FOULING MONITORING AND CLEANING OPTIMISATION IN A HEAT EXCHANGER NETWORK OF A CRUDE DISTILLATION UNIT

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ABSTRACT

Fouling in preheat networks of crude distillation units (CDU) plays an important role in energy consumption. In this work a procedure to monitor the performance of the heat exchanger network (HEN) and to optimize the cleaning strategies is presented.

The procedure is based on a rigorous simulation of the HEN using Hysys (from Aspen Technology). The simulation is used to estimate the service overall heat transfer coefficient with real operational data acquired from the unit's Plant Information System (PI). The clean overall heat transfer coefficient is calculated for each one of the individual heat exchangers with a rigorous simulation using TASC (rigorous heat exchanger simulator also from Aspen Technology), embedded into Hysys. A comparison between the service and clean overall heat transfer coefficients provides the actual performance for each individual heat exchanger and for the complete HEN.

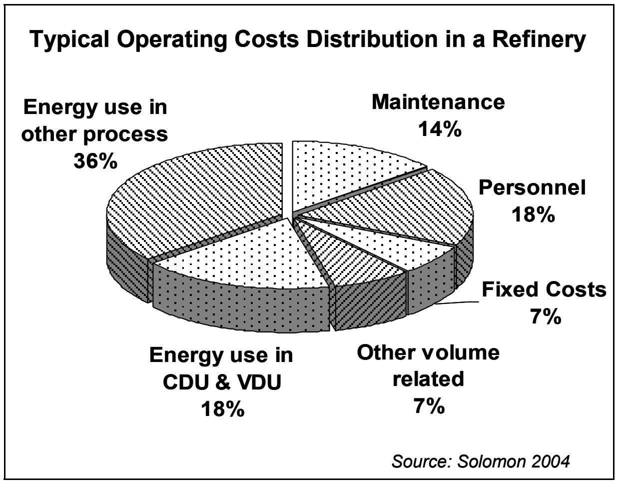
The first step is to collect the HEN operative data from the Plant Information System and to perform an ad-hoc pre-processing of each individual exchanger data (i.e., feed and product inlet and outlet temperatures and flow rates) in order to identify stable periods from which the mentioned calculations will be performed. As the feed/products flow rates and unit operating conditions are constantly changing, the steady intervals detection is a very important task because calculations performed with data of unstable operation time intervals could be erroneous and produce non-sense results.

The overall procedure is managed from an Excel environment, which performs the needed calls to PI and Hysys/TASC simulators in order to calculate each exchanger fouling and HEN overall performance under the actual fouling situation. Excel also commands the evaluation of the cleaning policies economics, searching between several pre-defined cleaning alternatives.

Results of the above mentioned methodology applied to a complex feed preheat HEN of the Topping IV CDU of REPSOL YPF Luján de Cuyo Refinery, Argentina, are presented.

INTRODUCTION

In the refining industry, the heat exchangers used for energy recovery suffer a progressive heat transfer efficiency loss due to fouling. The immediate consequences of this loss are a major consumption of energy in the furnaces and, in certain cases, the need to reduce throughput to compensate the low efficiency of the preheat train. In addition, Atmospheric and Vacuum units represent between 35% and 40% of the total process energy consumption in a refinery, it represents about a 18% of total operating costs (Fig. 1). Due to this, any saving that could be achieved in these units will have a great impact in reducing operating costs and greenhouse effect related gaseous emission.



Source: Solomon 2004

Fig. 1

The main objective of this work is to develop and implement a methodology to perform the heat exchangers network monitoring and cleaning optimisation, as well as the evaluation of the economic impact due to cleaning strategies. Also, to implement the software and information architecture needed to carry on those tasks in a periodic, routine and non-attended way.

DATA PROCESSING

The methodology was developed based on a particular case study for Topping IV Unit, at REPSOL YPF Luján de Cuyo Refinery, located in Mendoza Province, Argentina.

The first stage of the study consisted of a pre-processing of the historical data available to assure that the information to be used in the calculations belonged to a "stable" operating period of the Unit and that they did not contain gross measurements errors.

Initially the possibility was considered of classifying the quality of the information and stability of the process using statistical criteria (standard deviation) or the range calculated from maximum and minimum during a given period. They were collected from the historical information average on a daily basis, but after reviewing them, poor results were observed, possibly due to the cumulative effect of the disturbances suffered by the Plant during the day.

As a consequence, it was decided to collect data on a shorter basis (every 1 minute) to detect process steady periods to perform the calculations. Also, the usage of standard deviation as a possible index of steadiness detection was discarded, because it turned out to be a poor tool for detecting signal stability (as steady state refers). Standard deviation was more related to the signal noise than to its steadiness.

The steadiness of each time interval is defined using the range (maximum - minimum) during the period of study and a criterion of stability defined for every particular variable. The average values of all the variables, during the stable periods, are calculated in a space corresponding to a certain fraction of the given interval. For example, if the stability period lookup was for 2 hours, the average values were calculated for the last 30 minutes of this period.

