HYDRAULIC INVESTIGATION OF FOULING IN A CRUDE PREHEAT TRAIN

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Abstract. *In a petroleum refinery, a crude preheat train is a heat exchanger network that has the main goal to heat the crude oil that will be fed to the atmospheric distillation column. This network provides an energy integration scheme, which can reduce the fuel consumption in the fired heaters. During the operation, the thermal surfaces of the heat exchangers are subjected to fouling (e.g. presence of asphaltenes in the crude). This phenomenon affects the thermal effectiveness of the heat exchangers, adding additional thermal resistances in the system. As a consequence, there is a decrease of the heat transfer rate. In addition to this problem, fouling can also generate hydraulic restrictions because of the reduction of the flow area inside the tubes of the heat exchangers. Considering only the thermal consequences, there are many studies already developed in the literature, but in terms of the hydraulic restrictions, there are few studies analyzing this effect. Aiming to highlight the influence of the hydraulic aspects, this paper analyzes the increase of pressure loss in the heat exchangers of a crude preheat train during a certain period. This analysis is conducted through a mathematical tool for parameter estimation of the fouling thicknesses. Based on data of pressure drop and flow rate, the computational routine can determine the best set of thicknesses that reflects the hydraulic fouling impact. The application of the proposed procedure is illustrated through its application to operational time series data.*

Keywords*: fouling, pressure drop, crude preheat train.*

1. INTRODUCTION

In the refining process, the crude preheat train has the goal of heating the crude oil from ambient temperature to almost 380 ºC at the inlet of the atmospheric column. This train has a heat exchangers network which uses the energy from hot side streams of the atmospheric distillation tower to promote energy integration. The remaining heating comes from fuel burning in the furnace.

During the refining operation, fouling brings the undesired accumulation of materials from petroleum over the thermal surface of the heat exchangers and can impact the unit performance. This problem affects the thermal effectiveness of the system because reduces the overall heat transfer coefficient of the heat exchangers, generating an increase in the fuel consumption in the furnace. Another problem is that the pressure loss increases along the heat exchangers, due to the reduction of the flow area inside the equipment. In a more severe fouling scenario, hydraulic constraints may lead to a decreasing of the oil flow rate processed.

Aiming to diminish the thermal losses, several papers have focused on the development of techniques to mitigate the fouling effects (Panchal and Huangfu, 2000; Rodriguez and Smith, 2005; Seborg et al., 1989). One manner is to apply a cleaning scheduling for the heat exchangers. After the cleaning procedure, the heat exchanger is reassigned to the crude preheat train and the recovered heat transfer rate is increased. The exchanger cleaning brings costs and during the cleaning procedure the total heat transfer area is decreased and this operation policy involves a complex tradeoff. Several previous authors have approached this problem as an operational optimization problem (Lavaha and Bagajewicz, 2004; Markowski and Urbanie, 2005; Sanaye and Niroomand, 2007; Smaili et al, 2001).

Another alternative to handle fouling penalties is presented in Oliveira Filho (2007). This work describes an operating policy based on the optimization of stream splits, manipulating the flow rate through parallel branches according to the fouling status of the corresponding heat exchangers.

Tavares et al. (2010) expanded the analysis proposed in Oliveira Filho (2007) including the hydraulic effects in the model. The results show that a better operational point can be reached if there are hydraulic limitations in the heat exchanger network. Hydraulic aspects can affect significantly the plant operational condition and should be considered (Ishiyama et al., 2008).

In this context, aiming to understand the relationship between the hydraulic conditions and fouling in crude preheat trains, this paper proposes a hydraulic model for fouling evaluation. This analysis presents the application of a procedure of parameter estimation to determine the fouling thickness using some operational times series data.

2. HYDRAULIC MODEL

The hydraulic model for the determination of the pressure drop along the crude preheat train is composed of head loss relations for pipes, heat exchangers tubes and heat exchangers shells.

