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FOULING MONITORING IN DIESEL UNIT PREHEAT EXCHANGERS

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ABSTRACT

A method for monitoring the exchanger fouling resistance, R_f, based on the analysis of historical data from diesel desulphurization unit preheaters is presented. An important difficulty encountered in monitoring is the fact that the clean overall coefficient, U_c, value cannot remain constant at all times due to natural and inevitable changes in both shell-side and tube-side mass flow rates. This may cause large fluctuations and even unrealistic decreases in fouling resistance. Hence, fouling resistances need to be normalized. This has been overcome by obtaining two linear correlations and a non-linear correlation for U_c as a function of shell-side and/or tube-side flow rates, using the operational plant data of first two days after start up, during which exchanger was supposed not to be fouled.

The coefficients of the linear and non-linear models are calculated by Curve Fitting and Optimization Toolbox of MATLAB 2010.

Among the alternative models, non-linear model is preferred for updating the clean overall heat transfer coefficients. These values are then used to calculate the fouling resistances. Finally, the normalized fouling resistances are plotted for a period of 1710 days.

INTRODUCTION

There exists a tremendous amount of effort in reduction of energy consumptions in all oil refinery applications due to challenging refinery margins.

Fouling, not only for preheat exchangers of crude distillation units, but also for other units, is one of the most serious operating problem and source for energy loss in oil refineries. The worldwide costs, associated specifically with crude oil fouling in preheat trains were equated to around 20% of all heat exchanger fouling [Müller-Steinhagen, 2000].

The thermal and hydraulic performance of heat exchangers decreases continuously with time due to fouling, which is defined as the formation of deposits on heat transfer equipment. These deposits may be due to sedimentation, crystallization, organic and biological growths, chemical reactions, corrosion products, or a combination of all these effects [Bott, 1995; Zubair et. al., 2000]

The chemical reactions are usually complex and may involve the mechanisms such as: autoxidation, polymerization, cracking or coke formation [Bott, 1995]. The presence of oxygen, as a reactant, accelerates gum formation mechanism and therefore has a considerable effect on fouling rates. Heating of paraffinic hydrocarbon mixtures found in jet fuels, gas oils and similar products may result in the precipitation of gum-like material. Autoxidation forms a soluble oxidation product, with further oxidation to an insoluble polymer with molecular weights of 400-600 g/mol which may be formed on the wall or transported as particles to the wall [Bott, 1995].

The main operating variables that have effect on fouling are temperature -an increase of temperature favors chemical reaction with an exponential increase -, pressure -solubility of gas impurities (e.g. oxygen) increases with pressure that through autoxidation may enhance chemical reactions leading to deposition, and flow rate- attachment to the surface decreases with increasing velocity [Bott, 1995].

In organic fluid streams such as petroleum cuts, there may be a large number of reactants, precursors, which leads to reactions. The temperature field may dictate which reactions occur and where in the heat exchanger they occur. Hence generalized solutions to chemical reaction fouling problems are unlikely. The autoxidation of hydrocarbons has been identified as the main source of unwanted deposits in reviews of fuel storage stability, and in heat exchanger fouling in the temperature range from ambient to 300 ^oC [Watkinson and Wilson, 1997]. There exists also information in literature such as cracked stocks was found to enhance fouling in a gas oil and also a significant increase in fouling was noted when the gas oil was pre-saturated with oxygen, together with the numerous types of anti-foulant additives used in industry [Watkinson and Wilson, 1997].

The overall fouling resistance of a shell and tube (SHT) heat exchanger, R_f is an indicator of fouling, and careful monitoring is crucial. Traditionally R_f is computed from the difference between the two overall thermal resistances [Takemoto, 1997]:

$$R_f = 1/U_d - 1/U_c \quad (1)$$

Exact monitoring of R_f , addition to U_d, needs an updated overall thermal resistance of the exchangers for the new flow and operational conditions, but not fouled. Only with such kind of information, R_f monitoring would be more realistic, and therefore easier for further predictions of the exchanger performance.

METHODOLOGY

The fouling monitoring is of great importance in scheduling the cleaning in order to increase the performance of heat exchangers. In monitoring of R_f, among a number of exchangers; the preheat exchanger (where hot reactor effluent and cold feed are interacted) of diesel hydroprocessing unit (DHP) is selected due to its extensive fouling trend . DHP is designed to process diesel to remove sulfur and nitrogen content and adjusting the cold flow properties via treatment with hydrogen. The removal is performed by formation of H_2S and NH_3 in the reactor. Although the unit is designed to operate with a total feed-flow rate of 400 Sm^3/h, as a result of fouling inside the tubes of the preheat exchangers, the capacity has to be decreased. Consequently, the preheating performance of the exchangers becomes inefficient which in turn increases the duty of the combined feed fired-heater and energy consumption (Fig 1.). To overcome this problem, it is aimed to monitor the fouling rate of the exchangers online. For further improvements this will help us to analyze the main reasons of the fouling (feed quality, operating conditions etc.) and to schedule a maintenance program for preheat exchangers.

