Cleaning Schedule Operations in Heat Exchanger Networks

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Abstract. Heat exchanger networks have been known to be the essential parts in the chemical industries. Unfortunately, since the performance of heat exchanger can be decreasing in transferring the heat from hot stream into cold stream due to fouling, then cleaning the heat exchanger is needed to restore its initial performance periodically. A process of heating crude oil in a refinery plant was used as a case study. As many as eleven heat exchangers were used to heat crude oil before it was heated by a furnace to the temperature required to the crude unit distillation column. The purpose of this study is to determine the cleaning schedule of heat exchanger on the heat exchanger networks due to the decrease of the overall heat transfer coefficient by various percentage of the design value. A close study on the process of heat exchanger cleaning schedule in heat exchanger networks using the method of decreasing overall heat transfer coefficient as target. The result showed that the higher the fouling value the more often the heat exchanger is cleaned because the overall heat transfer coefficient decreases quickly.

1 Introduction

In a refinery plant one can generally find a lot of heat exchangers which are used in series-parallel to heat cold crude oil to a required temperature before it flows to a column furnace to a higher temperature in order that a somewhat perfect separation can be obtained. There can be many configurations from a set of heat exchangers to construct. If we only use hot and cold utilities to exchange the heat between steam/cooling water and process fluid, then we can imagine the huge amount of energy needed to operate the process. A heat integration concept is aimed at reducing energy consumption from hot and cold utilities by exchanging heat between hot streams and cold streams. By using pinch design method, then maximum energy recovery gained from the process will reduce the need of hot and cold utilities, and will also reduce energy cost as well. Figure 1 shows the process in a refinery plant where a crude oil is being heated through a series of heat exchangers [1]. There is neither hot utilities nor cold utilities used in the process. There are hot streams available as they are side stream products from pipe still of crude distillation unit. We have one cold stream and seven hot streams which are being heat-matched. Eleven heat exchangers process to process are needed without any heaters and coolers. A delta T minimum of 10 ^{o}C is given as a constraint due to the physical heat exchangers used. From Figure 1 we have a heat exchanger networks (HEN) where there are four independent heating processes (HE-01, HE-07, HE-09 and HE-10) and seven integrated heating processes (HE-02, HE-03, HE-04, HE-05, HE-06, HE-08 and HE-11). In order to get more understanding how the streams are matched between hot streams and cold streams, a grid diagram is proposed as shown in Figure 2. However, using complete heat integration one can have zero hot and cold utilities with eleven heat exchangers. Since the energy cost outweighs the annual capital cost, the configuration for HEN as given in Figure 2 will be the base case. A fouling problem arises when a heat exchanger operates continuously over time.

2 Process Descriptions

In this process, crude oil from the storage is pumped to HE-01 as cold stream. Its inlet temperature is 32–51°C and its outlet temperature is 72–93°C. The inlet temperature of hot stream is 128–150°C and leaving HE-01 at 61–110°C. For HE-02, the cold stream enters at 72–93°C and leaves at 83–105°C while the hot stream enters at 146–211°C and leaves at 82–115°C. The hot stream of HE-02 is the outlet of HE-06 hot stream. For HE-03, the cold stream enters at 83–105°C and leaves at 99–126°C while the hot stream enters at 137–170°C and leaves at 93–150°C. The hot stream of HE-03 is the outlet of HE-05 hot stream. The cold stream of HE-04 enters at 99–126°C and leaves at 108–139°C while the hot stream of HE-04 enters at 159–240°C and leaves at 110–200°C. The hot stream of HE-04 is the outlet of HE-

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08 hot stream. After leaving HE-04, crude oil is sent to desalter to remove salt from the crude oil.

