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INVESTIGATON OF FOULING RATES IN A HEAT EXCHANGER USING AN INNOVATIVE FOULING RIG

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ABSTRACT

Heat exchanger fouling is one of the leading problems in the refinery processing. It has serious implications on both economic and environmental constraints of a refinery, from reduced throughput to higher CO_2 emissions.

Fouling is a complex phenomenon, comprising of several mechanisms interacting with each other r. It may depend upon several parameters such as process fluid, operating conditions, exchanger geometry to cite a few. Thus the fouling rate prediction, from refinery data, is difficult. In this context, the current article presents the results of a novel fouling rig, designed to mimic refinery conditions for different exchanger technologies. Firstly, shell and tube exchanger was examined under various operating conditions. The results highlight an increase in fouling rates with increasing temperature and decreasing shear. The rates reported were in-line with plant data. Furthermore, test results also demonstrated that, under given conditions, cross flow plate exchanger fouled lesser than shell and tube exchanger.

INTRODUCTION

Fouling in an exchanger generates additional resistances to heat transfer, leads to a decrease of the thermal effectiveness and causes an increase of pressure drop. In case of a fouled preheat train to maintain stable crude inlet conditions to the distillation column, the additional energy is compensated by the furnace. This leads to huge refinery cost & detrimental environmental effects.

Hydrocarbon fouling is a complex phenomenon with several mechanisms interacting with one another take place concomitantly. They can be broadly classified in two categories (Epstein 1983):

- Fouling due to the fluid physico-chemical properties. These fouling mechanisms such as particulate combination or sedimentation are predominant at low temperatures (T<180°C).
- Fouling mechanism involving modification in chemical composition in fluid. Such fouling mechanism includes chemical reaction and corrosion and is more prominent at high temperature (T > 180°C).

In the hot end of crude preheat train, fouling is mainly due to chemical reaction fouling. It is located downstream of desalter & closer to furnace where temperatures are higher.

Chemical reaction fouling as defined by various empirical relations (Ebert & Panchal, 1995) can be modelled by two simultaneously acting but opposing phenomena:

- A deposition term that depends on hydrocarbon velocity (Reynolds number), bulk and wall temperatures and hydrocarbon composition.
- A suppression term that depends on hydrocarbon velocity and heat transfer surface geometry (shear stress).

To examine these complex phenomena in a controlled laboratory setup, which is also representative of plant conditions, a novel and innovative fouling rig was designed and commissioned. Using this pilot plant a study was undertaken to achieve the following objectives:

- Identify the main parameters involved in hydrocarbon fouling (crude oil and atmospheric distillation residue);
- Assess heat exchanger performance under fouling conditions;
- Investigate the impact of heat exchanger geometries on fouling tendency;
- Compare experimental results to fouling models prediction;
- Predict industrial heat exchanger fouling rates and improve the efficiency as well as the design of the pre-heat train.

The current article presents the key results of the study

EXPERIMENTAL SETUP

Fouling Rig Conception

The fouling rates often encountered in the refinery are of the order of few micrometers / few millimeters of deposit per month. This rate is relatively slow to measure in laboratory scale under short timescales. Thus, to fasten the crude evaluation tests, several fouling rigs, such as Alcor unit, wire test etc, described in literature crude are often heated by a high power external heating source. To illustrate, the crude oil tested in laboratory conditions such as Alcor group typically shows a drop in temperature of 1-20°C in a test span of 2 to 3 hours. However, the same drop in exchanger outlet temperature for similar crudes processed in the refinery would take few days or months.

Enhanced heat flux accelerates the reaction kinetics leading to increased fouling rates, potentially rendering to a non representative conditions in the pilot plants. Furthermore, most of the test rigs identified operated upon single or annular tube as the test section, a simplified geometry wherein fouling occurs only on one side (Watkinson et al., 2003; Benett et al., 2007). No fouling test rig that approached both hydrodynamic and thermal conditions of crude preheat train exchange, was identified in the literature.

Thus, an innovative test loop was designed to study the hydrocarbon fouling in a pre-heat train of a refinery. This pilot plant enabled to conduct test under controlled conditions mimicking typical refinery operating conditions (nature of fluids, velocity, temperatures and fouling rate). The fouling rig also allowed us to investigate the fouling behaviour of various heat exchanger technologies.

The pilot plant consists of five closed loops in cascade. Each loop is connected to the subsequent one with a heat exchanger. The test loop is illustrated in the figure 1.

