A NOVEL AND SIMPLE CRUDE OIL FOULING MODEL FOR PREHEAT SYSTEMS - A BRAZILIAN REFINERY CASE STUDY

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Abstract: Crude oil fouling is a complex phenomenon that usually occurs in refiner's heat exchangers. Such complexity is related to a wide range of factors which have influence in the fouling rate such as the fluid velocity, bulk and surface temperatures, fluids composition, heat exchangers design parameters, operating conditions, and others. In order to predict the fouling rate and extrapolate process inputs to other operating conditions and type of oils and blends, several models, most of them semi-empirical, is available in the literature. In this work, we propose a fouling model based on the mean fluid velocity and effective temperature and validate the results with operating data from a set of heat exchangers' pre-heat system from a refinery located in Brazil, obtaining errors of 10.19% and 2.84%.

Keywords: Fouling; Fouling model; Crude oil; Heat exchanger.

UM NOVO E SIMPLES MODELO DE DEPOSIÇÃO DE PETRÓLEO EM SISTEMAS DE PRÉ-AQUECIMENTO – UM ESTUDO DE CASO DE UMA REFINARIA BRASILEIRA

Resumo: A incrustação de petróleo bruto é um fenômeno complexo que geralmente ocorre em trocadores de calor das refinarias, devido à velocidade do fluido, as temperaturas de *bulk* e de superfície, às composições dos fluidos, parâmetros de projeto de trocadores de calor, condições operacionais e outros. A fim de prever a taxa de deposição e extrapolar as entradas do processo para outras condições operacionais e tipos de óleos e misturas, vários modelos têm sido propostos na literatura. Neste trabalho, é proposto um modelo de deposição baseado na velocidade média dos fluidos e na temperatura efetiva. Os resultados foram validados com dados de operação de trocadores de calor do sistema de pré-aquecimento de uma refinaria localizada no Brasil, obtendo-se erros de 10,19% e 2,84%.

Palavras-chave: Deposição; Modelo de deposição; Óleo cru; Trocador de calor.

1. INTRODUCTION

The fouling phenomena directly impacts the efficiency and effectiveness of heat exchangers, generating economic losses due to the increase in energy consumption. Such impact can be more significant when fouling occurs in preheat systems from crude oil refineries, where different types of oils and blends can drive fouling mechanisms on both tube and shell sides.

The fouling phenomena can be classified as, (a) adhering of substances formed by chemical reactions on the heat exchange surface material, (b) sedimentation of suspended particulates, (c) accumulation of products on the equipment surface as a consequence of corrosion reactions, (d) precipitation or crystallization of supersaturated substances on the process streams and (e) increase of biological microorganisms on the heat exchanger equipment surface. The fouling may also occur when two or more of these phenomena are combined and interact to each other. In some circumstances, certain mechanisms take place in a higher proportion, such as crystallization of inorganic compounds, corrosion, chemical reaction of organic compounds and fouling of particulates [1], [2].

The phenomenon of fouling in heat exchangers is a common and recurrent problem, especially in crude oil preheat systems. In this sense, the description of fouling as a mathematical model has been improved since the work of Kern et al. [3] which defined the fouling rate as a function of the difference between the rate of deposition and the rate of removal, Equation 1.

$$\text{Fouling rate} = \text{Rate of deposition} - \text{Rate of removal} \tag{1}$$

These two kinds of rates are basically how models are currently described, where reaction or transport-reaction based models are related to the rate of deposition, whilst shear-based or mass transfer models are related to the rate of removal. From this definition it is possible to realize the existence of a threshold fouling region, over which indicates the operation conditions (temperature and flow) where fouling may or may not occurs. This concept was theoretically stablished by Ebert and Panchal [4] and later experimentally proven by Knudsen et al. [5] using a pilot plant. One can locate the threshold by setting the fouling rate to zero, equating the terms and solving for temperature and flow velocity.

