AN APPROACH FOR MONITORING THE THERMAL PERFORMANCE OF HEAT EXCHANGER NETWORKS

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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 the monitoring of it becomes an important task. The large number of heat exchangers in the pre-heat train, the change in the operational conditions and the feedstock charge make the daily monitoring a difficult task. This work applies an approach for monitoring the performance of heat exchangers (Jerónimo, et al. 1997) and extends it to the monitoring of the whole train. The approach is based on the comparison of measured and predicted heat exchanger effectiveness. The measured value is computed from the four inlet/outlet temperatures of the heat exchanger unit. The predicted clean and dirt values of the effectiveness are calculated from classical literature relations as a function of NTU and of the flow heat capacity rate and they are continuously corrected by the changes of the mass flow rates. The expenses with additional fuel consumed by the furnaces, due to the heat exchanger performance reduction, are estimated. The obtained results show the approach feasibility and efficiency of the monitoring of heat exchanger networks.*

Keywords*. monitoring of thermal performance, heat exchangers, fouling*

1. Introduction

The deposition aggregation of materials, such corrosion products, microorganisms, inorganic particles, etc. on the surfaces of heat transfer equipment, characterizes the fouling phenomenon. The presence of such deposits increases the heat transfer resistance and reduces, along time, the thermal and hydraulic performance of such equipment.

In oil industry, heat transfer networks are employed to recover heat and consequently, diminish the energy consumption of the plant. Many of these heat exchangers are subjected to fouling and this industry sector is always interested to monitor the performance of them in order to find out the appropriate time for cleaning or to minimize it.

Recent studies have been conducted with the purpose to estimate the costs related to fouling. 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. Only in the oil refining industry of US, the expenditure with fouling surpass 2 billion dollars per year.

The heat exchanger performance is affected not only by the reduction of heat transfer by also by the increase of pressure losses in either side of the heat exchanger. The reduction of heat transfer must be compensated by adding heat in the furnace and therefore fuel consumption will be higher. In order to avoid reduction of flow rate due to the increase of pressure losses, the power to pump the fluids must be raised. As the increase of the fuel consumption cost is more significant than the raise of pump power expenditure, this work will emphasize the heat transfer part.

The present work will discuss a methodology found in the literature (Jerónimo, et al., 1997) with the purpose to monitor the thermal performance of heat exchangers. Their work is based on the evaluation of the measured and predicted heat exchanger effectiveness. The measured value is computed from the four inlet/outlet temperatures of the heat exchanger unit. The predicted clean and dirt values of the effectiveness are calculated from classical literature relations as a function of the Number of Transfer Unit (NTU) and of the flow heat capacity rate and they are continuously corrected by the changes of the mass flow rates. Fouling data obtained from a refining plant are compared with those predicted by the approach during a certain period. Besides, this method is extended to evaluate the performance of a whole train of heat exchangers, allowing the computation of economic losses due to fouling.

2. The Monitoring Approach for a Single Heat Exchanger

The effectiveness of a heat exchanger is defined as the ratio of the real heat transfer rate by the maximum heat transfer rate in a counter-flow heat exchanger. The maximum heat transfer rate is given by:

$$Q_{max} = \left(\dot{m}c_p\right)_{min} \Delta T_{max} \tag{1}$$

where $(\dot{m}c_p)_{\min}$ is the smallest product of mass flow rate and specific heat. $\Delta T_{\max}$ is the maximum temperature difference in the exchanger (= $T_{h1} - T_{c1}$). T_{h1} and T_{c1} are, respectively, the inlet temperature of the hot and cold flows. The real heat transfer rate is the product of the mass flow rate, specific heat and the temperature difference in either side of the heat exchanger:

$$\dot{Q} = \left(\dot{m}c_p\right)_h \left(T_{h1} - T_{h2}\right) = \left(\dot{m}c_p\right)_c \left(T_{c2} - T_{c1}\right) \tag{2}$$

where T_c *e* T_h are the cold and hot temperatures, respectively. The subscript 1 and 2 indicates, respectively, the inlet and outlet of the heat exchanger. $(\dot{m}c_p)_h$ and $(\dot{m}c_p)_c$ are, respectively, the heat capacity rates of the cold and hot flows - products of mass flow rate and the specific heat.

The effectiveness can be written as:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\text{máx}}} = \frac{\left(\dot{m}c_p\right)_h \left(T_{h2} - T_{h1}\right)}{\left(\dot{m}c_p\right)_h \left(T_{h1} - T_{c1}\right)} = \frac{T_{h1} - T_{h2}}{T_{h1} - T_{c1}} \tag{3}$$

The heat capacity rate of the cold flow is admitted higher than its hot counterpart. By rearranging Eq. (2), the ratio of the heat capacities can be defined as:

$$R = \frac{\left(\dot{m}c_p\right)_h}{\left(\dot{m}c_p\right)_c} = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{h2}} \tag{4}$$

Since the heat capacity of the hot flow is the smallest one, the Number of Transfer Unit (NTU) is:

$$NTU = \frac{UA}{(\dot{m}c_p)_h} \tag{5}$$

The effectiveness of heat exchangers can be obtained from the literature as function of R and NTU (Liu e Kakaç, 1998). For a heat exchanger with one pass in the shell and n passes in the tubes, the effectiveness is:

$$\varepsilon = \frac{2}{1 + R + \sqrt{\left(1 + R^2\right)}\,\dfrac{1 + e^{\left[-NTU\sqrt{\left(1+R^2\right)}\right]}}{1 - e^{\left[-NTU\sqrt{\left(1+R^2\right)}\right]}}} \text{x}100 \tag{6}$$

