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MAINTENANCE SCHEDULING AND OPTIMIZATION IN DIESEL HYDROPROCESSING UNIT- FEED/REACTOR EFFLUENT EXCHANGERS

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ABSTRACT

Fouling in diesel unit feed/reactor effluent heat exchangers is of great concern due to lowering of furnace inlet temperature and thus causing an increase in furnace heat load, consuming extra fuel energy and as a result of these, increasing the unit operational cost. As the delta temperature across the fired heater increases due to fouling, the unit feed flow also needs to be decreased but with a cost of huge margin loss. After a certain delta temperature in the furnace, then the unit needs to be shut down for cleaning action in the heat exchangers since no further temperature rise can be achieved due to the furnace limitations. Fouling monitoring and an optimized maintenance period projection for the future cycles has been a mandatory work for the process engineers in the recent years. In this study, the operational data (September, 2005 – December, 2011) gathered from Tüpraş İzmir Refinery Diesel Hydroprocessing Unit are utilized in the unit simulation in order to generate the models for fouling factor (R_f) and found that it is directly related with the unit charge type (from storage tank, or cracked diesel etc.). Genetic algorithm and simulation algorithm run simultaneously in order to optimize the system in terms of economic aspects. The algorithm includes an objective function to make a comparison between marginal process cost and maintenance cost due to unit shut down and extra fuel cost arising from operating the unit in relatively dirtier conditions. The constraints are defined according to the operational variables of the unit as well. The optimization results show the optimum time period to clean the exchangers.

INTRODUCTION

Diesel Hydroprocessing Unit (DHP) is designed to process diesel to remove sulfur and nitrogen content via treatment with hydrogen in the existence of the catalyst. The removal is performed by formation of H_2S and NH_3 in the reactor. The feed to the reactor is preheated in exchangers by the hot reactor effluent, before being charged to the reactor.

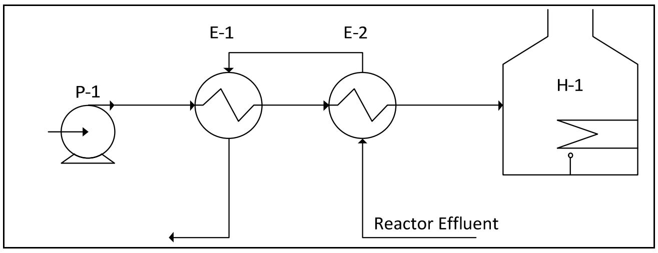

Figure 1: Simplified flow chart of equipment's

The preheat train consists of two exchangers as shown in Fig.1. E-1 and E-2 are shell and tube heat exchangers and consist of four shells which are installed in two parallel and two series configuration. The shells are identical and tubes have four passes per shell.

Although the unit is designed to operate with a total liquid feed flow rate of 400 Sm3/h, as a result of fouling inside the tubes of the preheat exchangers, furnace inlet temperature decreases and furnace duty increases for required constant furnace outlet temperature. Consequently, the preheating performance of the exchangers becomes inefficient causing an increase in energy consumption. As the furnace inlet temperature decreases, unit feed flow rate has to be decreased and since furnace duty cannot be increased after an allowable limit, unit has to be shut down for cleaning of the exchangers.

O, S and N contents in diesel are of great importance in the fouling of exchangers [1,2]. Oxygen dissolved in oil and/or oil products, by any means, may cause serious fouling problems due to free radical polymer formation reactions. Sulphur may be contained in diesel as either aromatic or alifatic sulphides. Aromatic sulfides causes fouling indirectly, wheras alifatic sulphides are thermally very reactive. They break C-S bonds to form H_2S. Also forming free hydrocarbon radicals, they initialize thermal cracking. Additionally, H_2S being formed, reacts with the tube surface material and iron sulphide is formed. This increases corrosion type of fouling. Existence of nitrogen dissolved in diesel may also cause complex polimerization reactions that increases fouling resistance [3].

