DISCUSSION OF USING FOULING RIG ANALYSIS TO MODEL INDUSTRIAL FOULING DATA

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ABSTRACT

'Dynamic fouling models' predict the rate of fouling of a specific fluid on a surface under its operating conditions. Use of such fouling models is a widely practiced methodology to manage fouling in oil refinery heat exchanger networks. The prediction models consist of fitting parameter(s) obtained through fitting the models to fouling data obtained from the field. Obtaining these fitting parameters from crude chemistry alone has been an area of interest in the fouling community.

Shell has been conducting crude oil fouling tests to understand the relationship between the crude chemistry and the fouling tendency that is then used to predict fouling behavior of specific crude blends processed at an operating refinery. This paper discusses steps that need to be addressed in the application of fouling model predictions from crude chemistry to model operating refinery exchangers.

INTRODUCTION

Preventive maintenance of heat exchangers subject to fouling through fouling prediction has become a widely practiced approach throughout the crude refining industry [1–3].

Understanding of hydrocarbon fouling has significantly progressed in the last decades (e.g., [4–12]). Fouling prediction has largely evolved under the following three approaches:

Approach 1

Experimental fouling data are analyzed for the rate of fouling, induction period, and deposit characterization. Such analysis has assisted in the construction of 'dynamic fouling models', which are prediction approaches where the rate of fouling is presented via the operating conditions such as the surface shear stress and the surface/film/bulk temperatures for a given fluid and a surface [13]. An example for the prediction of tubeside fouling is given below [14]:

$$\frac{dR_f}{dt} = C_1 \operatorname{Re}^{-0.66} \operatorname{Pr}^{-0.33} \exp\left(-\frac{E}{RT_f}\right) - C_2 \tau \quad (1)$$

Here, dR_f/dt is the rate of fouling, Re is the Reynolds number, Pr is the Prandtl number, *E* is the activation energy, *R* is the gas constant, T_f is the film temperature, and τ is the shear stress. C_1 and C_2 are dimensional constants.

Approach 2

Exchanger performance data obtained from the field are analyzed and combined with theory. The approach has been successfully used to identify the impact of fouling on the performance of operating exchangers. Examples include modeling crude oil fouling on both the tube and shell sides of the heat exchanger [15]:

$$\frac{dR_f}{dt} = \frac{C_3}{h} \exp\left(-\frac{E}{RT_f}\right)P$$
(2)

Here C_3 is the fouling propensity factor, *h* is the film heat transfer coefficient, and *P* is the probability of attachment of fouling precursors to the surface.

Modeling heavy hydrocarbon stream fouling [16],

$$\frac{dR_f}{dt} = C_4 \frac{\tau^{-1.2}}{\mu^{0.66}}$$
(3)

Here C_4 is a dimensional constant, and μ is the dynamic viscosity.

Such models assist in quantifying key questions from the refineries, including

- What is the cost of fouling?
- When and which exchangers should be cleaned?
- What are fouling projections for retrofit and revamp projects?

Approach 3

Instead of fitting dimensional constants (fouling model parameters) in the fouling model to either experimental or field data [e.g., fitting field data to Equation (2) to obtain constant C_3], these could be linked to the chemistry of the crude processed via a pre-constructed matrix of fouling model parameters. These parameters are obtained from fitting the fouling model equation to test data obtained via

processing a variety of crude chemistries (e.g., sweet to sour crudes, heavy to light crudes, etc.). The result as an example would give a list of constants (e.g., C_3 or C_4) for a range of crudes with different chemistry. The constant could then be used to model fouling in heat exchangers in the field that are processing similar crudes.

Accounting for fouling on crude blends would provide further insight on

- pricing on the crude based on the problems which may arise during processing
- fouling management when processing new crude blends

Figure 1 is an example combination plot of crude slate and the corresponding fouling resistance profile obtained from field data. The plot identifies the specific crude slate that is responsible for causing acute fouling.

This manuscript discusses how Approach 3 may be used at the operating plant. Shell has been conducting crude oil fouling tests to understand the relationship between the crude chemistry and the fouling tendency, which is then used to predict the fouling behavior of specific crude blends processed at an operating refinery (Fig. 2). Crude oil tests are performed in a fouling rig, and the rate of fouling for a series of operating condition is extracted. This is then repeated for different crudes (and blends). The information is then used to model fouling in an operating preheat train processing similar crudes (and blends). In the analysis, it is understood that the nature of the deposit could provide key information on the type of likely fouling mechanisms. Deposit characterization is, however, not performed for this particular test set or that from the plant; these would be part of future work.



