REAL TIME FOULING DIAGNOSIS AND HEAT EXCHANGER PERFORMANCE

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ABSTRACT

The issue of fouling in preheat trains of crude oil distillation units in Petrobras' refineries is a major concern, especially now, as heavier Brazilian crudes with higher asphaltene content are being refined. As the efficiency of the preheat train plays an important role in the energy consumption of a distillation unit, its performance must be tracked as precisely as possible in order to identify operational problems. This work describes an on-line heat exchanger performance evaluation system based on rigorous simulation of the equipment in order to predict both the operational and clean overall heat transfer coefficient. A real time comparison between these two values indicates the actual performance of the heat exchanger and of the preheat train. The use of a rigorous process simulator (Petrox from Petrobras) together with a rigorous calculation of the global heat transfer coefficient (using the program Xist from HTRI) allows one to consider aspects that are not usually taken into account in this kind of evaluation. These aspects include crude vaporization after the desalters, variations of crude and products composition with the distillation unit run. The system is being implemented at the biggest Petrobras refinery (360 000 bpd), in a 25 heat exchanger preheat train.

INTRODUCTION

As is well known, the design, using heat integration of the process streams, and operation of crude preheat trains plays an important role in reducing the energy consumption of crude distillation units (CDU's). Preheat train operation and performance must be tracked as precisely as possible in order to detect loss of heat transfer efficiency and avoid an increase on preflash tower reboiler duty, on atmospheric furnace duty, on water refrigeration consumption, on head loss of the system, or even a decrease of the unit throughput. All of these consequences bring an economic penalty to the unit.

Fouling is one of the major causes of a loss of performance of preheat trains. Its mitigation can be achieved through several methods, some of which can be applied together (Ebert and Panchal, 1995; Wiehe and Kennedy, 2000; ESDU, 2000; Bott, 2001; Wilson et al., 2001; Wilson, 2003; Yeap et al., 2004; Stark and Asomaning, 2003; Van den Berg at al., 2003; Asomaning, 2003). These methods can be subdivided into 3 distinct scales: (1) microscopic scale involving the physical-chemical understanding of the fouling precursors; (2) design scale, where the selection, thermal design and configuration of the heat exchanger can be manipulated to minimize the fouling and (3) industrial scale, where the heat exchanger network interaction and control strategies are used to minimize the fouling.

This paper aims to present the methodology used by Petrobras to work on the third scale. A computational tool, using C^{++}, has been developed to infer, on a real time basis, the thermal efficiency of each heat exchanger (measured by the fouling factor, for instance) as well as of the whole preheat train. This tool can help to choose which pieces of equipment should be removed for cleaning (Smaïli et al., 2001; O'Donnell et al., 2001) and also to help the crude unit operator to make decisions regarding the preheat operation so he can maximize the heat recovery from it. Also, the actual fouling factors that are being measured can be used by Cenpes (Petrobras R&D Center, in Rio de Janeiro, Brazil) heat exchanger design team in order to improve their design. Currently, in most cases, those factors are taken from tables presented by TEMA and do not always represent the reality regarding time dependency, crude and process stream composition and so forth.

This tool, named Fouling^{TR}, is connected to the refinery plant data information, the PI System, and acquires real time data (flowrates, pressures and temperatures) from the process streams and send them to the Petrobras rigorous process simulator (Petrox). As not all temperature and flowrate information needed to evaluate the whole preheat train performance are available, a particular simulation strategy was developed using the heat exchanger module and control module (control and manipulated variables) that, at the same time, reconciles the data and supplies all the missing operational information, closing mass and energy balances. After this simulation, the real time operational global heat transfer coefficient (Uop) can be inferred, as well as any other variable that a rigorous process simulator can provide.

Cenpes also developed a communication between Petrox and Xist, a program from Heat Transfer Research Institute (HTRI) used to design heat exchangers in a rigorous way. So, as it was done for Uop, a real time clean global heat transfer coefficient (Ucl) can be inferred, using the same operational inlet data for each heat exchanger and some geometric data. When comparing Uop and Ucl, a real time indication of the fouling formation can be obtained. This rigorous simulation of the heat exchanger network can also estimate the performance of each clean heat exchanger, i.e., its maximum heat load, the maximum cold outlet and minimum hot outlet temperatures. As the performance of the equipment is known, it can be derived, again using Petrox, what would be the benefit, regarding the preflash tower inlet temperature, if a specific heat exchanger is removed for cleaning and what would be its maximum value if the whole preheat train was cleaned.

The major advantage of this tool is that, in using a rigorous process simulation, crude composition can be much better characterized by many pseudocomponents as required, it can be updated as the crude changes, temperature dependency of properties such as thermal conductivity, density, viscosity and specific heat can be taken into account as well as the influence of the crude vaporization that occurs after the desalters. These aspects are not always considered in the literature (Jerónimo et al., 1997; Torin and Negrão, 2003, Rodera et al., 2003). Also, due to the use of Xist and its well-tested film coefficient correlations for shell and tube heat exchangers, the Ucl is also much better inferred.

This tool is being tested in one of the two CDUs in the biggest Petrobras refinery (Replan), located in São Paulo State, Brazil southeast. This refinery processes 360 000 bpd of Marlim crude (API 19.6 and high asphaltenes content (2.9% w)) from Campos basis in Rio de Janeiro State, Brazil southeast. The preheat train has 25 heat exchangers.

SIMULATION STRATEGY

In this section, the simulation strategy developed in this work and used in Fouling^{TR} will be briefly described. Figure 1 shows the preheat train scheme. The crude enters the CDU and the stream splits into 3 branches (1, 2 and 3). After going through the heat exchangers in the 3 branches, the streams combine and salt, sediments and water are removed by 2 desalters. The crude is again split into 2 branches (4 and 5) where it is heated up before entry to the preflash tower. It is important to say that there is a connection between branches 1 / 2 and branches 4 / 5 through 4 different hot streams. This connection, which increases the heat recovery, gives rise to numerical simulation convergence problems due to the presence of the flow loop.

The simulation strategy developed consists of first characterizing the crude and the hot streams by pseudocomponents using ASTM distillation and density information. These pseudocomponents and their distribution along the streams can always be updated as crude composition changes or as the CDU runs different campaigns. Besides the crude and process streams characterization, two models of the simulator are used: the heat exchanger model and the control model.