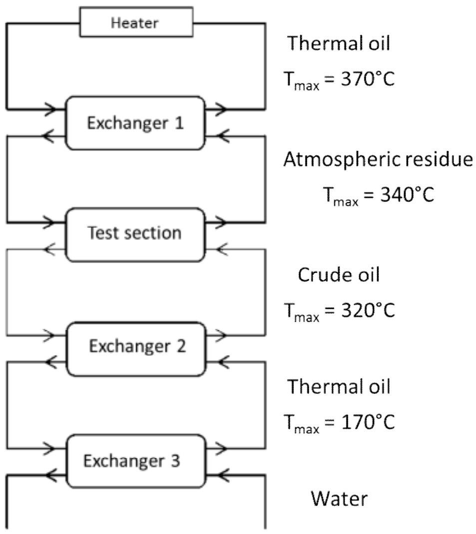

Fig 1: Schematic diagram of fouling rig

Since the fluids are operated in closed circuits, an inherent risk of depletion of fouling species present in the fluids was estimated. To manage such risks, several non–invasive sampling systems were also incorporated into the pilot to collect samples at regular time intervals during the test campaign. Several analyses were conducted to monitor any variations in fluids chemical composition. In case of detection of fluid modification, a fresh feed was planned to be used. However, as the rig is in cascade, the different parameters are interdependent on the one another, making it difficult to control the parameters and to decouple fouling in 2 sides of the exchanger. Thus a sensibility study for key parameters such as temperature of crude & residue was conducted prior to test campaign better handle the Rig.

The temperatures, pressure, exchanger geometry as well as hot side & cold side fluids of each loop were selected so as to simulate fouling conditions in a preheat train unit. As in refinery, fouling in pilot plant exchanger was expected to take place in both hot and cold side of test section (see figure 1). Indeed, fouling may also occur in exchangers that are in contact with crude oil or residue (Exchanger 1 and 2). Fouling is recorded in all heat exchangers during test-runs, through temperature and pressure measurement.

Test Sections

Shell and Tube heat exchanger. The first technology examined was shell and tube heat exchanger. It was designed to operate at similar heat flux, overall heat transfer coefficient, shear stress and also fabricated in standard material of construction as an industrial heat exchanger. Two crude oils were tested in this heat exchanger. The operating conditions used for this test campaign were chosen to be representative of a downstream desalter preheat train exchanger of a refinery. Dimensions of shell and tube exchanger and operating conditions are listed in table 1.

Table 1. Shell and Tube exchanger overall dimensions and operating conditions

Operating parameters	Range
Crude temperature (°C)	200-300
Inside tubes velocity ($m\cdot s^{-1}$)	1-2.3
Inside tubes pressure (bar)	25-30
Overall heat transfer coefficient ($W\cdot m^2\cdot K^{-1}$)	500-600
Duty per unit area ($kW\cdot m^{-2}$)	12.5
Tubes diameter (mm)	19.9
Test section diameter (mm)	270
Test section length (m)	2.5

Cross Flow plate heat exchangers. The second technology tested was a cross-flow plate heat exchanger. It was designed so as to transfer the same duty as the shell and tube heat exchanger under the same operating conditions. Author can't be provided further details on this exchanger because of confidentiality clause. In order to compare the two tests sections, tests were conducted with identical fluids and same pressures and temperature range. Furthermore, shear stresses were chosen to be representative of a pre-heat train of a refinery.

EXPERIMENTAL RESULTS

Influence of Operating Conditions

Fouling rates were calculated from temperature and flow rate measurements. Flow-meter as well as temperature sensors, with high precision PT100 thermocouple), were embedded at the inlets and outlets of each heat exchanger.

Indeed, as fouling is initiated the temperature profile changes and global heat transfer coefficient decreases. This coefficient is estimated by:

$$U = \frac{Q}{A \cdot LMTD} \quad (1)$$

U ($W \cdot m^{-2} \cdot K^{-1}$) depends on the heat exchanger duty Q (W), the heat transfer area A (m^2), and the logarithmic mean temperature difference LMTD (K).

Fouling resistance is defined as the drop in the inverse of overall heat transfer coefficient. The fouling resistances of the three heat exchangers in which hydrocarbons circulated were monitored during the test duration. Evolution of fouling resistances in these exchangers demonstrated that both sides of the test section (atmospheric distillation residue and crude oil) encountered fouling. Also, the analyses of fouling deposits extracted from both side of the exchanger confirmed the experimental results.

The experimental results determined corresponded well with the industrial data. This validated the proof of concept of the fouling test rig.

