Preheat Train Crude Distillation Fouling Propensity Evaluation by the Ebert and Panchal Model

M. Bories
TOTAL CERT

T. Patureaux
TOTAL CERT

PREHEAT TRAIN CRUDE DISTILLATION FOULING PROPENSITY EVALUATION BY THE EBERT AND PANCHAL MODEL

M. Bories and T. Patureaux, TOTAL
CERT, Refining Research Centre, Po Box27, 76700 Harfleur, FRANCE

Abstract

The Ebert and Panchal fouling model was used to assess the fouling tendency of the exchangers of an industrial crude distillation unit (CDU) preheat train. The ranking obtained through a monitoring and processing of the performances of the different exchangers matched quite well the predictions of the Ebert and Panchal fouling model. In the meantime, a first mitigation solution consisted in periodically cleaning heat exchangers and installing TURBOTAL[TM] tube inserts. Through the fouling monitoring of the equipped exchangers, the beneficial action of the TURBOTAL[TM] inserts is also made quite clear.

Introduction

Fouling of heat exchangers is one of the major concerns of the petroleum refining industry. It leads to operating problems, affects the efficiency of the heat recovery systems, and can seriously alter the profitability of a refinery (over consumption of fuel, throughput reduction during cleaning operations or because of pressure drop or furnace bottlenecking, increase of maintenance costs, etc).

One of the most critical systems is the preheat train of the crude distillation unit (CDU) which is a heavy energy consuming operation [1]. Of course, the problems can be alleviated by curative treatments: usage of anti-fouling additives [12], careful sequential ordering of the different processed crude or exchanger cleaning [4, 5], etc. The fact remains that a smart way to mitigate fouling is to take it into account at the design step of the exchangers [2]. In the refining industry where shell & tube exchangers remain the more widely used technology, the most popular ways are:

➢ Adapt the lay out to facilitate cleaning operations: bypasses, shells in parallel.
➢ Over design of the exchangers, considering that fouling cannot be avoided and will occur anyway. This is usually done by introducing a "fouling resistance" extracted from TEMA tables dating back a long time ago, the values of which depend on the type of fluids processed. This approach sometimes gives very disappointing results, as an over design might in fact increase the fouling rate and worsen the situation and the accuracy of these TEMA values has been reconsidered [3].
➢ Respect of unwritten guidelines, most often resulting from past experience, such as a minimum value for the velocity inside the tube to keep the fouling rate at an acceptable level. It is clear that it is not fully satisfactory as some exchangers exhibit a high fouling rate on the tube side despite a fluid velocity far higher than what was considered as a threshold value.

It is well known that for many types of fouling, the two key parameters influencing the fouling rate of a heat exchange surface are the film temperature and the fluid velocity at the vicinity of the surface. It appears clearly in the "Ebert and Panchal" model where the net growth of the fouling layer is described as the result of a competition between transformation – deposition of fouling species and peeling due to the shear stress exerted by the fluid [6-8].

The validity of this approach having been demonstrated by a statistical analysis of fouling data collected in Chevron and Exxon refineries, it was decided to determine whether it could explain the differences observed in the fouling rates of the exchangers of the preheat train of a TOTAL refinery CDU.

Context

A TOTAL refinery crude distillation unit was revamped to reach 22,000 T/day or 160,000 bbl/day crude oil capacity (see simplified schematic on Figure 1). Soon after the plant start-up, it appeared that the preheat train was experiencing heavy fouling leading to a significant furnace inlet temperature decrease with time and to a throughput reduction as the furnace bottlenecked, responsible for tremendous financial losses.

Preheat Train Monitoring and Heat exchanger fouling rates

It was decided to implement an in-house monitoring tool to follow the fouling rate of every exchanger and identify which ones could be critical. The following steps, already detailed elsewhere [11], are required to assess the fouling rates for every heat exchanger:

- Using accurate temperature and flow rate measurements, heat duty is calculated on both shell and tube sides.
- Duties are compared to detect either any inconsistent field measurements or exchanger by-passes. If so, new temperature or flow rate values are proposed based on a data validation algorithm.
- The actual overall heat transfer coefficient, U_a, is calculated by the following equation:

$$Q = (\dot{m}Cp\Delta T)_{shell} = (\dot{m}Cp\Delta T)_{Tube}$$
$$Q = U_a AF\Delta\Theta_{ml} \tag{1}$$

- The clean heat transfer coefficient, U_c, is calculated based on rigorous API and TEMA correlations allowing the assessment of the fluids physical properties and film heat transfer coefficients respectively.
- Fouling resistance is obtained by the following formula:

$$R_f = \frac{1}{U_a} - \frac{1}{U_c} \tag{2}$$

This fouling resistance is calculated at least once a day for every heat exchanger of the preheat train. The evolution of this fouling resistance with time, also called fouling rate, is given for some exchangers in Figure 2. Prior to TURBOTAL^{TM} installation, it appears that the fouling resistance is a linear function of time. Thus, fouling rate is constant, as given by the following equation:

$$R_f = Kt + B \qquad \frac{dRs}{dt} = K \tag{3}$$

The fouling rate, K, is given for every heat exchanger of the CDU preheat train in Figure 3. The linear regression coefficient goes from 0.447 (E2AB) to 0.924 (E6AB) with an average value of 0.76.