Changes of operation conditions and feedstock charges may alter the mass flow rate of products and also the compositions of the crud and products. This will modify the heat capacity rate ratio, R, and the overall heat transfer coefficient, U, of the heat exchanger. This variations cause changes in the effectiveness of the heat exchanger. Jerónimo et al. (1997) proposed some correlations to estimate the changes of NTU caused by variations of the mass flow rates. These correlation corrections are based on the Nusselt number of the shell and tube sides. Note that the changes in the crude and product properties are not taken into account in the correlations.

For a counter –flow heat exchanger, the following correlations are defined:

a) Fluid with the smaller heat capacity flowing in the shell side:

$$\frac{NTU}{(NTU)_d} = \frac{\left[(\dot{m}c_p)_{\min,d}/(\dot{m}c_p)_{\min}\right]^{1-b}}{\left\{1 + (UA/hA)_d\left[\left((\dot{m}c_p)_{\min,d}/(\dot{m}c_p)_{\min}\right)^{1-a}(R/R_d)^a - 1\right]\right\}} \tag{7}$$

b) Fluid with the smaller heat capacity flowing in the tube side:

$$\frac{NTU}{(NTU)_d} = \frac{\left[(\dot{m}c_p)_{\min,d}/(\dot{m}c_p)_{\min}\right]^{1-a}}{\left\{1 + (UA/hA)_d\left[\left((\dot{m}c_p)_{\min,d}/(\dot{m}c_p)_{\min}\right)^{1-b}(R/R_d)^b - 1\right]\right\}} \tag{8}$$

The index *d* refers to the design condition and *h* is the convection coefficient of the side with the highest $\dot{m}c_p$. According to the literature (Liu and Kakaç, 1998), *a* and *b* are 0,8 and 0,6, respectively. In case of the cold fluid heat capacity rate is the smaller one, R should be redefined as: $(mc_p)_c/(mc_p)_h$. The complete definition of correlations (7) and (8) can be found in Tonin (2003). The NTU design value is corrected to its value at an operation condition. Note that NTU design value may (dirt heat exchanger) or may not (clean heat exchanger) include fouling thermal resistance. With R and NTU corrected values, the effectiveness can be calculated by Eq. (6). The clean (ε_{cl}) and dirt (ε_f) effectiveness are compared with its measured counterpart value evaluated by Eq. (3). The comparison provides the actual stage of fouling of a heat exchanger.

Additionally, Jerónimo et al. (1997) define a index of fouling which quantifies the fouling level of a heat exchanger:

$$IF_j = \frac{(\varepsilon_{cl,j} - \varepsilon_{m,j})}{(\varepsilon_{cl,j} - \varepsilon_{f,j})} \tag{9}$$

where the IF_j is the index of fouling for the j heat exchanger. $\varepsilon_{cl,j}$ and $\varepsilon_{f,j}$ are, respectively, the predicted effectiveness for clean and dirt heat exchangers, both computed by employing Eq. (6). The effectiveness for the dirt heat exchanger is calculated by assuming an expected fouling resistance during the design. $\varepsilon_{m,j}$ is the measured effectiveness evaluated by Eq. (3) and is based on the actual measured values of temperature. The index of fouling equal to 0 represents a clean heat exchanger and the index of fouling equal to 1 means a dirt heat exchanger at a design fouling condition.

The simplicity of the method relies on the measurement of only four temperatures and the flow rate on either side of the heat exchanger.

3. The Monitoring Approach for a Heat Exchanger Network

In this section, the Jerónimo's et al. (1997) approach is extended for the monitoring of the whole heat exchanger network. Consider a train of heat exchanger where the hot heat capacity rate is always the smallest for all heat exchangers. In such case, the maximum heat available to be exchanged by the network in a certain time, $\dot{Q}_{máx,n}$, is given by:

$$\dot{Q}_{máx,n} = \dot{Q}_{máx,1} + \dot{Q}_{máx,2} + \dot{Q}_{máx,3} + \ldots + \dot{Q}_{máx,m} \tag{10}$$

or,

$$\dot{Q}_{máx,n} = \sum_{j=1}^{m} \left[(\dot{m}c_p)_h (T_{h1} - T_{c1}) \right]_j \tag{11}$$

where $\dot{Q}_{máx,j}$ is the maximum heat available for each heat exchanger. The amount of heat exchanged by the whole network ($\dot{Q}_n$) is computed as the sum of the heat transferred by each exchanger:

$$\dot{Q}_j = \sum_{j=1}^{m} \left[(\dot{m}c_p)_c (T_{c2} - T_{c1}) \right]_j \tag{12}$$

Assuming phase change does not take place along the crude flow, the measured effectiveness of the whole network ($\varepsilon_{m,n}$) can be written as:

$$\varepsilon_{m,n} = \frac{\dot{Q}_n}{\dot{Q}_{máx,n}} = \frac{\sum_{j=1}^{m} \left[(\dot{m}c_p)_c (T_{c2} - T_{c1}) \right]_j}{\sum_{j=1}^{m} \left[(\dot{m}c_p)_h (T_{h1} - T_{c1}) \right]_j} \text{x}100 \tag{13}$$