METHODOLOGY

In this study, a simulation algorithm is developed in order to calculate overall fouling resistance, R_f, by using real time data of diesel hydroprocessing unit (DHP) preheat exchangers. Data is taken for each stream such as flow rate, temperature, pressure, distillation and gravity from the process historian database (PHD) for the desired time period and heat exchanger design specifications such as tube number, tube diameter, configuration and heat transfer area are also entered. Traditionally R_f is computed from the difference between the two overall thermal resistances [4]:

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

Using the measured temperatures of shell and tube side inlet and outlet streams, flow rate and distillation data, physical properties such as density, viscosity and heat capacity are determined. Then, overall dirty heat transfer coefficient, U_d, is obtained by Eq.(2):

$$U_d = \frac{Q}{A(F\Delta T_{ln})} \quad (2)$$

The clean overall heat transfer coefficient, U_c, is determined for the same flow and operation conditions of that heat exchanger. For this purpose, an iterative algorithm is applied to determine the clean case outlet temperatures of shell and tube sides in the defined confidence interval of 0.1 ^{0}C. Firstly, an assumption is made for both tube and shell side inlet and outlet temperature difference to estimate the clean case outlet temperature data. Then, average temperature, all physical properties, individual heat transfer coefficients of streams at this average temperature and logarithmic mean temperature difference are calculated. Afterwards, overall energy balance using overall heat transfer coefficient, heat transfer area and logarithmic mean temperature and individual energy balances for both streams using heat transfer capacity, flow rate and temperature differences are performed by Newton-Raphson method to calculate the clean outlet temperatures for tube and shell sides iteratively. Iterations are performed until the assumed and estimated outlet temperature differences for shell and tube side are in the defined confidence interval.

In order to schedule a maintenance program for preheat exchangers, overall fouling resistance needs to be modeled for the defined future time interval. For this purpose, the factors causing the fouling are defined and formulated in a general equation (3) for future time estimation. The main reasons for fouling are; feed source, (whether it is cracked charge from FCC unit, straight run from crude oil distillation unit or import from outside sources); antifouling chemical usage and others. Therefore, the fouling resistance is obtained as a function of these parameters by analyzing 7 years of historical data in three periods.

$$R_f = R_{f-T} + R_{f-N} - R_{f-C} \quad (3)$$

where;

$$R_{f-T} = R_{fT_i} + (a_T R_{f\infty}\ (\theta_T(1+\theta_c))^{b_T})\ \Delta t \quad (4)$$

$$R_{f-N} = R_{fN_i} + R_{f\infty}\ \left(1 - e^{\frac{-t}{\kappa^{a_N}\tau}}\right)\Delta t \quad (5)$$

$$R_{f-C} = R_{fk_i} + (\ a_C R_{f\infty}\ \theta_k\left(1 - e^{-b_C\theta_k}\right))\ \Delta t \quad (6)$$

The terms in Equations (3) relate partial contributions to total fouling resistance, R_f, are associated with feed from tank (import diesel) and cracking units, combined effects of cracked feed and other effects, and the chemical usage rate respectively. If the feed is not from tank (import diesel) and cracking units (that is, under "normal" conditions), the fouling resistance R_f will be equal to just $R_{f\text{-}N}$. The two other terms $R_{f\text{-}T}$ and $R_{f\text{-}C}$ are extra fouling resistances associated with the usage of feed from tank or cracking units, and the chemical additive usage, respectively. The equations are established with using the seven years of historical data of the exchangers. This period is analyzed in terms of charge type (whether it is a straight run, cracked or import diesel) and the chemical usage process. To see the individual effects of these operational conditions, the fouling rates and the components (straight run, cracked or import diesel) in the combined charge are listed for the exchangers, that is to say for the import diesel effect (R_{fT}), the unit was operated only with import diesel for three years and analyzing the data results with the equation of R_{fT}. The similar procedure was reapplied for R_{fC} and R_{fN} With the most fitted equation form and constants, R_f, is formed.