The complexity associated with the prediction of fouling, or the poor understanding of such mechanisms have been motivated many other authors [2], [5], [6], [7] to propose a general model capable to predict the rate of fouling, for both rates of deposition and removal. In this work we propose a simple model that considers the influence of a mean fluid velocity and an effective temperature on the fouling rate. It was validated for an oil pre heat system from a Brazilian refinery company. A relatively small deviation shows the simplicity of the model to both experimental and operational plant data.

1.1. A Novel Fouling Model

The crude oil fouling mechanism is difficult to explain due to the many variables involved, such as temperature, flow regime, material surface properties, impurities, changes in oil properties during processing, residence time inside the heat exchanger and oil composition. To simplify the fouling prediction, the following assumptions are presented: (a) an increase in velocity, also increases the shear stress until a point where the deposition layers are removed at the same proportion as they are formed; (b) be able to predict the fouling rate for heat exchangers in operation with an uncertainty of 10% [8]; (c) be able to adapt to different types of data, being sensible to changes in fouling rate process, and identifying disturbances in the system; (d) adjustable parameters to disturbances, preserving the physical principles of the system; (e) to consider the effect of temperature in the in the "Arrhenius" term; (f) to consider the influence of the mean velocity on shear stress forces and convective heat transfer coefficient.

Although the fluid properties, such as density, viscosity, heat capacity, thermal conductivity, and others, have an important role on fouling, they are not well calculated with proper accuracy or are usually considered constant along the heat exchanger. As claimed by Polley et al. [9], those properties don't qualitatively affect the obtained results because the errors will impact only the model parameters that absorb the properties characteristics.

Therefore, the proposed model will depend on both available data from experiments or industrial plant process and is represented by Equation 2.

$$\frac{dR_f}{dt} = \alpha v_m^{\beta} \exp\left(\frac{-G}{T_m}\right) - \gamma v_m^2 \quad (2)$$

where α, β, G and γ are parameters to be estimated. The term v_m is the average velocity between the cold and hot fluids and T_m refers the average temperature between the tube and shell bulk temperatures.

The R_f term is then calculated using Equation 3, which is numerically represented for n points in a data set (R_f versus time (t)) .

$$R_{f(n+1)} = R_{fn} + \frac{dR_f}{dt}(t_{n+1} - t_n) \quad (3)$$

2. METHODOLOGY

The methodology presented herein involves two steps. The first one refers to the analysis and processing of refinery data and the second comprises the outliers' removal strategy based on an uncertainty propagation method [10].

The first step starts with the standardization of the time variation between measurements to the number of days. After converting the time, we multiply the R_f by a factor of 10^3 to make the data easier to read and manipulate. The temperature provided must be converted to Kelvin (K), and then the average temperature between the bulk temperatures on the shell and the tube sides are calculated. From the values of diameter and volumetric flow on both sides, it is possible to calculate the velocities of the hot and cold fluids and then compatibilize them in relation to the maximum velocity. With these procedures, the data is ready to be processed.

ISSN: 2357-7592

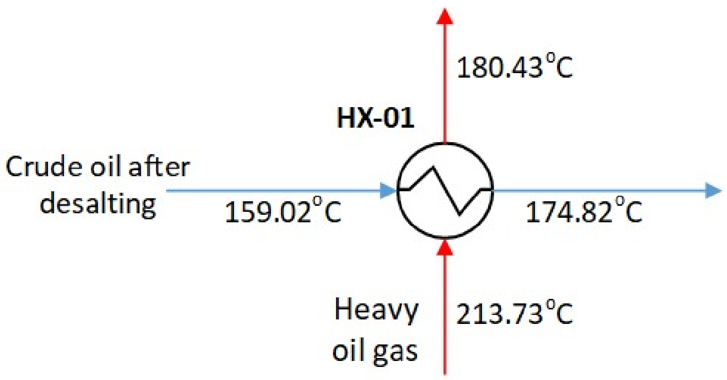
In the second step, initially, a mean value of the fouling resistance ($R_{f,m}$) is calculated for each heat exchanger data set. Then, the difference between each R_f point and the ($R_{f,m}$) is calculated. The next stage is related to the removal of the outliers, which can impact the model prediction, where a procedure proposed by Crittenden et. al. [10] to evaluate the measurement errors associated with each heat exchanger. Using this approach, the uncertainties propagation was used as a criterion to define a lower and upper bound, to check possible anomalies in the system in terms of cold and hot fluid temperatures and flowrates and to decide which R_f set of data will be analyzed and removed from the original databank.