Again, the approach consists in the comparison of the measured effectiveness of the train, Eq. (13), with its clean and dirt predicted counterparts. Note that the heat transfer in each heat exchanger can be computed by multiplying its effectiveness, Eq. (6), by the maximum possible heat exchanged in this HX. Considering the clean condition,

$$\dot{Q}_{cl,j} = (\dot{Q}_{máx} \varepsilon_{cl})_j = \left[(\dot{m}c_p)_h (T_{h1} - T_{c1}) \varepsilon_{cl} \right]_j \tag{14}$$

and the dirt expected condition:

$$\dot{Q}_{f,j} = \left(\dot{Q}_{máx}\varepsilon_{f}\right)_j = \left[\left(\dot{m}c_p\right)_h\left(T_{h1} - T_{c1}\right)\varepsilon_f\right]_j \tag{15}$$

For the whole network, the computed effectiveness of the clean heat exchanger will be:

$$\varepsilon_{cl,n} = \frac{\sum_{j=1}^{m}(\dot{Q}_{máx}\varepsilon_{cl})_j}{\dot{Q}_{máx,n}} = \frac{\sum_{j=1}^{m}\left\{\left[\left(\dot{m}c_p\right)_h\left(T_{h1} - T_{c1}\right)\right]\left(\varepsilon_{cl}\right)\right\}_j}{\sum_{j=1}^{m}\left[\left(\dot{m}c_p\right)_h\left(T_{h1} - T_{c1}\right)\right]_j} x100 \tag{16}$$

and of the dirt expected condition:

$$\varepsilon_{f,n} = \frac{\sum_{j=1}^{m}(\dot{Q}_{máx}\varepsilon_{f})_j}{\dot{Q}_{máx,n}} = \frac{\sum_{j=1}^{m}\left\{\left[\left(\dot{m}c_p\right)_h\left(T_{h1} - T_{c1}\right)\right]\left(\varepsilon_{f}\right)\right\}_j}{\sum_{j=1}^{m}\left[\left(\dot{m}c_p\right)_h\left(T_{h1} - T_{c1}\right)\right]_j} x100 \tag{17}$$

Therefore, the effectiveness of the network in operation ($\varepsilon_{m,n}$) can be compared with the effectiveness of the computed effectiveness of the clean ($\varepsilon_{cl,n}$) and dirt ($\varepsilon_{f,n}$) network.

An index of fouling of the whole network can also be defined:

$$IF_r = \frac{\left(\varepsilon_{cl,n} - \varepsilon_{m,n}\right)}{\left(\varepsilon_{cl,n} - \varepsilon_{f,n}\right)} \tag{18}$$

A percentage of weight for each heat exchanger is also defined in the present work:

$$PW_j = \frac{\dot{Q}_j}{\dot{Q}_n} x100 \tag{19}$$

where $\dot{Q}_j$ is the heat transfer in the j heat exchanger and $\dot{Q}_n$ is total heat exchanged by the whole network. This index indicates the contribution of each HX in the heat exchange by the whole network.

The reduction of the measured network effectiveness, when compared with the predicted clean, is employed to estimate the additional expenses with fuel burnt by the furnace. The fuel expenses per day are given by:

$$C_F = 86400.c_F.\dot{Q}_{máx,n}\left(\varepsilon_{cl,n} - \varepsilon_{m,n}\right) \qquad [US\$/day] \tag{20}$$

where c_F is the fuel cost per unit of energy (US$/J). The 86400 value represents a day in seconds.

4. Results

A branch of the pre-heat train of REPAR[#] refinery is employed to show the potential of the approach (Fig. (1)). As shown, the crude is pre-heated in three heat exchangers (HX-01, HX-02, HX-03) before the desalination unit (D-02 and D-05) and four (HX-04, HX-05, HX-06 and HX-07) after it. Vacuum residue, heavy and light gasoil, heavy diesel and heavy nafta are the distillation products which exchange heat with the crude. The analysis was conducted from October 1998 to April 2001.

4.1 Measurements

Temperatures were measured at the inlet and outlet of each heat exchanger by thermocouples type J. This kind of thermocouple has an application range of 0 to 750^{o}C and uncertainty of 2.2^{o}C. The flow rates are measured by orifice plates and their uncertainty are 5%. The combination of these uncertainties in the energy balance ($\dot{m}c_p\Delta T$) is 7.5%. Differences of heat transfer on each side of the heat exchangers higher than 7.5% implies the measurements were not appropriate. In these cases, comparison of values indicate the flow rates of products were not measured correctly and they were disregarded.

[#] President Getúlio Vargas' Refinery of PETROBRAS located in Araucária-PR.

The flow measurements were compared with the reduction of the crude level in the storage tanks and the difference is under 2%. Therefore, only the crude flow rate and the four temperatures for each heat exchanger were considered in the results below. Details about the uncertainty analysis can be found in Tonin (2003).