After a unit revamp, completed by Cenpes in 2001, temperature measurement devices were installed to measure crude temperatures after each heat exchanger. This instrumentation is of great value since the more operational data are available the better the simulation can be. Unfortunately, for the hot streams there are not so many data available (and that is why this particular simulation strategy had to be developed). So, these known crude temperatures are used as specified variables in the heat exchanger models. Crude flowrate is measured in branches 4 and 5 (after the desalter) and in branch 3 (before the desalter). The crude flowrate through the other 2 branches (1 and 2) is estimated by a control model, using an available hot stream temperature as the specified variable (controlled variable) and the crude flowrate as the manipulated variable. The hot stream flowrates were estimated likewise. Figures 2 and 3 show a typical simulation strategy for branches 1 and 4. There are some differences in the strategy used for each branch (1/2/3 and 4/5) due to the available data for each branch. Sometimes, different control models manipulate a hot stream temperature and flowrate, as can be seen in Figure 3. A control model specifying an available hot stream temperature also manipulated the split fraction in the splitter of Figure 3.

Clearly, this simulation strategy is strongly depends on the available operational measurements. What must be emphasized, though, is the use of important characteristics of the process simulator in order to model the heat exchanger network and close the heat and mass balances as precisely as possible.

REAL TIME SIMULATION

Once the models are all set up, real time data is acquired and the simulation can start. The data used is an average value within a 1-hour window. The first thing is to close heat and mass balances and to detect gross errors in those measurements. This is done using the simple heat exchanger models from Petrox. After that, all the operational data for the entire preheat train is available, including the Uop for each heat exchanger, the operational preflash inlet temperature, etc. This will be called Simulation 1.

Then, a second simulation is performed to estimate the Ucl for each heat exchanger alone. In this case (Simulation 2), its inlet conditions (hot and cold streams) are the same as for Simulation 1, except that there is no model specification (as there is for Simulation 1 - "cold stream outlet temperature") and the rigorous heat exchanger models (from Xist) are used. Figure 4 illustrates this procedure (compare with Figure 2). This approach gives, among other results, the maximum outlet conditions and the maximum heat load a heat exchanger could give for specified inlet conditions, assuming it is clean, with no fouling.

Uop and Ucl are compared, using Equation 1, to estimate the real time fouling factor for each heat exchanger. The same can be done for the heat load, giving the heat exchanger efficiency, as defined in Equation 2.

$$R_f = \frac{1}{U_{op}} - \frac{1}{U_{cl}} \tag{1}$$

$$\varepsilon = \frac{Q_{op}}{Q_{cl}} \tag{2}$$

A third simulation can be done to estimate the maximum possible heat recovery from the heat exchanger network, i.e., if all the heat exchangers were cleaned, what would be the maximum preflash inlet temperature. In this case, only heat exchanger network inlet conditions are set and are the same as for Simulation 1. Intermediate hot and cold streams conditions are calculated during the simulation. Again, rigorous heat exchanger models are used. Figure 5 illustrates this approach. Note that, unlike Simulation 2, the crude outlet condition from the first heat exchanger is the inlet condition for the second heat exchanger, and so forth. This means that the crude carries the clean heat exchanger influence from one piece of equipment to another. The same thing happens to some of the hot streams that connect branches 4 and 5 to branches 1 and 2, as stated earlier (Figure 1). So, Simulation 3 shows the interaction of all the preheat train exchangers and how each clean heat exchanger influences each another.

As Uop and Ucl are known for each piece of equipment, a fourth simulation can be performed in order to determine what would be the improvement on the preflash inlet temperature if a specific heat exchanger is removed and returned cleaned. The approach used in this Simulation 4 is similar to the one used in Simulation 3, regarding the connection among the heat exchangers, except that simple heat exchanger models are used and there is a global heat transfer coefficient specification for each of them, instead of the cold outlet temperature. The specification value can be chosen between the operational and clean global heat transfer coefficients, depending on what piece of equipment is removed for cleaning. For instance, if the first heat exchanger is cleaned, the simulation would be performed using the Ucl value as specification for heat exchanger 1 and the Uop value as specification for the others. Any combination can be tested and the choice is left to the CDU operator / engineer. Although it is not a cleaning scheduling optimization, this kind of simulation gives the refinery essential information that can help to evaluate when it is time to shut down the unit and clean exchangers. Studies to add a cleaning scheduling optimization to this tool are being done by Petrobras.

For all simulations, the log mean temperature difference correction factor is calculated using the procedure proposed recently by Fakheri (2003). Heat exchanger geometric data are obtained from their Data Sheet. Data required include shell diameter, baffle geometry, tube diameter, total number of tubes, number of tubes per pass, number of passes per tube, position of the streams and nozzle orientations,

It takes around 3 - 4 hours (on a Pentium IV 1.6 GHz) to complete all the simulations. So 6 - 8 results per day can be obtained.

RESULTS AND DISCUSSION

Although the system has been running on a real time basis since the beginning of 2005, some data were gathered off-line in order to build a historical background. It was not possible to track the preheat performance since the unit start-up due to some instrumentation issues. So, 50 dates (points), ranging from November/2003 to January/2005, were chosen, in which the preheat train was, approximately, running at steady state conditions. With these data, some trends were identified and are shown in this section, giving a brief illustration of the diagnostic capabilities of Fouling^{TR}.

The first important result that can be inferred is the preheat global efficiency, shown from Figures 6 to 9. Figure 6 presents the difference between the preflash inlet temperature in the operational mode (Simulation 1) and the clean mode (Simulation 3 - all preheat train is clean - no fouling): an increase over time in that temperature difference can be seen. Figure 7 shows the preheat global efficiency while Figures 8 and 9 illustrate estimates of the percentage of the crude that is vaporized at the end of the preheat in both modes. These crude vaporization estimates were only possible due to the use the rigorous process simulation method where these effects can be taken into account. All these trends indicate that the preheat train efficiency has been dropping since the end of 2003, i.e., the preheat train could recover more energy if all heat exchangers were clean. The current energy lost is around 17.5 MW, which must be supplied by the preflash reboiler furnace in order to maintain the current preflash tower flash zone temperature and pressure conditions. This extra fuel consumption (fuel gas and fuel oil) is costing US\$ 1.8 x 10^6/year to the refinery, without taking into account many other penalties that come with it, including releasing excess CO_2 to atmosphere and a loss of unit throughput.