Eq. 1 presents the energy equation for pipes, considering incompressible and isothermal flow (Fox et al., 2001):

$$\frac{P_1}{\rho g} + z_1 = \frac{P_2}{\rho g} + z_2 + F \tag{1}$$

where P_1 and P_2 represent, respectively, the stagnation pressure upstream and downstream of the pipe section, z_1 and z_2 are the elevations, F express the relationship between the flow rate and the head loss in each element.

Eq.2 shows the total head loss (F_{total}) that is the sum of the head loss for each element presented in the train. The F_p represents the head loss for pipes, F_t the head loss for tubes inside the heat exchangers and F_s the head loss in the shell side of the heat exchangers.

$$F_{total} = F_p + F_t + F_s \tag{2}$$

Eq.3 presents the function F_p that corresponds to the Darcy-Weisbach equation:

$$F_p = f\left(\frac{L_p}{D_{p,i}}\right)\frac{v_p^2}{2g} \tag{3}$$

where f is the Darcy friction factor, L_p is the tube length, $D_{p,i}$ is the inner diameter of the pipe, v_p is the fluid velocity and g is the acceleration of gravity.

Eq.4 presents the structure for F_p in terms of flow rate (m):

$$F_p = f\left(\frac{8L_p}{g\rho^2\pi^2 D_{p,i}^5}\right)m^2 \tag{4}$$

where ρ is the density of the fluid.

The Darcy friction factor can be calculated using the Eq. 5, the Churchill equation (1977):

$$f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + \left(\frac{1}{(A + B)^{1,5}}\right)\right]^{\frac{1}{12}} \tag{5}$$

where A e B are represented, by Eq. 6 and Eq. 7, respectively:

$$A = \left\{2,457\ln\left[\left(\frac{7}{\mathrm{Re}}\right)^{0,9} + 0,27\frac{\varepsilon}{D_{t,i}}\right]^{-1}\right\}^{16} \tag{6}$$

$$B = \left(\frac{37530}{\mathrm{Re}}\right)^{16} \tag{7}$$

where *Re* is the Reynolds Number and ε is the tube roughness.

Eq.8 presents the head loss for the tubes inside the heat exchangers (F_t). Fouling can be hydraulically described as a reduction of the heat exchanger tube diameter, diminishing the cross-sectional area available for flow.

$$F_t = f\left(\frac{L_t N_{pt}}{(D_{t,e} - 2\delta_t)}\right)\frac{v_t^2}{2g} = f\left(\frac{8 L_t N_{pt}}{g\rho^2\pi^2(D_{t,i} - 2\delta_f)^5 N_{tp}^2}\right)m^2 \tag{8}$$

where L_t is the tube length, $D_{t,e}$ is the outer diameter of the tube, $D_{t,i}$ is the inner diameter of the tube, δ_f is the fouling thickness, v_t is the velocity inside the tube, N_{pt} is the number of tube passes, N_{tp} is the number of tubes per pass and f is the Darcy friction factor.

Eq. 9 presents the term F_s for head loss in shell side of a heat exchanger (Kern, 1950), considering segmented baffles (25 % baffle cut):

$$F_s = \frac{f m^2 D_s (N_B + 1)}{g 2\rho^2 D_{eq} A_c{}^2} \tag{9}$$

where D_s is the diameter of the shell of the heat exchanger, D_e is the equivalent diameter and N_B is the number of baffles.

Eq. 10 represents the corresponding friction factor*:*

$$f = 1{,}79\,\mathrm{Re}^{-0{,}19} \tag{10}$$

Eq.11 shows the section area, including the fouling thickness in the outer diameter:

$$A_c = \frac{D_s (L_{tp} - (D_{t,e} + 2\delta_f))L_{bc}}{L_{tp}} \tag{11}$$

where $D_{t,e}$ is the outer diameter of the tubes presented in the heat exchanger and δ_f is the fouling thickness.

