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ANALYSIS OF A DEPOSITION MODEL IN HEAT EXCHANGERS APPLIED TO AN OIL PREHEATING BATTERY

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Abstract

The formation of deposits of unwanted material in heat exchangers of petroleum preheating batteries represents an important problem to be managed during the refining process. It causes a loss of operational and production efficiency, as well as an increase in costs. Thus, it is important to understand how this phenomenon can occur in equipment in order to minimize its adverse impacts. The objective of this work is to evaluate a model of deposition rate in heat exchangers, in a correlative and predictive way, from four sets of experimental data obtained from the literature, in order to extend this representation to preheating batteries. Initially, the model was tested with its original parameters, to verify the correlation of the model in relation to the experimental data; later, the parameters were then estimated and the prediction of the deposition rate was performed with these new values. It is intended to expand this study to other deposition models, so that it is possible to adopt an adequate mathematical model to predict this phenomenon from real data from an oil refinery.

Keywords

Fouling; heat exchangers; deposition threshold; mathematical modeling.

Introduction

Deposition is the unwanted accumulation of material on heated surfaces of thermal equipment. This is a common occurrence in oil preheating battery heat exchangers [1]. The deposit is formed by organic and inorganic particles, microorganisms, macromolecules and corrosion products, and can occur by different mechanisms, such as: (i) precipitation or crystallization of salts; (ii) sedimentation of particulate matter suspended in the fluid; (iii) chemical reactions between the components of the process fluid; (iv) corrosion; (v) biological growth; (vi) solidification or freezing [1].

In shell-and-tube heat exchangers, deposition can occur both on the shell and on the tube, where the decrease in the overall heat transfer coefficient (U) over time affects their thermal performance. The deposition layer causes an increase in thermal resistance (heat transfer resistances), as well as a decrease in the cross-sectional area on the tube side increases the pressure drop (head loss, ΔP) and restricts the fluid flow. As a consequence, there is an increase in energy consumption and also in consumption of utilities such as steam, fuel and cooling water, for example, as well as carbon dioxide emissions.

The factors that influence the rate of deposit formation are: the type of heat exchanger (geometry of the exchanger), material and surface finish of heat exchange, the composition of the fluid (type of oil to be processed), the properties of the fluid (density, viscosity, heat capacity and thermal conductivity) and operating conditions such as surface temperature (or film temperature, alternatively) and flow rate [2].

In the literature, there are mathematical models that allow predicting the deposition rate over time, using the following approaches: (i) deterministic models; (ii) semi-empirical models; and (iii) non-parametric methods, such as artificial neural networks [3]. The semi-empirical models consider the effects of operating conditions (temperature and velocity) and use experimental data for parameter estimation; play a central role in the literature, especially for the concept of threshold fouling models by Ebert and Panchal [4], being the basis for several models that were described later [5]. Most of these models are based on the presence of a chemical reaction, in the form of the Arrhenius equation, and try to represent the effect of the fluid flow velocity and the capacity to remove the deposit formed. Thus, they have a term that represents the deposition itself, and another that refers to the suppression (or removal) of the deposit, simultaneously.

The objective of this work is to evaluate the performance of the Ebert and Panchal [4] deposition model, in a correlative and predictive way, from four experimental data sets, in order to better study the behavior of this phenomenon in oil preheating batteries.

Methodology

In general, the mathematical models found in the literature constitute semi-empirical models that take into account operational conditions and use experimental data for parameter estimation, with great emphasis on the Ebert and Panchal model. This model was created to predict the linear rate at initial deposition conditions (where the deposition rate is close to zero). The first term of this model is a function of the film temperature, related to the chemical reaction mechanism, and the second suppression term, linked to the shear stress. According to Eq. (1).

$$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(-\frac{Ea}{RT_f}\right) - \gamma \tau_w \qquad (1)$$

Table 1. Parameters of Eq. (1)

α	β	E	γ
$30.2\text{x}10^{6}$	-0.88	68	$1.45\text{x}10^{-4}$

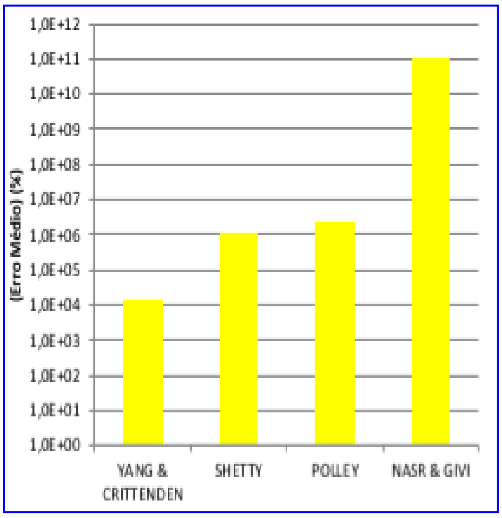
The strategy to evaluate the performance of a given model is mainly given by its correlative and predictive capacity. In the correlative step, the model is used to correlate the experimental data, in order to verify the agreement of the data by this model, by their respective deviations. In a later step, we try to estimate the model parameters and observe its predictive capacity regarding extrapolation to experimental conditions different from those in which the parameters were estimated.