The same fouling resistance function written as a function of chemical usage rate and different charge sources is applied to two exchangers with different parameters since fouling occurs in a similar way in these exchangers. These models are utilized to project fouling trend of the exchangers with a given feed rate (and source distribution) and chemical usage rate. After defining the unit operating conditions, these parameters are used as an input to the optimization function.

The optimization system consists of an objective function, which relates the unit shut down and operating costs as follows;

$$F = \sum_{i=1}^{N}[Unit\ operating\ cost - y_i\ (Exchanger\ cleaning\ cost)] \quad (7)$$

yi is a binary variable (yi = 0 or 1). It represents whether or not i-th exchanger is considered in cleaning program. The value of yi is determined by a genetic algorithm and is substituted into equation (7). This function is generated for the whole projected period. The first term in Equation (7) refers to the non-cleaned operating expenses of the unit which is mainly the difference of heat loads to the furnace placed after the exchangers between the clean and dirty conditions.

On the other hand, the second term in Equation (7) consists of mainly three components. Individual exchanger cleaning cost (maintenance cost) and the cost of extra fuel that will be used in the furnace due to shut down of that specific exchanger during maintenance depending on the by-pass value of the exchanger (z). The last one is the marginal operating cost of the unit which should be considered when these exchangers are not spared and cannot be by-passed. This valu e is unit specific and can briefly be defined as difference between the costs of feed to this unit and products from this unit.

The objective function is formed as a function of total operating cost of the network due to fouling formation during the whole duration of operation. Then the function is in the form of (8):

$$F = \sum_{i=1}^{N} \left[\frac{(Q_D - Q_C)_i}{FG_{calvalue}} \times FG_{cost} - y_i \left((Cleaning\ cost)_i + z_i \times \frac{Extra\ Q_i}{FG_{calvalue}} \times FG_{cost} + (1 - z_i) \times Marginal\ process\ cost \right) \right] \quad (8)$$

Applying the following constraints reduces the solution space as well as the amount of computations for finding the optimal cleaning schedule by minimizing *F in* Eq. (8)

- *By–passing of the exchangers (z values):* The exchangers in DHP unit are not spared, thus they cannot by-passed.
- *Combined shut-down of exchanger groups:* Since these exchangers cannot be by-passed, maintenance for these two exchangers should be programmed together.
- *High and low limits of unit operating conditions*: The maximum allowable difference between inlet and outlet temperatures of the furnace is the limit in this unit.

The problem that is defined in equation (8) and the related constraints is a MINLP problem and in this study, the problem is solved using a genetic algorithm.

The Genetic Based Algorithm : In this study, a hybrid algorithm based on the general principles of GA's and Nonlinear Simplex [5] was used to search for the optimum values of continuous and discrete design parameters of the problem that are generated randomly using the following relationships.

$$x_{i+1} = x_i + r v_{mh} e_h \quad (9)$$

$$y = LB + INT\,(u \times sr + 0.5) \quad (10)$$

where x_i is the current optimum for the continuous variables. r shows the random numbers in the interval of [-0.5, 0.5] and u is the integer variable that can be either 0 or 1. e_h is the vector of the h^{th} coordinate direction and v_{mh} is the component of the step vector (v_m) along the same direction. LB and sr are the vectors of the lower bounds and the search region for discrete variables respectively. The values of the components of v_m were determined as 2.5 using the test functions taken from literature [6]. The value of sr was taken as 1 to generate only 0 and 1 values by using the relations 2 and 3. The discrete variables were used to determine the alternative heat exchangers to be cleaned.

The basic steps of the genetic based algorithm (6) are given as follows:

- Encoding and initial population:

The algorithm uses real value encoding and the initial population, consisting of points in the feasible search space, is randomly created with a particular population size that is chosen as 10xN where N is the number of the variables.