Considering these results, the assumption of a linear fouling behaviour in crude preheat exchangers is quite consistent, as was already observed elsewhere [12]. However, an asymptotic or equilibrium fouling rate is expected and should occur after a sufficient period of time, indicating the existence of flow velocity dependent removal mechanisms and/or perhaps deposition rate decrease mechanism [13].

From Figure 3, it is obvious that exchangers upstream the desalter unit present much lower fouling rates than those placed downstream. Unlike usual observations, the exchanger presenting the highest fouling rate is the hottest one just before the furnace. In the present case, exchangers E5ACBD and E5EGFH show higher fouling rates than the exchanger E8ACBD, which is the last one before the furnace. On the other hand, the E8ACBD tube side fluid velocity is around 1.6 m/s, which is a relatively high value. Still, this exchanger exhibits a very high fouling rate showing that velocity must not be considered as the only criteria for safe design.

Preheat train overall fouling trend: NFIT

Because of frequent changes in process conditions due to the crude slate, a reliable tool is needed to assess the effect of every individual fouling resistance on the preheat train overall fouling trend. For this purpose, Normalized Furnace Inlet Temperature (NFIT) is commonly used. As a first step, a set of data is selected as a Base Case, preferably under clean conditions. The set of flows, feed temperatures and properties are then used with calculated fouling resistances from the current cases to calculate all the exchanger exit temperature and the NFIT (outlet of the last exchanger before the furnace). Hence, the change in NFIT over monitoring period is due only to changes in fouling resistances. Fouling cost can then be assessed by determining the additional duty required to restore NFIT to its original value.

The evolution of the NFIT with time is given in Figure 5. It can be seen that over a period of three months after start-up, the NFIT decrease is about 0.5°C/day, which is ten times higher than commonly observed NFIT losses in other refineries.

Fouling mitigation techniques used

The first way to overcome this important fouling is to clean heat exchangers at regular intervals. The selection of the exchanger to clean is not made on advanced optimisation technique for network cleaning but rather on the maximum achievable NFIT recovery determined by a simple simulation program. In Figure 5, the NFIT recovery achieved after several individual heat

exchanger cleanings can be seen. However, this benefit is rapidly lost after a few weeks, as several exchangers are prone to rapid fouling.

Thus, another fouling mitigation technique was considered. TURBOTAL[TM] devices were installed in heat exchanger tubes after they had been cleaned. This device is commonly used in TOTAL refineries. It was developed by TOTAL research in the 80's and supplied by PETROVAL S.A based in France.

TURBOTAL[TM] device is a rigid helicoidal insert, held at the upstream end of the exchanger tubes by a system allowing rotation around the axis under the fluid drag (see Figure 4). The downstream end of the insert is free, and remains unattached. The basic idea was to develop a device set in motion by the fluid itself and which would be able to scrub continuously the inside surface of the tube, thus eliminating deposits at their early stage of formation. More details can be found elsewhere about this device, its operating principle and design and its implementation in refineries [9,10].

Exchangers E5ACBD, E5EGFH, E8ACBD and E6AB were equipped with TURBOTAL[TM] devices after cleaning. In Figure 2, it can be seen that the fouling rate of the equipped exchangers was significantly reduced. It is more interesting to quantify the effect of the TURBOTAL[TM] device on the preheat train overall fouling trend. For this purpose, we refer to the NFIT calculation, shown on Figure 5. After exchangers E5ACBD and E8ACBD had been cleaned and equipped with tube inserts, the NFIT decrease rate was improved from 0.52°C/day to 0.29°C/day and then to 0.2°C/day after E5ACBD, E8ACBD and E6AB had been cleaned and equipped with TURBOTAL[TM] inserts respectively. Since E5EGFH was equipped in November 2001, although it is not shown here (instrumentation problems during the first 2002 six months), the NFIT decrease rate was reduced to 0.15°C/day from June to November 2002. Thus, TURBOTAL[TM] appears to be an effective tool to mitigate fouling as preheat train overall fouling trend was reduced by a factor of four. Moreover, exchangers equipped with TURBOTAL[TM] inserts exhibit an asymptotic like fouling rate.

Despite this large fouling rate reduction due to the TURBOTAL[TM] device, the situation is still unacceptable, as the NFIT decrease rate is 4 times higher than observed in other refineries. It appears that some exchangers present an intrinsic fouling trend due to poor design. In the coming discussion, the Ebert and

Panchal fouling model is used to see whether the exchangers fouling trend could be predicted.

(Ebert and Panchal) Model Brief Description

One of the major breakthroughs in crude oil fouling was the establishment of a fouling model capable to provide some threshold operating conditions below which fouling is expected to be minimal. These threshold conditions provide a starting point for shell and tube exchanger design. The Ebert and Panchal (E&P) model [6, 7] can be used to predict tube side fouling conditions for crude oil and is expressed as a competition between deposition and removal terms:

$$\frac{dR_f}{dt} = \alpha \, \mathrm{Re}^{-0.66} \, \mathrm{Pr}^{-0.33} \exp\left(-\frac{E}{RT_{film}}\right) - \gamma \tau_w \quad (\,4\,)$$

where α, γ and activation energy E are adjustable parameters and would be expected to vary between crude oils. However, in our study, we used parameters as defined by Ebert and Panchal [6], whatever the origin of the crude.