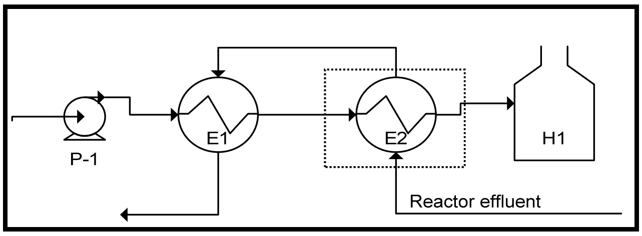

Fig.1. Simplified flow chart of equipment

The preheat train consists of two exchangers and the one before the heater is examined (E-2; in dashed box). E-2 is a shell and tube heat exchanger and consists of four shells which are installed in two parallel and two series configuration. The shells are identical and tubes have four passes per shell arranged in square pitch. The results and the experiences gained will be used later for other heat exchangers of Diesel unit in the plant which have similar configurations and streams.

The fouling is basically calculated by equation (1). The dirty (or fouled) overall heat transfer coefficient, Ud, can be calculated by equations (2) and (3), using the measured values of four temperatures $T_{shell,in}$, $T_{shell,out}$, $T_{tube,in}$, $T_{tube,out}$, and two flow rates m_t, m_s, being for the tube and shell sides, respectively.

$$Q = m_t \, c_p \, (T_{tube\ out} - T_{tube\ in}) \quad (2)$$

$$U_d = \frac{Q}{A \times F \times \Delta T_{LM}} \quad (3)$$

The clean overall heat transfer coefficient, U_c, however, can be determined at initial time but it needs to be updated due to inevitable changes in mt and ms.

In this study, a realistic semi-emprical mathematical model is obtained using the mass flow-rates of shell and tube sides in order to update U_c for new operational conditions. Hence the empirical formulation of U_c is performed by correlating it with tube and shell flow rates in different models.

Calculation of U_c utilizes the operational data in first two days of start-up (in hourly basis) under the assumption that the exchangers are fully clean in this period and the calculated heat transfer coefficient is equal to clean heat transfer coefficient. Correction to logarithmic mean temperature difference, F, and the specific heats, cp , of tube side, are also assumed to remain unchanged and they are taken as 0.93, 0.654 kcal/kgK, respectively. A is the heat transfer area of exchanger of which the design value is known to be 1843 m^2.

RESULTS & DISCUSSION

In modeling fouling character of exchangers, the main affecting parameters are the velocities through the tube and shell, in addition with the geometrical properties of the exchanger. In this study, three different models are used to obtain the clean heat transfer coefficient for varying flow rates in the exchanger. Namely; the heat transfer coefficient is correlated with mass flow rates in 1) tube linearly, 2) shell linearly and 3) tube and shell non-linearly. The effects of exchanger parameters are embedded in the constants of these models. Since both tube and shell flows contribute to the clean heat transfer coefficient, the constants generated in the first and second models are generally used to create the third model.

MODEL 1. U_c is a function of tube side mass flow rate only:

The values of U_c are calculated using the data recorded hourly, by Eqs. 2 and 3. Although the mass flow-rates of tube and shell sides vary simultaneously, U_c may be assumed to be the function of mass flow-rates of the tube side only. The variation of U_c is plotted in Fig. 2 using MATLAB 2010.The coefficients of the trend line are calculated using the least square method and given in equation (4):

$$U_c = 1.6147 \, m_t - 67.921 \quad (4)$$

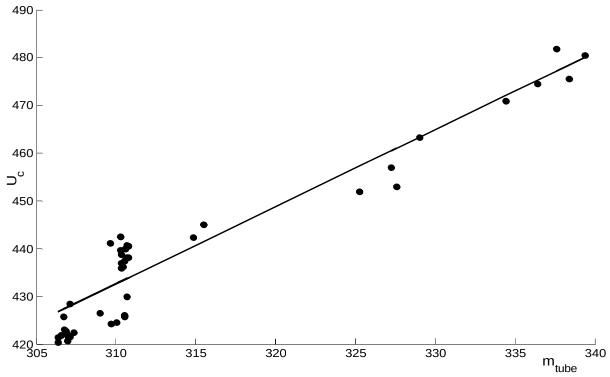

Fig.2. U_c (kcal/hm^{2}K) vs. mass flow-rate of tube side (ton/hr)