The Ebert and Panchal model was tested for the data sets using the original parameters determined by the authors of the model. Deposition rates and their mean relative error associated with the predicted value by the model and that experimentally measured value were determined. Thus, it is possible to know the degree of correlation of the model in relation to the different sets of data, for the respective experimental conditions (temperature, flow rate and physicochemical properties of the oils). In a subsequent procedure, we estimate the model parameters according to the regression of the experimental data used. Thus, the model and the dataset were tested again for new parameter values, which were adjusted from the minimization of the squares of the errors between the value of the deposition rate predicted by the models and the deposition rate measured experimentally (Math 2). The minimization of the squares of errors was performed using the solver tool, available in Microsoft Excel®.

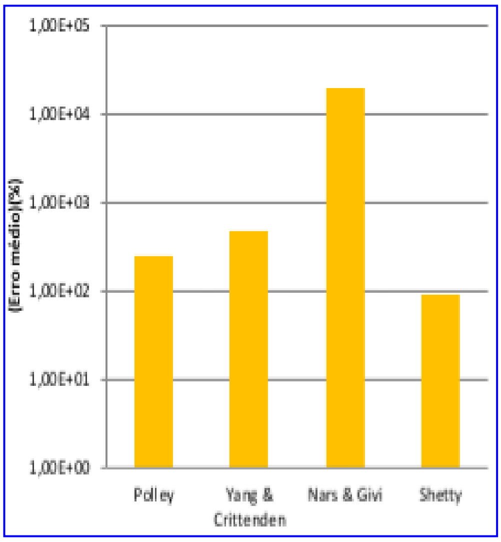
Four experimental datasets were selected: (i) Polley et al.[6], (ii) Nasr and Givi [7], (iii) Yang and Crittenden [8], and (iv) Shetty et al.[9]. Polley et al. were reported for an Alaskan oil (oil density: 961 kg/m³ at 16.6 °C; °API 16). Nasr and Givi [7] reported the data for an Australian light oil (°API 47, and very low resin and asphaltene contents). The authors tested velocity and temperature ranges from 0.25 to 0.4 m/s and 180 to 245 °C, respectively. Yang and Crittenden [8] obtained data with a Mexican crude oil (°API 21.1), velocity range between 0.5 and 4.0 m/s. Shetty et al. [9] obtained data for three different oils (°API between 18 and 47). Despite using a smaller velocity variation (0.49 m/s in 12 of the 15 experiments, and 0.35 m/s in the other three), temperatures were considerably higher than in the other selected data, between 243 and 334 °C.

Results and Discussion

Fig. 1 shows the average relative error results for both steps, original and adjusted parameters. Better results were found in the second stage, as expected, since new parameter values were estimated with the minimization of errors; however, the error values remained relatively high.



(a)



(b)

Figure 1 – Average relative error in applying the Ebert and Panchal [4] model to the four selected data sets. (a): Original; e (b) Adjusted Parameters.

Table 2. Adjusted Parameters

	Crittenden et al.	Polley et al.	Nasr & Givi	Shetty et al.
α	2.22x10^{7}	2.21x10^{7}	1.12 x10^{7}	1.12 x10^{7}
β	-1,61	-1.70	-4.35	-4.35
E	52,18	48.00	26.06	68
γ	-5,64x10^{-7}	-3.82x10^{-8}	5.52x10^{-8}	-2.35x10^{-3}

The relative average error in Fig. (1a) reaches 1.0x10^{11} for the Nasr and Givi dataset [7]. In Fig. 1b), when the parameters are regressed for each data set, the maximum average error for these authors decreases to 1.0x10^{4}. The smallest mean error for the datasets used were those obtained with Shetty et al. [9], close to 100% error, far from acceptable values for deposition rate models, which would be in the 20% range, according to Wilson et al. [3]. Thus, although the order of magnitude of the values calculated for the deposition rate is small, the errors obtained with the model are relatively high. This shows the limitation of the model in predicting the deposition, behaving as a local model in view of the heterogeneity of the data set used, both in relation to the type of oil, the type of apparatus and experimental conditions (temperature and flow velocity).

Conclusions

In this work, a deposition rate model was evaluated, in a correlative and predictive way, from four sets of experimental data obtained from the literature. The results showed deviation values relatively far from the acceptable range of 20%, to be considered a good model. However, the heterogeneity of the data and the different conditions tested make it difficult to adequately represent the deposition rate by the model. A sensitivity study of the calculations to the parameters and properties involved can help to identify the limits of applicability of the model. It is intended to expand this study to other deposition models, so that it is possible to adopt an adequate mathematical model to predict this phenomenon from real data from an oil refinery. This study is important not only to maintain the operational performance of these equipment, but also to identify the most appropriate period for a cleaning schedule.

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Responsibility Notice

The authors are the only responsible for the paper content.

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