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SIMULATION AND OPTIMIZATION OF HEAT EXCHANGERS CLEANING SCHEDULES

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Abstract. In oil refining, heat exchangers networks are employed to recover heat and therefore save energy of the plant. However, many heat exchangers in the crude oil pre-heat trains are under high risk of fouling. Under fouling conditions, the thermal performance of heat exchangers is continuously reduced and its supervision becomes an important task. The large number of heat exchangers in pre-heat trains and the change of operation conditions and feedstock charges make the daily supervision a difficult task. The current works has two aims: i) the simulation of the thermal behavior of heat exchanger networks under fouling condition and; ii) the optimization of the heat exchanger cleaning schedule. Steady state energy balances are employed to evaluate the outlet temperatures of the heat exchanger streams. The flow is considered single-phased and the fouling thermal resistance is assumed to increase linearly. Simulations results are corroborated with experimental data. The optimization criterion is based on the operational and maintenance cost of fouling.

Keywords. Heat exchangers, Fouling, Simulation, Optimization, Pre-heat train

1. Introduction

Heat exchangers in oil refineries are under risk high of fouling, which reduces significantly their thermal performance over time. The consumption of fuel is thus increased in the furnaces in order to compensate this loss. Frequently, the operation of the heat exchangers is interrupted for maintenance and cleaning. According to Bailey (1999), the US process industry expends more than 5 billion dollars per year with fouling related problems, such as maintenance costs, production and energy losses. The expenditure with fouling of only the US oil refining industry surpasses 2 billion dollars per year.

The identification of the optimal period for cleaning is not a trivial task. The number of heat exchanger in a network (eg. in the pre-heat train, the number may reach 50), the different rate of fouling and interdependence of these components are the reasons for that. Besides, the prediction of the thermal performance reduction and consequently the economic losses related to that is a complex assignment. The simulation of the heat exchanger network is an approach to diagnose the performance of these equipments over time and therefore, it can be employed to estimate losses. Previous work on the subject has been performed (Smaïli et al. 2002).

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2. Mathematical Model

2.1 Conservation Equations

Although the problem is transient it is considered quasi-static; in other words, the thermal inertia of the heat exchangers is small compared to the time changes of the operation conditions. Additionally, no phase change of the fluids within the heat exchangers is admitted. Therefore, the heat balance of each heat exchanger can be written as:

$$\dot{Q} = \left(\dot{m}c_p\right)_h \left(T_{h1} - T_{h2}\right) = \left(\dot{m}c_p\right)_c \left(T_{c2} - T_{c1}\right) = \left(\dot{m}c_p\right)_{\min} \left(T_{h1} - T_{c1}\right)\varepsilon \quad (1)$$

Alternatively, the energy balance can be written to evaluate the outlet temperature of the fluid streams:

$$T_{2c} = T_{1c} + \frac{\left(\dot{m}c_p\right)_{min}}{\left(\dot{m}c_p\right)_c}\left(T_{1h} - T_{1c}\right)\cdot\varepsilon \tag{2}$$

$$T_{2h} = T_{1h} - \frac{\left(\dot{m}c_p\right)_{min}}{\left(\dot{m}c_p\right)_h}\left(T_{1h} - T_{1c}\right)\cdot\varepsilon \tag{3}$$

where $\dot{m}$ is the mass flow rate, c_p, the specific heat of the fluid at constant pressure and T, the temperature of the fluid. The h, c, 1 and 2 subscripts refer to the hot and cold streams and to the inlet and outlet conditions of the heat exchangers, respectively. The subscript *min* means the smallest heat capacity between the cold and hot streams. ε is the effectiveness of the heat exchanger. For a shell and tube heat exchanger with one pass in the shell and n even passes in the tubes, the effectiveness is (Incropera e DeWitt, 1998):

$$\varepsilon = \frac{2}{1 + R + \sqrt{(1+R^2)}\,\dfrac{1+e^{\left[-NTU\sqrt{(1+R^2)}\right]}}{1-e^{\left[-NTU\sqrt{(1+R^2)}\right]}}} \tag{4}$$

Note that effectiveness is a function of the heat capacity ratio:

$$R = \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_{max}} \tag{5}$$

and the Number of Transfer Units (NTU):

$$NTU = \frac{UA}{(\dot{m}c_p)_{min}} \tag{6}$$

and A is the heat transfer area. U is the overall heat transfer coefficient expressed as:

$$\frac{1}{UA} = \frac{1}{U_oA_o} = \frac{1}{U_iA_i} = \frac{1}{(UA)_L} + R_{tf} = \frac{1}{h_iA_i} + \frac{1}{h_oA_o} + R_{tf} \tag{7}$$

where the indices o and i represent, respectively, the shell and tube and the index L indicates the clean heat exchanger. R_{tf} is the fouling thermal resistance on both heat exchanger sides and h is the convection heat transfer coefficient that can be obtained from the literature (Kakaç and Liu, 1998). These convection coefficients are a function of the geometry, flow rates and fluid properties.