The equivalent diameter, for tube layout 30º and 90º, are presented in Eq. 12 and Eq. 13, respectively:

$$D_{eq} = (4L^2{}_{tp}\ )/(\pi D_{t,e}) - D_{t,e} \tag{12}$$

$$D_{eq} = (3{,}44L^2{}_{tp}\ )/(\pi D_{t,e}) - D_{t,e} \tag{13}$$

3. PARAMETER ESTIMATION

Based on time series data of flow rate and pressure drop in crude preheat trains is possible to apply a parameter estimation procedure to determine the fouling thickness. In fact, each heat exchanger along a crude preheat train may present a particular fouling behavior, however, the usual availability of process instrumentation in atmospheric distillation units only provides information of the pressure drop along an entire branch of the crude preheat train, instead of data for individual heat exchangers. Therefore, the proposed procedure evaluates an "effective" value of fouling thickness for each branch of the crude preheat train. Despite the loss of information for individual exchangers, this "lumped" parameter is still useful to diagnose the behavior the system as a whole.

The corresponding mathematical problem of the parameter estimation procedure consists in the minimization of the sum of the differences between simulated and measured pressure drops during a period of time:

$$\text{Min } F_{obj} = \sum(\Delta P_{sim} - \Delta P_{med}(\delta_f))^2 \tag{14}$$

where F_{obj} is the objective function and the subscripts *sim* e *med* represent the simulated and the measured values. This problem is solved using the golden section method (Edgard and Himmelblau, 1988).

Considering a lack of information of the train piping, this problem can also be extended to identify the set of pipe lengths. In this case, it is selected a time series data after a general heat exchanger cleaning (i.e. $\delta_f = 0$) and the parameter to be estimated becomes the pipe lengths. The corresponding problem is solved using the simplex method of nonlinear optimization (Edgard and Himmelblau, 1988).

4. RESULTS

In order to illustrate the potentiality of the proposed procedure, it is presented its application to a set of data from a Brazilian refinery.

4.1. Example Data

The investigated branch of the considered crude preheat train is presented in Fig.1.

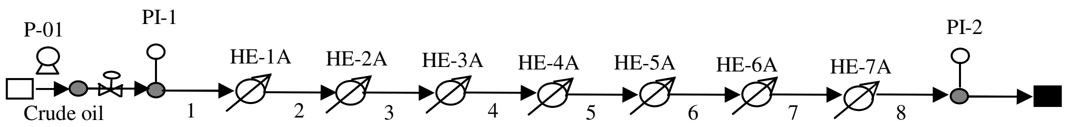

Fig. 1. Flowsheet of a branch of the crude preheat train.
Cold streams pipes: continuous line (numbered), PI – pressure indicator, HE – heat exchanger, P- pump.

The properties of the crude oil are assumed constant along the branch: the density is 866 kg/m^3 and the viscosity is $0{,}7.10^{-3}$ Pa.s. Table 1 presents the pipeline specifications. The roughness of all pipes is 46.10^{-6} mm

Table 1. Pipeline specifications

Pipeline	1	2	3	4	5	6	7	8
Diameter (m)	0,3048	0,2540	0,3048	0,3556	0,3556	0,4064	0,4572	0,4572

Table 2 presents the tube side fluid in heat exchangers. There is only one heat exchanger that has the crude oil pass through the shell side.

Table 2. Tube side fluid in Heat Exchangers

Heat exchangers	Tube side fluid
HE-1A	cold
HE-2A	hot
HE-3A	cold
HE-4A	cold
HE-5A	cold
HE-6A	cold
HE-7A	cold

Table 3 shows the data for cold tube side of heat exchangers and Table 4 the data for cold shell side of heat exchanger.