Crude oil from desalter is sent to HE-05 as cold stream. Its inlet temperature is 103–135°C and its outlet temperature is 127–151°C. The inlet temperature of hot stream is 154–187°C and leaving HE-05 at 137–170°C. For HE-06, the cold stream enters at 127–151°C and leaves at 131–157°C while the hot stream enters at 162-225°C and leaves at 146–211°C. For HE-07, the cold stream enters at 131–157°C and leaves at 135–163°C while the hot stream enters at 254–281°C and leaves at 145–200°C. The cold stream of HE-08 enters at 135–163°C and leaves at 149–188°C while the hot stream of HE-08 enters at 269–296°C and leaves at 189–217°C. The hot stream of HE-08 is the outlet of HE-11 hot stream. For HE-09, the cold stream enters at 149–188°C and leaves at 164–213°C while the hot stream enters at 269–296°C and leaves at 189–217°C. For HE-10, the cold stream enters at 164–213°C and leaves at 175–241°C while the hot stream enters at 314–338°C and leaves at 209–271°C. The cold stream of HE-11 enters at 175–241°C and leaves at 186–253°C while the hot stream of HE-11 enters at 314–337°C and leaves at 228–313°C. After leaving HE-11, crude oil is sent to furnace. The outlet temperature of furnace is 350°C. In this process, there are four independent heating processes (HE-01, HE-07, HE-09 and HE-10) and seven integrated heating processes (HE-02, HE-03, HE-04, HE-05, HE-06, HE-08 and HE-11).

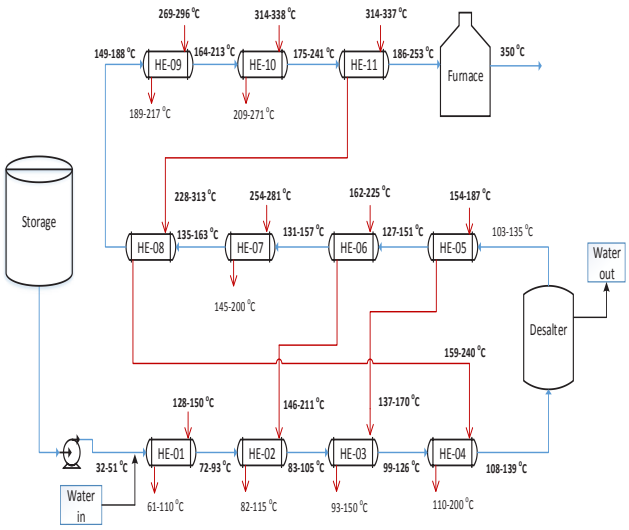

Fig. 1. The schematic diagram of the HEN in crude refinery.

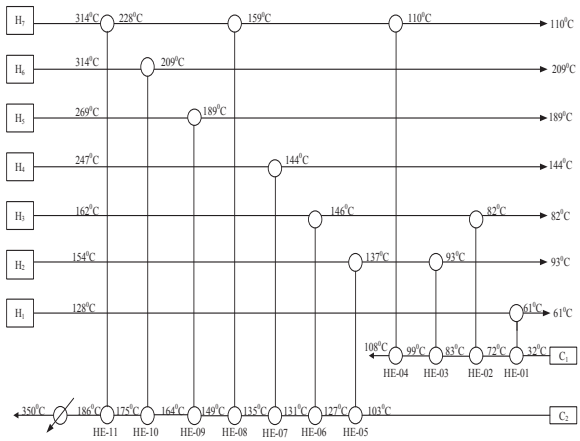

Fig. 2. Grid Diagram of Heat Integration with ΔTmin 10°C.

3 Heat Exchanger Networks

In any process flow sheet, there are several streams that need to be heated and there are some that need to be cooled before entering the next step. For that reason, cooling water is needed to lower the hot process streams while steam is needed for heating the cold process streams. If we only use hot and cold utilities to exchange the heat between cooling water/steam and process fluid, then we can imagine the huge amount of energy needed to operate the process.

A heat exchanger networks (HEN) is an arrangement of heat exchangers; in which cold and hot process streams and hot and cold utility streams interchange energy. The purpose of the HEN is to recover energy from the hot process streams to heat up cold process streams using the least amount of hot and cold utility streams, while achieving specified outlet target temperatures of the process streams [2].

4 Heat Exchanger

Heat exchangers are devices that provide the transfer of thermal energy between two or more fluids at different temperatures [3]. Traditionally, the heat exchanger performance analysis and simulation are performed using steady-state energy balance across the heat exchanger. The energy balance on the hot and cold fluid together with the heat transfer equation constitute the model of heat exchangers. Under the assumptions that there is no heat loss to the surrounding and the heat loss of hot streams shall be equal to heat gained by cold streams, therefore

$$Q_c = Q_h = m_c\, c_{p,c}\, (T_{c,o} - T_{c,i}) = m_h\, c_{p,h}\, (T_{h,i} - T_{h,o}) \qquad (1)$$

Where:

m_c: mass flow rate of the cold fluid (crude oil) (kg/hr)

m_h: mass flow rate of the hot fluid (kg/hr)