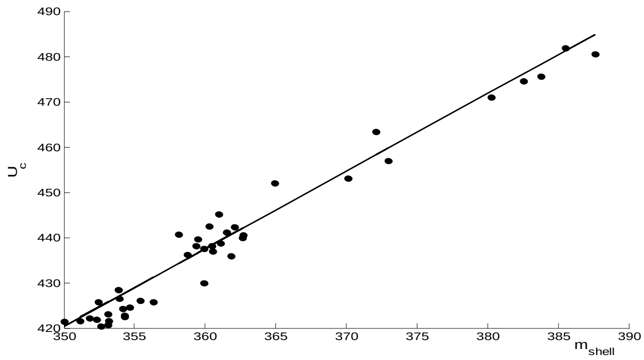

Fig. 3. U_c (kcal/hm^{2}K) vs. mass flow-rate of shell side (ton/hr).

The sum of square of the differences between the values of the experimental and model overall coefficients calculated by equations (3) and (4), respectively, is defined as S in equation (5). The value of S is important to be able to compare the different mathematical models that are used in the calculation of updated values of U_c:

$$S = \sum_{n=1}^{N} \left(U_{c,exp} - U_{c,m}\right)^2 \qquad (5)$$

where $U_{c,exp}$ and $U_{c,m}$ are experimental and model values of clean overall heat transfer coefficient U_c, and N was taken as 45, the number of feasible data during two days.

The calculated value of S for Model 1 is given in Table 4.

MODEL 2. U_c is a function of shell-side mass flow rate only:

The values of U_c are calculated using the data recorded hourly, equations (2) and (3). Although the mass flow-rates of tube and shell sides vary simultaneously, U_c is now assumed to be the function of mass flow-rates of shell side only. The variation of U_c is plotted in Fig. 3 using MATLAB 2010. The coefficients of the trend line are calculated using the least square method and given in equation (6).

$$U_c = 1.7139\ m_s\text{-}179.49 \qquad (6)$$

The calculated value of S for Model 2 is given in Table 4 for the same number of data.

MODEL 3. U_c is a function of both shell and tube side mass flow rates:

In this semi-emprical model, equation (7), U_c is assumed to be the function of the both shell and tube side mass flow rates. All other parameters other than flow rates are represented by the parameters (K, L):

$$\frac{1}{U_c} = \frac{1}{K m_t^a} + \frac{1}{L m_s^b} \qquad (7)$$

The final form of the Model 3 is given in equation (8).

$$U_c = \frac{L m_s^b\ m_t^a}{M m_s^b + m_t^a} \qquad (8)$$

The values of U_c are calculated using the data recorded hourly, by equation (2) and equation (3). U_c is assumed as function of mass flow-rates of shell and tube side only. The other effects are represented by the parameters L and M. The variation of U_c is plotted in Fig. 4 using MATLAB 2010.

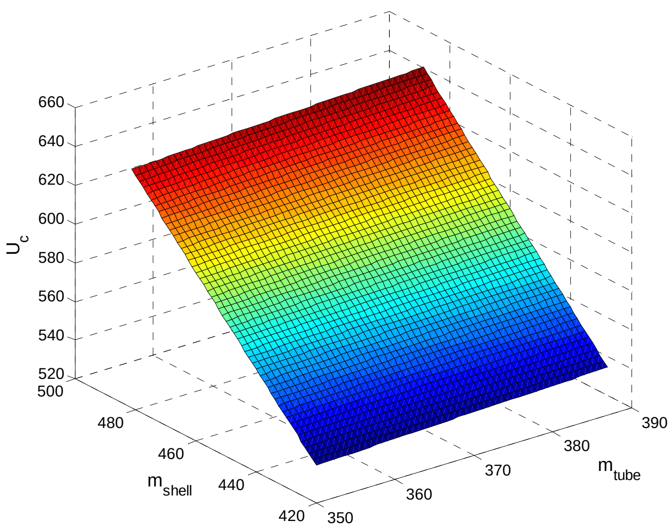

Fig. 4. U_c (kcal/hm^{2}K) vs. mass flow-rates of shell side (ton/hr) and tube side (ton/hr).

The problem is taken as an unconstrained non-linear optimization problem with the same objective function given in equation (5).

The optimization (minimization) problem is aimed to solve for the optimum values of a, b, L, M. The problem involves many local minima, and initial values of parameters are important for obtaining the global optimum.

The problem is solved by Genetic Algorithm (GA) of MATLAB 2010 Optimization Toolbox using the values of parameters of the algorithm in the Table 1.

Table 1. Parameters of Genetical Algorithm

Population size	Crossover fraction	Migration fraction	Elite count
25	0.8	0.2	2

The number of iteration and the solution of the problem with GA is given in Table 2.