Table 3. Heat Exchangers data with crude oil in the tube side

Heat exchangers	Inner diameter (m)	Tube length (m)	Passes on shell and tube	Number of tubes
HE-1A	0,01485	6,096	1-2	1520
HE-3A	0,01485	6,096	1-2	1628
HE-4A	0,01485	6,096	1-2	1640
HE-5A	0,01485	6,096	1-2	1750
HE-6A	0,01485	6,096	1-2	(1750x2)*
HE-7A	0,0221	6,096	1-2	1403

*This heat exchanger has two shells

Table 4. Heat Exchangers data with crude oil in the shell side

Heat exchanger	Outer diameter (m)	Tube length (m)	Shell diameter (m)	Tube Pitch (m)	Tube Layout	Baffle spacing (m)
HE-2A	0,01905	6,096	1,016	0,02540	90º	0,27

4.2. Example Results

The operational time series was measured from 02/2007 to 03/2008. Fig. 2 and Fig. 3 present the series data in terms of hours for flow rate and pressure drop, respectively.

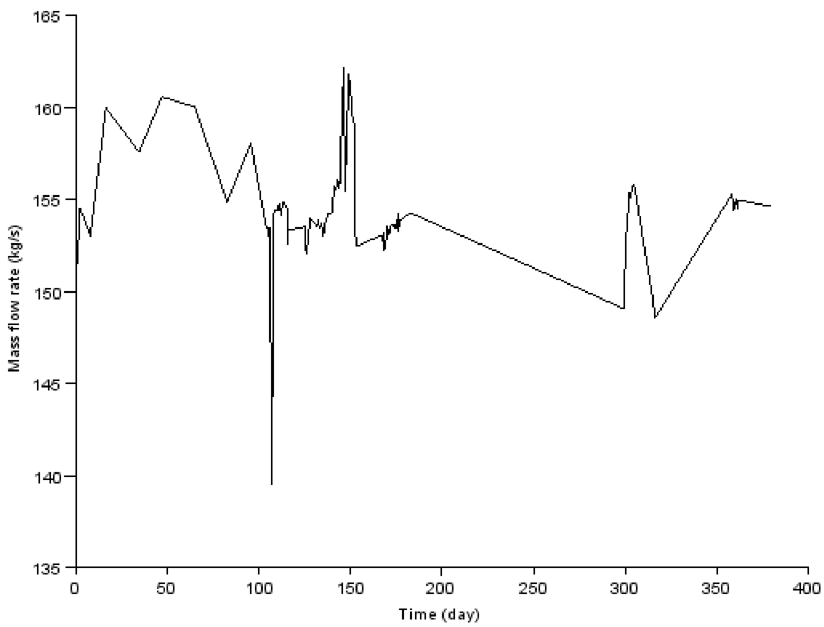

Fig. 2.Time series of mass flow rate

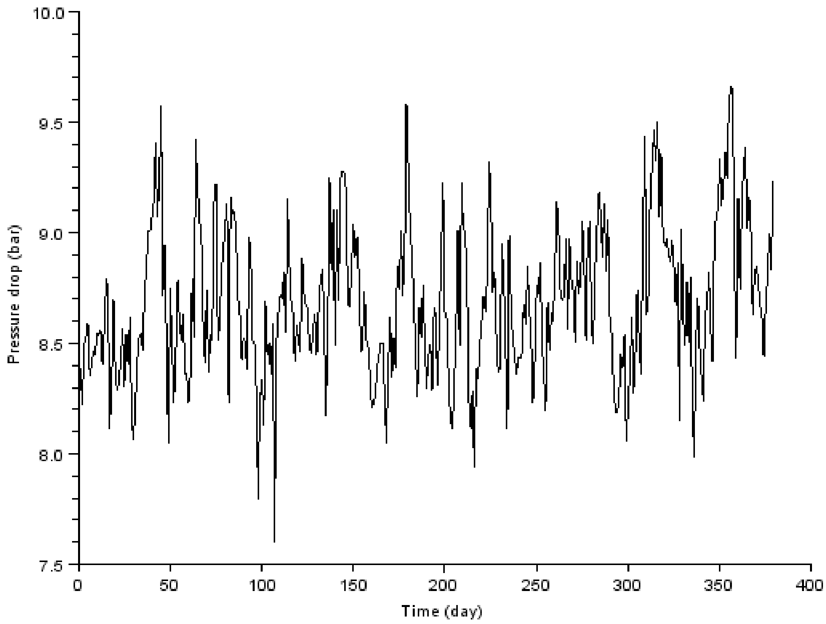

Fig. 3. Time series of pressure drop

In order to proceed to the parameter estimation of the pipe length, it was selected a previous set of data right after the cleaning of the heat exchangers. Table 5 present the results obtained for each tube.