As a second stage of data checking, once steadiness was detected, heat balances are calculated for both sides of every heat exchanger. The goal is to check if the heat exchanged on each side match. As a reference, it was pointed out that a type J thermocouple has a range from 0 to 750 ºC, with an uncertainty of 2.25 ºC and that the rates measured by plate orifice have an uncertainty of 5 % (Tonin *et al*, 2003). Therefore, the major total uncertainty in the heat duty calculation of each side is 7.5 %. Considering this previous value, the maximum technically expected error would be 15 %. Heat differences between both sides of the exchanger larger than this percentage can indicate that the measurements would not be acceptable for calculations. This acceptance percentage was considered in our methodology as a starting value, but other percentages can be used for gross errors detection. In fact, for some particular equipment, the heat calculation errors can be significantly larger than the mentioned 15 % due to diverse factors (for example, errors in both flow and temperature measurements larger than the technically expected maximum percentage).

DEVELOPED SOFTWARE

Several software tools were developed to execute all the steps and necessary calculations for the project implementation. The objective was that the whole sequence, from data collection and validation, up to the heat exchangers train simulations and fouling factors calculation, as well as the results write back again in the PI system, could be performed automatically. The tasks sequence is controlled from a main application developed in Visual Basic and embedded in Excel. The calculation sequence is initiated from the VB application every time the procedure is executed (daily or weekly) according to a user defined frequency.

The presented methodology involves the building of a single Hysys simulation file containing the model needed to perform the required calculations. Hysys model includes the necessary information to carry on all the calculations, from the heat exchangers mechanical design and crude oil and products characterization up to the pre-flash column simulation that removes light compounds from crude, located before the last section of HEN, prior to the feed furnace.

In the calculation steps where a more rigorous simulation of the heat exchangers is necessary, TASC is invoked from the Hysys model.

The application manager performs, as first task, the data collection from PI, the detection of the steady periods and calculation of the average values to be used in the calculations. The stability information is stored in files that were created by the automated data process applications.

The required information to execute a model run is provided in another Excel spreadsheet where this information will be loaded to allow the interaction between the application and the simulator.

CALCULATION METHODOLOGY

As a first step for heat exchanger fouling monitoring the actual global heat transfer coefficients (U_a) are usually calculated over time. Then, calculation of the fouling factor R_f is carried out, comparing the former with the value of U corresponding to the clean equipment (U_c).

In our methodology, a time varying U_c will be estimated for each exchanger from the inlet conditions of shell and tubes sides (rates and inlet temperatures of both fluids). Therefore, U_c will not remain constant in time, because process conditions are constantly changing or modified (different rates and inlet temperatures as consequence of changes in the unit operation).

The data processing sequence and calculations carried out by the application are as follows:

1. Collection of historical information of the needed signals sampled every 1 minute, during the period under study. Historical raw data files are generated.
2. Data processing for the calculation of auxiliary or complementary variables (e.g., average of redundant temperatures, sum of several flow-rates, etc). Historical data processed files are generated.
3. Steady state intervals searched during the considered period or fixed periodic sampling with a given frequency (both options are available). Averaged data values files containing the samples of the steady periods are generated.
4. Actual fouling factor calculations for each heat exchanger, using the methodology explained bellow. Fouling factor and calculation results files are generated.
5. Results of fouling factors validation and writing back validated calculated data into the plant information system.
6. Evaluation of cleaning alternatives. Impact evaluation for a given set of a-priori defined cleaning alternatives in terms of energy consumption in the furnace. This is done activating and deactivating Hysys model lines from the main Excel application where calculation for the equipments involved in each case study are defined. Files containing the different cleaning alternatives economical impact are generated.

Actual fouling factors calculation

The methodology mentioned in step 4. above includes the following steps:

a. Average heat duty calculation for each heat exchanger

Simple heaters / coolers in the Hysys model are used to calculate the heat exchanged through each side of all the equipment. The comparison between the heats of hot and cold sides is externally done, from the Excel embedded application manager.

The overall exchanged heat should be calculated by the average of both sides but, as mentioned before, errors above the technically expected 15% maximum could appear. Therefore, a confidence factor (C_f) is used in the calculation. If C_f=1, the heat duty calculated for the crude side is more reliable. If C_f=0 the confidence is 100% on the product side heat duty calculation. If C_f is near 1 the temperatures calculated during the overall heat exchanger train simulation for the crude side will be more similar to the measured ones, but the fouling factor calculation will be more disperse (see *Fouling Factor calculation with different Confidence Factors* on Results section). The confidence factor is a user defined parameter that must be configured for each one of the heat exchangers.

b. Clean global heat transfer coefficient calculation using rigorous simulation

To calculate the clean global heat transfer coefficient, a rigorous simulation is employed. TASC rigorous simulator is used for this step, with actual rates and inlet temperatures given as input for each heat exchanger, defining a fouling factor equal to 0.0. The "clean" outlet temperatures are calculated and the U_c is reported. It is equivalent to calculate the individual film heat transfer coefficients for each side of the heat exchanger.

c. Actual global heat transfer coefficient

The actual global heat transfer coefficient (U_a) needed to exchange the average heat duty estimated in a) is calculated using the Adjust operation in Hysys and a simple model for heat exchangers.

d. Fouling factor calculation

The fouling factors for each piece of equipment are calculated with the actual and clean global heat transfer coefficients determined in b) and c), respectively.

