# Crude Oil Fouling Mitigation by Products Thermal Management in Heat Exchangers

**Ogboo Chikere Aja, Reuben Brandon Huan Chung Lee and Saw Chun Lin**

**Abstract** The management and maintenance of process plants involves huge amount of money. In the maintaining the heat exchangers, fouling effect has been identified as one of the major cost which also contribute to loss of production when the exchanger is out of service. This is applicable in the oil and gas industries which involves fouling of crude preheat train as a result of asphaltene precipitation and other fouling factors. The rate of fouling in the preheat train has been identified to be a function of temperature difference in the heat exchanger between the thermal source and the crude flow. This study focus on reducing the rate of fouling by varying the flow rate of the high temperature products through the heat exchangers in order to mitigate the fouling rate of occurrence. The study was conducted using MATLAB SIMULINK. The crude preheat train of four heat exchanges network was modeled in SIMULINK. The model was simulated under various flow rates and temperatures. The results showed that at fixed products mass flow rate of 2 kg/s with flow velocity of 0.06 m/s while the crude inlet temperature were varied from 303 to 312 K, the rate of fouling drops with increase in inlet temperature. A consideration of constant crude inlet temperature of 303 K with varied mass flow rate of the products from 1.6 kg/s in the increment of 0.2 to 2.4 kg/s showed that the rate of fouling dropped most at lower product mass flow rate. The simulation is done over a period of 10,000 min. The fouling factor that is obtained from the simulation period is lower than the actual result. The average fouling factor for the crude oil through the heat exchanger network is approximately 0.003.

**Keywords** Crude oil fouling · Crude preheat train · Fouling factor

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## 1 Introduction

Fouling in the crude preheat train is caused by the inverse precipitation of asphaltene at varying temperatures [1]. Fouling as a result of precipitation of asphaltene affects the energy required to heat the fluid as well as create pressure build-up along the crude flow line as a result of the deposits in the internal surface of the tube [2]. This is a major challenge in the refining industry as it reduces the production rate thus, increase cost and time for maintenance.

In a shell and tube heat exchanger where two fluids of varying thermo-physical properties and temperatures are transported with the aim of heat recovery, the variation in their temperature results in fouling as in the case of crude oil at low temperature and refined products at high temperature leading to asphaltene precipitation in the crude oil [3]. The greater the temperature difference the lower the solvating power of crude, which increases the precipitation of asphaltene. With the precipitation of fouling in a heat exchanger tube, the pressure increases, thus requiring high pumping power which then lead to increase in cost of production as well as loss of production. On cost consideration, fouling effect lead to loss of USD 15 Billion in the USA and USD 2.5 Billion in the UK on mitigation and maintenance of preheat trains [4].

A significant amount on research have been done on fouling mitigation in crude preheat train that is mainly focused on the use of chemicals to reduce the precipitation effect of asphaltene in crude transport tube. At high temperature difference between the channel carrying the hot fluid and the channel carrying the low temperature crude, the chemical for asphaltene precipitation mitigation tends to be ineffective. Temperature difference between the crude transport tube section and the product transport shell section has been identified as a major factor causing fouling [5, 6] but the management has not been proposed. Thus, this study investigated the management of the temperature difference and the rate of fouling by mass flow rate control and temperature variations at the different heat exchangers. The mass flow rate will also play an important part for the efficiency of the heat exchanger. So, with the suitable temperature range, the flow process and the thermal field can be analyzed to obtain suitable mass flow rate range to increase the efficiency of the heat exchanger thus develop an optimized model for the heat exchanger network (HEN).

The main objective of the research is to stimulate the flow integration between the cold fluid, crude oil and hot fluid, product to reduce the temperature difference ($\Delta T$) with an aim to mitigate fouling in the heat exchanger. Besides, the research is to investigate the impact of mass flow rate ($\dot{m}$) of the product (shell side) of the heat exchanger to mitigate fouling. Thus a model of the preheat train heat exchanger is modelled to control the temperature difference and enhance the production efficiency with the identification of the fouling factor at different inlet temperature of the crude oil and the different mass flow rate of the product that is flowing through the shell side of the heat exchanger.

