EVALUATION AND PREDICTION OF THE THERMAL AND HYDRAULIC IMPACT OF CRUDE OIL FOULING ON EXCHANGER PERFORMANCE USING PRESSURE MEASUREMENTS

K. S. Chunangad, R. Y. Chang and R. P. Casebolt

ExxonMobil Research and Engineering, 22777 Springwoods Village Pkwy, Spring, TX 77389, USA
krishnan.s.chunangad@exxonmobil.com

ABSTRACT

The overall energy efficiency of a refinery is highly affected by the performance of its crude preheat train which is often severely hindered by fouling. Over the last twenty years, significant efforts have been made to develop design methods for crude preheat exchangers that use models describing the dynamics of the fouling process. The papers by Wilson et. al. (2005 and 2015) provide a summary review of developments in the use of threshold fouling models to predict crude oil fouling rates. One area that has however not received adequate attention is the use of pressure measurements to quantify the impact of crude oil fouling on exchanger pressure drop. The work described in this paper seeks to rectify that situation.

This paper reports on the analysis of operating data collected on exchangers from seven different crude preheat trains covering several run-cycles. The data includes pressure drop measurements as well as thermal performance measurements. It covers over 100 years of operation with a wide range of feedstocks and operating conditions and different tube metallurgies. The data has been analyzed using the dynamic and distributed mathematical model developed by Coletti and Macchietto (2011) and implemented in the Hexxcell Studio™ software, in four distinct phases. The simultaneous consideration of temperatures and pressures allowed estimating the growth of fouling thermal resistance and hydraulic resistance (fouling layer thickness) with time in the exchangers. In conclusion, the combined data from all seven preheat trains has been used to estimate the fouling parameters in the Ebert-Panchal (1999) model with deposit thermal conductivity, for specific exchanger groups sorted by temperature, shear stress and metallurgy, with satisfactory accuracy.

The above parameters would be used to develop an appropriate design and evaluation method for crude preheat exchangers to minimize fouling and maximize thermal-hydraulic performance over the run-cycle.

INTRODUCTION

In a previous project (referred to as Phase 0), the thermal data of several heat exchangers in six crude preheat trains was used to estimate the fouling parameters in the Ebert-Panchal (1999) model and this was used to develop a design method for crude preheat exchangers to determine the fouling thermal resistance (fouling factor) as a function of process conditions (film temperature, shear stress) and metallurgy. This method, however, did not account for the hydraulic impact of fouling, as there was no pressure drop data to determine the fouling hydraulic resistance (fouling layer thickness).

In this work, the daily thermal and hydraulic data with crude on the tubeside on 25 heat exchangers between the desalter and the furnaces on two different crude preheat trains was collected over a 5 year period. This amounts to > 100 years of operating data including flow-rates, inlet/outlet temperatures and inlet/outlet pressure readings.

The dynamic and distributed mathematical model developed by Coletti and Macchietto (2011), which integrates thermal and hydraulic aspects, was chosen to analyze the above thermal-hydraulic data set. This model solves a moving boundary problem that captures the growth of fouling layer with time along the tube-length and the corresponding reduction in flow cross-sectional area and its impact on the tubeside performance. It uses the Ebert-Panchal (1999) model for the local fouling thermal resistance and accounts for curvature effects in heat flux, variations of physical properties with temperature and detailed heat exchanger configuration. In this work, the full capabilities of this mathematical model, as implemented in the Hexxcell Studio software, have been used.

Firstly, we report on the analysis of the thermal-hydraulic data set, to estimate the fouling parameters in the Ebert-Panchal (1999) model with deposit thermal conductivity, for individual exchangers and groups of exchangers. Secondly, we test the ability of these parameters to predict the measured thermal performance of twelve exchangers in six different preheat trains over 23 run-cycles from the previous project. Finally, all the data from the seven preheat trains are divided into groups sorted by metallurgy, shear stress and film temperature and the fouling parameters with deposit thermal conductivity are estimated for each group. The key learnings from the analyses of each phase are discussed with related graphs.

METHODOLOGY AND RESULTS

The work has been performed in four phases. Phase 1 included analysis of the collected data for consistency, reconciliation of data with known errors and filtering out

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grossly inconsistent data and data with heat balance errors > 25%. The data analysis also identified the cleaning events and run-cycles with sufficient continuous data between cleaning events. After filtering and reconciliation, approx. 60% of the data in terms of number of units (14 out of 25) and data points (61 out of 108 years), equivalent to 58 run-cycles, could be selected for further study. The run-cycles varied in length from 102 days to 1584 days between cleaning.