Effect of cleaning individual heat exchangers on the performance of the whole train

The cleaning cases have been pre-programmed in advance supposing the heat exchangers can be one by one individually cleaned, cleaned by pairs or groups or all the train simultaneously. The objective is to determine the impact of cleaning on the inlet temperature of the furnace and so, on the energy consumption of the unit.

This effect of cleaning evaluation is an optimization of detecting the heat exchanger/s that have to be cleaned when the unit is turndown or shutdown by planning reasons, in order to achieve the maximum energy savings. But is not an optimization to find the optimum period between cleanings because the real operational situation of the units in

Argentine refineries is that they can not reduce throughput or shutdown only for cleaning heat exchangers.

The simulation case cleaning evaluations is the one that includes the complete HEN with the values of U_a calculated in step c), except for those heat exchangers that are being cleaned. In this cases U_c are used, but this value is not necessarily the U corresponding to deep clean condition (R_f=0.0), because the fouling factor after cleaning depends on the cleaning method. Even the U_c or R_f values after cleaning can be fixed by the user, and a good reference could be the U_a value obtained for each equipment after a given cleaning procedure, calculated from historical data.

CASE STUDY: TOPPING IV, LUJÁN DE CUYO REFINERY

The methodology developed in this project was applied to the particular case of Topping IV CDU at REPSOL YPF Luján de Cuyo Refinery. This Unit has an 18 heat exchangers train used to preheat the crude before the feed furnace. The process diagram of the HEN is shown in Fig. 2.

The white triangles represent existing rate measurements, and the grey ones are temperature measures.

Heat exchangers before desalter:

- CE-34 (crude / LGO from CE-3B)
- CE-2B / CE-2A (crude - kerosene PA, two shells in series, simulated individually because there are intermediate temperature measurements on both sides, crude and product)
- CE-35 (crude / VLGO PA)
- CE-1 (crude / kerosene product)
- CE-3AB (crude / LGO from LGO stripper, two shells in series, simulated together because there is not intermediate temperature measurement on crude side)

Between desalter and preflash column:

- CE-4 (desalted crude / HGO PA, two shells in series, simulated together because there are not intermediate temperature measurements, it is called CE-4AB).
- CE-5D / CE-5C / CE-5B / CE-5A (desalted crude / VHGO, four shells in series, simulated individually because there are intermediate temperature measurements on both sides, crude and product)

Between preflash column (flashed crude) and furnace:

- CE-6E / CE-6D (two shells in series, flashed crude / asphalt, simulated individually because there are intermediate temperature measurements on both sides)
- CE-6BC (flashed crude / asphalt, two shells in series, simulated together because there is not intermediate temperature measurement on product side)
- CE-6A (flashed crude / asphalt).

In all cases where there are redundant temperature measurements, the average was assumed.

Several views of the Hysys model developed for this case study are presented in Fig. 3.

In the first line simple heaters / coolers are used to calculate the duty exchanged on both sides of each heat exchanger.

In line #2 there is rigorous simulation models calling TASC, to calculate the U_c under actual operation conditions.

In line #3, the U_a needed to exchange the actual duty is calculated using the available Adjust operations in Hysys.

Finally, line #4, where overall HEN is simulated, is used to evaluate the impact of cleaning cases on the inlet furnace temperature.