From the equation above, when $\dfrac{dR_f}{dt} = 0$ either no or asymptotic fouling occurs. However, this model was not developed to predict asymptotic fouling but to provide certain combinations of film temperature, T_{film}, and tube flow velocity giving rise to zero or negligible fouling. These film temperature and fluid velocity combinations under which the fouling rate equals zero can be plotted on a graph as shown on Figure 6. In this graph, the film temperature is defined as:

$$T_{film} = \left(T_{wall} + T_t\right)/2 \qquad (\,5\,)$$

where T_t is the bulk temperature of the fluid flowing in tubes. The wall shear stress τ_w is linked to bulk velocity through the friction factor:

$$\tau_w = \frac{1}{2}\rho v^2 f \quad with \quad f = \frac{0.0791}{\mathrm{Re}^{1/4}} \qquad (\,6\,)$$

Without considering heat transfer resistance through tube wall, wall temperature is reliably assessed by the following formula:

$$T_{wall} = \frac{h_o d_o T_s + h_i d_i T_t}{h_o + h_i} \qquad (\,7\,)$$

where h_o, h_i and d_o, d_i are tube outside and inside film heat transfer coefficient and diameter respectively.

T_s and T_t are bulk temperatures on shell and tube sides respectively.

Two specific zones are defined whether exchanger operating conditions lie above or below the fouling threshold conditions: a fouling zone for low velocities and high film temperatures as expected and a very low fouling zone below the threshold line, respectively.

Operating conditions, mainly feed and product flowrates, are expected to vary on a daily basis due to crude slate changes and to throughput reduction due to fouling. For convenience in the coming discussion, a representative set of data is considered. A field case very close to revamping project design case, regarding crude oil type and throughput, is selected and studied in detail. Measured operating conditions corresponding to that base case, such as flowrates, exchanger inlet and outlet temperatures, are described in Table 1, along with film and wall temperatures at exchanger both ends, calculated by equations 5 and 7.

Ranking of the fouling trend of the exchangers with the Ebert and Panchal model

The model was used in the following simple and conservative way. Each exchanger has a hot and cold extremity. If the inside conditions of the hot extremity are not in the fouling zone on the E&P diagram, there is then a good chance for the whole exchanger to exhibit a moderate fouling rate. Furthermore, the fouling propensity of a given exchanger can be measured by the gap between the velocity threshold value obtained on the fouling curve and the real value of the fluid velocity in the tubes.

Data for exchangers of the preheat train are plotted on the E&P fouling diagram (Figure 6). Only hot ends are reported with film temperatures and velocities values given in Table 1. Notice that density evolution with temperature is taken into account in the velocity assessment.

From Figure 6, it can be seen that most of the exchangers are very close but below the threshold line. As throughput is reduced, those exchangers will come closer and eventually cross the threshold line. Crude throughput for the Base Case is 22,000 T/day whereas minimum crude throughput observed over the monitoring period is 15,500T/day. A high fouling rate is expected for exchanger E5EGFH as it is located in the fouling region, above the threshold line. At the

other extreme, E58 is far below the threshold line, meaning that its fouling rate should be very low.

The exchangers are then displayed on a plot of wall temperature against bulk temperature (see Figure 7). On this temperature field plot diagram, each exchanger is plotted as a line linking its terminal temperatures, with wall temperature as the y-axis and cold stream temperature on the x-axis. If film heat transfer coefficients are not available to assess either film or wall temperature, hot side temperature can be used as a conservative estimate of this quantity. Also plotted on this diagram are sets of loci showing wall temperatures at which fouling starts for a given bulk velocity and tube diameter, according to Ebert and Panchal model (equation 4). An exchanger lying below the locus corresponding to its crude bulk velocity will not experience significant fouling. In Figure 7, several bulk velocities are displayed ranging from 0.5 to 1.5 m/s.

This temperature field plot diagram allows assessment of several pieces of information at once [14, 16]:
➢ Fouling threshold velocities at both ends of individual exchangers.
➢ Reliable estimation of the exchanger temperature driving forces and duties.
➢ Full fouling trend comparison between all the exchangers of the network.
➢ Identification of possible exchanger rearrangements within the network to mitigate its fouling.

Considering wall and bulk temperatures given in Table 1, exchangers are plotted on the field temperature diagram on Figure 7. For the E58 unit, as the line representing this exchanger is located below 0.5m/s, the fouling rate should be high if the crude bulk velocity was less than 0.5m/s. This is not the case, as the real bulk velocity is around 4m/s (see Figure 7 and Table 1). The E5EGFH line is above 1m/s and below 1.5m/s threshold velocity lines. If the bulk velocity is greater than 1.5 m/s, it is expected that very low fouling will occur. As bulk velocity is 1m/s in E5EGFH tubes, this exchanger is likely to foul rapidly. An increase of the bulk velocity should be considered viatubes plugging or an increase of the tube passes.

The fouling trend of each individual exchanger can then be estimated and is defined as the difference between bulk velocity and threshold velocity read from the temperature plot diagram. As an example, for E58 unit, the bulk velocity is 4m/s and the threshold velocity is estimated to be 0.5m/s, giving a fouling

trend of 3.5m/s. For E5EGFH, bulk and threshold velocities are 1m/s and 1.5m/s respectively, giving a negative fouling trend of –0.5m/s. It is expected that fouling rate increases as the exchanger fouling trend value decreases.

A zero exchanger fouling trend value, as defined previously, means that the exchanger is located on the threshold line defined by the E&P model on a film temperature versus bulk velocity diagram, shown in Figure 6. Negative fouling trend values indicate a move towards the fouling zone.