$c_{p,c}$: specific heat of the cold fluid (W hr/kg °C

$c_{p,h}$: specific heat of the hot fluid (W hr/kg °C)

$T_{c,o}$: outlet temperature of the cold fluid (°C)

$T_{h,o}$: outlet temperature of the hot fluid (°C)

$T_{h,i}$: inlet temperature of the hot fluid (°C)

For the performance of another heat exchangers use equation below:

$$Q = U\,A\,\Delta T_{LMTD} \quad (2)$$

where:
Q: heat duty (W)
U: overall heat transfer coefficient (W/m^2 °C)
A: heat transfer surface area (m^2)
ΔT_{LMTD}: log mean temperature difference (^{o}C)
ΔT Log Mean Temperature Difference (ΔT_{LMTD}) is defined as

$$\Delta T\ \Delta T_{LMTD} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{ln\left(\frac{T_{h,o} - T_{c,i}}{T_{h,i} - T_{c,o}}\right)} \quad (3)$$

5 Fouling resistance and Overall heat transfer coefficient

Fouling is a major unresolved problem of significant interest in the field of heat transfer [4]. Fouling is the accumulation of undesired material at the heat transfer surfaces. It is transient process that begins with a clean heat transfer surface and continues until the point where the surface become fouled to the point where the heat exchanger can no longer be used effectively. At this point, the heat exchanger must be taken out of service and cleaned [5].

The correlation between fouling resistance and overall heat transfer coefficient can be described as

$$\frac{1}{U_{f(t)}} = \frac{1}{U_c} + R_{f(t)} \quad (4)$$

$$U_{f(t)} = \frac{U_c}{1 + U_c \cdot R_{f(t)}} \quad (5)$$

Where:
R_f: fouling resistance (m^2 °C/W)
U_f: overall heat transfer coefficient dirt (W/m^2 °C)
U_c: overall heat transfer coefficient clean (W/m^2 °C)
t: time (day)
Fouling resistance, R_f, as follows:

$$R_{f\,(t)} = R_{f\infty}\left(1 - exp^{-\beta t}\right) \quad (6)$$

Where:
$R_{f\infty}$: asymptotic fouling resistance (m^2 °C/W)
β: constant fouling formation with time (1/day)

The characteristic decrease in overall heat transfer coefficient dirt (U_f) follows the exponential function as given below:

$$U_{f(t)} = A\,e^{-Bt} \quad (7)$$

The characteristic and relation between U_f and t should be investigated. The value of U_f varies by t, where t is production period. Variable A is determined at initial condition and variable B is determined at final condition [6].

So we can determine the characteristic of overall heat transfer coefficient (U) for one period. The characteristic decrease in heat transfer coefficient (U) follows the exponential function as given below:

$$U_{f(t)} = \frac{U_c}{1 + U_c \cdot R_{f(t)}} + \left(U_c - \frac{U_c}{1 + U_c \cdot R_{f(t)}}\right) e^{-\beta t} \quad (8)$$

The characteristic and relation between U_f and t should be investigated. The value of U_f varies by t, where t is production period. Variable U_c, β are known from data. For the process cleaning scheduling was done on decrease by 20% U_c from each HE. In order to get more understanding how the streams are matched between hot streams and cold streams, a grid diagram is proposed with ΔT_{min} is equal to 10°C.

Table 1. Data.for Uc, R_f dan β

HE	U_c	$R_{f\infty}$	β (1/day)
HE-01	678	$9{,}57\times10^{-04}$	$1{,}99\times10^{-02}$
HE-02	483	$7{,}14\times10^{-03}$	$2{,}26\times10^{-02}$
HE-03	583	$8{,}03\times10^{-03}$	$2{,}96\times10^{-02}$
HE-04	359	$6{,}23\times10^{-03}$	$1{,}74\times10^{-02}$
HE-05	487	$7{,}74\times10^{-03}$	$2{,}14\times10^{-02}$
HE-06	649	$3{,}72\times10^{-03}$	$1{,}94\times10^{-02}$
HE-07	148	$2{,}61\times10^{-03}$	$1{,}67\times10^{-02}$
HE-08	357	$3{,}69\times10^{-03}$	$1{,}48\times10^{-02}$
HE-09	540	$3{,}42\times10^{-03}$	$1{,}51\times10^{-02}$
HE-10	640	$6{,}04\times10^{-03}$	$1{,}22\times10^{-02}$
HE-11	465	$4{,}48\times10^{-03}$	$3{,}46\times10^{-02}$

6 Result and Discussion

This section discusses the fouling resistance model, the total of cleaning and the overall heat transfer coefficient model each heat exchanger.