Fig. 1: Combination plot of crude slate processed and fouling resistance profile over time.

METHODOLOGY

Test

A range of tests have been performed at Shell to quantify the rate of intube fouling for a variety of crudes and crude blends covering a range of tubeside velocities, shear stresses, Reynolds numbers, and surface/bulk temperatures.

The test provides the following relationship:

 $C = f_1$ (crude chemistry)

Here *C* is the fouling model parameter.

Fouling rate = f_2 (*C*, operating condition)

Here f_1 and f_2 are different functions derived from the test data.



Fig. 2. Schematic process flow of utilizing laboratory fouling result to predict plant fouling behavior.

Case study model

For this discussion, one crude preheat train processes similar crude blends as those for which tests were performed. The schematic of the crude refinery preheat train model, shown in Fig. 3, highlights one possible configuration observed in the field. The model was constructed via HTRI SmartPMTM, a commercial software tool used for

performance monitoring and predictive maintenance of heat exchanger networks. The following information was required to construct the model:

- Detailed heat exchanger geometries
- PFDs and P&ID diagrams
- Monitoring data
- Stream thermo-physical properties with variation on a daily basis

Data reconciliation generates the fouling resistance profiles of all the operating exchangers. A simulation of the entire preheat train was performed to recreate the historical behavior via the fouling model parameter, *C*, that was generated using the crude blend properties.

This example network includes 38 shells. The heat exchangers would be processing either raw,

desalted, or flashed crude, with crude on either the tube side or the shell side. Some units experience only crude fouling, while others experience both crude-side and product-side fouling, as summarized in Table 1. However, only those located in the post flash section are in the range of the operating conditions of the tests.



Fig. 3. Schematic of a network preheat train.

Table 1. Summary of number of exchangers located on the preheat train.

	Raw crude		Desalted crude		Flashed crude	
	PS-NF	PS-F	PS-NF	PS-F	PS-NF	PS-F
Crude on tube-side	4	2	6 (3 OL)	2	1*	0
Crude on shell-side	9	0	5	2	4 (2 OL)	3

PS = Product stream; F = Fouling; NF = Non-fouling; OL = Off line

* The performance profile of this exchanger is shown in Fig. 4.

DISCUSSION

The crude chemistry of the crude used for the test matches the crude chemistry of the the crude in the cold sections of the preheat train (upstream of the desalter). However, the tests were conducted at conditions of the hot section (the post flash section of the preheat train).

Figure 3 illustrates the dynamic behavior of the plant. In the post flash section, E19AB were offline when the analysis was performed; E20ABC had crude on the shell side and residue stream on the tube side. E21AB are not segmental baffle units. For E18, a heat transfer enhancement technique is employed.

As the tests were performed on the tube side and the conditions of the tests closely resemble the operating conditions of E18, the fouling prediction was generated for E18 (Figure 4). Figure 4 plots the operating conditions (Reynolds number, cold-side skin temperature, tubeside wall shear stress, and tubeside velocity) obtained from monitoring data (marked as 'Field') and prediction (marked as 'prediction via crude chemistry'). However, the model does not account for the existence of the heat transfer enhancement device used for E18. The plot shows periods where the fouling model matches well (Period A) with the field observation. In the latter half (Period B), there is significant deviation (under prediction) via the fouling model. Period A may imply that the enhancement was not functioning properly or the fouling model underpredicted the plant performance.

The reason for the noisy profile in Period B is unclear and currently under investigation. As there have not been records of any operational activities (e.g., bypassing), possibilities of how such unaccounted operations affect this profile are being explored.

The observation raises several areas of interest that are discussed below.

Experimental analysis

Fouling surface. Fouling tests are conducted on a clean surface compared to an operating exchanger where fouling is likely to occur on a soiled surface. In one source [17], the contact angle of melted asphaltenes on a clean surface is reported to be larger than a fouled (coke) surface, implying that the asphaltenes have a higher probability of attaching to a fouled surface. It is also often observed in the industry that degree of cleaning in industrial unit strongly dictates how rapidly the performance drops when the unit is back online. E.g. a report indicated that a "cleaned" tube bundles retained significant amounts of residual fouling which triggered additional deposition when the tube bundles were placed back in service causing rapid decay in heat transfer [18]. Further understanding of such surface effects when translating the experimental result to the field may be required.