A fouling index (I_f) is used to compare experimental results and is given by:

$$I_f = \frac{U_t}{U_{t=0}} \quad (2)$$

Where, $U_{t=0}$ is the overall heat transfer coefficient at the beginning of the test (clean heat exchanger) and U_t is the overall heat transfer coefficient at time t. Figure 2 represents the fouling index of one of the fouling tests.

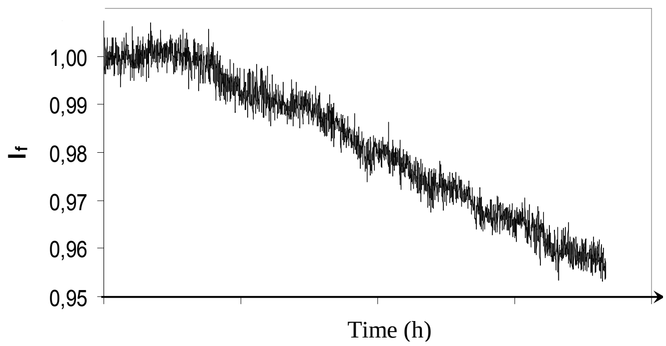

Fig 2: Fouling Index versus time

In figure 2, the drop in I_f with time signifies a loss in thermal efficiency of the exchanger due to fouling on both side of heat exchanger surface.

Tests were carried at 3 different crude velocities keeping the temperature constant and vice versa. Each test lasted at least 10 days.

Figure 3 represents the fouling index versus time for tests made at three different velocities (u1<u2<u3). The result is illustrated in the figure below.

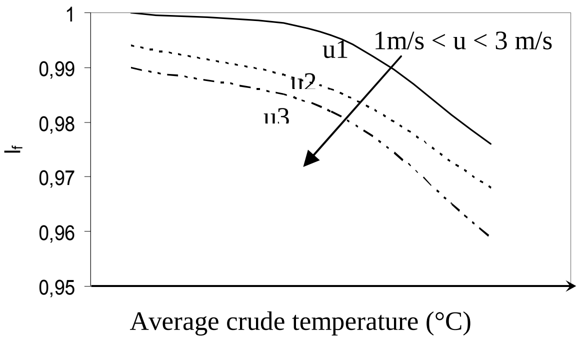

Fig 3: Effect of velocity and temperature on fouling index

For each temperature, results show that fouling index increases with an increase in crude velocity, indicating that fouling rate decreases with velocity. This can be attributed to the fact that as velocity increases, the shear stress increases thus enhancing deposit suppression rates.

Furthermore, it was demonstrated that fouling index decreases non-linearly with increasing bulk and film temperatures. An increase of the temperature promotes chemical reactions and thus exponentially boosts fouling deposit rates.

Influence of crude composition

Two crude oils were tested on the test loop, namely crude A and crude B each with each having 1 %w/w of asphaltenes. Using HLPS test (Hot Liquid Process Simulator), Crude A was determined to be a low fouling crude, whereas crude B to be a medium fouling crude. Figure 4 represents the fouling index of a test conducted with these two crudes at the same temperature and velocity.

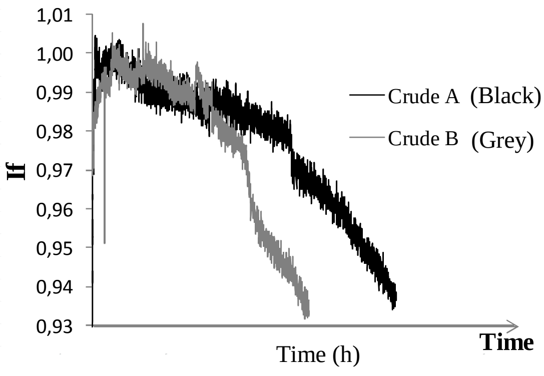

Fig 4: Effect of crude composition on fouling index

The same initial fouling index value was obtained with the two crudes. Nevertheless, fouling index of crude B decreased more quickly with time than that of crude A. This comparison confirms the effect of crude composition on fouling in the pilot plant. The author believes that the sudden fall observed in the I_f value in the middle of test may be due to sudden fluctuation in utilities operating conditions (flow-rate, temperature) in the rig.

Influence of heat exchanger geometry

The impact of heat exchanger technology was also examined during the test campaign. The two test sections were operated at same volumetric flow and shear stress. Figure 5 represents the fouling index for tests conducted at the same crude oil volumetric flow.