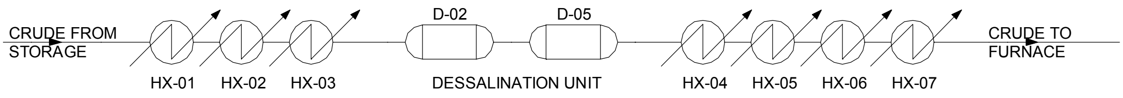

Figure 1. Analyzed heat exchanger network.

4.2 Thermal performance of a single heat exchanger

In order to demonstrate the predicted effectiveness agrees with its measured counterpart, a heat exchanger that does not foul was analyzed. Figure (2) shows the measured (Eq. (3)) and predicted clean values (Eq. (6)) of the effectiveness for HX-04, which does not become dirty as shown by Tonin (2003). As can be seen, the curves are in good agreement showing the prediction is effective. This demonstrates the approach to correct the effectiveness with mass flow rate is appropriate and that the changes of the fluid properties do not affect the effectiveness (The effect of the fluid flow properties on the effectiveness was presented in another work (Lima and Negrão, 2003)). This also indicates the fouling does not take place in that heat exchanger once the measured values coincide with the clean ones.

Figure (3) shows a comparison of measured and predicted clean and dirt values of the effectiveness for HX-01. The clean and dirt predicted values establish the range the measured effectiveness must lie. Before the start of operation in October 1998, all heat exchangers were cleaned. One can see the measured and predicted clean effectiveness were very close to each other for approximately one year of operation. After October 1999 until July 2000, the measured and predicted clean values began to deviate from each other indicating the start of the fouling process. From July 2000 to October 2000, the measured reaches the predicted dirt effectiveness. In other words, the level of fouling reached the maximum fouling thermal resistance established in the design. From this period to April 2001, the measured value is smaller than the predicted dirt effectiveness.

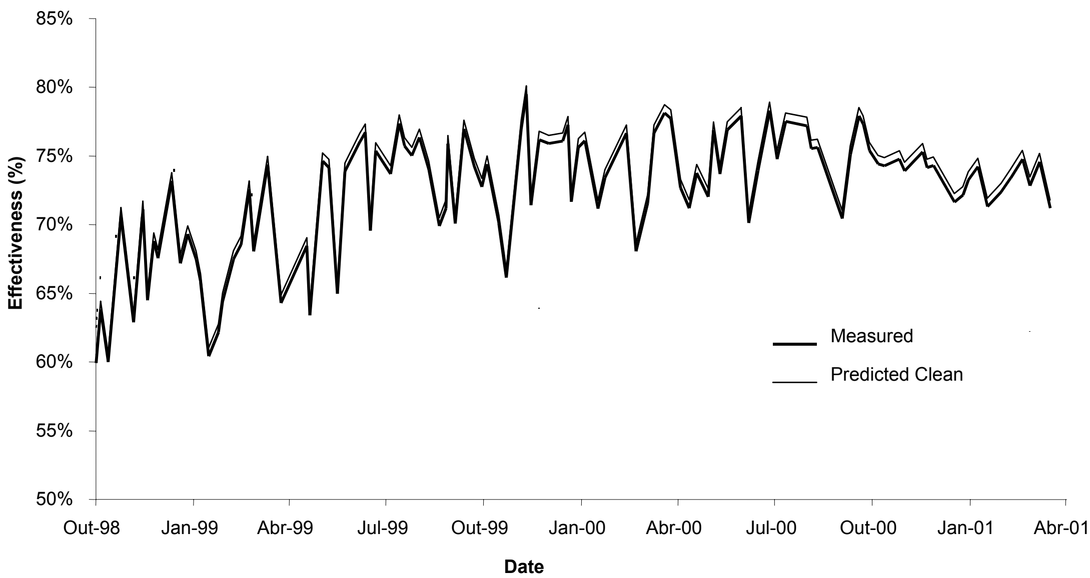

Figure 2. Comparison of the measured and predicted clean effectiveness of HX-04.

In Fig. (4), the index of fouling of HX-01 is shown. The IF is equal to zero the heat exchanger is clean and if it is 1 the HX is dirt at an expected design value. Any value above one means a heat exchanger dirtier than the designer would expect. The index of fouling is almost constant (nearly zero) until February 2000. This means the fouling is not significant. From February to October 2000 (8 months), fouling increases exponentially and the IF reaches its design expected value. As previously identified by the refinery staff, the cause of so high fouling rate was the deposition of corrosion products coming from the distillation tower. In April 2001, the average index of fouling is 1,8, in other words, 80% higher than expected in the design.

Figure (5) and (6) present the results for one more heat exchanger. Note that the thermal resistance of the fouling (index of fouling) increases at an almost constant rate and does not reach the expected dirt condition. The highest index of fouling achieved was approximately 62% of that expected in the design.

