlet temperature for most of Period 2, suggesting that the thermal resistance is too low for the thickness considered (deposit conductivity too high). However, if an average inorganic conductivity equivalent to SiO_2 (Case b) is used, the temperature prediction follows more accurately the plant measurements.

It should be noted that only fouling on the tube-side is being considered here while shell-side fouling, which is reported in the original paper [15], was neglected. However, using pressure drops measurements to estimate the fouling parameters allows capturing the deposition rate on the tube-side independently from the shell-side thermal performance. Both shell-side and tube-side fouling resistances are accounted for with the tube-side effective thermal conductivity, which therefore should be equal (if there is no shell-side fouling) or lower than the actual tube-side conductivity. It can be concluded that the fouling deposit is most likely composed of ca. 20% of organic material and ca. 80% of inorganic material with an effective conductivity equal to or higher than that of SiO_2, although this is subject to the accuracy of the data and the assumptions made in the model inputs and formulation.

Finally, simulations for Period 1 were run using the deposit compositions, thermal conductivity and fouling parameters estimated in Period 2. The simulation results throughout the entire field study (Periods 1 and 2) are shown in Figure 4 and Figure 5. Remarkably, given the assumptions made, the simulation results broadly predict the plant measurements in both periods for Case (b), with noticeable under-estimation of outlet temperature for Case (a), and slight over-estimation of outlet temperature for Case (c).

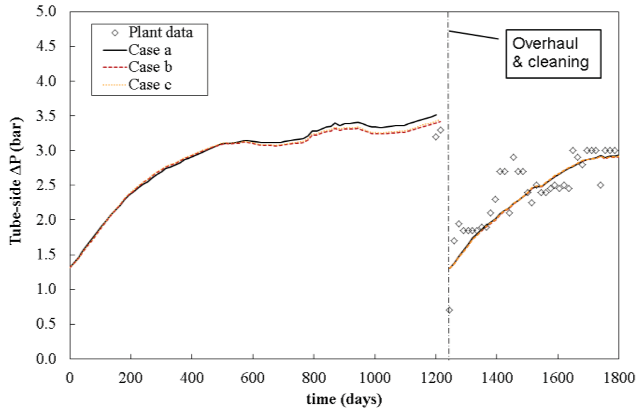

Figure 4 Model simulations vs. plant measurements for tube-side pressure drop in E155AB.

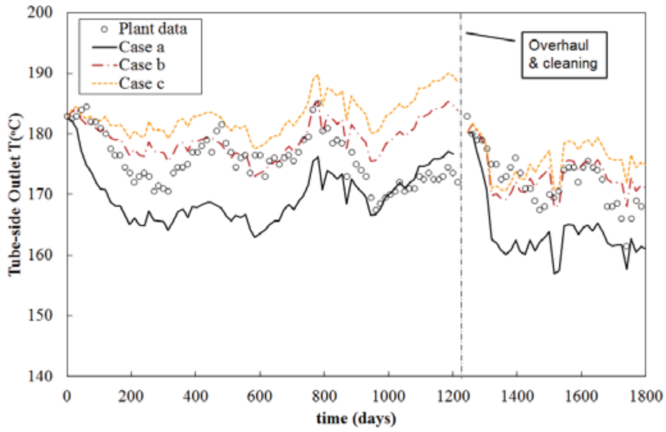

Figure 5 Model simulations vs. plant measurements for tube-side outlet T in E155AB.

CONCLUSIONS

A detailed dynamic, distributed model for heat exchangers undergoing crude oil fouling [2] has been modified to account for the effect of inorganic material on layer conductivity. The model successfully captures both temperatures and pressure drops over two operating periods of the heat exchanger most adversely affected by fouling in a field study at Esfahan refinery [15]. Trends in plant measurements, both before and after a major overhaul, are well captured despite the considerable number of assumptions used. This confirms the advantages of using a detailed model based on first principles that captures different phenomena involved with fouling and their interactions.

The case study presented highlights the importance of accounting for composition of the fouling layer in the deposits to explain the reduction observed in both thermal and hydraulic performance of E155AB as fouling builds-up. By comparing model predictions with plant data it has been possible to infer the presence of the inorganic material in the fouling layer. Whilst the information on the exact inorganic species present in the fouling layer is subject to the mixing model used (Eqns. 4 and 5) and should be used with caution, the model has been proven useful, in the case study presented, to estimate the thermal conductivity of the inorganic portion of the deposits for a given ratio of organic vs. inorganic species. The thermal-conductivity required to obtain good agreement is well aligned with the results of the analytical characterization of the deposits collected during shutdown. If this information were available to the refinery during operations, it would have enabled to detect the cause (inefficiency at the desalter) much before than evidenced by the pressure drops problems. The introduction of composition on the description of the crude oil fouling layer is, to the authors' knowledge, a novel contribution to the literature.

A second novel contribution is the use of plant pressure drop measurements to fit fouling model parameters which has proven useful to calculate the thickness and thermal conductivity of the deposit.

This work shows the potential application of advanced thermo-hydraulic and fouling models to performance problem diagnosis, exploration of retrofit options, and detection of abnormal behaviour due to unexpected change in fouling composition. The development of models with the ability to handle multicomponent deposit is currently under way.

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