These are important results but those trends alone can not provide any information on which branch, or more specifically, which piece of equipment is causing the loss of efficiency. Among the 5 branches, it was possible to detect that branch 4 (after the desalter) is responsible for much of this energy loss as is illustrated in Figure 10. This branch could achieve a crude temperature of up to 275ºC but is actually heating up the crude to around 260ºC. This temperature has been decreasing since November 2003. For branch 5, the temperature difference is around 10ºC. It must be emphasized that crude vaporization takes place in branches 4 and 5, the worst branches, and the use of a rigorous process simulation with a heat exchanger design tool, such as Fouling^{TR}, can provide a much better analysis of what is happening. Among the 7 heat exchangers of branch 4, the first and second ones after the desalter seem to be in bad condition. Figure 11 presents the fouling factor behavior for the first heat exchanger. A very strong increase in fouling factor can be observed indicating that this heat exchanger is increasingly underperforming. The fouling factor is almost 3 times higher than the design value. Figure 12 shows the heat exchanger efficiency, also indicating that this heat exchanger is operating badly. Figures 13 and 14 present the fouling factor and efficiency curves for the second heat exchanger of branch 4. The low efficiency (around 50%) and a very high fouling factor are indications that this piece of equipment is already fouled. Note that the fouling factor is almost 6 times the design value, which is also affecting the heat exchanger performance. The first and second heat exchangers of branch 5 show similar behavior, although the fouling factor increase is smoother. The first heat exchangers of branches 1 and 2 (before the desalter), at the cold part of the preheat train, also show some fouling, as can be seen from Figures 15 and 16 for branch 1.

Table 1. Temperature improvement at preflash inlet

Heat exchanger	Branch	Delta (ºC)
Second	5	2.5
Second	4	2.0
First	5	1.4
First	4	1.2
First	1	0.3
First	2	0.2
All	4	5.5

Based on current data, Table 1 shows the temperature improvement at the preflash inlet if these heat exchangers were removed for cleaning. These are the results from the fourth simulation as mentioned before. As can be seen, if all branch 4 exchangers were removed for cleaning, the delta would be 5.5ºC (around 1/3 of the current loss). Of course these economic gains (in terms of less fuel burning in the preflash reboiler furnace) should be compared to the cost of a unit turnaround for cleaning. As said before, this is not a cleaning scheduling optimization exercise but guidance to the refinery to take the decision.

As said before, this tool also allows the comparison between the actual fouling factor and the design one (see Figures 11, 13 and 15). This latter value is taken from TEMA Standards or based on Petrobras experience with previous heat exchanger designs. In both cases, it does not always represent well the actual crudes being processed by Petrobras. Sometimes, the actual fouling factor is higher than the design one, sometimes it is lower. It did not show, for all the 25 heat exchangers, a common pattern. For some heat exchangers it does not even represent the asymptotic value. As shown in Figure 11, where the fouling factor is increasing linearly, there is not, at least for now, any asymptotic behavior and the fouling factor is much higher than the design value. All of these differences contribute to an unoptimized heat exchanger design and, in consequence, unoptimized heat exchanger and preheat operation. It also affects the optimum results obtained by cleaning scheduling optimization, since it relies on the asymptotic fouling factor values. All of these results are being used by Cenpes to improve heat exchanger design. As this kind of analysis is performed on other Crude Distillation Units or even other processes within a preheat train, such as Delayed Coke Units or Catalytic Cracking Units, a better and bigger fouling factor databank can be built.

This is just a brief description of the Fouling^{TR} capability. Many other results and data can be plotted and used in improved preheat train analysis, operation, optimization and maintenance as, for instance, possible wrong temperature and flowrates measurements can be identified using the reconciled data.

CONCLUSIONS

1. A tool was developed to evaluate, on a real time basis, the performance of a preheat train. This tool uses rigorous process simulation with rigorous heat exchanger design so a more accurate global heat transfer coefficient (operational and clean modes) and fouling factor can be estimated.
2. It was possible to identify a decrease on the preheat train efficiency and which branch and piece of equipment is being responsible for that. This loss of efficiency is costing US$ 1.8 million a year for the refinery besides the environmental penalty that this fuel burning incurs.
3. These results and trends are being fed to the refinery, which will decide when to remove fouled heat exchangers for cleaning.
4. Fouling factor values closer to the Petrobras reality are being obtained, which will certainly improve the heat exchanger design performed by CENPES.
5. Nowadays, the tool is running on line at Replan, gathering real time data.

NOMENCLATURE

Q	heat load, kW
U	global heat transfer coefficient, kW/m^2 K
R_f	fouling factor, m^2 K/W
ε	heat exchanger efficiency, dimensionless