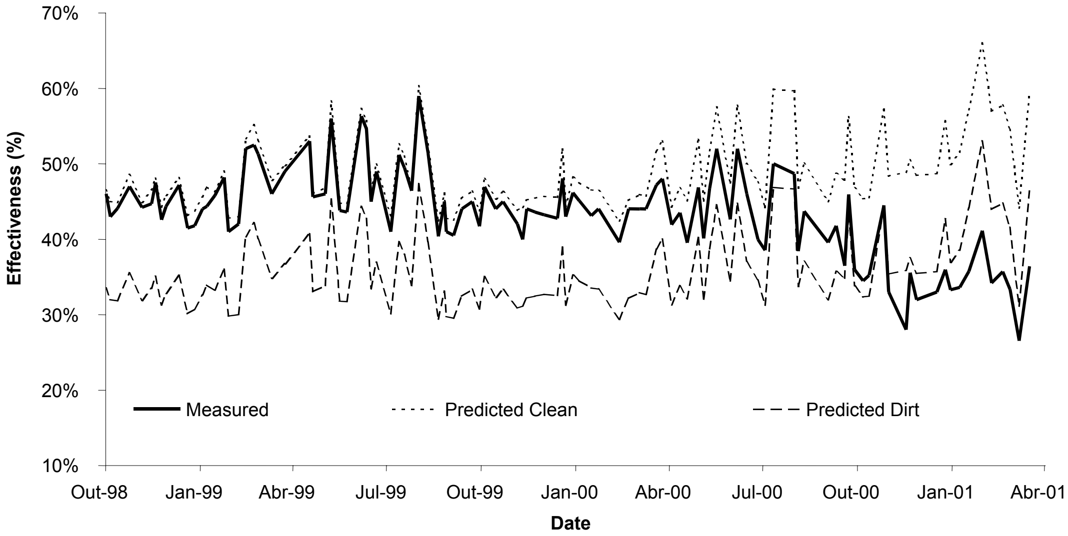

Figure 3. Comparison of the measured and predicted clean and dirt effectiveness of the HX-01.

As shown by Tonin (2003), for the other heat exchangers (HX-02, HX-05, and HX-07), the effectiveness and the index of fouling are similar to the HX-03's. The indices of fouling increase at a constant but different rate.

The results above show the Jerónimo's et al. (1997) approach is valid for monitoring the performance of heat exchangers. This implies the changes of the thermal physical properties, either of the crude or of the products, do not affect significantly the effectiveness.

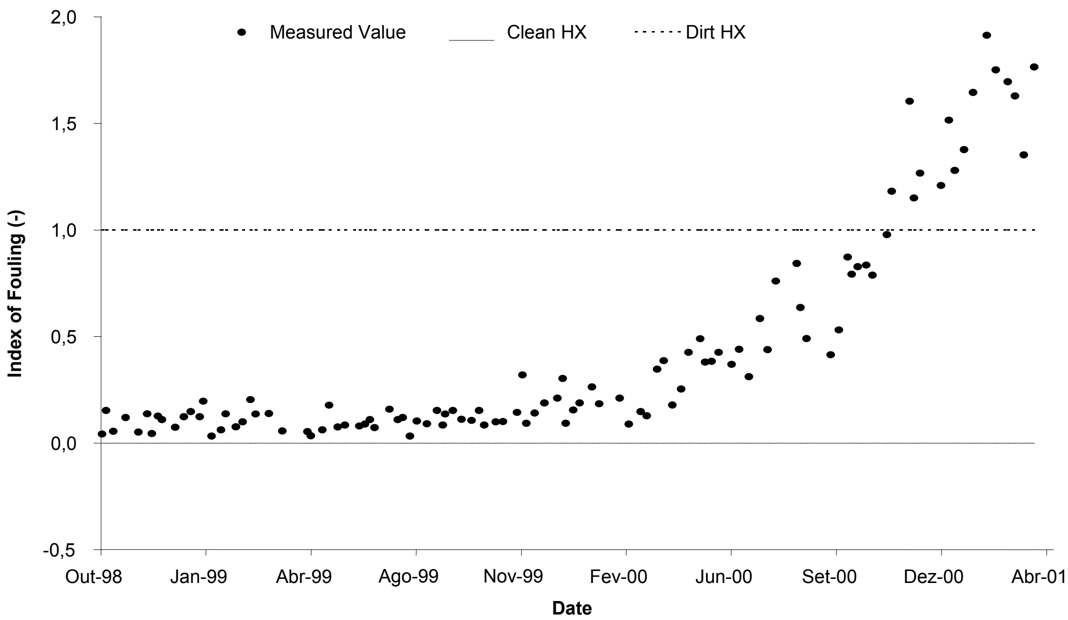

Figure 4. Index of fouling for the HX-01.

4.3 Thermal Performance of the Whole Network

Figure (7) presents the measured effectiveness of the network of Fig. (1) and compares it with the predicted clean and dirt values of the effectiveness. A similar behavior observed in the monitoring of a single heat exchanger can be seen in the monitoring the whole network. In other words, the measured effectiveness and predicted ones show the same tendency – the same frequency of oscillation. From October 1998 to October 1999 (12 months), the network worked almost clean. After November, the performance of the network began to reduce and one year later, October 2000, the effectiveness reached its dirt expected condition. This represents a lost of approximately 10% of the effectiveness. For about six months (from October 2000 to April 2001), the network operated in its dirt design condition. If the stopping criterion for cleaning was the thermal fouling established in the design, the heat exchangers should have been cleaned in October 2000. If the decision for cleaning were taken in this period, an excessive additional fuel would not have been spent in the furnace. The stopping decision is a clear example of the importance for the monitoring.