Table 2. Present of result.

HE	R_f at t = 360	Total of Cleaning	U_f at 80%	U_f at t = 360
HE-01	$9{,}56\times10^{-4}$	6	544,32	411,510
HE-02	$7{,}14\times10^{-3}$	15	390,89	108,674
HE-03	$8{,}03\times10^{-3}$	20	471,41	102,675
HE-04	$6{,}22\times10^{-3}$	10	289,46	111,521
HE-05	$7{,}74\times10^{-3}$	14	390,76	102,328
HE-06	$3{,}71\times10^{-3}$	13	523,32	190,784
HE-07	$2{,}61\times10^{-3}$	3	118,56	106,908
HE-08	$3{,}67\times10^{-3}$	7	285,84	155,475
HE-09	$3{,}40\times10^{-3}$	9	434,75	191,761
HE-10	$5{,}97\times10^{-3}$	10	512,49	139,191
HE-11	$4{,}48\times10^{-3}$	16	365,57	150,930

R_f fouling resistance at each heat exchanger is different. In Figure 3 it can be observed that there is an increase in fouling resistance or an increase in the level of impurities on the heat exchanger. Where for the highest end value of the highest or dirtiest fouling resistance at HE-03 is $8{,}03\times10^{-3}$ (m^2 °C/W) and the lowest fouling resistance value at HE-01 $9{,}56\times10^{-4}$ (m^2 °C/W).

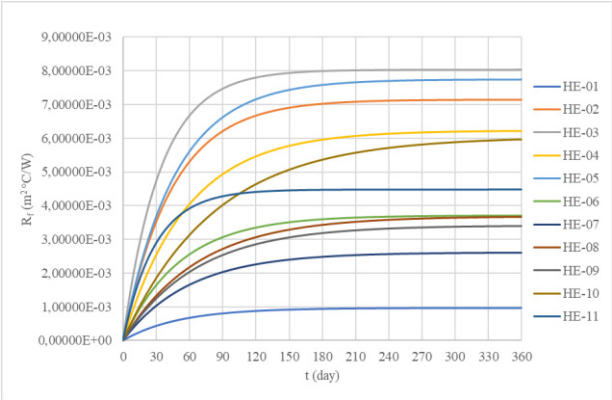

Fig. 3. Fouling resistance all heat exchanger.

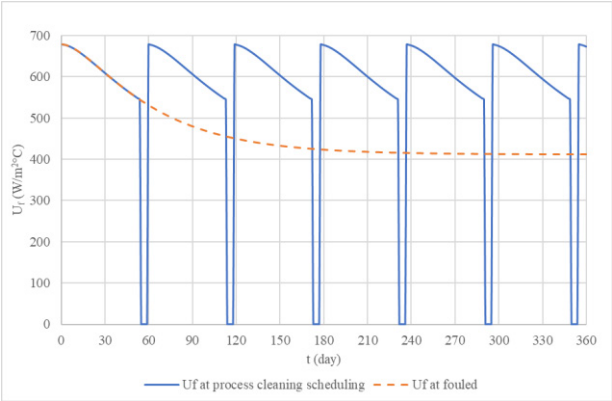

Fig. 4. Cleaning scheduling at HE-01.

In the HE-01 with initial value U_c 678 (W/m^2 °C), U_f at 360 days fouled condition value was 411,51 (W/m^2 °C) and U_f at 80% value was 542,4 (W/m^2 °C). The total of process cleaning 6 times in 360 days, U_f at day 54 value was 544,3245 (W/m^2 °C) and first process cleaning at day 55 in the HE-01.

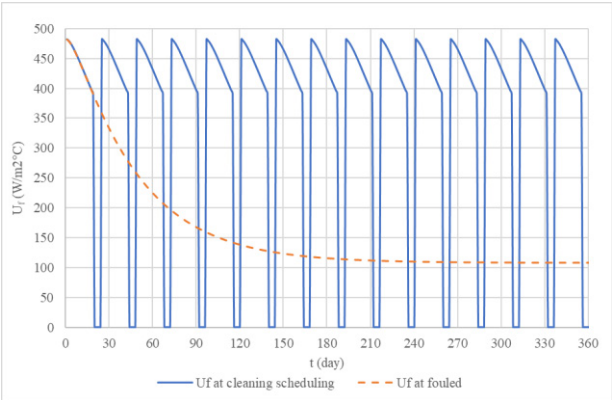

Fig. 5. Cleaning scheduling at HE-02.