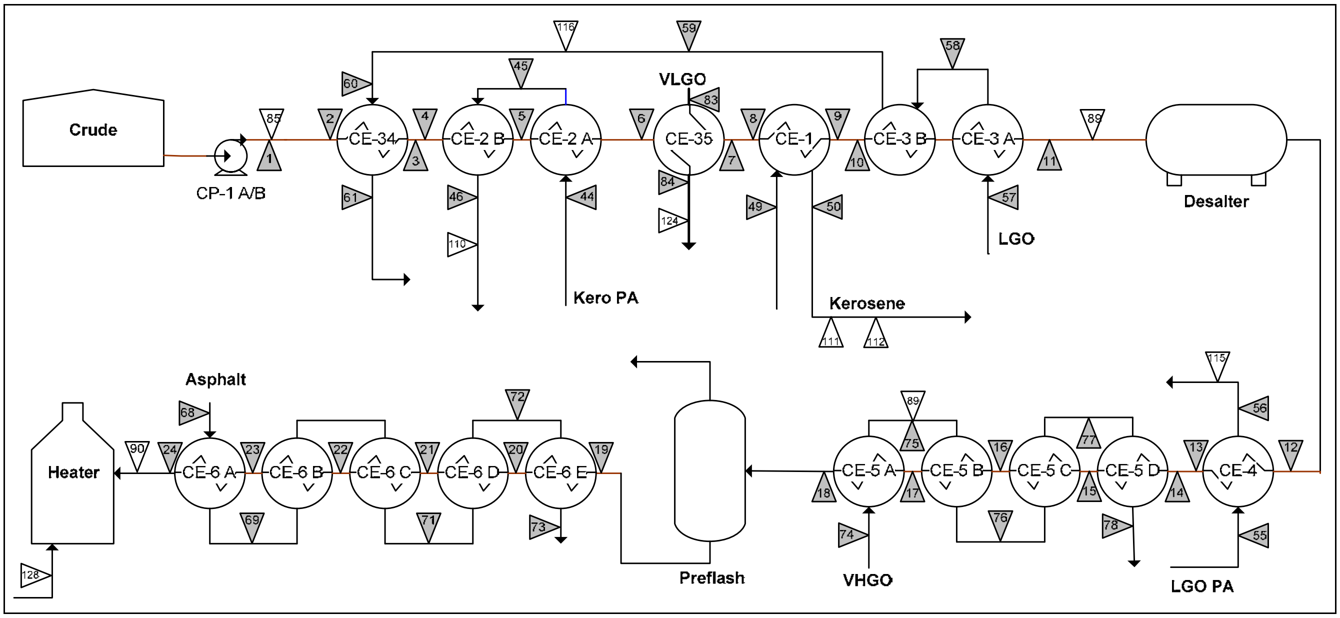


Fig. 2: Topping IV HEN configuration

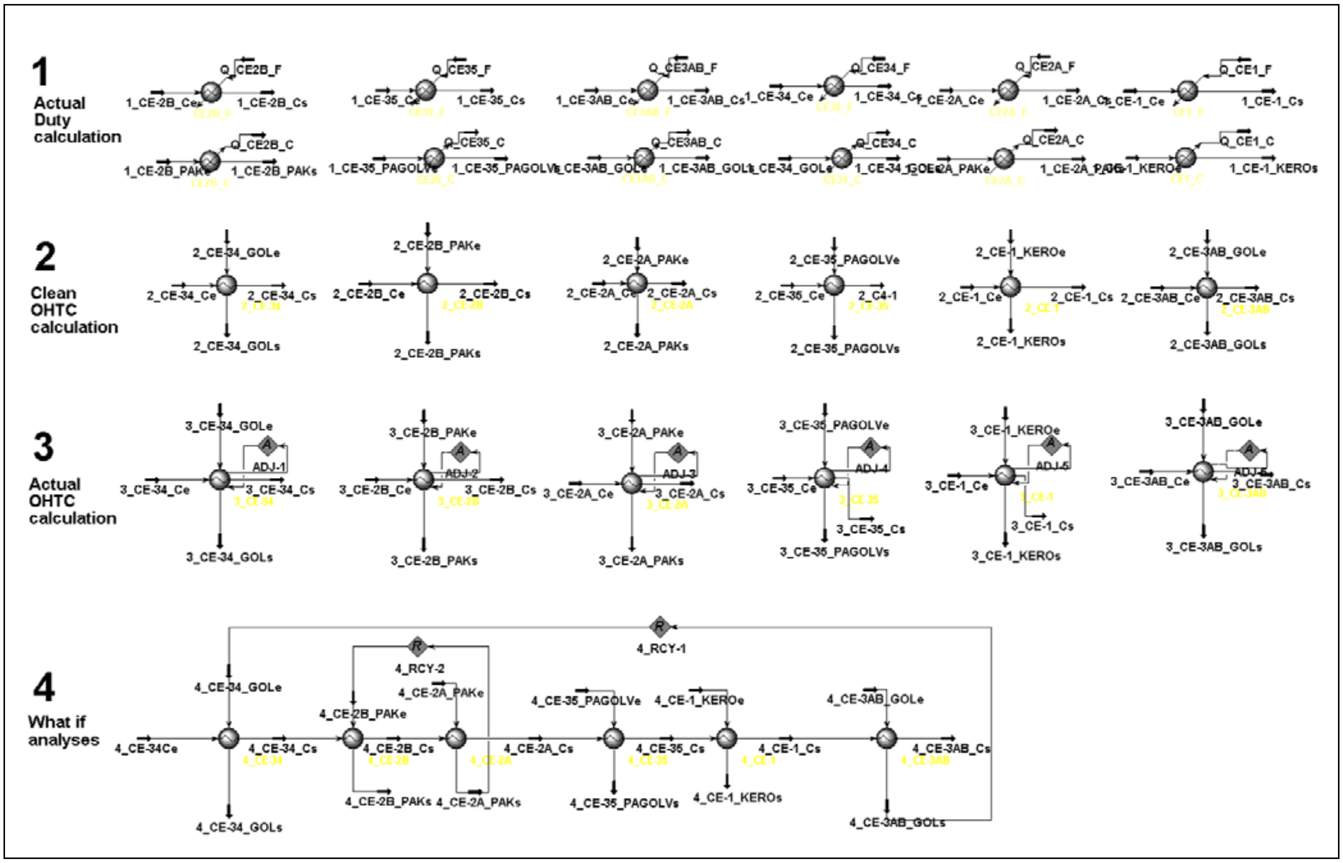


Fig. 3: Hysys model view

Steady state detection

For a tags collection list (approximately 70 existing tags in PI) chosen from the Topping IV diagram, data was collected once a minute since January 2005 up to January 2007. Raw data was inspected and analyzed in order to determine an appropriate period of time in which maximum, minimum, range, average and stability could be calculated properly (e.g., 120 minutes). Fig. 4 shows an example corresponding to one day of April, 2005, data collection period for the CE-1 heat exchanger. Red vertical lines show periods of detected steadiness.

Grey bands in Fig. 4 show the 120 minutes intervals where steadiness for a particular heat exchanger was detected. It could be seen that data was stable during those periods (more or less horizontal flat lines) while unstable zones did not fulfilled the detection criteria.

In Fig. 5 one month of data (June, 2005) are shown for all of the CE-6E heat exchanger tags. Vertical lines show stable operation periods. As can be seen, considerable variation occurred during this period. There is a region where steady points were not detected, approximately in the first third of the above mentioned period; it could be noted by the vertical lines and grey zones absence.

Fig. 6 shows a detailed portion of data collection corresponding to 3 days of June, 2005 for CE-6E heat exchanger. Simultaneous steadiness periods of 1 hour have been highlighted. For the overall explored period, all the variables averages to be used in the R_f calculation for this heat exchanger were calculated. It could be noticed that the methodology used, based in the range of each variable, was able to detect periods where the curves are flat (steady) and discard others where the curves have notorious variations.