As a constraint an uncertainty coefficient between 95 and 100% was used, ensuring that the error be minimized, respecting the similarities between the calculated and acquired values.

3. CASE STUDY

The case study comprises the application of the proposed model to data from a heat exchanger pre-heat system from at the Brazilian Refinery Unit. The heat exchanger operates with heavy oil (cold fluid) after being processed in a desalter and a stream of heavy oil gas (hot fluid). Figure 1 shows the heating system and the average temperatures of hot and cold fluids at the inlet and outlet streams.

Figure 1 – Crude oil heating system.



For the heat exchanger there is a certain number of outliers, which are the values of R_f that exceeds the upper and lower limits imposed by the uncertainty propagation error related to $R_{f,m}$. **Erro! Fonte de referência não encontrada.**1 shows the percentages of outliers and the uncertainty propagation present in the heat exchanger data.

Table 1 - Outliers and uncertainty propagation percentage for the heat exchanger in the pre-heat system.

Heat exchanger	HX-01
UNCERTAINTY PROPAGATION	10%

ISSN: 2357-7592

OUTLIERS	27%

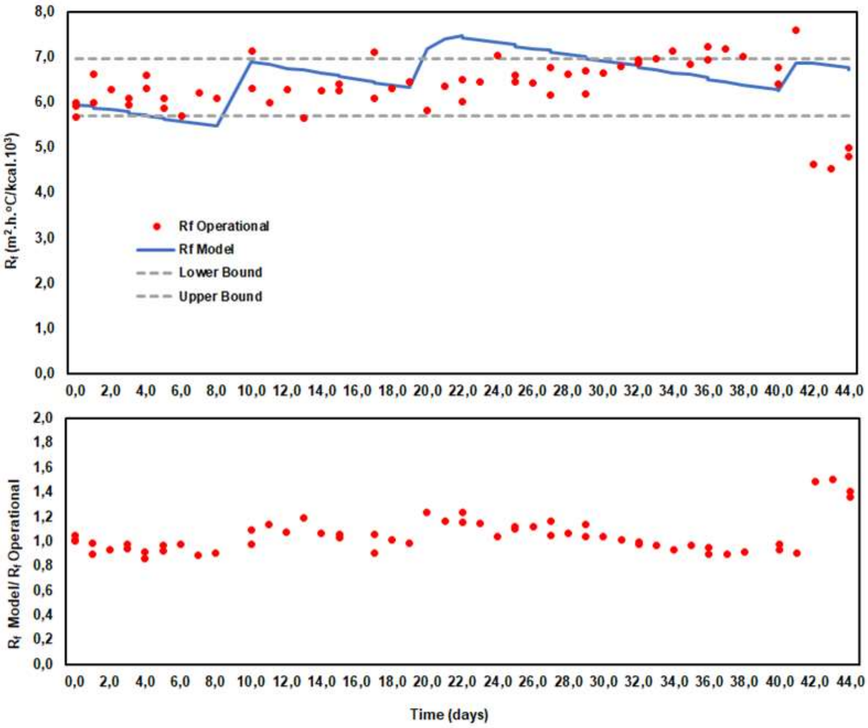
Erro! Fonte de referência não encontrada. shows the estimated parameters for the model applied for each heat exchanger and the error (ε%) associated with and without outliers' removal.

Table 1 – Estimated parameters for the model applied for the heat exchanger and the error (%) considering the presence of outliers and its removal.