## 2 Methodology

Figure 1 indicates the overall heat exchanger network. The heat exchanger network consists of 4 different heat exchanger block. Each heat exchanger will have different product with different properties and temperature flowing through it. The mass flow rate of the crude oil is set to be 1 kg/s throughout the entire simulation. It is also important to bear in mind that the output temperature of the first heat exchanger will be the input temperature of the second heat exchanger and so forth. With the energy equation, the heat flux for the crude oil and the product is equal as shown in Eq. 1.

$$\dot{Q}_{Crude} = \dot{Q}_{product}$$
$$\dot{m}_{Crude} * C_{P\,crude} * \Delta T_{Crude} = \dot{m}_{product} * C_{P\,Product} * \Delta T_{product} \tag{1}$$

The overall heat transfer coefficient multiply the total fluid area (*UA*) value for each individual heat exchanger can be calculated by using its total thermal resistance ($R_{total}$). The total resistance equation for the heat exchanger is shown in Eq. 2.

$$R_{total} = \frac{1}{h_{crude} 2\pi r_{in} L} + \frac{\ln\left(\frac{r_{out}}{r_{in}}\right)}{2\pi k_{tube} L} + \frac{1}{h_{product} 2\pi r_{out} L} \tag{2}$$

After the total resistance is found, the total number of tubes is divided with the total resistance to obtain the *UA* value as shown in Eq. 3.

$$UA = \frac{n}{R_{total}} \tag{3}$$

From Eq. 2, there is an unknown value for the convective heat transfer, *h*. We assume that the flow of the fluid is fully developed and is in laminar flow, we can easily determine the convective heat transfer value with the Eq. 4.

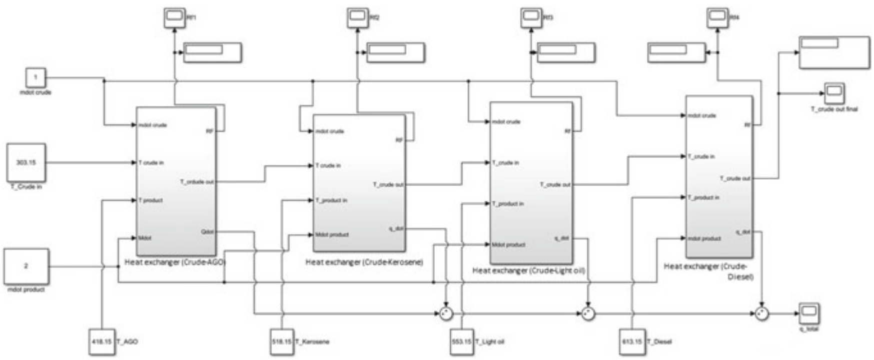


**Fig. 1** Heat exchanger network

$$h_c = \frac{Nu.K}{D} \tag{4}$$

where, $Nu$ = Nusselt Number, $K$ = thermal conductivity of different fluid and $D$ is the characteristic length (in our case the diameter).

In addition, to obtain the heat flux of the system, the E-NTU method is applied, Eq. 5.

$$\dot{Q}_{product} = \in C_{min}\left(T_{product} - T_{crudeoil}\right) \tag{5}$$

where, $(\dot{m}_{product}) * (C_{P\,Product})$ and $(\dot{m}_{crude}) * (C_{P\,crude})$ whichever product with the lesser amount will be the $C = C_{min}$ and the maximum will be the $C_{max}$.

The effectiveness of the heat exchanger, $\epsilon$ can be calculated with Eq. 6 and is being insert back to Eq. 5 to obtain the heat flow.

$$\epsilon = \frac{1 - \exp(-NTU(1 - C_r))}{1 - C_r * \exp(-NTU(1 - C_r))} \tag{6}$$

where, $C_r = \frac{C_{min}}{C_{max}}$ while $NTU = \frac{UA}{C_{min}}$.

The SIMULINK diagram of the heat flow governed by Eq. 5 is shown in Fig. 2.

Once the heat flow is found, it is now possible to determine the output temperature of the crude oil through a heat exchanger with the energy equation. The standard heat energy equation from Eq. 1 is modified to calculate the output temperature with respect to time as shown in Eq. 7.

$$\int_0^{t_f}\left[(T_i - T_o)_{crude} * \dot{m}_{crude} * \left(C_{p\,crude}\right) + \dot{Q}_{product}\right] * [W_{Crude} * UA]dt = T_o(t) \tag{7}$$

where, $t_f = final\,time\,(minutes)$, $W_{Crude}$ = mass of crude = $\rho_{crude} * Volume\,of\,crude$.

The SIMULINK model of the energy balance which is defined by Eq. 7 is shown in Fig. 3.

However, to determine the fouling factor (Rf), it would require the temperature difference of the crude and the heat flow ($\dot{Q}$). Equation 8 is used to determine the fouling factor.

$$R_f = \frac{1}{U(t)A} - \frac{1}{U(0)A} \tag{8}$$

where, $(t)A = \frac{\Delta T_{Crude}}{\dot{Q}}$.