In the HE-02 with initial value U_c 483 (W/m^2 °C), U_f at 360 for fouled condition 108,674 (W/m^2 °C) and U_f at 80% value was 386,4 (W/m^2 °C). The total of process cleaning 15 times in 360 days, U_f at day 19 value was 390,8917 (W/m^2 °C) and first process cleaning at day 20 in the HE-02.

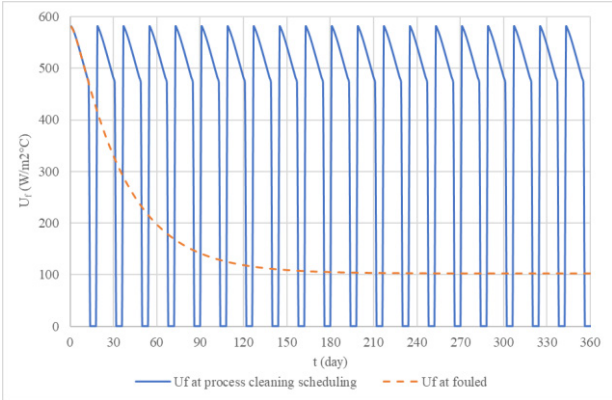

Fig. 6. Cleaning scheduling at HE-03.

In the HE-03 with initial value U_c 583 (W/m^2 °C), U_f at 360 for fouled condition 102,675 (W/m^2 °C) and U_f and at 80% value was 466,4 (W/m^2 °C). The total of process cleaning 20 times in 360 days, U_f at day 13 value was 471,4086 (W/m^2 °C) and first process cleaning at day 14.

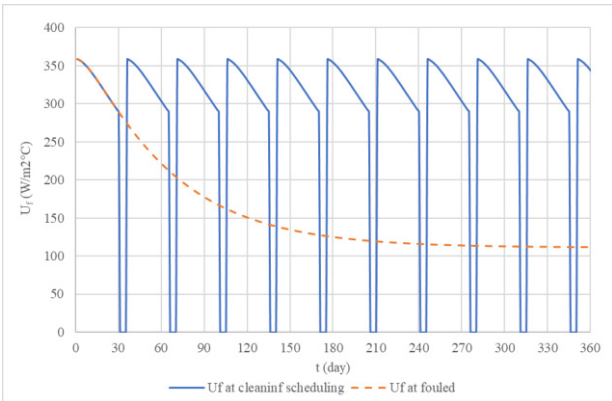

Fig. 7. Cleaning scheduling at HE-04.

In the HE-04 with initial value U_c 359 (W/m^2 °C), U_f at 360 for fouled condition 111,521 (W/m^2 °C) and U_f and at 80% value was 287,2 (W/m^2 °C). The total of process cleaning 10 times in 360 days, U_f at day 30 value was 289,461(W/m^2 °C) and first process cleaning at day 31 the page

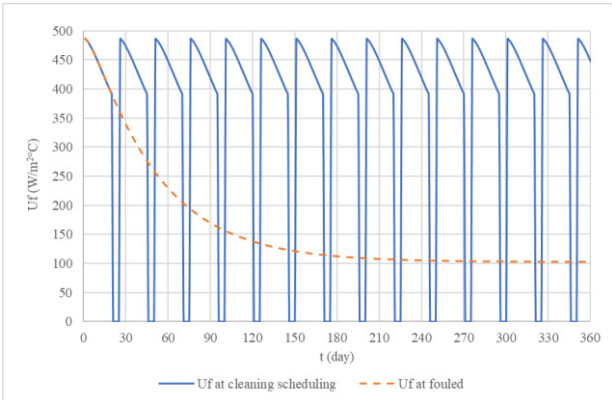

Fig. 8. Cleaning scheduling at HE-05.

In the HE-05 with initial value U_c 487 (W/m^2 °C), U_f at 360 for fouled condition 102,328 (W/m^2 °C) and U_f and at 80% value was 389,6 (W/m^2 °C). The total of process

cleaning 14 times in 360 days, U_f at day 20 value was 390,760 (W/m^2 °C) and first process cleaning at day 21.