- The generation of a new population:

Each new population is formed by applying the following operators:

1. Reproduction: Reproduction is the first operator applied on a population and the strings that have the best fitting values are picked from the current population and duplicates of them are inserted in the mating pool (elitist strategy).
2. Crossover: In the algorithm, the single point crossover is preferred and the strings are cut randomly and the right side portion of both strings swaps among themselves to create the binary variables of the new strings. The continuous variables of the new strings are created by applying the following crossover operators [2].

$$x_{offspring_1} = \frac{1-t}{2} x_1 + \frac{1+t}{2} x_2 \quad (11)$$

$$x_{offspring_2} = \frac{1+t}{2} x_1 + \frac{1-t}{2} x_2 \quad (12)$$

where t is a real number between 0 and 1. The value of t was calculated as 0.2 by using the test functions taken from literature [6].

3. Mutation: The position of the strings is determined randomly and a mutation operator is applied for that position. If the variable at the determined position is binary, it was changed depending on the current value. Otherwise,

the continuous variables were replaced by the value at the same position of the different strings that are determined randomly in the current population.

4. Generation of new random vectors: Although the generation of new random vectors in each new population is not the general operator of the GA's, it is used and the probability value is determined experimentally. In this step, the reflection and expansion functions of the nonlinear simplex algorithm [5] are applied to the strings that have the same discrete values for the treatment of the continuous variables of the problem.

The proposed values of the percentages of reproduction, crossover, mutation and generation are given in Table 1.

Table 1: The probability values of the operators of the genetic based algorithm

P_R	P_C	P_M	P_G
30	40	5	25

- Termination criteria:

GA's do not guarantee convergence to a global optimum solution, hence a suitable stopping criterion is required. The constant number of generations or different termination criteria can be used to terminate the GA's. In the present algorithm, the following termination criterion was used.

$$\text{abs}(F_{Avg_i} - F_{Avg_{i-25}}) \leq \in \quad (13)$$

F_{Avg_i} and $F_{Avg_{i-25}}$ are the average objective function values for 25 consecutive generations.

The algorithm behind the solution of the optimization problem is shown in Figure 2.

After generation of "*y*" values for the exchangers, R_f model is utilized to see the fouling behavior of each and every heat exchanger in the train within the desired timeline which is an user input variable. Since R_f is modeled as a function of daily time, the results are obtained for the next day. Therefore, for monthly scheduling, the obtained R_f values are cumulated for the end of month, and by using this value and last real value of R_f, the clean and dirty case scenario are compared with respect to heat loads to the furnace and the required fuel usage.

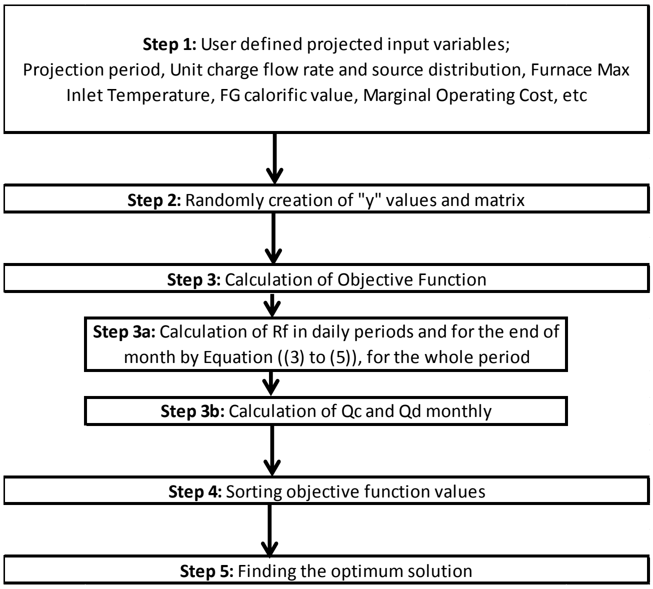

Figure 2: Solution Algorithm of optimization function

For the last step the value of the objective function is calculated and stored. This continues with generation of new "y" values and calculation of new objective function values. The algorithm ends with sorting these values and selecting the minimum one.