Table 5. Pipeline results

Pipeline	1	2	3	4	5	6	7	8
Length (m)	20,9	0,0	550,6	14,7	313,6	603,6	81,6	211,1

It is important to point that since these pipes are interconnected in series and there are only two pressure indicators at the system extremities, these results must be interpreted considering the sum of the lengths as an effective result.

After that, it was estimated the fouling thickness. Fig. 4 present the values obtained for the total operational data. During this period, the values estimated ranged from 0,12 mm to 0,54 mm. It can be observed that there is an increase trend, revealing the fouling tendency of the crude preheat train.

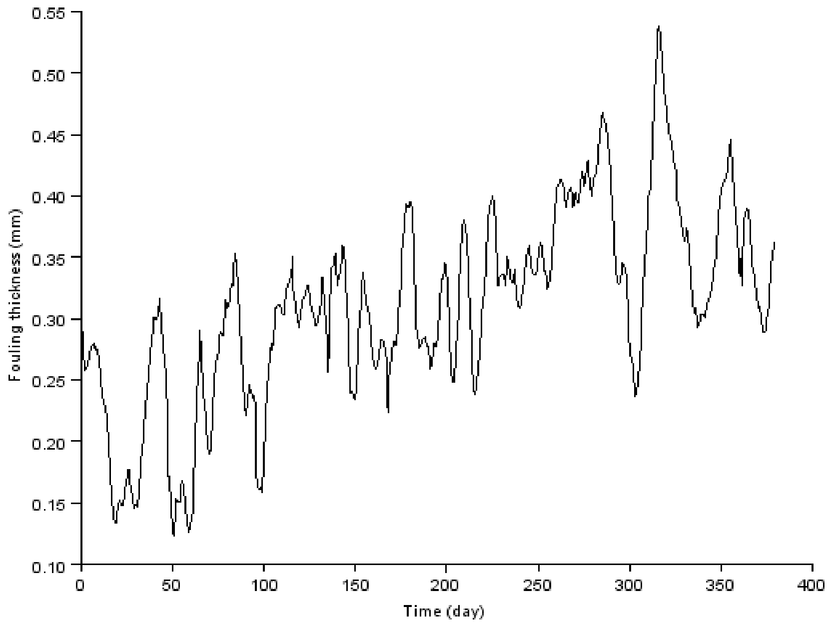

Fig. 4. Time series of calculated fouling thickness

Fig. 5 shows the results of the calculated pressure drop (continuous line) and the operational data (individual points) with time for the branch investigated. The procedure was able to provide a good adherence for the hydraulic model to the measured data.

