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Optimization on Scheduling for Cleaning Heat Exchangers in the Heat Exchanger Networks

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In the process at a plant that incorporating heat integration for energy recovery, fouling or formation of deposits on the heat exchanger often causes operational problems in production. Increasing the energy consumption resulted in higher operating expenses. Expenses can be reduced if the cleaning is done on a regular basis. Therefore, how to schedule the cleaning for heat exchangers in an industrial complex becomes more important. Scheduling for cleaning heat exchangers can be based on knowledge of the thermal behaviour of the fouling resistance against time. This works is aimed at developing mathematical models for optimization on scheduling for cleaning heat exchangers in heat exchanger networks and its application in the chemical industry in general. Given an increase in fouling, which is very closely linked to the function of time, one tries to determine how frequent cleaning action is and the time in which the exchanger must be cleaned so that industrial operations can run optimally.

1. Introduction

Heat exchanger always cannot be separated from the problem of fouling. Fouling is the formation of deposits on the area of heat transfer surface. The impact of fouling is reduces heat exchanger device efficiency and process output with related to the increasing operation cost (Ishiyama et al., 2011a). Georgiadis (2000) has reported one common way to reduce fouling is to apply operations cleaning in place (CIP) for the processes that are affected by fouling quickly. According to Markowski et al. (2005), some important things to note for online cleaning the heat exchanger is the scheduling of cleaning actions on the single exchangers in Heat Exchanger Networks (HEN) and analyze the formation of fouling in the exchangers. So that optimization is required for scheduling cleaning. Several methods for the optimization of cleaning schedules for a single heat exchanger have been proposed in the literature. Epstein (1979) work on calculation for optimal cycle in evaporator, Casado (1990) used a detailed cost model to calculate the optimal cleaning cycle by exploring the major operating trade-offs. Sheikh et al (1996) presented a reliability based cleaning strategy by incorporating uncertaintly in a linear fouling model. And more recently extended to networks of heat exchanger was reported by Markowski et al. (2005). Pogiatziz et al. (2012) worked on scheduling the cleaning of single heat exchanger subject with regard to fouling and ageing. Assis et al. (2013) proposed an identification of the optimal set of the cleaning heat exchanger during a plant shutdown. Gonçalves et al. (2014) studied about the optimization of cleaning schedules in crude preheat trains in petroleum refineries. Recently, Du et al. (2015) proposed a method into MINLP model to find the minimum operating cost. Finally, this work will present to show another approach to optimize the scheduling for cleaning heat exchanger in accordance with the design.

2. Model formulation

2.1 Fouling model

Ishiyama et al. (2011b) reported that a fouling deposit is modelled as a single homogeneous layer, the deposit thickness; δ (m) is usually determined by the effect of heat transfer. if the thickness of fouling deposit was thin, it is will have an impact on heat transfer, which can be described as fouling resistance, R_f, as follows:

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$$R_f = \frac{\delta}{\lambda} \tag{1}$$

Where λ is a deposit thermal conductivity in W·m^{-1} °C^{-1}. In design, R_f also is related with:

$$R_{f=}R_{f,in} + R_{f,out} \tag{2}$$

$R_{f,in}$ is a fouling factor for the inner pipe at its inside diameter and $R_{f,out}$ is a fouling factor for the annulus fluid at the outside diameter of the inner pipe. So, the overall heat transfer coefficient, U_f in W·m^{-2}·°C^{-1}, is related to that the clean state, U_c in W·m^{-2}·°C^{-1}, by:

$$\frac{1}{U_f} = \frac{1}{U_c} + R_f \tag{3}$$

Or can be modified:

$$U_f = \frac{U_c}{1 + U_c . R_f} \tag{4}$$

Kern (1983) explained that in practice, R_f value can be obtained from experience when the devices need be cleaned only once a year (or in one operation period). It depends on the radius of used pipe and also the fluid material that flow inside this device. Assumed that heat transfer area, A in m^2 are constant. This make sense in the fouling problem there will be significant changes in the energy recovery. Exponential approach is used to explain how the heat transfer coefficient (U_f) decreases with time as a result of fouling.

$$U_f = A . e^{-B.t} \tag{5}$$

Variable A and B can be determined by taking into account the initial and final conditions of operation.