	With outlier	Without outlier
α	0.01	0.75
β	-15.59	1.26
G	0.75	1.00
ɣ	0.08	0.74
ε (%)	10.19	2.84

Figure 2 presents the behavior of the operational and predicted R_f value over time with the outliers. On the other hand, in Figure 3, the behavior of the operational and predicted R_f value over time without the outliers.

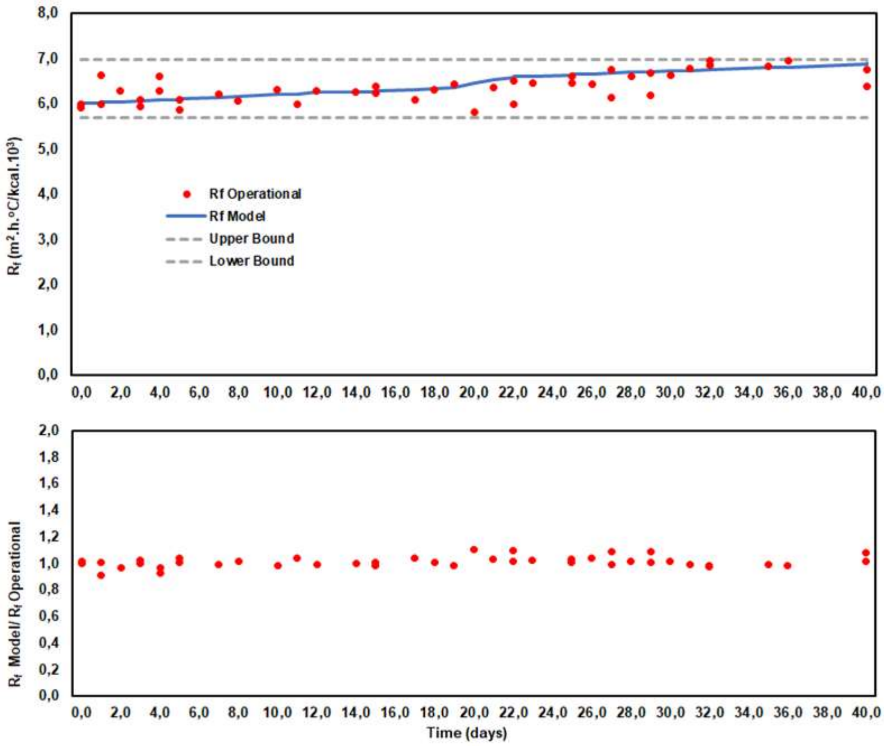
Figure 2 – R_f prediction and operational data with outliers.



ISSN: 2357-7592

Analyzing the heat exchanger database, it was found that on day 10 there was a decrease in the flow of hot and cold fluid of 22.78% and 20.72% respectively in relation to the mean of the flows. Though, these variations did not change the inlet and outlet temperatures of the fluids, they impacted the R_f value. On day 41.52 there was a 21% decrease in the cold fluid flow, with this variation the cold fluid outlet temperature increased 3.2% and the hot fluid temperature 3.36% in relation to the average. The other outlier points did not show expressive variations in the temperatures of hot and cold fluids and in the flow rates and, therefore, may not be caused by these parameters.

Figure 3 – R_f prediction and operational data without outliers.



It was observed that after the outlier's removal, the range of R_f was located between the upper and lower limit of the uncertainty propagation decreased. In this case, the curve of the calculated R_f was smoother and closer to the operational R_f. Regarding the relation between the calculated and operational value of R_f, it was verified that the amplitude decreased approaching one, which is the ideal value.

4. CONCLUSION

This paper presents a novel and simple model to predict the fouling rate of crude oils, especially those present in preheat systems of refineries. One advantage of this model is to consider only the velocity and an effective temperature to predict the fouling rate. The good results is an indication of how reliable the model is to predict and extrapolate for new crude oil data.

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