In Phase 2, the advanced dynamic thermal-hydraulic model of Coletti and Macchietto (2011) and the estimation/simulation methodology implemented in the Hexxcell Studio software, were used to generate estimates of the Ebert-Panchal (1999) fouling parameters (α, E_a, γ) and deposit thermal conductivity (k_f) in the below equations, from the selected run-cycles.

$$\frac{dR_f}{dt} = \alpha Re^{-0.66} Pr^{-0.33} \exp\left(\frac{-E_a}{R.T_f}\right) - \gamma\tau \qquad (1)$$

$$\frac{dt_f}{dt} = k_f \frac{dR_f}{dt} \qquad (2)$$

In Phase 2a, fouling parameters with deposit thermal conductivity were estimated for every run-cycle of each heat exchanger using model-based parameter estimation techniques that give the best fit to the operating data. The results showed that the model could fit the data with an accuracy of $\pm$10% for heat duty and $\pm$0.2 bar for pressure drops, in most cases. See sample Validation Report in Fig. 1.

The green bands in the figure provide information on the measurement accuracy. For heat duty, it reflects the differences in the calculations using tubeside and shellside information. For outlet temperatures on one side, it shows the variation between the measured value and that calculated from other side duty. For pressure measurements, it reflects the accuracy of the pressure meters, assumed typically as 10kPa. If model predictions are within the green band, they are as good as the quality of the plant data. The red band is for the region where the model predictions are outside the plant data uncertainty. Some of the key observations from this phase are as follows:

(a) Multiple combinations of (α, E_a), γ and k_f could explain the same fouling rates, if there is not enough variation in the correlated variables to find a unique set of parameters.

(b) The Ebert-Panchal model cannot track large drops in flow rate and under-predicts the fouling layer thickness or sharp increases in flow rate where it over-predicts the thickness, due to linear relationship of fouling rate to shear stress, τ.

In Phase 2b, fouling parameters with deposit thermal conductivity were estimated for groups of heat exchangers consisting of multiple run-cycles of different heat exchangers in the same temperature region, shear and metallurgy, and across crude preheat trains. This provided a wide range of conditions, flows and temperatures for the correlated variables, allowing identification of a unique set of parameters, including finding optimum γ values for describing both linear and asymptotic evolutions of R_f. The hydraulic data was useful in finding the optimum γ values and reducing uncertainty in the average deposit thermal

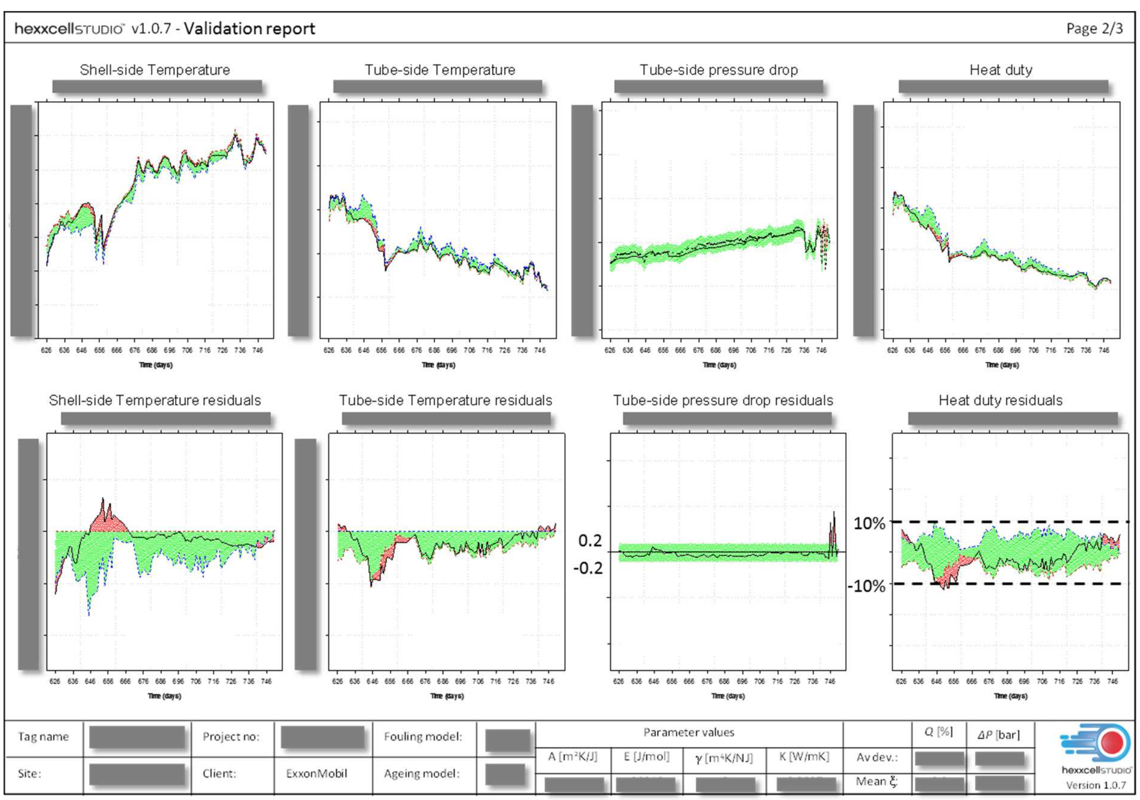

Fig. 1 Sample Validation Report – Measurement versus Simulation for one exchanger