Subscript

op	operational
cl	clean

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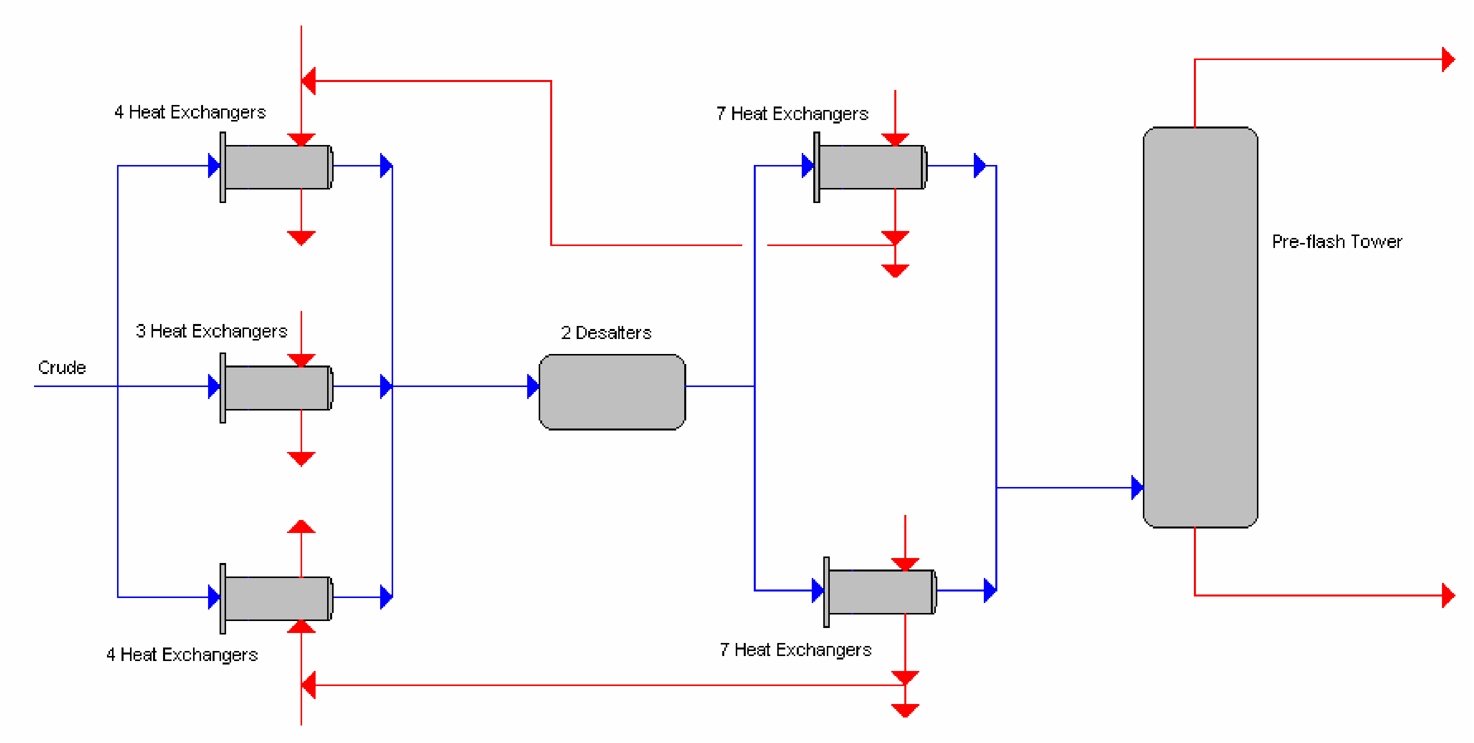