Crude treatment. Fouling tests are widely performed in rigs on raw crude, with a few on desalted crude. However, the crude properties in a preheat train vary from raw crude to desalted crude to flashed crude. It is difficult to get desalted crude for the tests because sampling is difficult.

Test geometry. Test geometry may not match with exchanger geometries in the field; that is, not all exchangers in the field process crude on the tube side. Hence, incorporating models that account for geometry [e.g., Equation (2)] to fit test data would be important.

Fouling stream. In an operating exchanger, there are instances where both the crude and the product stream foul. Hence, the segregation of tubeside and shellside fouling is important for prediction studies [16].

Test conditions. The range of tests performed does not cover the operating conditions of the exchangers in the entire preheat train. The viability of result extrapolation needs to be explored.

Once through and recirculation: Comparison of fouling test results for once-through and recirculating modes of operation needs attention as discussed by Cibotti et al. [19].

Residence time. The residence time of the crude in a heat exchanger may be several orders of magnitude greater than the residence time of the crude in a test rig.

Further discussions on the translation of fouling rig data to a field heat exchanger through accounting for both the impact of operating conditions and the context of the results obtained from the test rig have been discussed in literature [20].

Plant data analysis

If all operational strategies are not accounted for when reconciling plant data, the interpretation of field data may be erroneous.

All plant data consists of measurement uncertainties. Flow rates are commonly measured via Orifice meters recording volumetric flow usually at standard conditions. The conversion to the standard from the actual condition employs a predefined density relationship. The majority of refineries do not adjust the density relationship for different crude blends. Reporting of mass flow measurements via Coriolis meters are less frequent but may be available depending on the plant. Flow rates in flow splits may not always be measured. The flows would spontaneously adjust to equalize pressure drop in the absence of control valves. Online temperature measurements of the streams are common. However, depending on the refinery, the online temperature measurements may be sparse and would be combined with the use of temperature gun measurements. The readings from the temperature guns are likely to be less reliable because the reading is not the direct temperature measurement of the fluid. Most temperatures for streams connecting shells in series are not measured due to physical constraint on accessing the stream. A regorous data reconciliation method is essential on evaluating missing/incorrect flows and temperature readings. Pressure measurements are the least available. However, these measurements are critical in assessing two-phase flow behavior (crude boiling), product stream condensation, and hydraulic limits. Table 2 summarizes possible causes of errors in the field fouling resistance profile.

A heat exchanger can undergo changes in geometry, such as blockage of tubes or modification

of baffle arrangement and geometry during its service lifetime. These modifications may not be recorded in the design sheet due to poor information control. There are also uncertainties in the thermophysical properties of the associated streams. Most of the volumetric flow measurements are recorded after converting to standard conditions based on a pre-defined density correlation. These correlations are not updated regularly to reflect changes in the fluid being processed.

The correlations used to estimate film heat transfer coefficients, usually embedded in software, carry uncertainty as they are usually semi-empirical and correlated over a limited number of different fluids. All these factors contribute to uncertainty in the film heat transfer coefficients.

One methodology in handling this uncertainty is to include a correction term to the heat transfer coefficient relationship:

$$\frac{1}{UA_{o}} = \frac{1}{h_{o}A_{o}} + \frac{1}{h_{i}A_{i}} + \frac{R_{f,i}}{A_{i,cl}} + \frac{R_{f,o}}{A_{o,cl}} + \frac{R_{w}}{A_{o}} + f_{e}$$
(4)

Here A_o is the external heat transfer area, A_i is the internal heat transfer area, and R_w is the wall resistance. The subscript *cl* denotes clean conditions. f_e is a lumped uncertainty in the equation.

If the cause of the uncertainty is the exchanger geometry and the crude physical properties, applying correction terms to h_i and h_o would be a more direct approach.

Equation [4] can thus be rewritten as

$$\frac{1}{UA_o} = \frac{1}{c_i} \left(\frac{1}{h_o A_o} \right) + \frac{1}{c_o} \left(\frac{1}{h_i A_i} \right) + \frac{R_{f,i}}{A_{i,cl}} + \frac{R_{f,o}}{A_{o,cl}} + \frac{R_w}{A_o}$$
(5)

Here, c_i and c_o are correction factors for the film transfer coefficients.

Use of Equation (5) had been previously illustrated at the 2013 Heat Exchanger Fouling and Cleaning Conference [21].