2.2 Fouling Model

Tonin (2003) showed that the Index of Fouling proposed by Jerónimo et al. (1997) and the thermal resistance of fouling are directly related. Therefore, Madi et al. (2004) proposed the following relationship in order to estimate the fouling thermal resistance as a function of time:

$$R_{tf}(t) = R_{tfd}(t)\cdot IF(t) \tag{8}$$

where R_{tfd} is the thermal resistance of fouling defined at the design stage of the heat exchanger (TEMA, 1978) and IF is the index of fouling. For the heat exchangers presented in current work, the index of fouling rises linearly with time and therefore, the fouling thermal resistance.

2.3 Method of solution

A general simulation program was developed in order to simulate any network configuration, which can be defined by the program user.

The model solution provides the evaluation of the outlet temperatures of all heat exchanger. Equations (1) and (2), written for each heat exchanger, yield a set of linear equations, as the flow rates and fluid properties are considered known values. These equations are interdependent and, therefore, they need to be solved simultaneously. In the current work, an iterative procedure is employed on the solution of the linear equations. The iterative solution approach was found to be easy to implement for a general network algorithm.

2.4 Cost Analysis

The additional fuel expenses due to fouling per unit of time can be computed by:

$$\dot{C}_L(t) = c_F\left(\dot{Q}_0 - \dot{Q}(t)\right) \tag{9}$$

where $\dot{Q}_0$ is the heat exchange rate by the network at time zero (all heat exchangers are clean), $\dot{Q}(t)$ is the heat exchange rate at a certain date (fouled heat exchangers) and c_F is the fuel cost per unit of heat.
The extra fuel expenses due to fouling can be expressed by:

$$C_T = \int_0^{t_F} \dot{C}_L dt + C_m \tag{10}$$

where C_T is the total cost and C_m is the cleaning cost of the heat exchangers. t_F is the considered time horizon. The integral represents the additional expenses due to the performance losses of the network. As those values are evaluated at different dates, they are all converted to present values, employing an interest rate of 8% per year.

3.0 Results

3.1 Model Verification

First of all the model results are compared to measured data. Four heat exchangers of an oil pre-heat train (Refinery President Getúlio Vargas of Petrobras, located in Araucária-PR) were chosen for the comparison. Figure 1 shows these four heat exchangers, named TC-04, TC-05, TC-06 and TC-07. All heat exchangers are shell-and-tube type, where the oil flows within the tubes and the products (hot fluids) in the shell. The oil flow rate is the same for all heat exchangers and the product streams have independent inlet flow rates and temperatures. The flow rates and inlet temperatures of the products change continuously over time. Fouling thermal resistance curves, developed by Madi et al. (2004), are employed for each heat exchanger.

In this comparison, the heat exchangers were considered isolated; in other words, both oil and products inlet temperatures (measured values) are employed as boundary conditions of the problem. Figure 2 presents the outlet oil temperature of the heat exchanger TC-05 for a period of 29 months. The variation of the temperature is not only related to inlet temperature and flow rate changes but also because of fouling thermal resistance. Note that the maximum temperature difference between measured and computed values is in the order of 5°C. In the simulations, the changes of thermophysical properties of the fluids were not considered. Besides, the measured and calculated curves show similar behavior, indicating the fouling model is adequate. For the TC-06 heat exchanger, the maximum difference of measured and calculated values is 4°C (see Figure 3) and the curves also show similar results. The simulated results for the other heat exchangers are also corroborated with measured data.

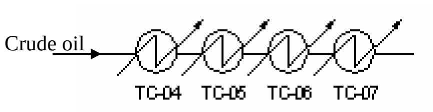

Figure 1 – Heat exchanger network.

3.2 Potentialities

The simulation allows the performance reduction evaluation of the heat exchanger network due to fouling and consequently, the prediction of extra fuel consumption in the furnace over time. Additionally, the removal of one or more heat exchangers from the network for cleaning can be the simulated.

A case study was conducted to estimate the performance reduction of the network of Figure 1. The boundary conditions of the problem are considered constant over time: the mass flow rates and the product inlet temperatures for all heat exchangers and also and the oil inlet temperature of heat exchanger TC-04. The thermophysical properties of the oil and products are also considered constant values. All the heat exchangers were admitted clean at the plant operation start-up (the fouling thermal resistances of all heat exchangers are null).