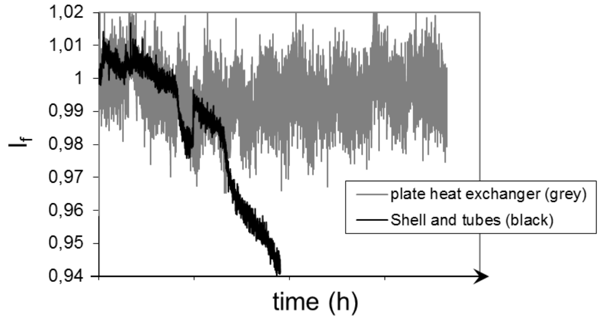

Fig 5: Influence of the heat exchanger geometry on fouling index at the same volumetric flow.

Figure 6 represents the fouling index for tests conducted at the same shear stress on the two test sections.

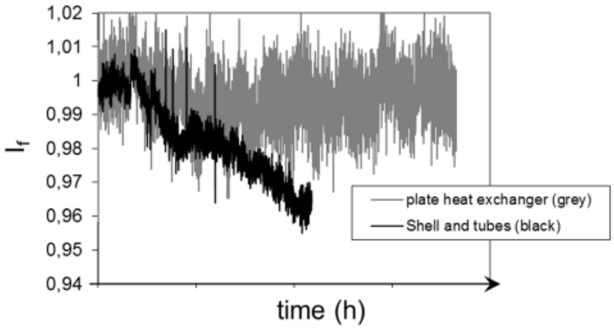

Fig 6: Influence of the heat exchanger geometry on fouling index at the same shear stress.

In Figure 5 and 6, the fouling index of the shell and tube heat exchanger decreases with time whereas the fouling index of the plate heat exchanger remains almost constant. It seems that in a plate heat exchanger the fouling tendency is mitigated under the given operating conditions due to higher turbulence.

Use of fouling model

Several fouling models have been established to predict the fouling rates based on operating temperature and flow rates. Ebert and Panchal and its variant are among the most frequently used models.

The Ebert and Panchal model (Ebert and Panchal, 1999) is based on the fouling threshold concept which corresponds to theoretical zero fouling for a given operating temperature and velocity. From the model, typically at low temperatures and high velocities, fouling rates can be minimized. The fouling rate is estimated by taking the difference of two opposing factors, a deposit term and a suppression term:

$$\frac{dR_f}{dt} = \alpha \cdot \mathrm{Re}^{\beta} \cdot \mathrm{Pr}^{-0.33} \cdot \exp\left(\frac{-Ea}{RT_{fi}}\right) - \gamma \cdot \tau \qquad (3)$$

Where α, β and γ are constant, E_a is the activation energy, T_{fi} is the film temperature and τ the shear stress.
Later using the above model, several other variants of the threshold models were established.

Panchal et al., 1995 [8] proposed a modified version in 1999 by introducing the Prandlt number in the deposition term:

$$\frac{dR_f}{dt} = \alpha \cdot \mathrm{Re}^{\beta} \cdot \exp\left(\frac{-Ea}{\mathrm{R} \cdot \mathrm{T}_{\mathrm{fi}}}\right) - \gamma \cdot \tau \qquad (4)$$

The use of the Prandlt number allows to take into account the variations of crude chemical properties with temperature.

Polley et al., 2002 basing on the same hypothesis, proposed a modified version of the Ebert and Panchal model. The new equation was:

$$\frac{dR_f}{dt} = \alpha \cdot \mathrm{Re}^{-0.8} \cdot \mathrm{Pr}^{-0.33} \cdot \exp\left(\frac{-Ea}{RT_{\mathrm{surf}}}\right) - \gamma \cdot \mathrm{Re}^{0.8} \qquad (5)$$

For this model, Polley et al., departing from the film temperature, used wall temperature to determine deposition terms. Also, one of the parameters (β), the exponent to Reynolds's number, was also fixed to 0.8. Furthermore, in the suppression term, the shear stress term was replaced by Reynolds number to the power 0.8.

Nasr and Givi, 2006 used experimental results of Saleh (Saleh et al., 2005) to establish another variant of the threshold fouling model:

$$\frac{dR_f}{dt} = \alpha \cdot \mathrm{Re}^{-\beta} \cdot \exp\left(\frac{-Ea}{RT_{film}}\right) - \gamma \cdot \mathrm{Re}^{0.4} \qquad (6)$$

To examine each of the models, the prediction of the models were compared with the experimental results obtained during the test campaign with the pilot plant. In total 10 test results were used. For each test, theoretical film or wall temperature were estimated by each model. The figure 7 presents, for each test, the percentage of difference between experimental results and fouling models predictions.