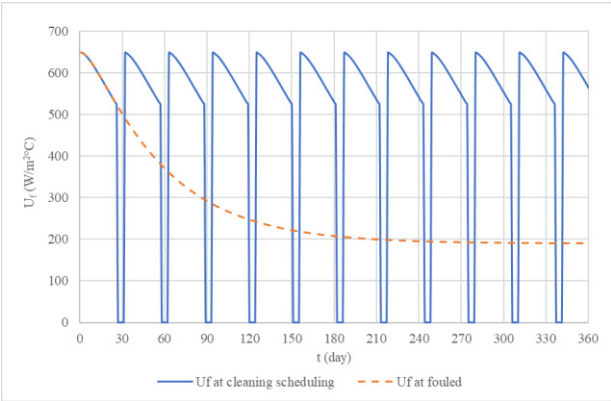

Fig. 9. Cleaning scheduling at HE-06.

In the HE-06 with initial value U_c 649 (W/m^2 °C), U_f at 360 for fouled condition 190,784 (W/m_2 °C) and U_f and at 80% value was 519,2 (W/m_2 °C). The total of process cleaning 11 times in 360 days, U_f at day 26 value was 523,321 (W/m2 °C) and year first process cleaning at day 27.

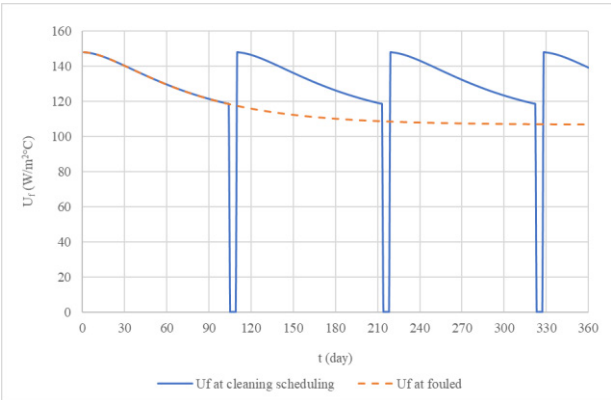

Fig. 10. Cleaning scheduling at HE-07.

In the HE-07 with initial value U_c 148 (W/m^2 °C), U_f at 360 for fouled condition 106,908 (W/m^2 °C) and U_f and at 80% value was 118,4 (W/m^2 °C). The total of process cleaning 3 times in 360 days, U_f at day 104 value was 118,560 (W/m^2 °C) and first process cleaning at day 105.

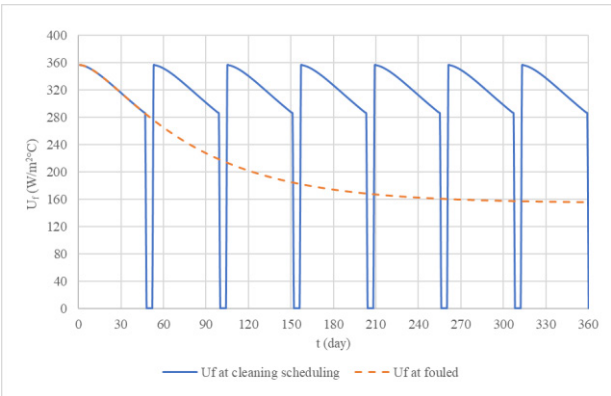

Fig. 11. Cleaning scheduling at HE-08.

In the HE-08 with initial value U_c 357 (W/m^2 °C), U_f at 360 for fouled condition 155,475 (W/m^2 °C) and U_f and at 80% value was 285,6 (W/m^2 °C). The total of process cleaning 7 times in 360 days, U_f at day 47 value was 285,838 (W/m^2 °C) and first process cleaning at day 48.

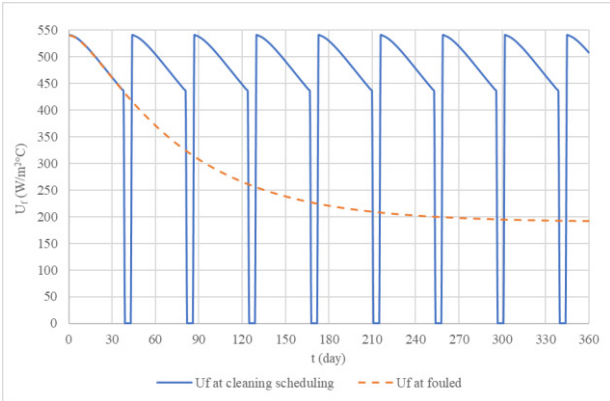

Fig. 12. Cleaning scheduling at HE-09.