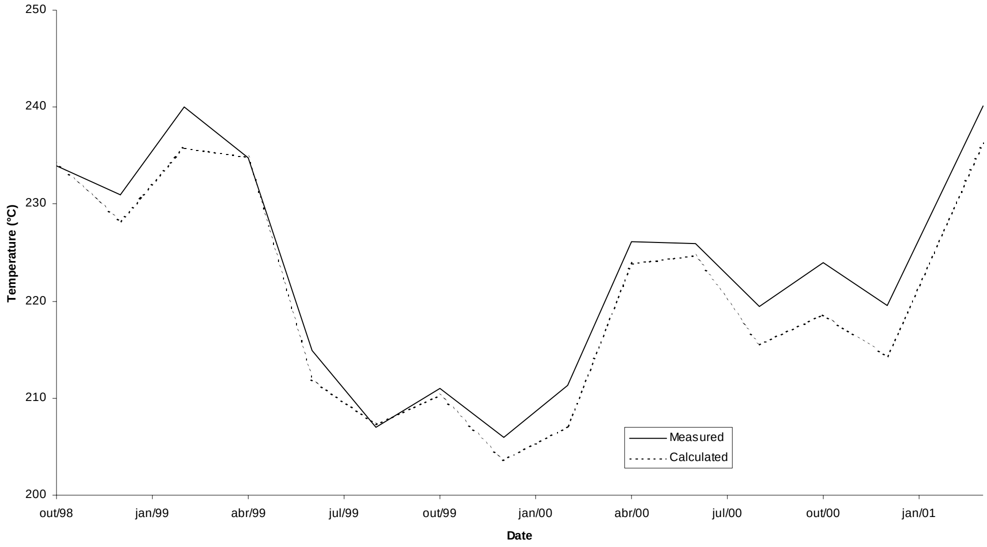

Figure 2 – Outlet oil temperature at heat exchanger TC-05.

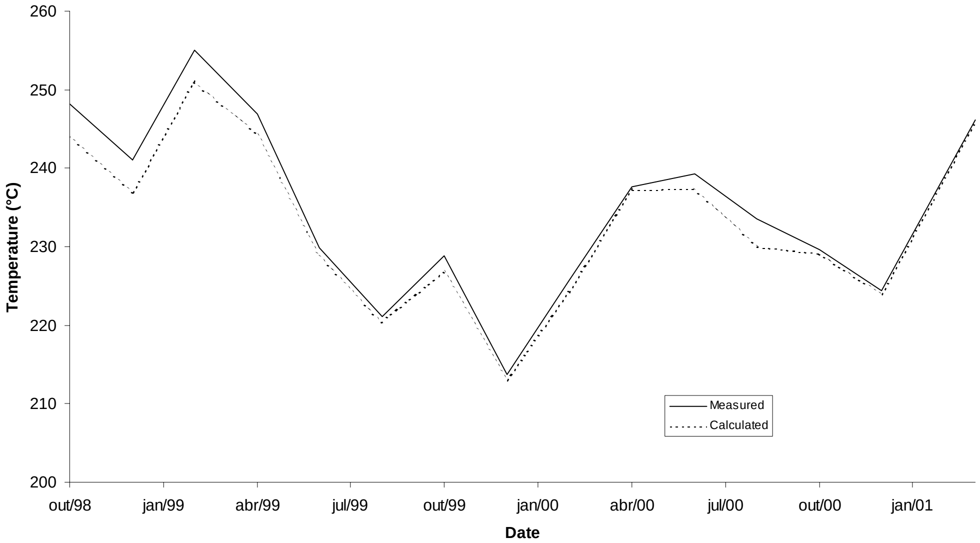

Figure 3 – Outlet oil temperature at heat exchanger TC-06.

Figure 4 shows the total heat rate of the network over a 30-month period. Between the tenth and twelfth months and between the twentieth and twenty second months the heat exchangers TC-6 and TC-07 were, respectively, removed for cleaning. During those periods, the network works with a by-pass at the removed heat exchanger position. After the cleaning time, the removed heat exchanger returns completely clean to its original position. The fouling and withdrawal effect of the heat exchanger on the network performance is clearly shown in Figure 4; the heat transfer rate reduction implies higher fuel consumption in the furnaces in order to reach the oil distillation temperature. One can see the cleaning of the heat exchanger TC-07 has a greater impact on the recovery of the network performance. Despite the fouling rates of both heat exchangers being similar, the second one was dirtier at its cleaning time. Additionally, the heat transfer rate of heat exchanger TC-07 is higher and therefore, its cleaning effect is more significant on the thermal performance of the network.