All the exchanger fouling trend values were estimated and reported in Table 2. This approach yields the following ranking of fouling tendencies (from low to high fouling rate)

1 = E58; 2 = E83; $3 \cong 4$ E6AB and E7; $5 \cong 6$ E8ACBD and E5ACBD; 7= E8182; 8 = E5EGFH

Comparison with field results

The ranking predicted by the E&P model matches quite well the fouling rates obtained through the daily monitoring and processing of the exchanger performances prior to the implementation of inserts. See with an exception for the E8182, Table 2. For example, E58 and E5EGFH were predicted to present the lowest and highest fouling tendencies, with fouling trend values of 3.55 and –0.52, which are in good agreement with the observed highest and lowest fouling rates of $0.04.10^{-4}$ and $1.91.10^{-4}$ (m^2.°C/kcal), respectively.

Conclusion

It is clear from this study that the Ebert and Panchal model which accounts both for hydrodynamic and thermal conditions inside the tube is able to predict the fouling tendency of the exchangers of the preheating train of a CDU unit. The ranking predicted by the model is very close to the one obtained by following the thermal performances of the train. The predictions would likely be even better if values of the model parameters had been adapted each time for the crude being processed. This model provides very promising perspectives:
➤ At the design step to avoid fouling conditions by construction (possible use of EXPRESS, ESDU software).
➤ Incorporate this model to identify retrofit scenarios for network fouling mitigation [14], making the

best usage of the available pressure drop by avoiding extra low fouling rates at the expense of unjustified high pressure drops.
➤ Without reliable CDU preheat train fouling monitoring, identify critical exchangers that could be equipped with TURBOTAL^{TM} inserts.

On top of that, the monitoring of the train has once again demonstrated the efficiency of TURBOTAL^{TM} technology as a curative tool for fouling mitigation.

More efforts should be undertaken in the assessment of threshold models for various crude oils, such as the work on going in HTRI [15], and now in CERT after the recent start-up of a lab-scale fouling pilot plant giving the possibility to build threshold models for tubes equipped with inserts.

Nomenclature   **(SI UNITS)**

A	tube outside area	m^2
Cp	fluid specific heat	J/kg
E	activation energy	J/kmol
f	friction factor	-
F	exchanger heat transfer efficiency	-
h$_i$	film heat transfer coefficient	W/m^{2}K
$\dot{m}$	mass flowrate	kg/s
Q	heat duty	W
Pr	Prandtl Number	-
R	perfect gas constant (8314J/kmolK)	J/kmolK
Re	Reynolds Number	-
R$_f$	fouling resistance	(m^{2}K/W)
T$_{film}$	film temperature	K
T$_{wall}$	wall temperature	K
T	bulk temperature	K
U	overall heat transfer coefficient	W/m^{2}K
v	tube bulk velocity	m/s
ρ	fluid density	kg/m^3
τ_w	wall shear stress	N/m^2
ΔT	(inlet – outlet) bulk temperatures	K
$\Delta \Theta_{ml}$	mean logarithmic temperature	K
α, β	E&P model constants	-

Subscripts
o, i refer to tube outside and inside
s, t refer to exchanger shell and tube side
a,c refer to dirty and clean heat transfer coefficient