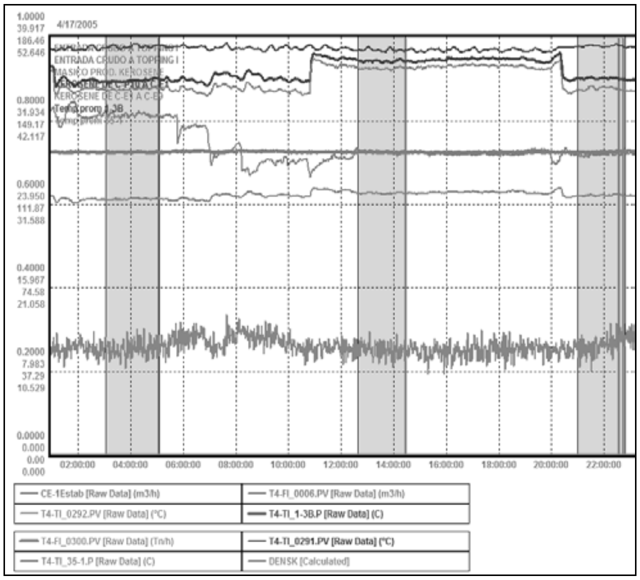


Fig. 4: steady state periods for CE-1

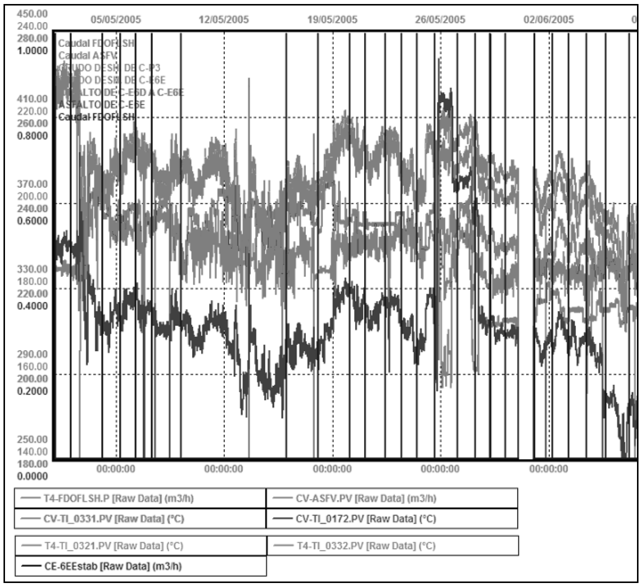


Fig. 5: steady state periods for CE-6E

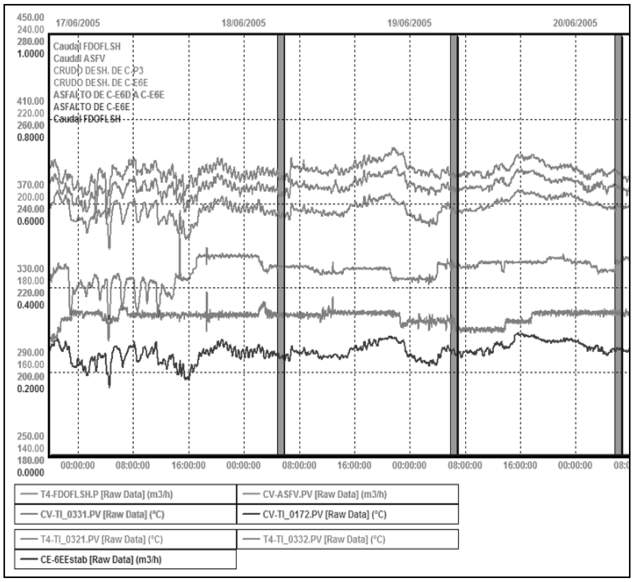


Fig. 6: steady state periods for CE-6E

RESULTS

The results obtained by the methodology application to the Case Study are the following.

Fouling Factors calculation with “stable” data

An ad-hoc calculation procedure was developed to inspect all the sampled data and find the steady periods. The steadiness for all the variables related to a given heat exchanger was simultaneously searched. The range (i.e., maximum minus minimum value) of a given moving back horizon time period was inspected. A given tolerance was defined for each tag or variable. Once all the variables (typically, 2 flow-rates and 4 temperatures per heat exchanger) were found to be stable, the proper average value is calculated at a fraction of the assumed moving period. For the crude unit, 120-minute period was used because such a period is approximately the time needed to reach steady state after a disturbance.

As an example, in Fig. 7 can be shown the calculated fouling factors for CE-2B heat exchanger during March / April, 2006 period. Black squares correspond to constant, equally spaced data, every 23 hrs, without stability estimation. White squares correspond to calculations performed during steady periods detected with the above described methodology. It can be clearly seen the non-steady samples calculated points (black squares) are much more disperse that the others. Encircled are the calculated points with the higher and notorious differences with respect to the stable (steady) periods. In this particular heat exchanger, the use of stability considerations to search the steady data samples helps to calculate smoother and coherent fouling factors.

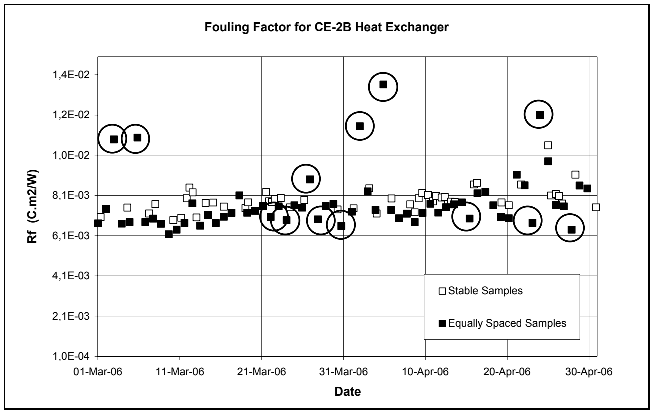


Fig. 7

Similarly, on a long term plot, as presented in Fig. 8 for the heat exchanger CE-5A, the fouling factors calculated under a period of more than one year using stable samples do not show noise. The calculations using equally spaced samples show noise and a bigger dispersion.

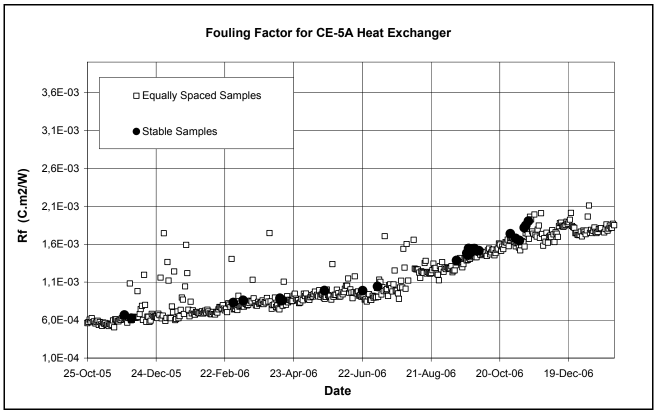


Fig. 8

Impact of cleaning on fouling factor

In Fig. 9, the effect of a chemical cleaning on heat exchangers CE-5C and CE-5D is shown. The effect of such a cleaning was clearly captured by our proposed methodology. It is interesting to note how much smoother both plots are after the cleaning, especially for heat exchanger CE-5C, whose plot was noisy in the time period previous to the cleaning.

All the shells of CE-5 heat exchanger (A, B, C & D) have the same geometry and same fluids on both sides. Fig. 10 shows the fouling factor for shell A for the same period than Fig. 9. CE-5A bundle was replaced in November 2004. It is evident that the fouling factor value for this new bundle is almost the same than the R_f values for shells C&D after the cleaning.