conductivity. The performance predictions with these parameters, compared to actual data, are satisfactory, though less accurate than those determined from individual run-cycles of heat exchangers. One important observation from this phase is that a single set of parameters with optimum γ and thermal conductivity (k_f) could predict the performance of the hottest exchangers in two crude preheat trains processing different crudes, reasonably well.

In Phase 3, the fouling model parameters with deposit thermal conductivity determined in Phase 2b, were used to predict the measured thermal performance of twelve exchangers in six different preheat trains over 23 run-cycles from the previous project (Phase 0). For heat exchangers in the same refinery with operating conditions similar to those from which the parameters were estimated, the performance predictions were reasonably good ($\pm$20% for heat duty).

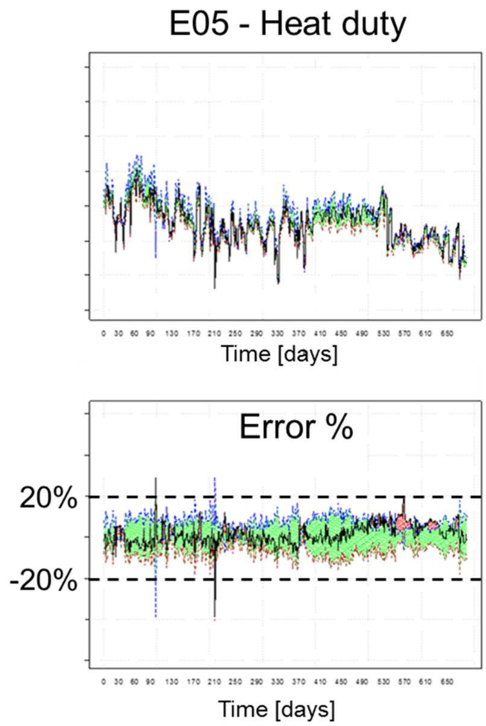

Fig. 2 Performance prediction of exchanger with similar operating conditions in same refinery

This was also true for heat exchangers with similar operating conditions from other refineries when the crude slates were similar. But when the crude compositions were significantly different, the performance predictions of those heat exchangers were with large errors (>$\pm$50% for heat duty). In one exchanger, the performance was predicted well for the first 45 days with a specific set of parameters, after which there was a constant offset in the heat duty prediction, which pointed to a change in crude slate and related fouling behavior since the operating conditions were fairly unchanged. See Fig. 2 and Fig. 3.

In Phase 4, all the available heat exchangers with thermal-hydraulic data and thermal-only data from the seven crude preheat trains were divided into groups sorted by metallurgy, shear stress and temperature. The advanced dynamic thermal-hydraulic model and estimation/simulation methodology implemented in the Hexxcell Studio software were used to generate average estimates of the Ebert-Panchal (1999) fouling parameters (α, E_a and γ) and deposit thermal conductivity (k_f), for each group. Then, the performance predictions with these parameters were compared with the actual data on the individual exchangers. Some key observations from this phase are as follows:

(a) In some cases, the performance predictions were better than those in Phase 2b due to better grouping of exchangers, while in other cases, the performance predictions were less accurate because of the larger size groups with varied data.

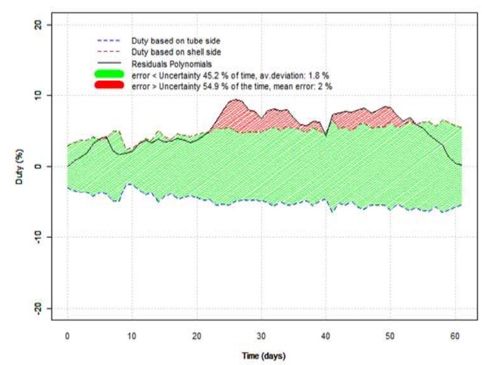

Fig. 4 Residuals in heat duty predicted for an exchanger using parameters from another group