References

1. Pugh S.J., Hewitt G.F., Müller Steinhagen H., *Heat Exchanger Fouling in the Preheat Train of a Crude Oil Distillation Unit- The Development of a User Guide*, Proc. Heat Exchanger Fouling & Technical Solutions, Davos, Switzerland, July 8-13 2001.
2. Chenoweth J.M., *General Design of Heat Exchangers for fouling conditions*, Proc of the Advances in Fouling Science and Technology, Alvor, Algarve, Portuga), p463 May 18-30 1987
3. Chenoweth J.M, *The TEMA Standards Fouling Section: Another Look*, Proc of Fouling Mitigation of Industrial Heat-Exchanger Equipment, San Luis Obispo, California, USA, p 61, June 1995
4. Wilson D.I., Vassiladis V.S., *Mitigation of Refinery Fouling by Management of Cleaning*, Proc of Understanding Heat Exchanger Design Fouling and Its Mitigation, Pascoli, Italy, p 299, May 1997
5. Georgiadis M.C., Papageorgiou L.G. Macchietto S., *Optimal Cleaning Policies in Heat Exchanger Networks under Rapid Fouling,* Ind. Eng. Chem., pp441-454, 39, 2000
6. Ebert W. and Panchal C.B., *Analysis of Exxon Crude-Oil-Slip-Stream Coking Data*, Proc of Fouling Mitigation of Industrial Heat-Exchanger Equipment, San Luis Obispo, California, USA, p 451, June 1995
7. Panchal C.B., Kuru WC et al., *Threshold conditions for Crude Oil Fouling,* Proc of Understanding Heat Exchanger Design Fouling and Its Mitigation, Pascoli, Italy, p 273, May 1997
8. Knudsen J.G., Lin D. and Ebert WA., *The Determination of the Threshold Fouling Curve for Crude Oil*, Proc of Understanding Heat Exchanger Design Fouling and Its Mitigation, Pascoli, Italy, p 265, May 1997
9. Haquet Y., Loutaty R. and Patureaux T., *TURBOTAL : A Mechanical Mean for Continuously Fighting Tubular Heat Exchangers Fouling,* Proc of Fouling Mitigation of Industrial Heat-Exchanger Equipment, San Luis Obispo, California, USA, p 503, June 1995
10. Jardin F. and Krueger A.W., *Sucessful Fouling Mitigation in Crude Refining and Chemical Plant Operation by Means of Mechanical Online Cleaning Devices: Spirelf, Turbotal and Fixotal*, Proc. Heat Exchanger Fouling & Technical Solutions, Davos, Switzerland, July 8-13 2001
11. Crittenden B.D., Kolaczkowski S.T. and Downey I.L., *Fouling of Crude Preheat Exchangers*, TransIChemE, Vol70, Part A, p547, November 1992
12. Engineering Science Data Unit (ESDU), *Heat Exchanger Fouling in the Preheat Train of Crude Oil Distillation Units*, ESDU Item 0016, ESDU International Ltd., London UK, 2000
13. T aborek J., Aoki T., *et al., Fouling: The Major Unresolved Problem in Heat Transfer*, Chemical Engineering Progress, V68, N°2, p59, February 1972
14. Yeap B.L., Wilson D.I., Polley G.T. and Pugh S.J., *Incorporation of fouling Models into the Design of Heat Transfer Networks*, Proc. Heat Exchanger Fouling & Technical Solutions, Davos, Switzerland, July 8-13 2001
15. Pale J.W., *History of Fouling Research at HTRI and Strategy for the Future*, Proc. Heat Exchanger Fouling & Technical Solutions, Davos, Switzerland, July 8-13 2001
16. Wilson D.I., Polley G.T. Pugh S.J., *Mitigation of Crude Oil Preheat Train Fouling*, Heat Transfer Engineering, V23, N°1, pp24-37, 2002
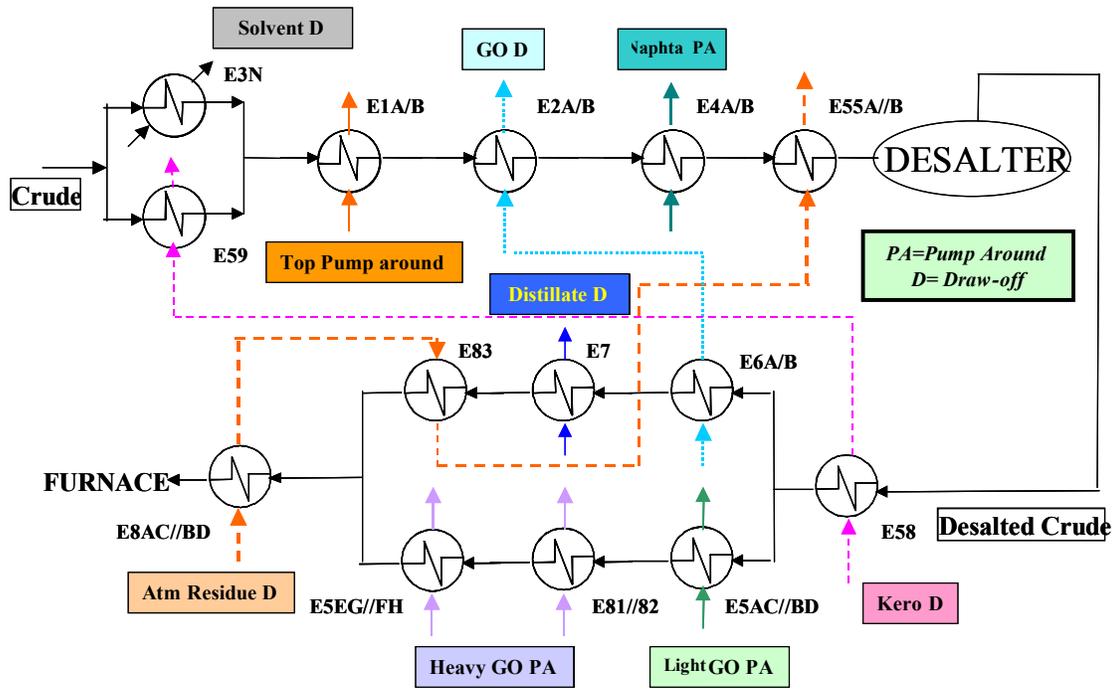
Figures
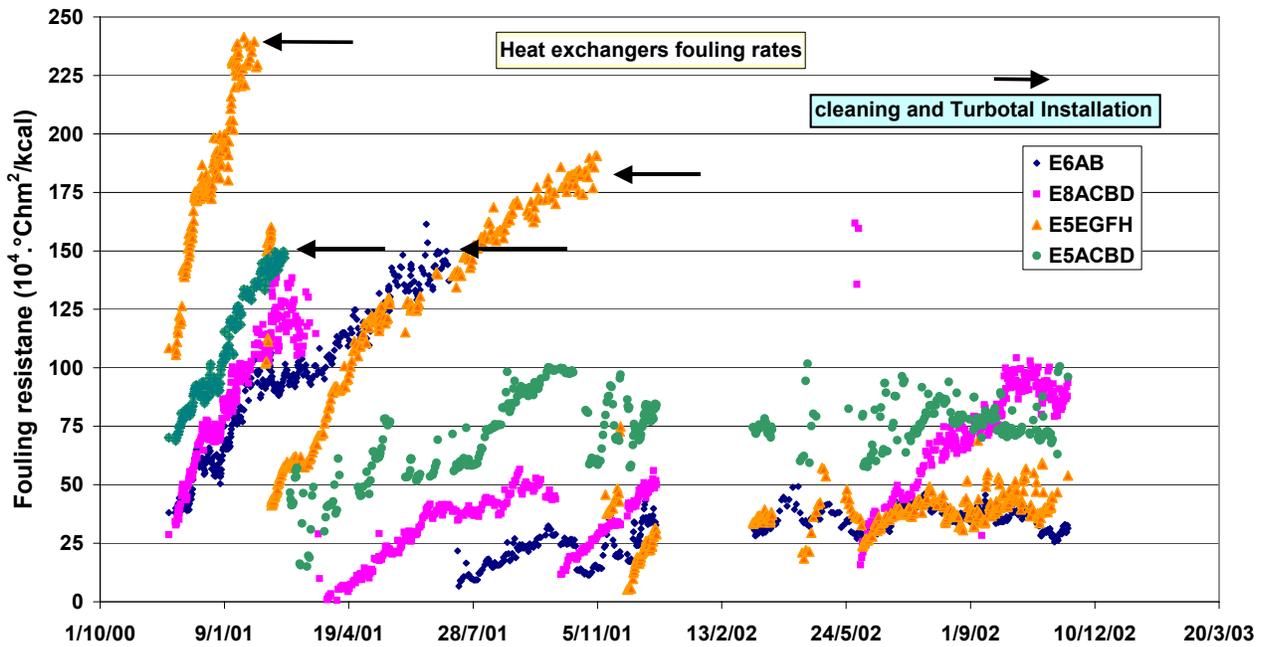