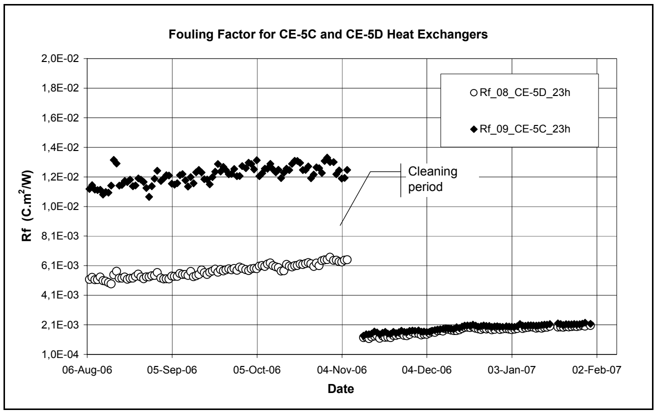


Fig. 9

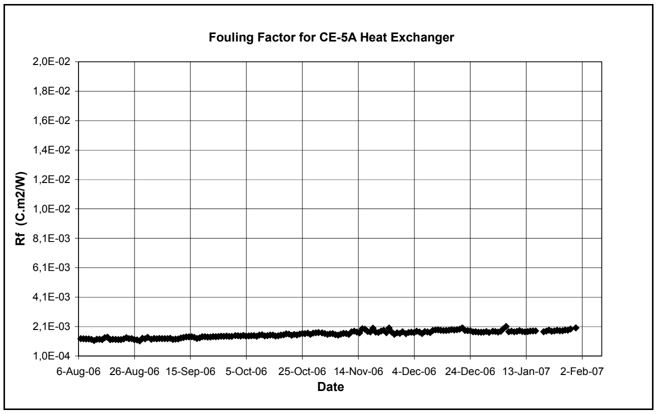


Fig. 10

Also, Fig. 11 shows the effect of cleaning on CE-4AB. It can be seeing that the cleaning was not as effective as in case show in Fig. 9, this is because the cleaning method was different. For exchangers CE-5 C&D a mechanical cleaning was done, but in case of CE-4 AB it was a countercurrent wash with light gas oil.

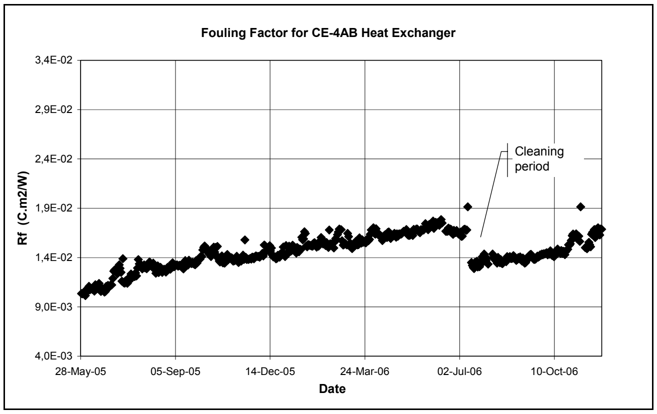


Fig. 11

Fouling factors based on Uc calculated with actual process conditions versus Uc constant design value

To produce a trend for the heat exchangers fouling factors involves usually the calculation of the actual global heat transfer coefficients (U_a) over time and comparing them with the design clean heat transfer coefficient (U_c). This U_c should only be valid for process conditions similar to those of design, but not for others. Under our methodology, however, U_c is not supposed to remain constant but updated based on the current process conditions (feed rates and inlet temperatures).

Comparison between fouling factors calculated with a constant overall heat transfer coefficient (black squares) versus our methodology (white squares) is shown in Fig. 12, where some periods of time with very different noise and variability of both trends can be seen (Periods 1 and 2).

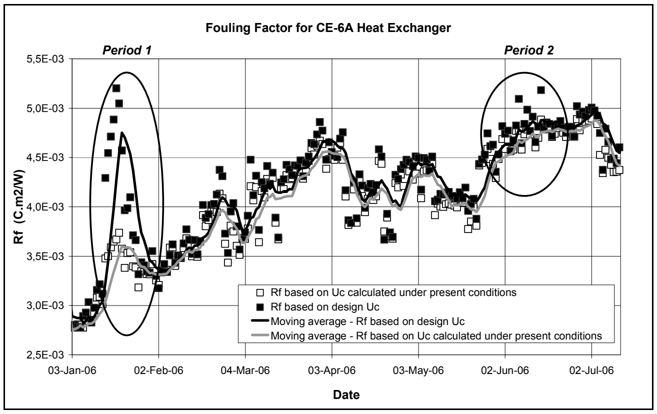


Fig. 12

Also, moving averages smoothing trends have been plotted (continuous lines). It can be shown how smoother the plot of our proposed calculation methodology is against the one that uses a "fixed nominal" global heat transfer coefficient to compute the fouling factor. During Period 1, the statistical variance of fouling calculated by the traditional method was 10 times higher than the variance of our proposed calculation. During period 2 it was 4 times higher.