Fig. 1 Preheat train scheme

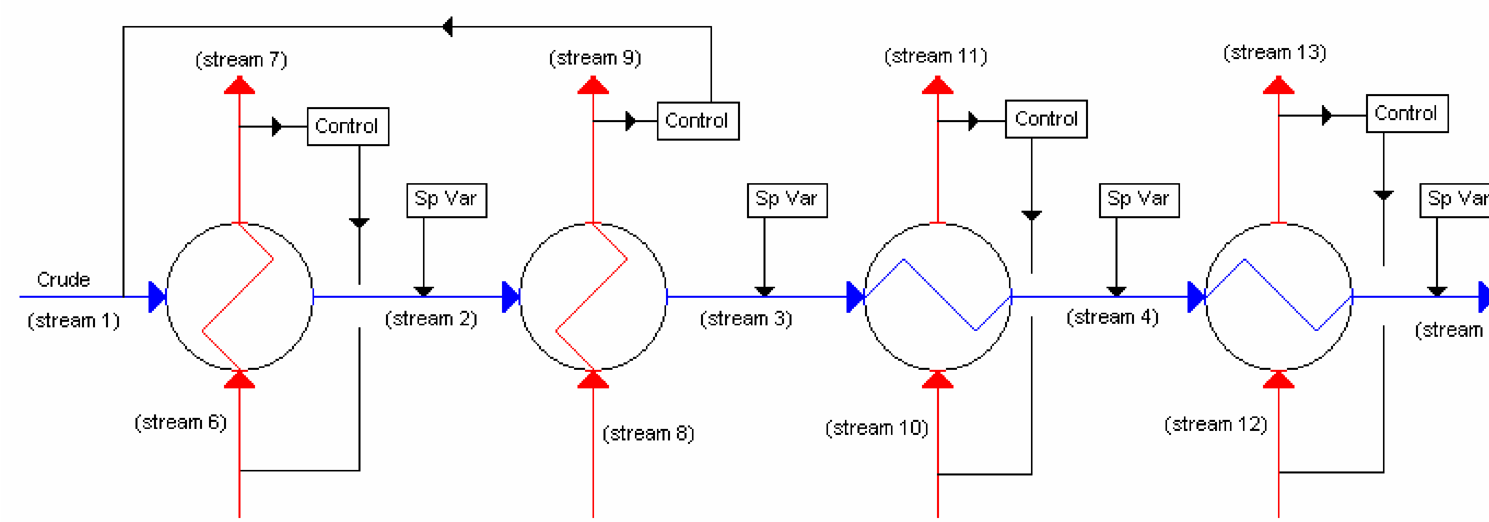

Fig. 2 Typical simulation strategy for branch 1, before the desalters

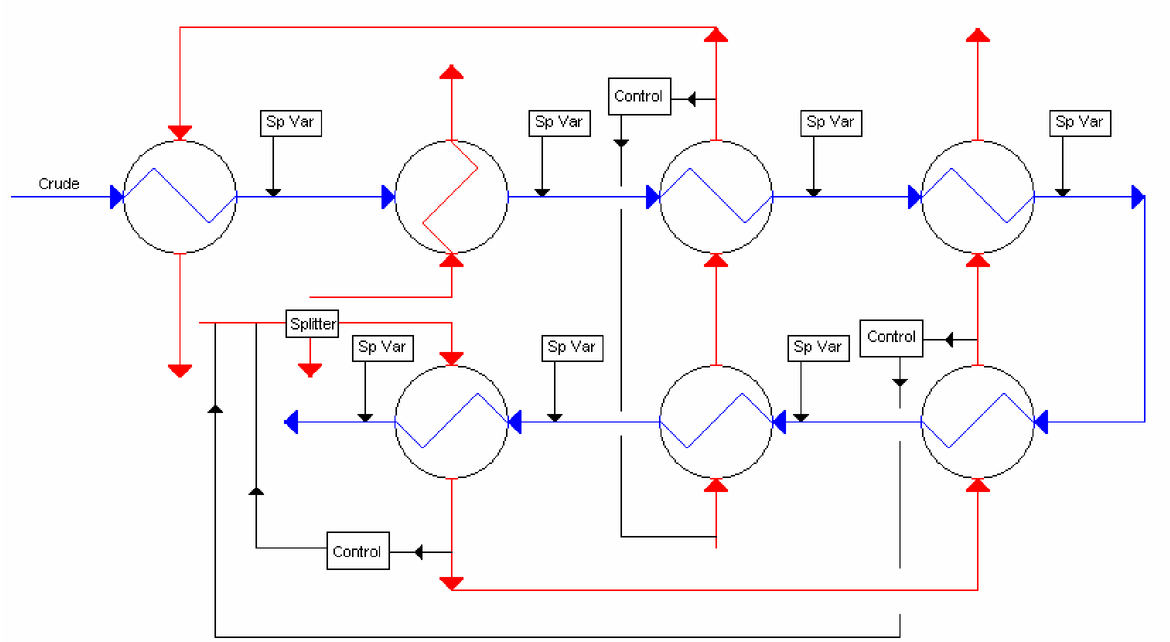

Fig. 3 Typical simulation strategy for branch 4, after the desalters

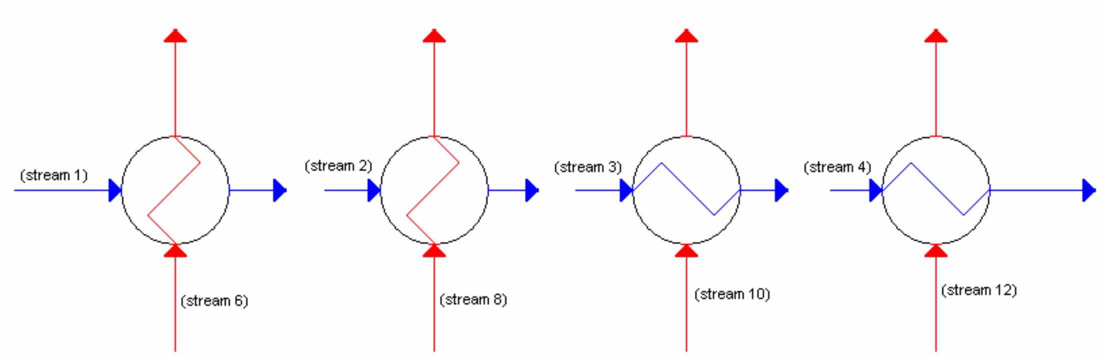

Fig. 4 Example of Simulation 2 approach

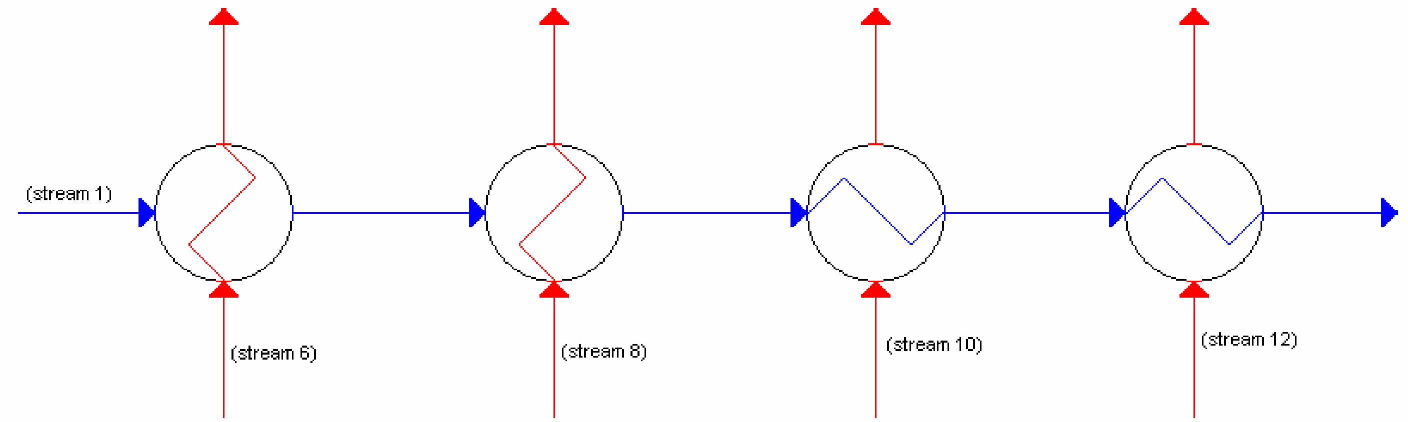

Fig. 5 Example of Simulation 3 approach

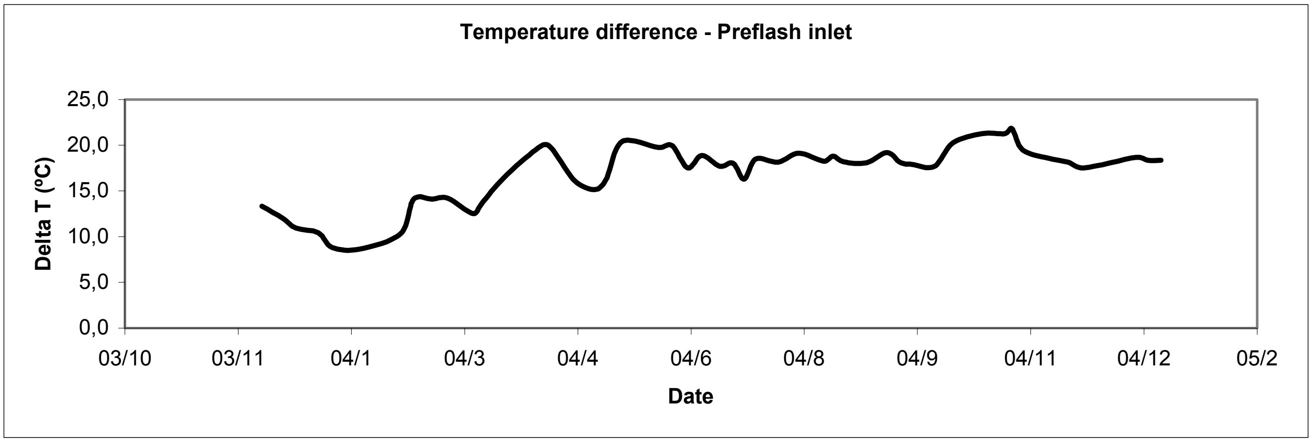

Fig. 6 Temperature difference at preflash inlet (clean minus operational temperatures)