In the HE-09 with initial value U_c 540 (W/m^2 °C), U_f at 360 for fouled condition 191,761 (W/m_2 °C) and Uf and at 80% value was 432 (W/m_2 °C). The total of process cleaning 8 times in 360 days, U_f at day 38 value was 434,750 (W/m^2 °C) and first process cleaning at day 39.

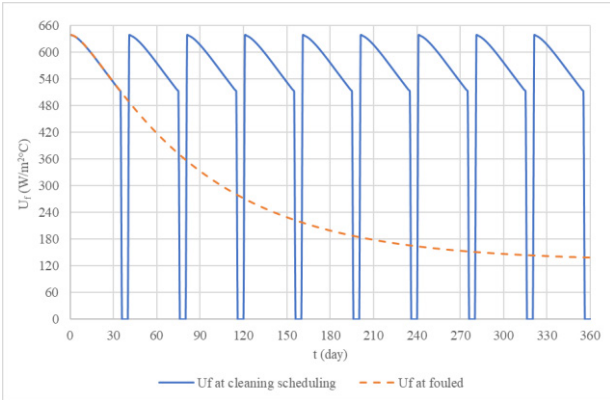

Fig. 13. Cleaning scheduling at HE-10.

In the HE-10 with initial value U_c 640 (W/m^2 °C), U_f at 360 for fouled condition 139,191 (W/m^2 °C) and U_f and at 80% value was 512 (W/m^2 °C). The total of process cleaning 9 times in 360 days, U_f at day 35 value was 512,489 (W/m^2 °C) and year first process cleaning at day 36.

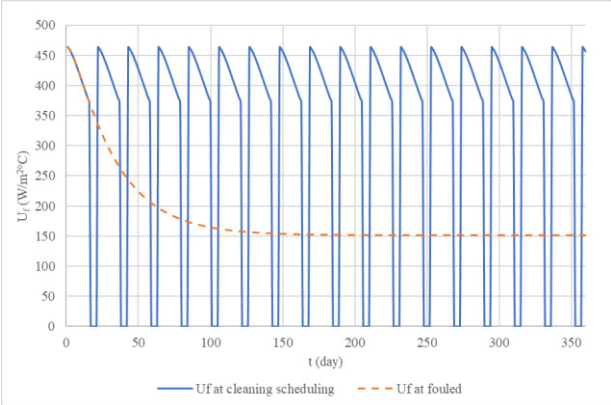

Fig. 14. Cleaning scheduling at HE-11.

In the HE-11 with initial value U_c 465 (W/m^2 °C), U_f at 360 for fouled condition 150,93 (W/m^2 °C) and U_f and at 80% value was 372 (W/m^2 °C). The total of process cleaning 17 times in 360 days, U_f at day 16 value was 372,154 (W/m^2 ^{o}C) and first process cleaning at day 17.

7 Conclusions

Scheduling for cleaning is required by looking at the decrease of U over time especially when the value of B is high enough that U will decrease very fast. Smaller values of B is then required when heat exchangers are kept in operation. In other words, infrequent cleaning operation can be implemented. Process cleaning scheduling by decrease Uc at value 80% can be implemented and give result process cleaning frequently.

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References

1. T. R. Biyanto, H.Y. Fibrianto, M. Ramasamy, J. App. Therm. Eng. **108**, 1436-1450 (2016).
2. R. Tellez and B. Young, *Heat Exchanger Network Optimization and Controllability Using Design Reliability Theory*, (Proceedings of the Canadian Design Engineering Network Conference, McGill University, Montreal, Quebec. 2004).
3. S. Kakaç, H. Liu, *Heat Exchangers: Selection, Rating, and Thermal Design* (CRC Press, Boca Raton, FL, 1998).
4. Z. Jin., X. Chen, Q. Dong. and M. Liu, J. Het. Trans. As. Resch., **41**, 33–42 (2012).
5. R. Smith, *Chemical Process Design and Integration* (John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, 2005).
6. D. Licindo, R. Handogo, and J.P. Sutikno, J. Chem. Eng. Trans., **45**, 835–840 (2015).