Figure 1: Preheat exchanger network scheme

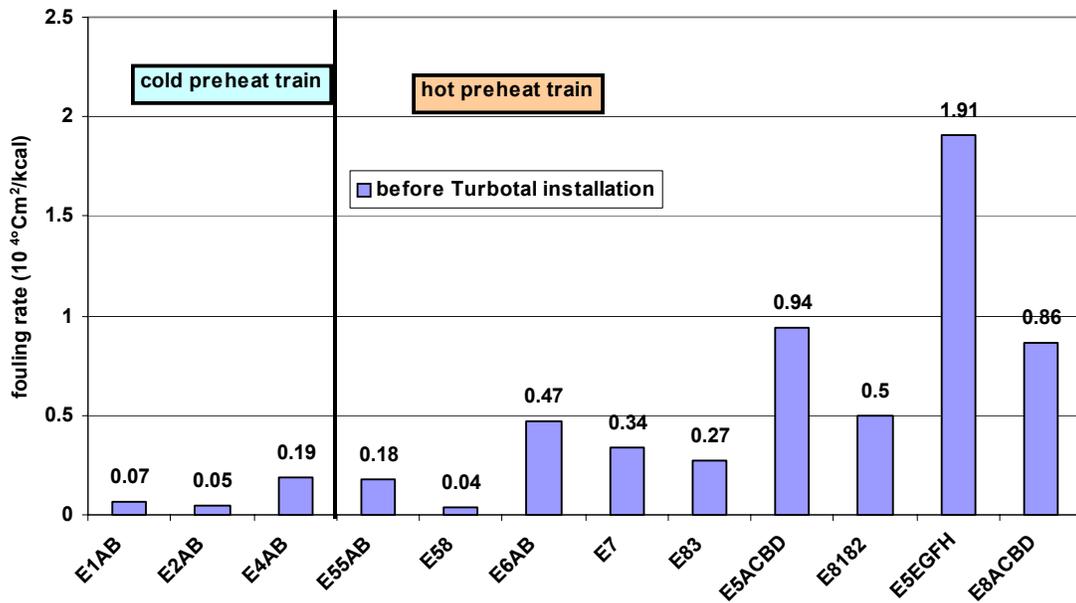**Figure 2: Evolution with time of some heat exchanger fouling resistances**
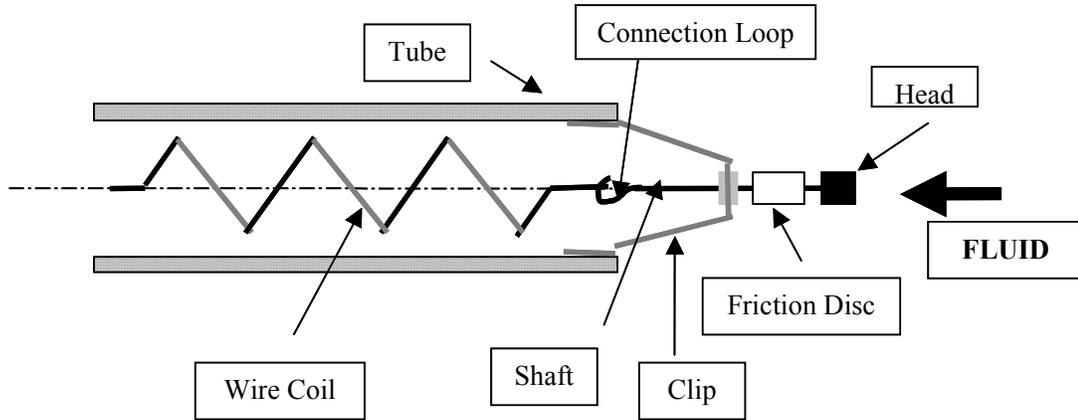
Figure 3: Exchanger fouling rates