Although not shown some exchangers began to foul before October 1999 (HX-02, HX-03, HX-05, HX-06 and HX-07) and some others reach the design dirt condition before October 2000 (HX-06 and HX-07). This means the performance of whole network may not be compromised with the complete degradation of one or more heat exchangers. Besides, the degradation of one heat exchanger may be compensated by others ahead in the network. Figure (8) shows the index of fouling for the whole network.

During the monitoring, the contribution of each heat exchanger in the network can be computed by Eq. (19). This percentage of weight is shown in Figure (9) for HX-01, HX-04 and HX-06. In October 1998, these indices are, respectively, 23, 15 and 5%. This show the importance of HX-01 in the heat exchanged by the network, either because of the high temperature difference between the flows or because its higher dimension. For example, HX-01 exchanges 4 times more heat than HX-06. As can be seen, the contribution of HX-01 and HX-06 reduces with time, which is justified by the existence of fouling. Considering the heat transfer in HX-04 is not affected by fouling, its percentage of weight increases because of the reduction of the total heat exchanged by the network and because the augmentation of heat transferred by HX-04.

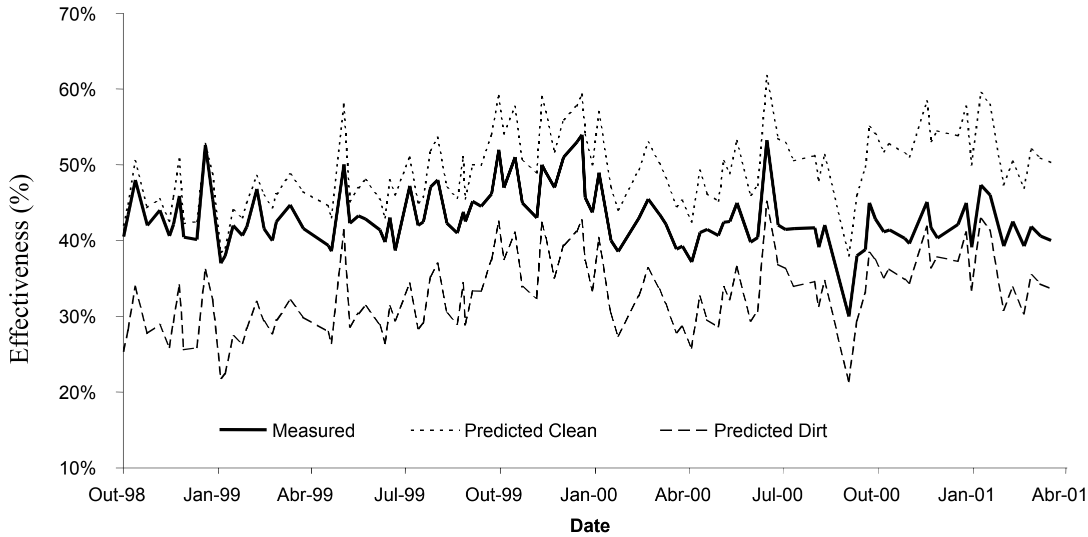

Figure 5. Comparison of the measured and predicted clean and dirt effectiveness of HX-03.

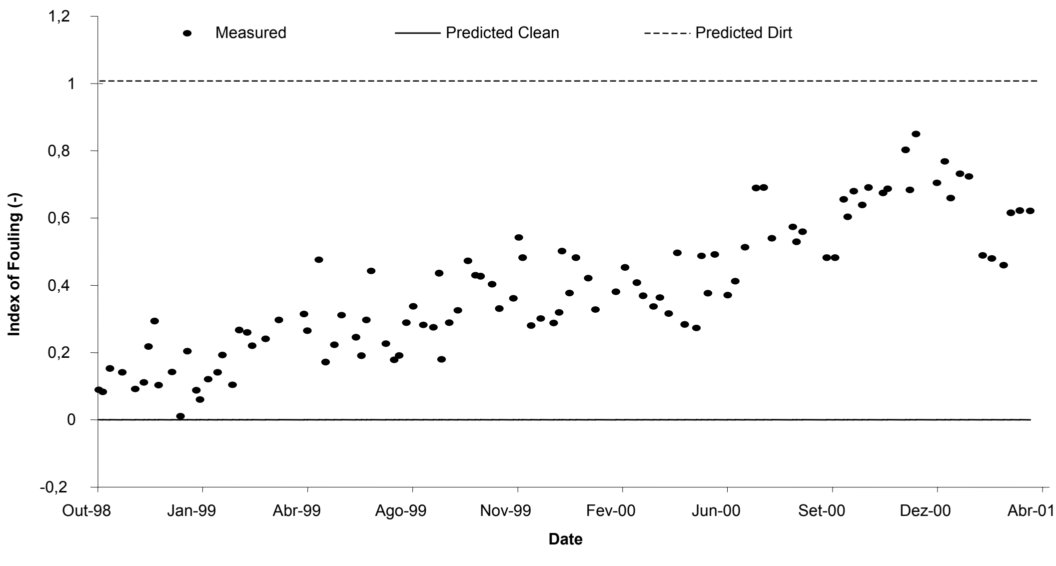

Figure 6. Index of fouling for the HX-03.