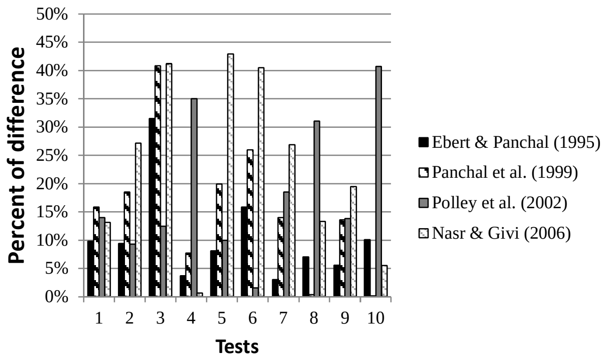

Fig 7: Comparison between shell and tube experimental results and fouling models prediction.

Fouling rates predicted by the model Ebert and Panchal (1999) were a good fit to most of the values measured by the fouling rig. Nasr and Givi model prediction corresponded well to the experimental data for tests at low velocities. (1, 4, 8 and 10).

Experimental results of standard shell and tube exchanger were also compared with experimental data found in the literature. The Panchal et al. empirical model, used frequently to predict industrial fouling rates, was optimized to fit with experimental data to minimize the errors [Bories and Patureaux, 2003]. The figure 7 represents the model prediction before (solid line) and after optimization (dotted line), in the graph. In this chart, blank markers signify non fouling tests and shaded markers are for fouling test.

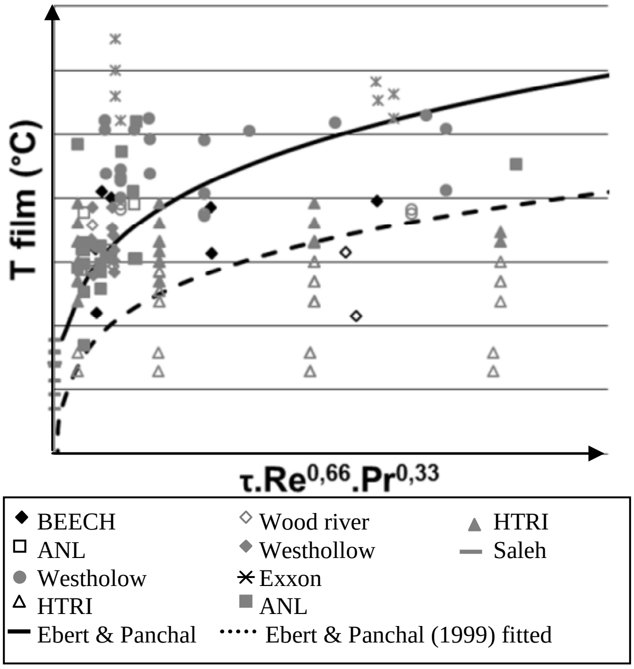

Fig 8: Models prediction on experimental data

For low $\tau{\cdot}Re^{0.66}{\cdot}Pr^{0.33}$, fouling results are widely scattered, values suggesting high variance and lack of repeatable measures. Nevertheless, for high $\tau{\cdot}Re^{0.66}{\cdot}Pr^{0.33}$, model optimization allows to reduce the difference between experimental and predicted results. Thus, the optimized model enabled to predict well at higher flows.

CONCLUSIONS

A novel test fouling rig was designed and commissioned to investigate the fouling behaviour of various heat exchanger technologies. Firstly, the influence of various operating parameters was assessed in a standard shell and tube heat exchanger. The results highlighted that fouling rate decreases with increasing velocity and decreasing temperature. Furthermore, it was also shown that the under given conditions use of a cross flow plate heat exchanger allowed to reduce the fouling rates as compared to that in a shell and tube heat exchanger.

NOMENCLATURE

A Area, m^2
C_p Heat capacity, J/kgK
I_f Fouling Index, dimensionless
LMTD Log mean temperature difference (K)
Pr Prandtl Number, dimensionless
R Universal gas constant, J/K mol
Re Reynold number, Dρv/μ, dimensionless
R_f Fouling Resistance, m^2K/W
t Time, s
T Temperature, K
U Overall heat transfer coefficient W/m^2K
v velocity,m/s
α Fouling model parameter, m^2K/J
β Fouling model parameter, dimensionless
γ Fouling model parameter, m^2K/J-Pa
μ Dynamic viscosity, Pas

Subscript

t time
fi Film
surf Surface

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