2.2 Optimization of cleaning model

The change value of U_f gives an effect on the total amount of energy recovery, which can be expressed as follow:

$$Q_{rec} = U_f \cdot A \cdot \Delta T_{LMTD} \tag{6}$$

Where Q_{rec} is a heat recovery duty in MW and ΔT_{LMTD} is log mean temperature difference in °C. If cleaning schedule for HEN consist of amount of j heat exchanger device during the period of operation t_e in some plant. The ultimate goal of scheduling for cleaning is to minimize the utility cost of the operation as:

$$Utility\ Cost = (Q_H + Q_C) \cdot k_q + n_j \cdot k_c \tag{7}$$

Subject to constraint:

$$Q_H = \left(\sum \int_0^{t_c} q_{C,i} . dt\right) - \sum Q_{rec,j} \tag{8}$$

$$Q_C = \left(\sum \int_0^{t_c} q_{H,i} . dt\right) - \sum Q_{rec,j} \tag{9}$$

$$Q_{rec,j} = n_j . \int_0^{t_{clean}} U_f . A . \Delta T_{LMTD} . dt \tag{10}$$

$$t_{clean} = \frac{t_e}{n_j} \tag{11}$$

Where n_j is number of cleaning in each exchanger (j=1, 2, …), then q_C is a heat duty in cold stream and q_H is a heat duty in hot stream. Taking Assume that each cleaning actions can be done quickly, So, the time required for cleaning is very small when compared with the period of production t_e. Utility cost depends on the cleaning actions taken on the single exchangers n_j ($n_j \neq n_{j+1}$) and time intervals between operating and cleaning. The amount of energy recovered is affected by energy cost constants k_q and cost cleaning that are dependent on the number of each cleaning action on a single heat exchanger k_c.

3. Example of scheduling of cleaning action

From the data of process streams in Table1, it can be determined heat integration using Pinch method as expressed by Liew et al. (2014). The author explained the methodologies for heat exchanger arrangements in total site heat integration network. The integrated results are shown in Figure.1. In this condition, heat exchanger device (HE) was in pristine condition or can be referred as an initial condition when the device is in clean condition. The data of resistance thermal of fouling (R_f) are also in Table 1.

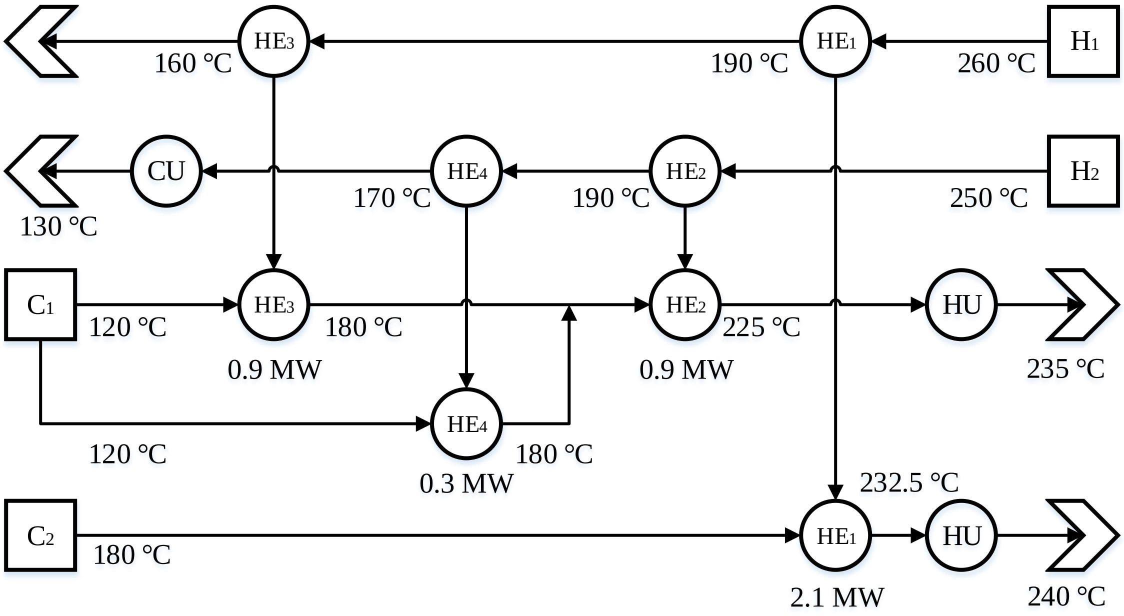

Figure 1: Integrated temperature distribution in a HEN at $\Delta T_{min} = 10$ °C

Table 1: Value of stream process data

Stream	Fluid	T_{in} (°C)	T_{out} (°C)	m.cp (KW/°C)	$R_{f,in}$ ($m^2 \cdot °C \cdot W^{-1}$)	$R_{f,out}$ ($m^2 \cdot °C \cdot W^{-1}$)
H1	Iso-Butane	260	160	30	0.005	0.005
H2	Toluene	250	130	15	0.005	0.005
C1	Benzene	120	235	20	0.005	0.005
C2	Butane	180	240	40	0.005	0.005