Employing the simulation results of the network without any cleaning over a 36-month period, a curve of additional fuel expenses in the furnace can be calculated by equation (9) (see Figure 5). All the single values shown in Figure 5 are present values computed by employing an 8% interest rate. The present value of any future value is zero as time tends to infinity and therefore the curve is asymptotic. The integration of such curve results in US$ 480,275.39. That is the expenses with additional fuel over 36 months without any cleaning in the period.

3.3 Optimization

The optimization purpose is the minimization of equation (10), assuming the cleaning of a certain heat exchanger can take place at any month during the plant operation time. During the cleaning month, a particular heat exchanger is removed from the network and the oil is by-passed to the next one.

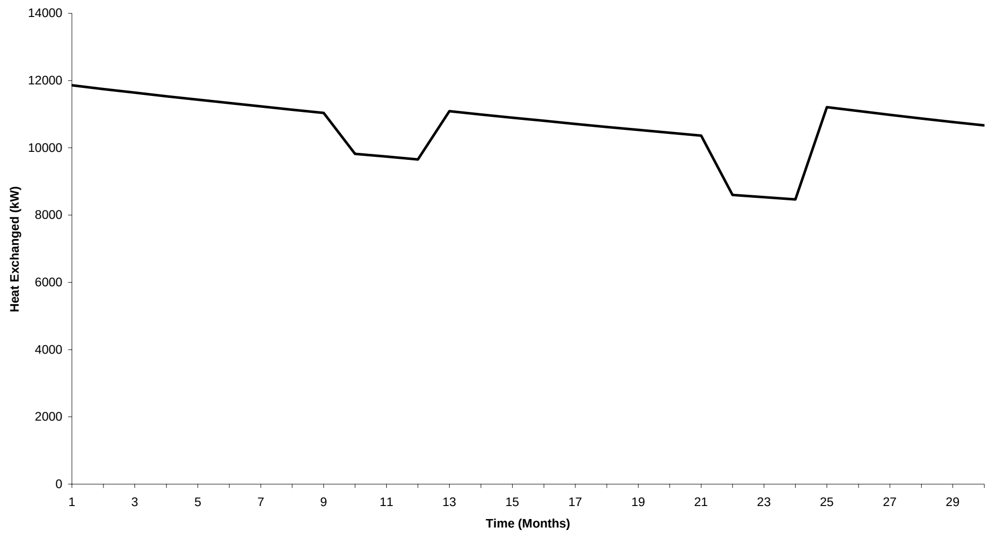

Figure 4 – Change of heat transfer rate of the network of Figure 1 over time.

The integration of equation (10) along 36 months, considering the cleaning of heat exchanger TC-06 at each month, is shown in Figure 6. Each point represents the present value of the integration. The value at time zero is the result of the integration without cleaning (US$ 480,275.39), the value at month one is the integration when the heat exchanger is removed for cleaning in the first month of operation, and so on. The cleaning at the first two months provides expenses higher than that without cleaning. From this time on, the total expenses reduce, until a minimum value is found. The smaller value (US$ 397,283.53) is reached at the eighteenth month. This value is 17% lower than the total expenses without cleaning. One can see the variation of the expenses from 16th to 21st month is under 0.5%. Therefore, the cleaning could take place during this period without great losses, providing more flexibility to the operation and maintenance staff.

The optimum cleaning time of heat exchanger TC-05 also takes place at the eighteenth month. The minimum value is US$ 446,233.12 and it is 7% lower than total expenses without cleaning. Although the fouling thermal resistance of the heat exchanger TC-05 is higher than that of the heat exchanger TC-07 the cleaning of the first provides a lower reduction of the optimum total expenses because its heat transfer area is smaller. The cleaning of both heat exchangers at the eighteenth month reduces the total expenses to US$ 372,129.17. This value represents 22.5% lower than the total expenses of the network without cleaning.

If heat exchangers TC-05, TC-06 and TC-07 are cleaned in the eighteenth month the total expenses are reduced to US$ 340,476.32. On the other hand, if all heat exchangers are removed for cleaning in the eighteenth month the total expenses are US$ 365,569.45. According to this criterion, the heat exchanger TC-04 should not be cleaned along the 36 months of the plant operation.