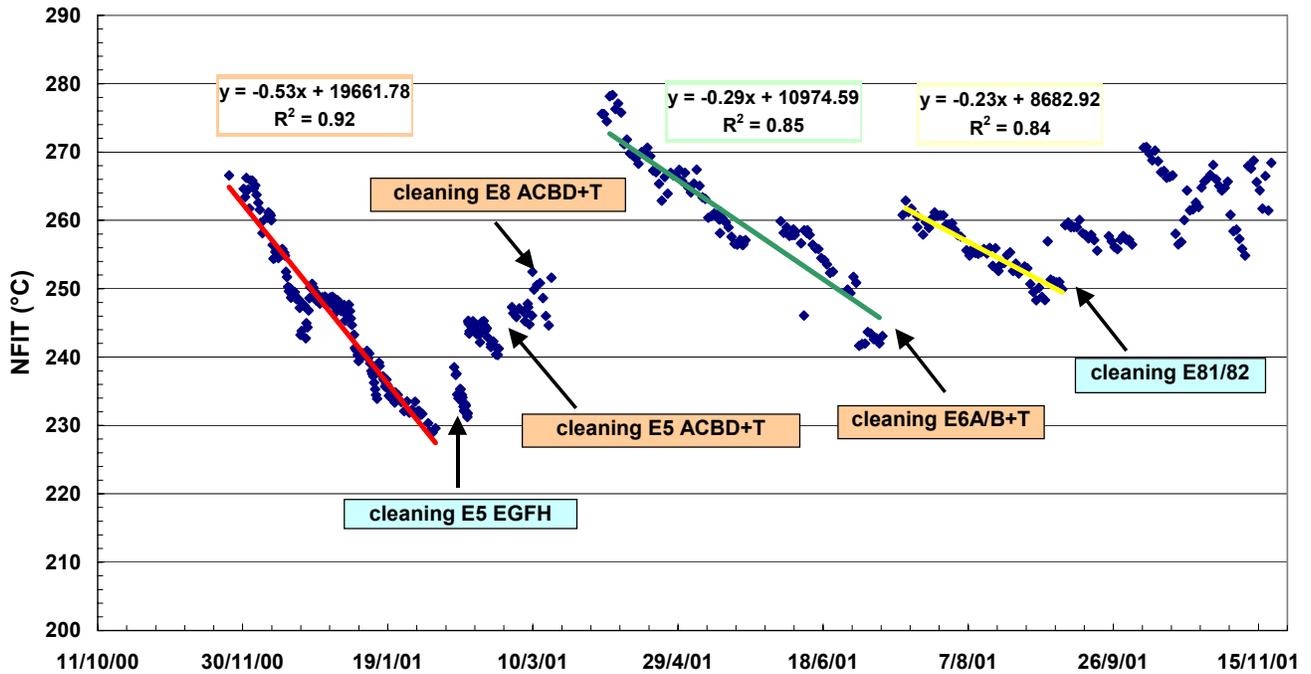**Figure 4: Simplified TURBOTAL^{TM} sketch**