4.4 Additional fuel expenses

As the fouling increases, the heating of the crude diminishes and the demand for fuel increases in the furnace in order to keep the distillation temperature. Equation (20) allows the evaluation of the additional expenses with the fuel burnt in the furnace. Figure (10) shows the evolution of the expenses with time. After October 1999, when the measured effectiveness deviates from the predicted clean effectiveness, the additional expenses with fuel augments with time because of the reduction of the network thermal performance. By April 2001, this value is approximately US$ 1000/day that represents approximately 10% reduction of the network effectiveness. Considering the network has worked for six month at the dirt expected condition, US$ 200.000,00 would be spent with additional fuel. These expenses are related to only one of four branches of the pre-heat train.

5. Conclusion

In crude pre-heating, the composition and the fluid flow rates of the products change with time. Consequently the overall heat transfer coefficient varies. In order to avoid the complete evaluation of the overall coefficient, Jerónimo et al. (1997) define an approach with two procedures: 1) evaluation of the effectiveness based on measured values of temperatures and 2) prediction of clean and dirt effectiveness of the heat exchanger. The predicted values of the effectiveness are computed as a function of the heat capacity rates of the flows.

Comparisons show the changes of mass flow rates are very important to predict the effectiveness and that variations of thermal physical properties do not affect it. Although the composition of the crude and of processed products change periodically, the approach was successfully applied.

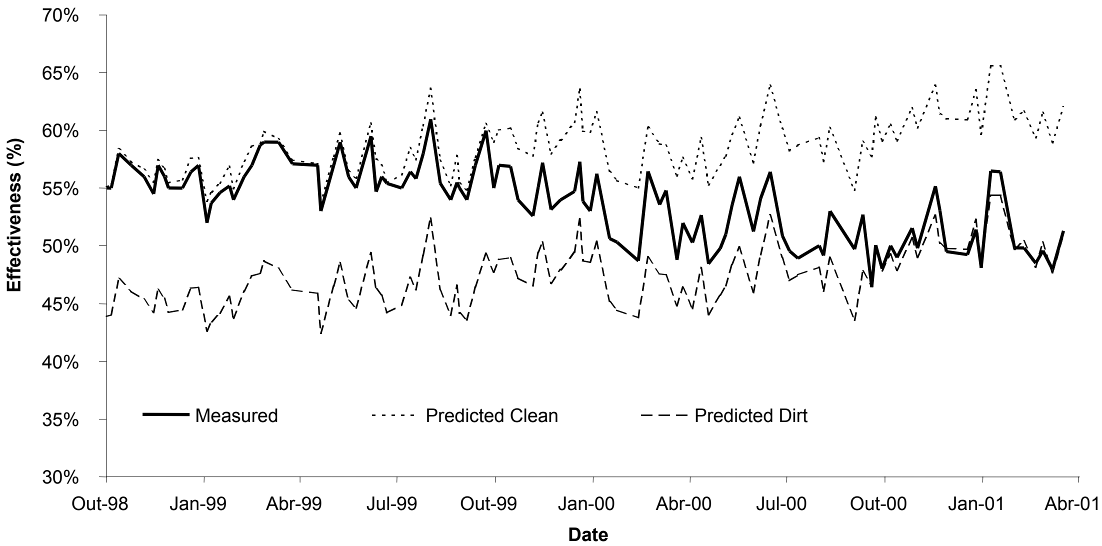

Figure 7. Effectiveness of the network of Fig. (1).

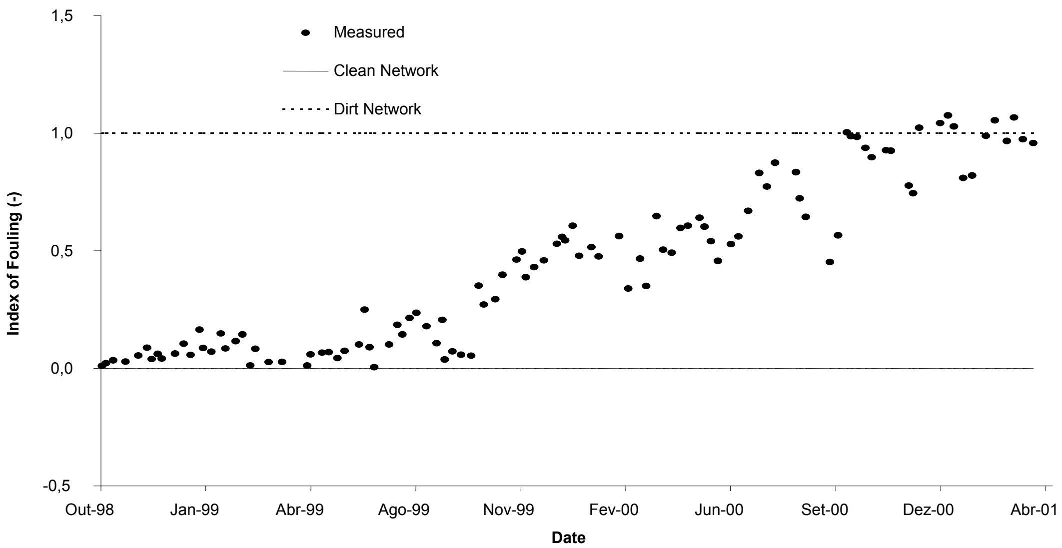

Figure 8. Index of Fouling of the network of Fig. (1).