RESULTS & DISCUSSION

Analysis of fouling rate in the exchangers results with a fouling trend given in Figure 3.

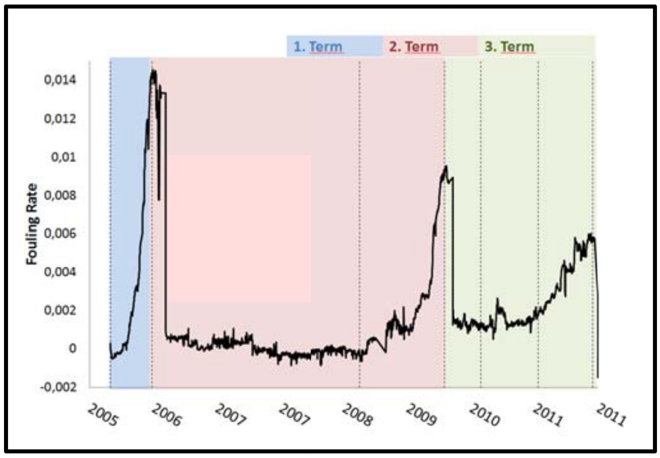

Figure 3: Fouling trend of Heat Exchanger E-2

As can be seen in Figure 3, the fouling trend is analyzed in three terms representing each cycle of the exchanger. Getting deep into the details of operational conditions, shows that, the reason of the high rate of fouling in the first term is the usage of import diesel with cracked feed. This high fouling rate in this situation can be attributed to saturation of unsaturated hydrocarbons in cracked feed with import diesel. In the second term, the feed to the unit is only the import diesel. This shows that, the fouling is promoted not only with import diesel but with combination of cracked feed. In the last period of Figure 3, dispersant is injected to the feed to suppress fouling formation though the feed is a combined cracked and import. This is why the slope in this period is smaller compared to the other terms. By using the models given in Equation from (3) to (6), the constants for general R_f equation are determined as in Table 2.

Table 2: Constants of R_f models

		E-1	E-2
$R_{f\text{-}T}$	a_T	0.058	0.058
	b_T	3.2	3.2
$R_{f\text{-}N}$	a_N	52	46.5
	T	6001	6001
$R_{f\text{-}C}$	a_C	-0.008	-0.00254
	b_C	2000	1763
$R_{f\text{-}\infty}$ **(h m^2 °C/kcal)**		0.00865	0.011

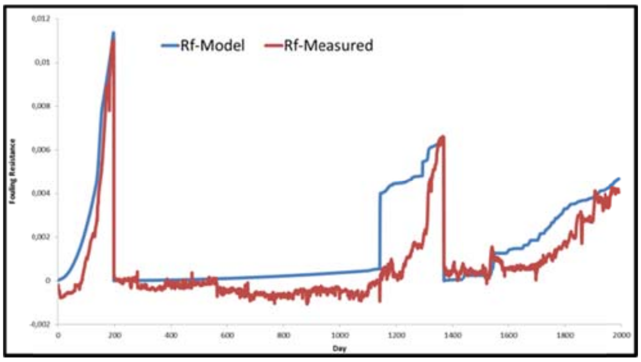

Figure 4: Comparison of modeled and measured fouling rate (E-2)

Comparison of the modeled and measured fouling rate can be seen in Figure 4. Though there exists some deviations from real time data, modeled fouling rate is in consistency with the measured fouling.

The solution of the genetic algorithm is performed via the algorithm given in Figure 2. User input variables can be classified as estimations of projected operational parameters, charge source distribution and cost parameters as summarized in Table 3. An example for the optimization problem has been made for which the input values can also be seen in Table 3. These values represent the actual last values of the unit. Therefore for the whole optimization time-line, it is assumed that same operating conditions are applied.