4. Conclusions

The current work presents an approach to simulate and optimize the cleaning schedule of heat exchanger networks due to fouling. This is useful for pre-heat trains of oil refinery plants. The modeling is based on the energy balance of heat exchangers. A linear fouling model is employed in order to predict the reduction of heat exchanger performance. The objective function is the additional fuel expenses in the furnace and the heat exchangers maintenance cost. A small network comprising four heat exchangers was chosen as a case study, and the heat exchangers have different fouling rates.

The simulation results were compared with measured values over 29 months and the differences are small. The fouling effect in the simulation results is similar to its counterpart in the measured data. Besides, the simulation can evaluate the network heat recovery and the removal effect of a heat exchanger on the network performance. The additional fuel expenses in the furnace are the difference between the clean network heat recovery and the heat recovery at a particular month.

The integration of the losses over a certain period provides the total additional expenses. The withdrawn of a heat exchanger each month for cleaning shows the total expenses has a minimum value. The optimization was conducted independently for each heat exchanger – the cleaning effect of a certain heat exchanger is not considered on the optimum of another heat exchanger. The results also show that cleaning three, out of four, heat exchangers at a certain month is cheaper than cleaning one, two or four.

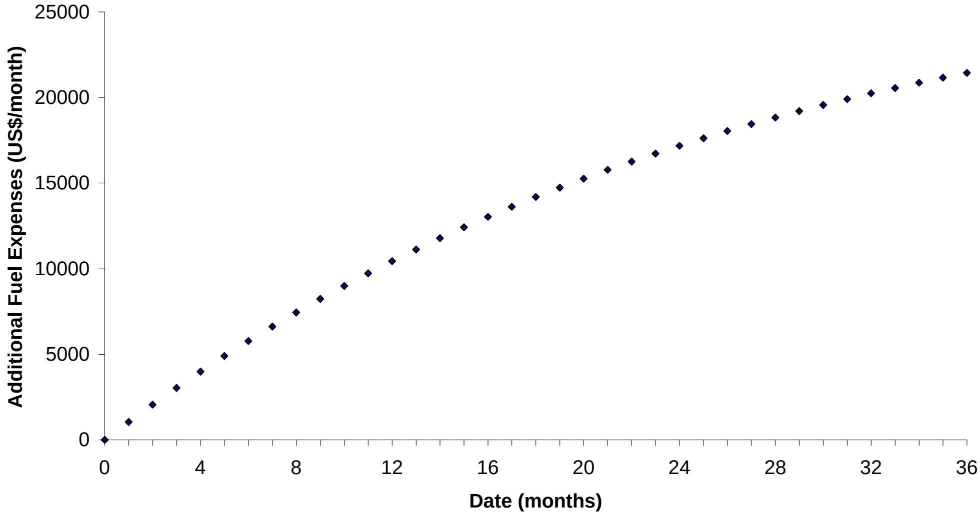

Figure 5 – Additional fuel expenses.

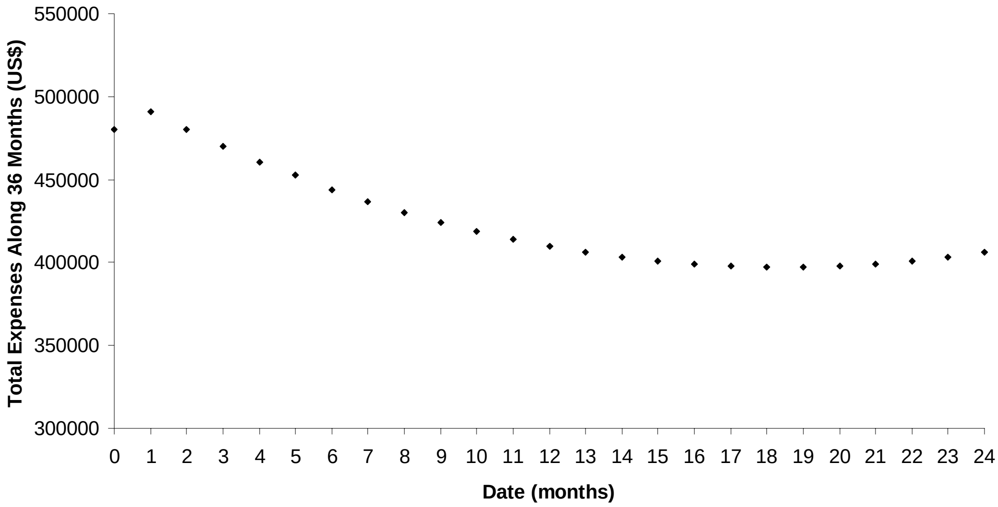

Figure 6 – Total additional expenses over 36 months when the heat exchanger TC-07 is cleaned each month.

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