Table 2. Results of Genetical Algorithm

S	L	M	a	B	number of iteration
932.752	3.433	1.671	1.407	1.001	90

The number of iteration, 90, of GA seems to be not high enough, and also objective function final value not low enough, in compared with earlier experiences. Therefore, we decided to try another algorithm, which has been used successfully for this type of optimization problems, Nelder-Mead simplex algorithm [Fan and Erwie, 2007; Laursen and Le Riche, 2004].

The vector of initial parameter values required for this method is taken as the solution of the problem with GA. Nelder-Mead simplex algorithm is available in the "fminsearch" option of nonlinear optimization methods of MATLAB 2010. The parameter values of Model 3 are given in Table 3.

Table 3. Results of Nelder-Mead Algorithm

S	L	M	a	B	number of iteration
462.939	10.946	0.151	2.343	1.001	1453

The objective function values vs. number of iteration in Nelder-Mead technique are plotted in Fig.5.

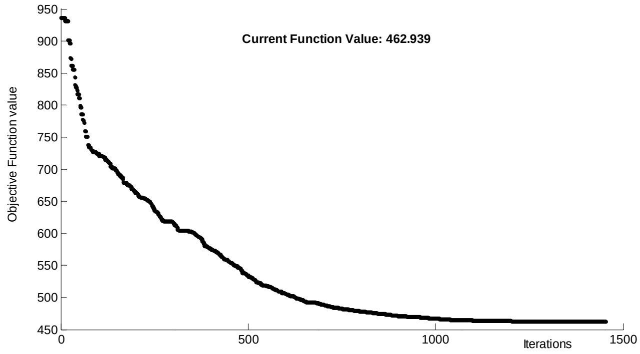

Fig. 5. S vs. number of iteration.

Table 4 lists the minimum objective function values for all the models.

Table 4. S values for the models

Model	S
1	1616.93
2	919.64
3	462.94

The sum of the squares of the differences between the values of clean overall coefficients calculated by equation (3) and model equations are compared. It was observed that the model involving mass flow-rates of both shell and tube sides equation (8) is more preferable.

Using Model 3 to update U_c values, the clean overall heat transfer coefficients are calculated and the values of fouled overall heat transfer coefficients are determined by equation (3), for the entire service period of 1710 days. Then the fouling resistances are calculated using the equation (1) and shown in Fig. 6.

Fig. 6. R_f vs. time

Four different periods are observed in Fig. 6. After the first start up, rundown cracked feed (visbreaker gasoil and light cycle oil) is charged into the unit together with feed from the tank besides rundown gasoil from the crude unit for the first 200 days. The presence of oxygen in the tank saturates the gasoil and acts as a reactant in gum formation mechanism (free radical polymerization). This makes a marked increase in fouling resistance and a performance loss in heat exchanger which in turn increases the combined feed fired heater duty. After the first cleaning, R_f decreases sharply and the second period starts. Straight run gasoil from the crude unit was charged into the unit with rundown cracked feed which did not cause any increase in fouling resistance. When the feed from the tank is started to be charged again to the unit after the day 1400^{th} (third period), R_f starts to rise again. Here it should be noted that, the rate of fouling is much lower compared to the first case. The reason is that, in this period no cracked feed was fed to the unit. After the second maintenance program performed at the days of 1600 (fourth period), although the unit was fed from the tank together with straight run gasoil from the crude unit, due to anti-foulant chemical program applied to the exchangers, the increase rate of fouling was managed to be kept low.

CONCLUSIONS

- The fouling behavior of a heat exchanger in diesel hydro-processing unit of TÜPRAŞ Izmir Refinery is modeled according to real time data of the exchanger by correlating tube and shell flows with calculated heat transfer coefficients on daily basis.
- The results obtained from the model are consistent with the operational applications; that is, the fouling character of the exchanger is explained by the feed of the unit as well as the anti-foulant chemicals used in the exchanger.

NOMENCLATURE

A heat transfer area of exchanger, m^2
c_p specific heat, kcal/kgK
F correction factor, dimensionless
K parameter of model 3
L parameter of model 3
M parameter of model 3
m mass flow rate, ton/hr
Q heat transfer rate, $mc_p\Delta T$, kcal/hr
R_f fouling resistance, $1/U_d - 1/U_c$, m^2Kh/kcal
S sum of square of the deviations, $(kcal/hm^2K)^2$
T temperature, K
U_c clean heat transfer coefficient, kcal/m^2hK
U_d dirty heat transfer coefficient, $Q/(AF\Delta T_{LM})$, kcal/hm^2K
ΔT_{LM} log mean temperature difference, $((T_{s,i}- T_{t,o})-(T_{s,o}- T_{t,i})) / \ln((T_{s,I}-T_{t,o})-(T_{s,o}- T_{t,i}))$, K

Subscript

c clean
d dirty
exp experimental
i in
m model
o out
s shell
t tube

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