Similar smoothness curves can be see for exchanger CE-6BC, as shown in Fig. 13 (note the smoother averaging curves for our proposed calculation methodology).

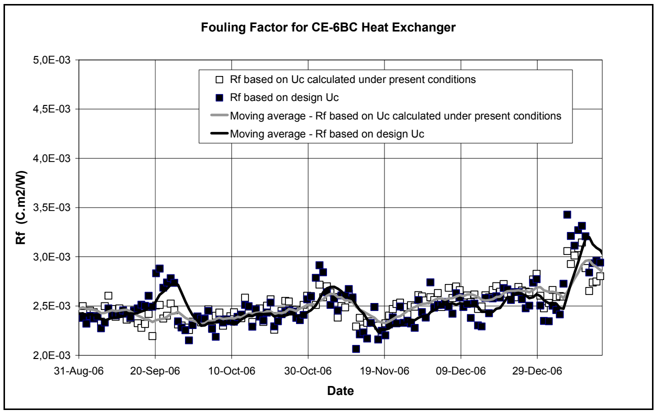


Fig. 13

Fouling Factor calculation with different Confidence Factors

Every heat exchanger can be provided with a confidence factor as a configuration parameter as part of the proposed calculation methodology. This value is used to evaluate the overall heat duty based on the individually calculated duties for both sides of the equipment (shell and tubes). Several calculations over the analyzed period were made to evaluate the confidence factor influence on the fouling factor (Rf) calculation, concluding that calculation dispersion is lower when confidence factor is nearest to 0.50. Dispersion was evaluated based on the global transfer coefficient standard deviation.

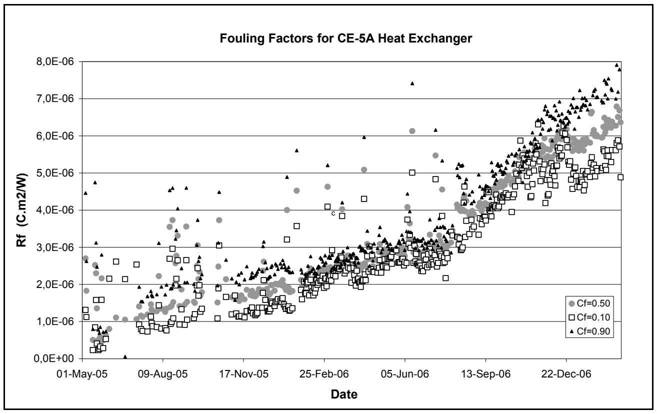


Fig. 14

Due to real time data uncertainties, duty calculated differences will result in a mismatch between calculated temperatures and actual process data. The error propagates from one piece of equipment to the other, perhaps giving, at the end of the train, as a result of accumulated effects, a big error on the furnace inlet temperature calculation. As one of the main objectives of this work is to predict heat exchangers cleaning influence on the furnace inlet temperature, seems to be a good practice to use confidence factors between 0.5 and 1.0. If confidence factor is nearest to 0.5, equal weight is given to tube and shell side data. It is preferably to use C_f close to 1.0 (i.e., more confidence on crude side temperatures). Choosing the confidence factor close to 1.0 will tend to minimize the furnace inlet temperature calculation mismatch.

CONCLUSIONS

A methodology within an industrial, practical application framework, as opposite to an academic theoretical treatment, was developed. The calculation methodology and procedures used both already available commercial standard software and several pieces of ad-hoc programmed routines. In particular, REPSOL YPF has corporate network licenses of the commercial software used and no extra cost in licenses was incurred.

Processing a good portion of the historic data already stored in the plant information system provided a good representation of the HEN fouling factors evolution during time and the historical cleaning procedures and effects were very well identified.

Performing the calculations with data from stable, steady periods, generated less disperse and more coherent results, minimizing the impact of process instability on the calculated fouling factors.

The data and results for individual heat exchangers must be analyzed particularly for each case, with engineering criteria, to determine the confidence factor that better fits each exchanger.

The proposed methodology of calculating the U_c from actual process conditions, instead of using an U_c design value, generates fouling factors curves with no variations due to changes in unit operation (rates and temperatures different from design).

To have confidence calculations for fouling factors allows the user to simulate the complete HEN under different cleaning scenarios in order to choose the one with major economic benefit.

FURTHER WORK

Future work will try to find a practical way to predict fouling factors trends over time using the historically calculated data. This prediction would be used to analyze different future cleaning scenarios, anticipate the need of cleanings and evaluate their economic impact.

NOMENCLATURE

C_f	Confidence factor
HGO	Heavy Gas Oil
LGO	Light Gas Oil
PA	Pump Around
Q	Duty
R_f	Fouling factor
U	Global heat transfer coefficient
VLGO	Vacuum Light Gas Oil

Subscript

c	clean
a	actual

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