Table 2: Calculated value of U_c and U_f

HE No.	U_c ($W \cdot m^{-2} \cdot °C^{-1}$)	U_f ($W \cdot m^{-2} \cdot °C^{-1}$)
1	50.17593	33.41143
2	34.985682	25.91807
3	56.42526	36.07171
4	48.334566	32.58483

U_c were calculated as given by Kern (1983) using double pipe heat exchanger calculation. U_f were calculated using Eq(4). The results were given in Table 2. it can be explained that $U_f = U_c$ at $t = 0$. Values of A and B were as given in Eq(5) can be calculated and it was tabulated in Table 3. A question may be posed that heat transfer coefficient associated with time. This case can be explained as follows. It is assumed that the initial conditions, heat exchanger (HE) device is in the clean state. The final state (as a fouled) could be known using Eq(4). Then exponential approach is used to explain the decrease such as:
For HE 1, in which U_c and U_f value is consecutively 50.17593 W m^{-2} $°C^{-1}$ and 33.41143 W m^{-2} $°C^{-1}$ (along 300 days operation). Then it can be written when at $t = 0$ d (initial condition), $U_f = 50.17593$ W $m^{-2} \cdot °C^{-1}$ then at $t = 300$ d (at the end of period), $U_f = 33.41143$ W $m^{-2} \cdot °C^{-1}$. By entering the value $t = 0$ at the initial condition, variable A will be found equal to 50.17593 W $m^{-2} \cdot °C^{-1}$, or it is concluded that A is equal with U_c. further, at the final condition, by entering the value t equal 300 d and value of A equal 50.17593 $W \cdot m^{-2} \cdot °C^{-1}$, the value of variable B could be found as 0.001355. And finally, the function U_f will be obtained with respect to time (t), see Table 3.

4. Table 3: Calculated U_f valueResult of scheduling cleaning action

By considering the integrated heat network illustrated in Figure 1, the following constants are determined as follows:

- Energy cost constants (k_q) = 0.005 $/KW.
- Cost of each cleaning action (k_c) = 10.000 $/action.
- Long duration of production period (t_e) = 300 d.

Table 4 below is the sample result of the operating cost calculation for HE 1. So, it can be concluded as in Figure 2. From the graph, it can be seen that n_j=5 (for HE 1) is the value that gives a minimum total operating cost. Assuming one year is 300 d. if the same steps are repeated for each exchanger 2,3 and 4, the result obtained are shown in Figure 3, Figure 4, and Figure 5.

Table 4: The Optimum result of scheduling cleaning action for HE 1

n_1	Energy cost ($/y)	Cleaning cost ($/y)	Total operating cost ($/y)
1	563,439	10,000	573,439
2	150,261	20,000	170,261
3	68,270	30,000	98,270
4	38,831	40,000	78,831
5	25,019	50,000	75,019
6	17,452	60,000	77,452