As inlet/outlet temperatures of HX and one mass flow rate are measured continually, the use the approach indicates, at each time, the level of fouling and the contribution of each exchanger in the network. Additionally, the approach allows the evaluation of the expenses with fuel burnt in the furnace due to the reduction of the thermal performance of the network.

Finally, the method provides satisfactory results and very import information for the oil refining professionals. The use of the method can be extended to other industrial process. However, some care must be taken if the thermal physical properties of the fluids suffer significant changes.

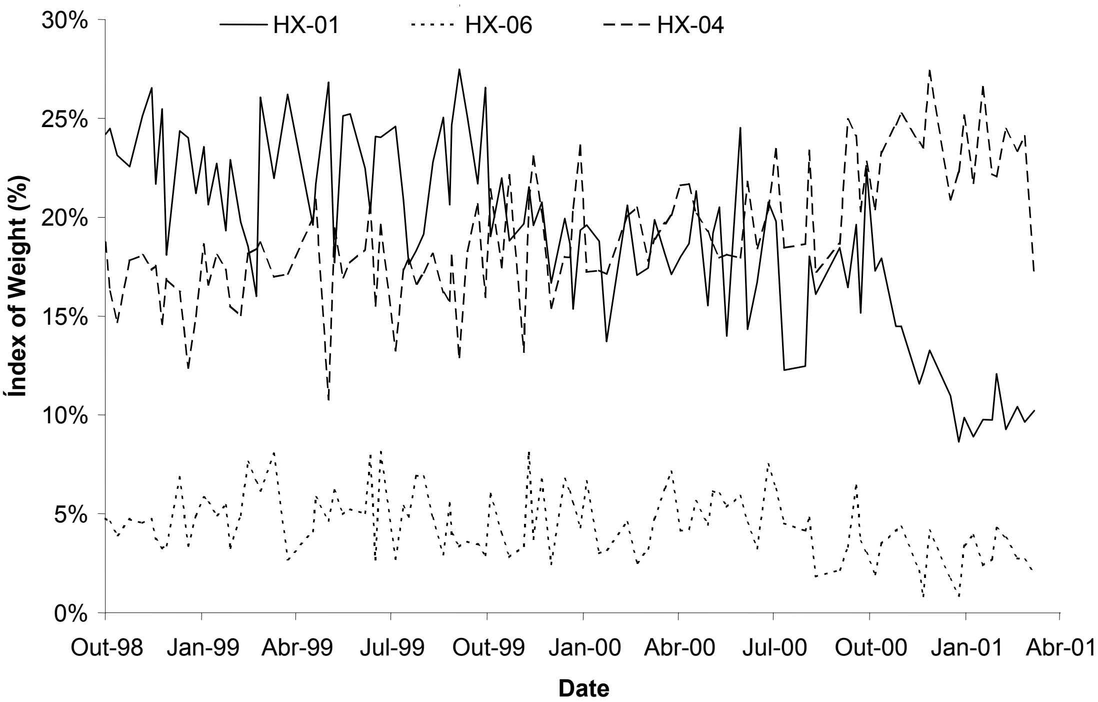

Figure 9. Index of weight for HX-01, HX-04 and HX-06.

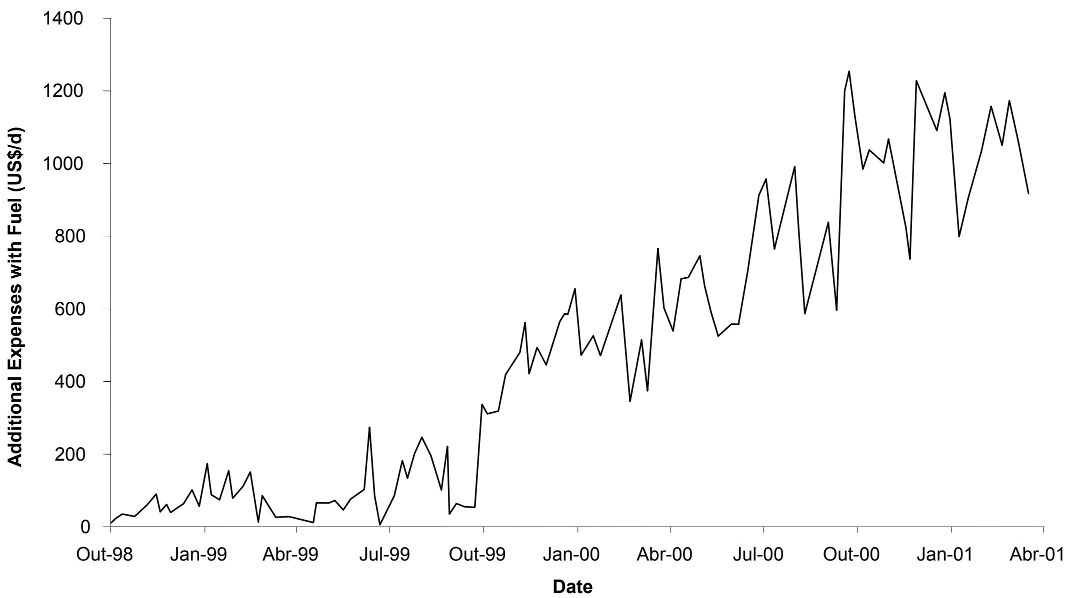

Figure 10. Additional expenses with fuel.

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