Table 3: User Defined Inputs

Type	Parameters	Value
Unit Data	Furnace Maximum Delta temperature	70°C
	Unit Maximum Flow Rate (Sm3/h)	400
	Unit Operating Flow Rate	Last operating value
	Fuel Gas Calorific Value (kcal/kg)	9128
	Fuel Gas Density (kg/Nm3)	0.79
	Charge Temperature	Last operating value
Feed Data	Charge From Tank (Ratio)	0.28
	Cracked Charge (Ratio)	0.00
	Chemical Injection Rate (ppm)	20
Cost Date	Individual Exchanger Cleaning Cost (TL/h)	Last operating value
	Marginal Process Cost (TL/h)	Last operating value
	Fuel Gas Cost (TL/ton)	Last operating value
Span	Time Period (month)	12
Z	By-passing of exchangers	0

The solution of the optimization problem is presented in the matrix form as given in Table 4. The "month" column of the matrix refers to number of months passed from the date of running the simulation. The "Delta T" column shows the furnace inlet and outlet temperature difference.

Table 4: Results of Optimization problem

Month	E-1	E-2	Delta T
1	0	0	52
2	0	0	54
3	0	0	56
4	0	0	58
5	0	0	60
6	0	0	62
7	0	0	64
8	0	0	65
9	0	0	67
10	0	0	69
11	**1**	**1**	**70**
12	0	0	43

Since the main constraint of the unit is the maximum heat load of the furnace (allowable maximum delta T= 70°C, (Table 4) the optimization results are obtained at this maximum limit.

The optimization results show that F values increase as fouling increase since as fouling increase delta between Qd and Qc increases. As can be seen in Table 4, at the 11th

month after the simulation started, the unit needs to be shut down for cleaning of heat exchangers. The results of the optimization show that, due to increased fouling resistance in the exchangers, the delta temperature across the furnace difference increases with time. After the exchangers are cleaned (11^{th} month), delta T of the furnace again drops to lower values. This analysis is performed assuming that all user input variables are constant during the projected period; the chemical is fed with 20 ppm of rate and the feeding from tank is always with a fraction of 0.28. However, to get a more accurate optimization study, it is better to re-optimize in every changing condition.

CONCLUSIONS

Fouling monitoring is of great concern to improve unit performance and to control extra energy consumptions. For this purpose, fouling resistance of Diesel Hydroprocessing Unit Feed/Effluent preheat exchangers are simulated and modeled using the historical data. The models are generated as a function of different feed sources for each exchanger present in the network and are utilized in optimization of maintenance scheduling.

The results of the optimization show consistency with the operational data. Outlet temperatures from the exchangers drop as fouling occurs which leads to higher temperature difference and hence higher energy consumption in the furnace. However, it should be noted that the result of the optimization problem can vary depending on the initial projection estimations. Therefore, to get a more realistic solution, it is better to run the simulation periodically with updated operational variables.

NOMENCLATURE

F: Objective Function
FCC: Fluid Catalytic Cracking
FG: Fuel Gas
N: Number of exchangers, number of variables
R: Fouling resistance (h.m^2 °C/kcal)
$R_{f-\infty}$: Highest Fouling resistance (h.m^2 °C/kcal)
y: Exchanger cleaning parameter (1: Cleaned, 0: Not cleaned)
Q: Heat transfer rate (kcal/h)
U: Heat transfer coefficient (kcal/m^2 °C)
z: Exchanger by-pass parameter
(1: Can be by-passed, 2: Cannot be by-passed)
θ: Feed from defined source
κ: unit utilization (current charge/maximum sustained charge)
t: time (day)

Subscript

c: clean
C: chemical additives usage
d: dirty
f: fouling
i: Exchanger
N: Normal
T: tank

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