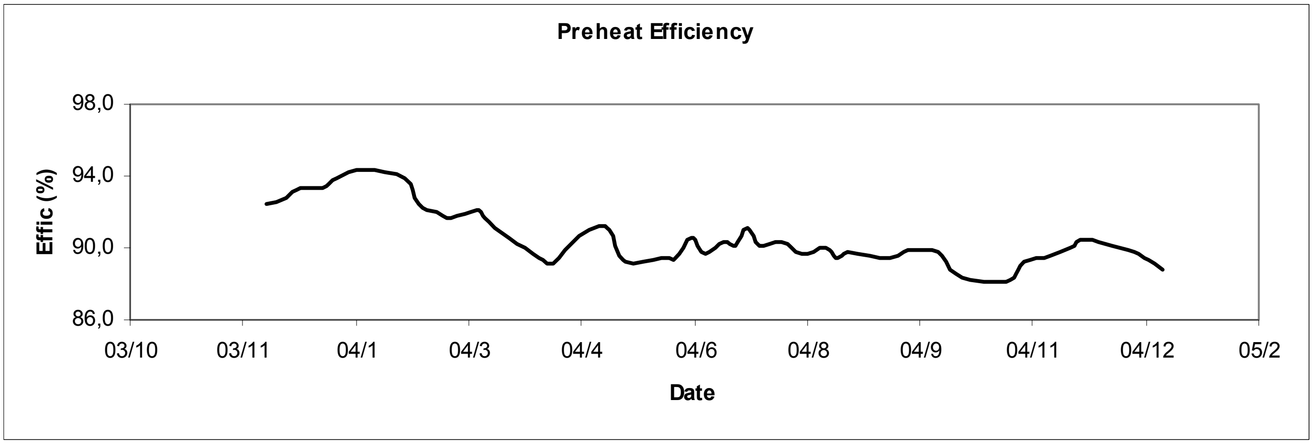

Fig. 7 Preheat global efficiency

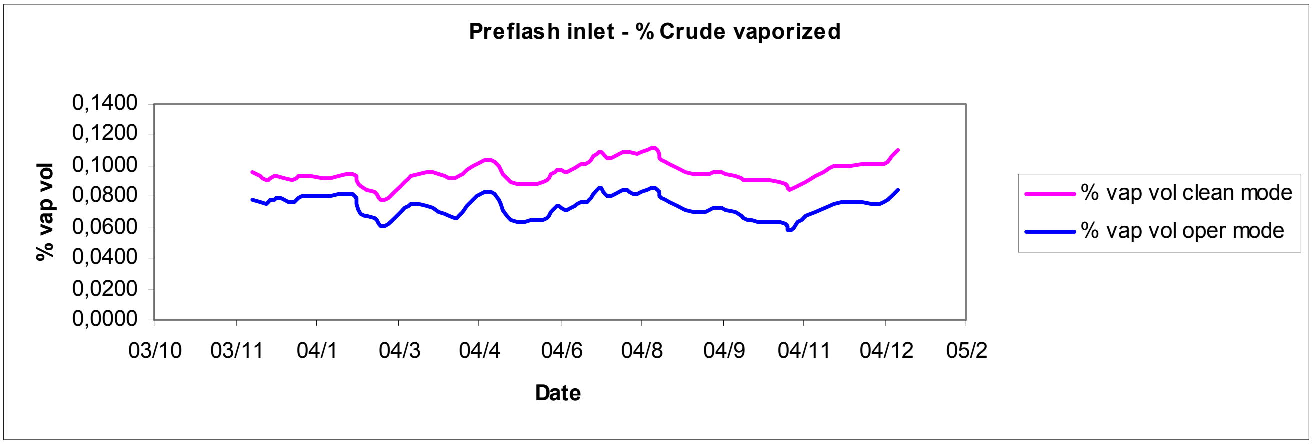

Fig. 8 Preflash inlet - % crude vaporized

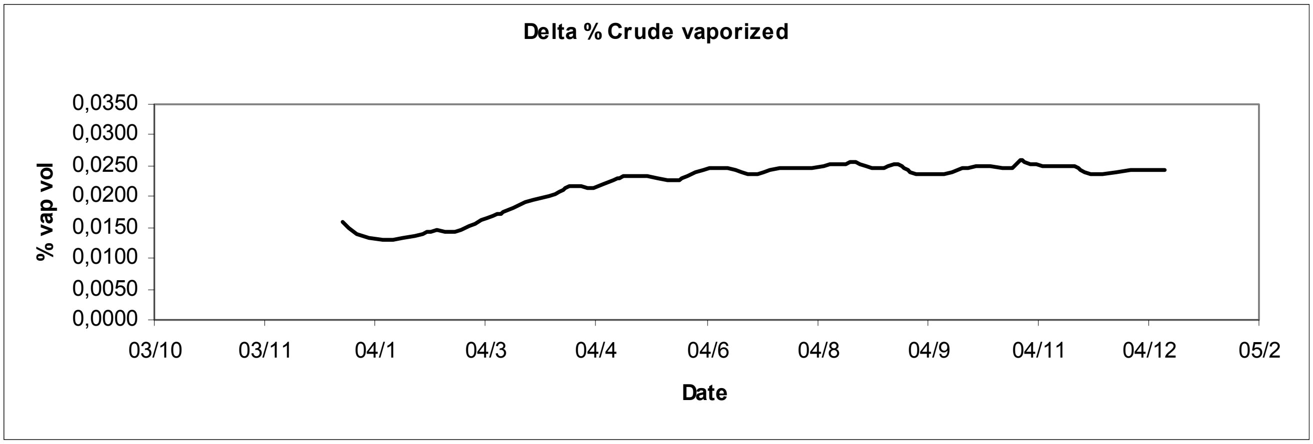

Fig. 9 Preflash inlet - delta % crude vaporized

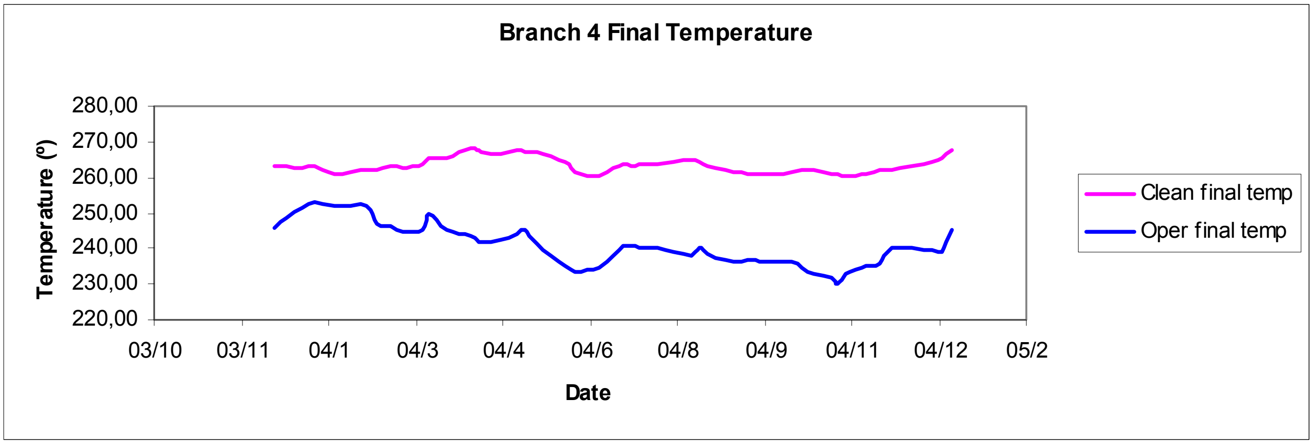

Fig. 10 Branch 4 final temperature