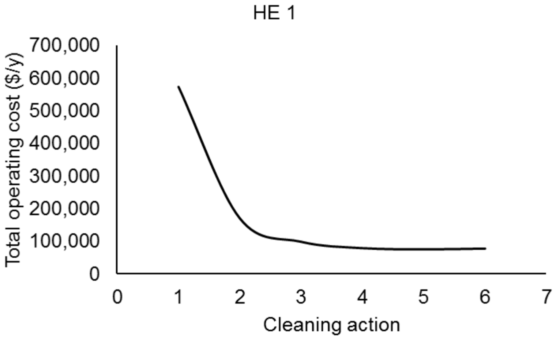

Figure 2: Relationship between operating cost and cleaning action in HE 1

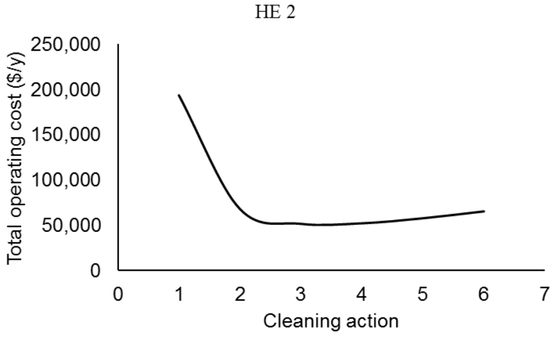

Figure 3: Relationship between operating cost and cleaning action in HE 2

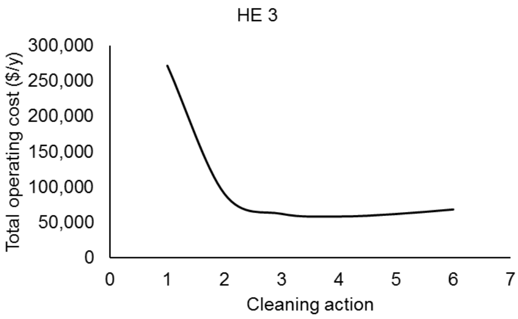

Figure 4: Relationship between operating cost and cleaning action in HE 3

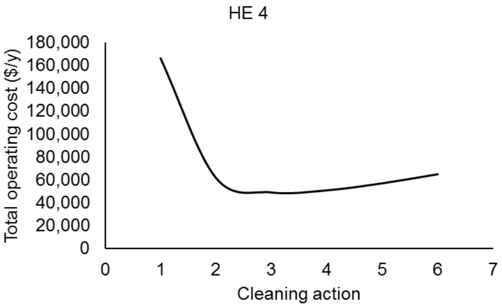

Figure 5: Relationship between operating cost and cleaning action in HE 4

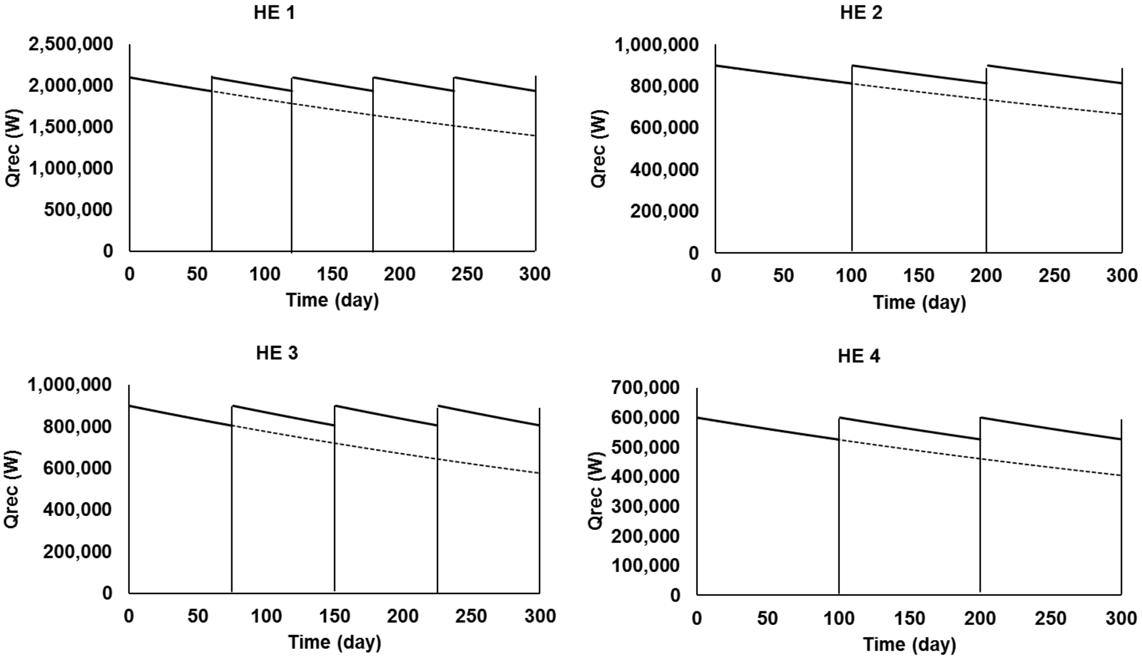

Figure 6: Final heating capacity optimal schedule for case study

The scheduling for cleaning actions can be optimised using the model described above. This result becomes possible, because at the end of production period the plant will be cleaned thoroughly (shutdown period). The results can be seen in Figure 6 (dash line showed the behaviour Q_{rec} without cleaning) and can be summarized in Table 5. The minimum value of the utility cost that needs to be added is $ 224,399.

Table 5: The Optimum result of scheduling for cleaning in the case study

HE no.	Number of cleaning action (n_j)	Total operating cost ($)
1	5	75,019
2	3	51,768
3	4	58,175
4	3	39,437

5. Conclusion

By assuming when known the time behaviour of thermal resistance of fouling, a model have been developed with propose to determine the scheduling for cleaning heat exchanger in some networks. It is formulated the optimal cleaning schedule with the target to the minimum utility cost in which the value of energy from utility required and the cost of every cleaning are also taken into account. There is an example of a HEN comprising with 4 heat exchangers to illustrate this model. The cleaning action scheduled in accordance to the decreasing approach of heat transfer coefficient which depends on the type of fluid and used heat exchanger device. This solution can maintain the efficiency of HE devices nearly 90 % of the maximum value of energy recovery.

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