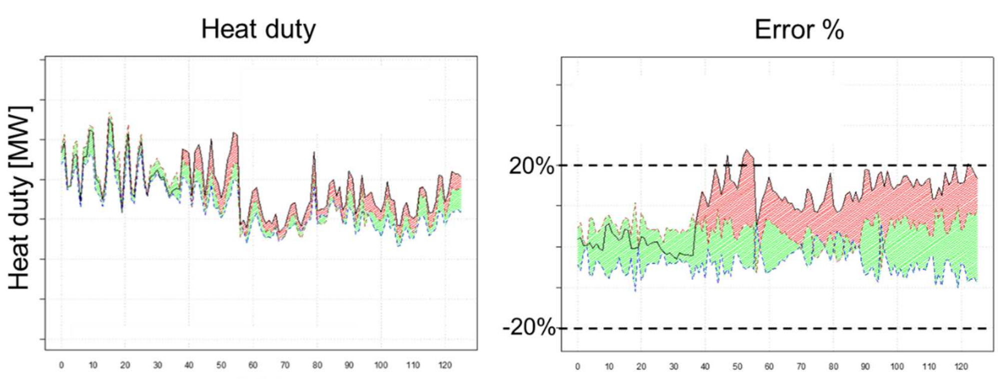

Fig. 3 Performance prediction of exchanger with similar operating conditions in different refinery

(b) For one exchanger, the performance predictions were better using parameters from another group than from its own group. Careful analysis showed that the operating conditions of this exchanger matched better with the exchangers in the other group, than those in its own group. This highlighted the importance of matching operating conditions more than other aspects such as metallurgy. See Fig. 4.

ANALYSIS AND LIMITATIONS

This work highlighted the following attributes and limitations of the Ebert-Panchal (1999) model.

- It is a semi-empirical model developed for organic fouling at high temperatures (> 204 °C) where chemical reaction is dominant. In these conditions, the parameter estimations for individual items and groups are more accurate and also, these parameters appear to be more portable across run-cycles, units and refineries.
- Network effects are important. Analysis of the performance of parallel branches of a crude preheat train showed that the level of fouling in upstream exchangers due to low shear or high shear, has an appreciable effect on the fouling rates of downstream exchangers in the same temperature region in parallel branches. This conveys that concentration of fouling precursors in the stream, the transport of those materials to the wall and the attachment mechanism could all be important, which are not accounted for in this model.
- The fouling rate has a linear relationship to wall shear stress in this model, which limits its ability to track large changes in the flow rate. Though linear, this suppression term (second term on right side of Eqn.(1)), is still valuable. See Fig. 5 for an example of a prediction with and without the suppression term for an item that experienced a sharp increase in flow rate.

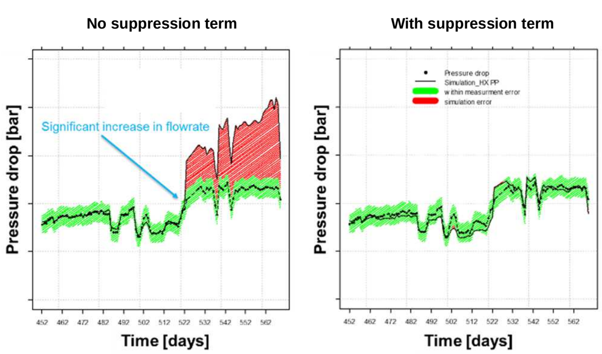

Fig. 5 Performance prediction of an exchanger with and without the suppression term

Pressure drop data was critically important to correlate the growth of fouling thermal resistance and fouling layer thickness with time through the deposit thermal conductivity. A fixed k_f-value was determined along with the fouling parameters for each group. The k_f-values determined for the different groups varied from 0.2 - 1.0 W/m K, which showed its variation across the train. There was not sufficient data to determine the variation of k_f with time, within each group.

A significant uncertainty with this work is the amount of shellside fouling. In most items, inspection data suggested that the dominant fouling was on the tubeside and so, all fouling was attributed to the tubeside. In some items, where shellside cleaning was not performed, the shellside fouling resistance was determined from the performance evaluation at start-of-run and maintained through the full run-cycle.

CONCLUSIONS

1. Pressure drop data, in addition to thermal data, are essential for evaluating the thermal and hydraulic impact of fouling.
2. Results show that the Ebert-Panchal (1999) fouling parameters with deposit thermal conductivity, when coupled with a detailed dynamic thermal-hydraulic heat exchanger model, can be successfully fitted to temperature and pressure drop data with satisfactory accuracy.
3. An improved design and evaluation method for crude preheat exchangers can be developed that accounts for the dynamic fouling deposition process by using the appropriate set of fouling parameters with k_f-value, for predicting the thermal and hydraulic performance of the exchanger over the desired run-length.

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NOMENCLATURE

E_a	activation energy	J/mol
k_f	fouling deposit thermal conductivity	W/m K
Pr	Prandtl number	dimensionless
R	universal gas constant	J/kg mol
Re	Reynolds number	dimensionless
R_f	fouling thermal resistance	m^2 K/W
T_f	film temperature	K
t_f	fouling layer thickness	m
t	time	s

Greek letters

α	deposition parameter	m^2 K/J
γ	suppression parameter	m^4 K/N J
τ	shear stress	Pa

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