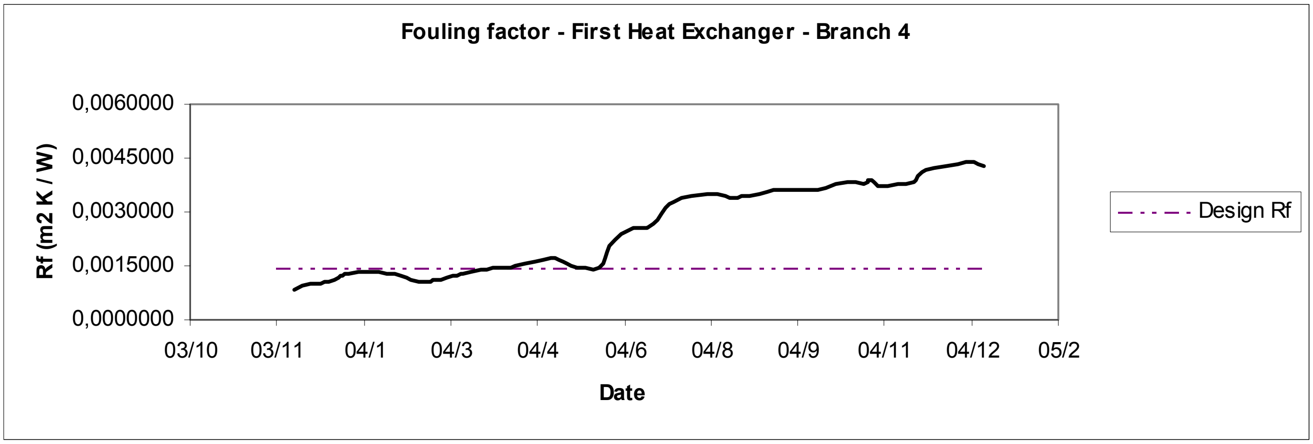

Fig. 11 Fouling factor for the first heat exchanger of branch 4

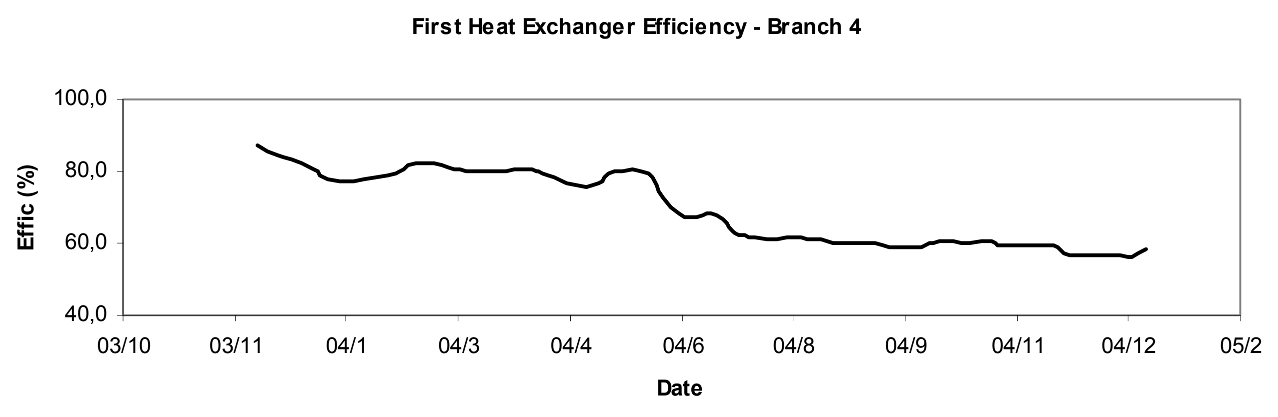

Fig. 12 Efficiency for the first heat exchanger of branch 4

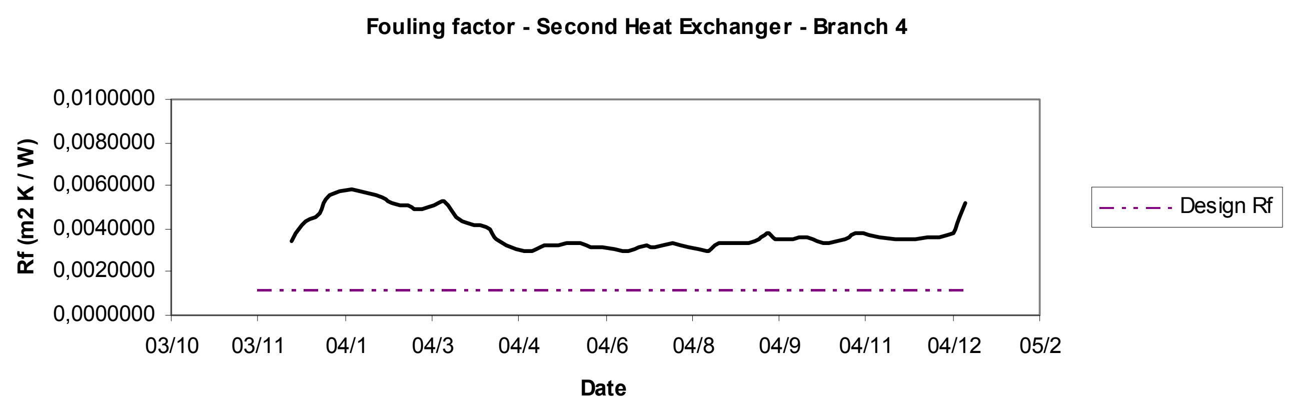

Fig. 13 Fouling factor for the second heat exchanger of branch 4