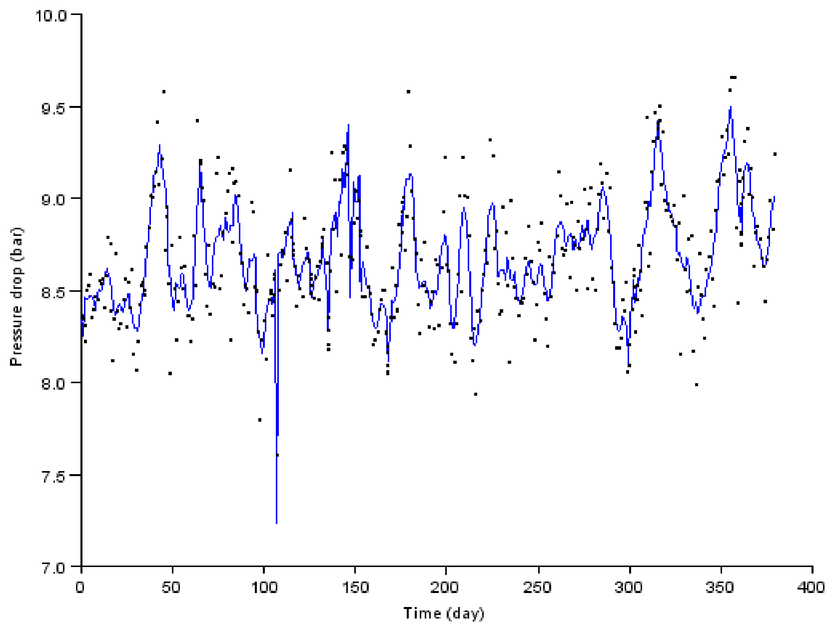

Fig. 5. Graph of the calculated pressure drop (continuous line) and the corresponding operational data (individual points)

The time series of the fouling roughness can be related to the fouling factor, considering the thermal resistance of a cylindrical layer:

$$R_f = \frac{D_{t,i} \ln(D_{t,i} / (D_{t,i} - 2\delta_f)}{2k_f} \tag{15}$$

For a assumed fouling thermal conductivity of 0.5 W/mK (Ishiyama et al., 2008), the corresponding time series of fouling factor for the first heat exchanger is shown in Fig. 6, where the fouling factor ranges from 0.0002480 m^2K/W to 0.001118 m^2K/W.

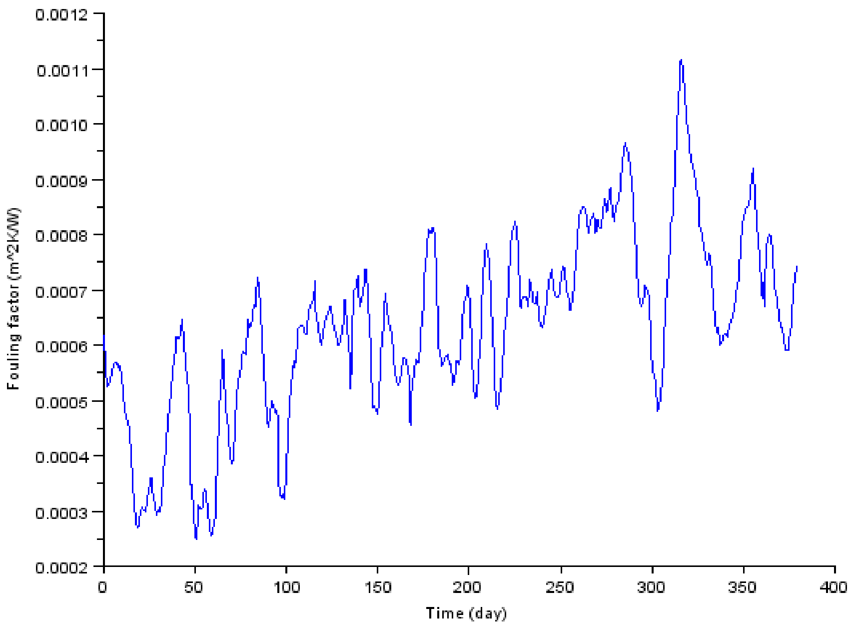

Fig. 6Time series of fouling factor

5. CONCLUSIONS

This paper discusses a procedure for determination of the fouling thickness in branches of crude preheat trains. The proposed procedure can be employed to diagnose the fouling increase during the refinery operation. The solution of a parameter estimation problem allow the identification of the fouling thickness in order to minimize the difference between calculated and measured pressure drop. The potentiality of the proposal is illustrated through its application for a real crude prehat train.

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