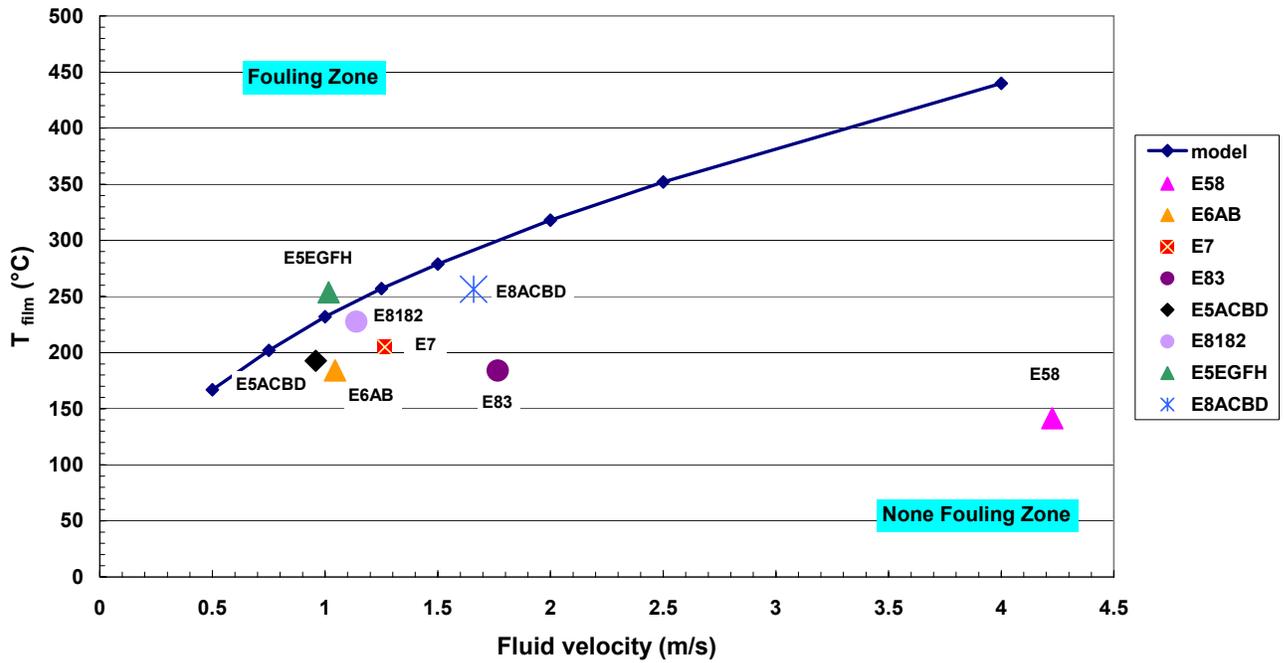**Figure 5: NFIT evolution with time**

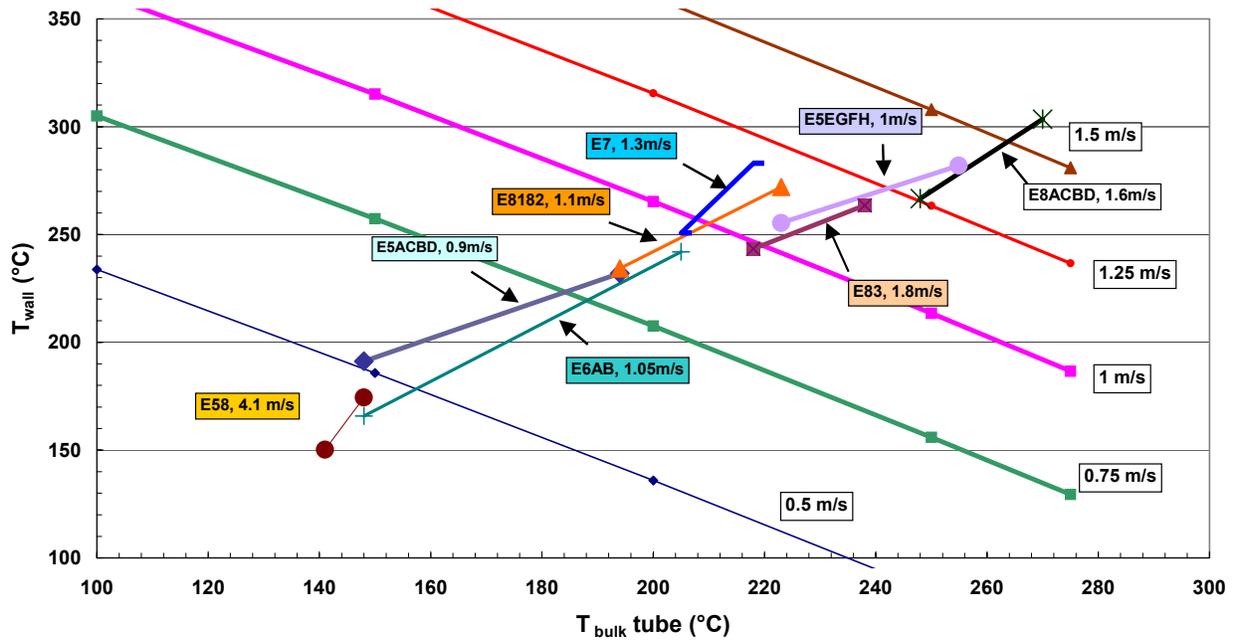**Figure 6: Base Case exchangers position in the Ebert and Panchal fouling diagram**

Figure 7: Base case exchangers positioning on a temperature field plot

	E58	E6AB	E7	E83	E5ABCD	E8182	E5EFGH	E8ABCD
ID Tube (mm)	14.8	14.8	14.8	19.1	14.8	14.8	14.8	14.8
OD Tube (mm)	19.1	19.1	19.1	25.4	19.1	19.1	19.1	19.1
Tube flowrate (T/h)	919.4	367.8	367.8	367.8	551.7	551.7	551.7	919.4
Shell flowrate (T/h)	85.9	222.9	81.6	347.2	600	500	500	347.2
Tube inlet T (°C)	141	148	205	218	148	194	223	248
Shell outlet T (°C)	171	177	296	278	210	268	274	298
Tube outlet T (°C)	148	205	218	238	194	223	255	270
Shell inlet T (°C)	234	264	348	298	249	297	297	355
hi (kcal/hm^2°C)	2876	1071	1384	1712	952	1184	1129	1733
he (kcal/hm^2°C)	985	1328	1081	947	1700	1806	1569	671
Inlet wall T (°C)	150	166	251	243	191	243	255	265
Outlet wall T (°C)	174	242	283	263	232	272	282	298
Inlet film T (°C)	146	157	228	231	170	219	239	256
Outlet film T (°C)	161	223	251	251	213	247	268	284
Tube bulk velocity (m/s)	4.05	1.04	1.29	1.83	0.90	1.09	0.98	1.64

Table 1: Operating conditions considered

	E58	E6AB	E7	E83	E5ACBD	E8182	E5EGFH	E8ACBD
Threshold velocity (m/s)	0.5	1	1.25	1.25	1	1.25	1.5	1.75
Minimum observed fluid velocity (m/s)	2.9	0.89	1.08	1.52	0.55	0.66	0.59	1.12
Base Case fluid velocity (m/s)	4.05	1.04	1.29	1.83	0.9	1.09	0.98	1.64
Maximum observed fluid velocity (m/s)	4.33	1.26	1.53	2.16	1.02	1.21	1.1	1.68
Fouling Trend from Base Case (m/s)	3.55	0.04	0.04	0.58	-0.1	-0.16	-0.52	-0.11
Predicted Fouling trend	1	$4 \approx 3$	$3 \approx 4$	2	$6 \approx 5$	7	8	$5 \approx 6$
Observed fouling rate (10^4 m^2°C/kcal)	0.04	0.47	0.34	0.27	0.94	0.5	1.91	0.86

Table 2: Predicted fouling trend versus observed fouling rate