Uncertainty	Comments			
Monitoring data	<i>Flow rates</i> : Unmeasured flow, errors in density correlations, broken/erroneous readings.			
	<i>Temperature</i> : Missing measurements, broken/erroneous readings (usually identified via heat balance).			
	<i>Pressure</i> : Less frequent measurements but important information on thermo-hydraulic performance.			
Thermo-physical properties	Thermo-physical properties are not always updated. Inaccuracies in the properties generated from thermo-physical properties and extrapolation of physical property measurements may introduce errors.			
Heat exchanger geometry	All geometry details are not always available. In cases where all details are available, a mismatch in geometrical conditions may be observed (especially for preheat trains constructed before the 1970s).			
Film heat transfer coefficient	The correlations used to evaluate film heat transfer coefficients are not necessarily tested for the heat exchanger stream. Reliable correlations must be used.			
Operation	Bypassing : Partial bypassing of exchangers is not always recorded (the information may be available on the white board from where the information is lost).			
	Heat loss: Heat loss from shells to the surroundings may occur.			
	Side stream injection: Injection of water, caustic, or antifoulants.			
	Desalter operation: Control of desalter operation.			
	Mechanical failure: These can include tube rupture			
	<i>Cleaning events</i> : Unreported cleaning events could mask the interpretation of fouling profiles.			

Table 2. List of uncertainties in preheat trains of an oil refinery.



Fig 4. Combination plot of crude-side Reynolds number, cold-side skin temperature, tubeside wall shear stress, tubeside velocity, and fouling resistance. Two sets of data are present on each plot: Field data (obtained from plant monitoring data) and prediction via crude chemistry (obtained from fouling model parameter from test rig results). Period A identifies a region with good agreement between prediction and field data. Period B shows the region where prediction and field data deviate.

Partial bypassing

It is common that partial bypassing of exchangers goes unrecorded in practice. Bypasses that are unaccounted for could result in overprediction of fouling resistance profiles [22]. As an example, Figure 5 illustrates a single exchanger with a bypass.



Figure 5. Exchanger with active bypass.

In some instances, the bypass 'A' is active (partial bypass). The illustration shows the total crude flow rate (FC_TOTAL) and the measured flow rate across the exchanger (FC_in), so the bypass flow can be calculated. If we assume that FC_in is not available and that FC_TOTAL is completely going through the exchanger (no bypass flow), the fouling resistance profile in Figure 6(a) is obtained. If the correct bypass flow is taken into account, the fouling resistance profile shown in Figure 6(b) is obtained.



Figure 6. Fouling resistance profile (a) without accounting bypass flow; (b) accounting bypass flow. The vertical regions marked A and B shows periods where the bypass was active.

The vertical regions marked A and B in Figure 6 are periods where the bypass is active. In Figure 6(a), Region A gives an overprediction and deviation from the correct profile. The discontinuity may be incorrectly interpreted as deposit removal or an unreported cleaning event. Also the slope of the fouling resistance profile changes, which may mislead how the crude chemistry has affected the fouling rate. Region B introduces noise to the data due to the unaccounted bypass (Figure 6(a)).

The analysis of field data and the translation of test results to the field data require systematic elimination of the possible questions discussed for both 'experimental data analysis' and 'plant data analysis'.

CONCLUSIONS

- Linking crude chemistry to predict fouling model parameters is important and could have significant applications in the plant.
- Application of test results to the field requires further research.
- Analysis of plant data could be challenging if not all operational strategies are recorded together with the monitoring data.

NOMENCLATURE

- A Heat transfer area, m^2
- *C* Fouling model parameter
- C_1 Dimensional constant, m² K W⁻¹ day⁻¹
- C_2 Dimensional constant, m² K W⁻¹ day⁻¹ Pa⁻¹
- C_3 Dimensional constant, h⁻¹
- C₄ Dimensional constant
- c_i, c_o Calibration factor
- *E* Activation energy, J mol⁻¹
- $f_{\rm e}$ Lumped uncertainty in R_f , K W⁻¹
- *h* Film transfer coefficient, W $m^{-2} K^{-1}$
- *P* Probability of attachment
- Pr Prandtl number
- $R_{\rm f}$ Fouling resistance, m² K W⁻¹
- R_w Wall resistance, m² K W⁻¹
- Re Reynolds number
- T Temperature, °C
- U Overall heat transfer coefficient, W m⁻² K⁻¹

Symbols

- μ Viscosity, Pa s
- au Shear stress, Pa

Subscripts

- cl Clean
- *i* Internal
- o External

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