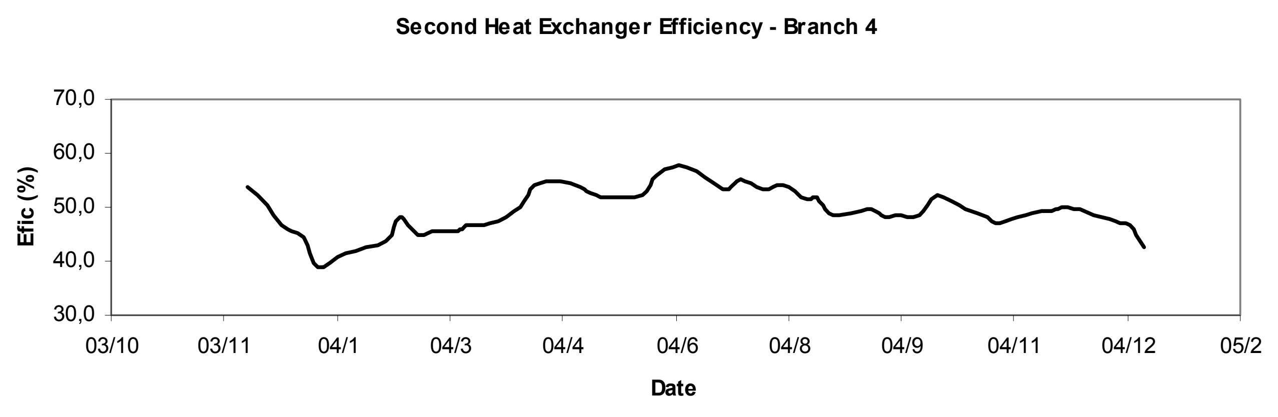

Fig. 14 Efficiency for the second heat exchanger of branch 4

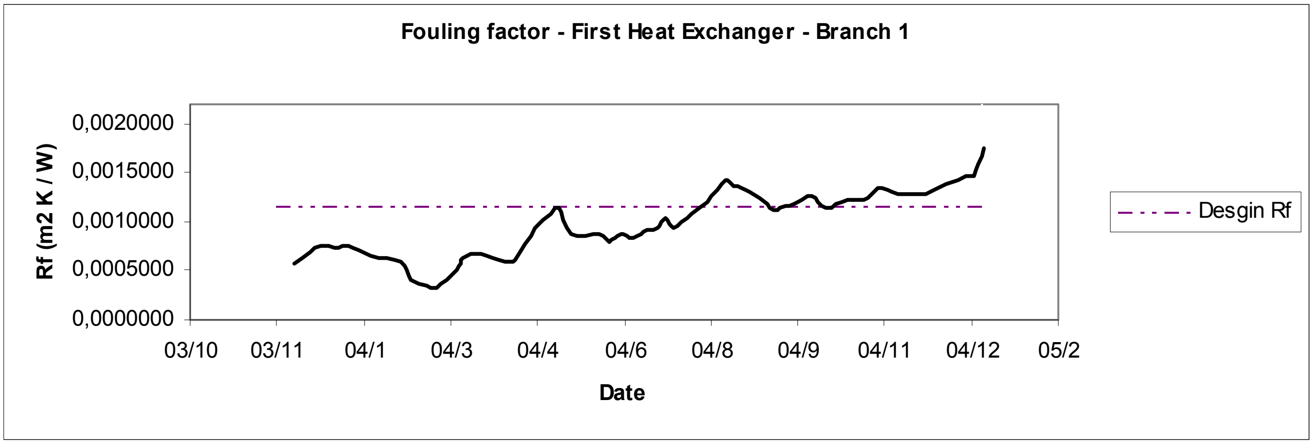

Fig. 15 Fouling factor for the first heat exchanger of branch 1

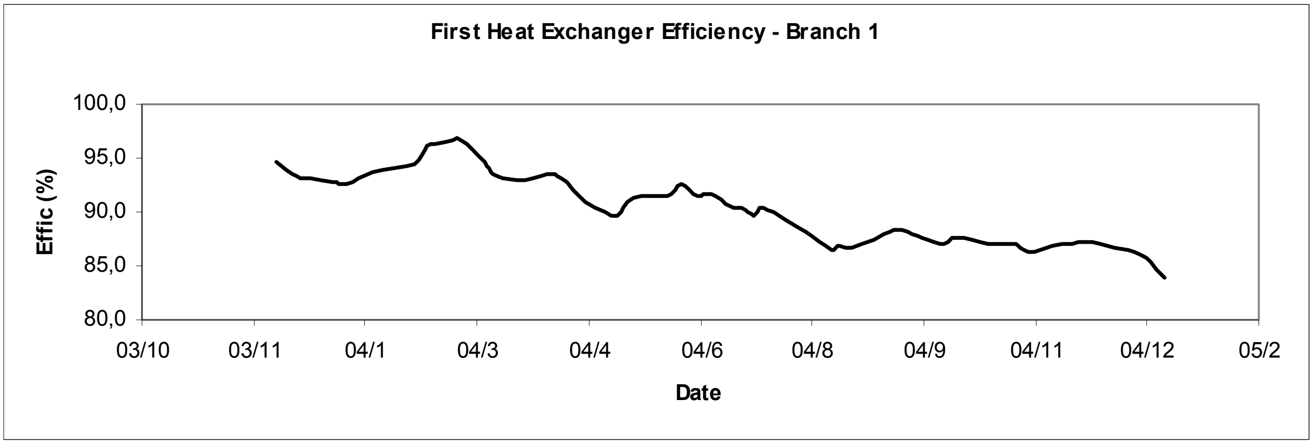

Fig. 16 Efficiency for the first heat exchanger of branch 1