$U(t)A$ is the overall heat transfer at a particular time multiply the Area of heat transfer. Thus when $U(0)A$ is at the initial time of $t = 0$. In other term, the term $\frac{1}{U(t)A}$ simply means when the heat exchanger is dirty and when $\frac{1}{U(0)A}$ signifies the heat exchanger is clean. The SIMULINK model that prescribes Eq. 8 is shown in Fig. 4.

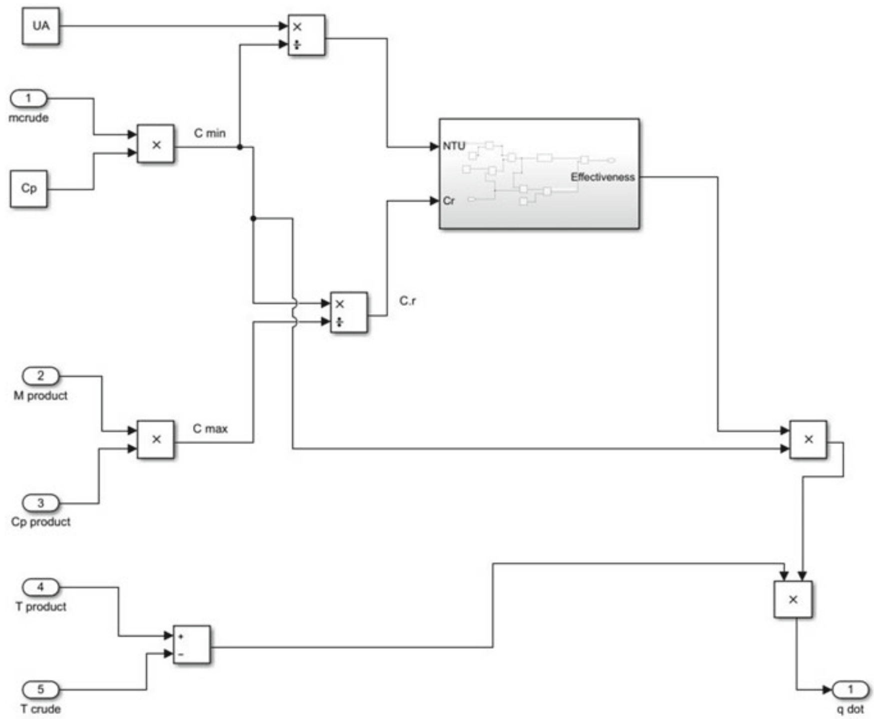


**Fig. 2** Thermal energy flow field

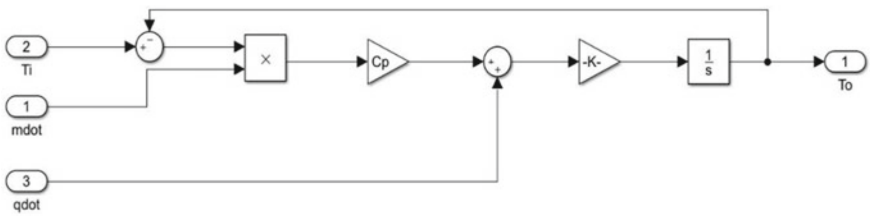


**Fig. 3** Energy balance

## 3 Results and Discussions

The results are presented with respect to the temperature effects and the effect of mass flow rates on the rate of fouling in the preheat train.

(a) Exit Crude Temperature Gradients Considering Inlet Crude Temperature of 303.15 K

The first simulation was done with the inlet temperature of 303.15 K and the mass flow rate of 2 kg/s. In Fig. 5, it indicates the final temperature of the crude when it

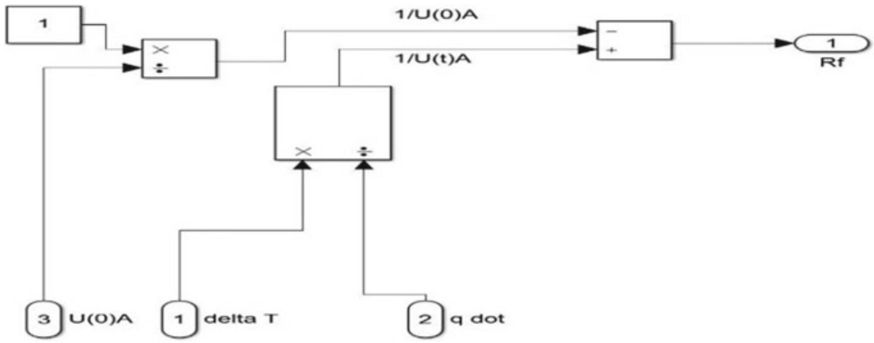


**Fig. 4** Fouling factor

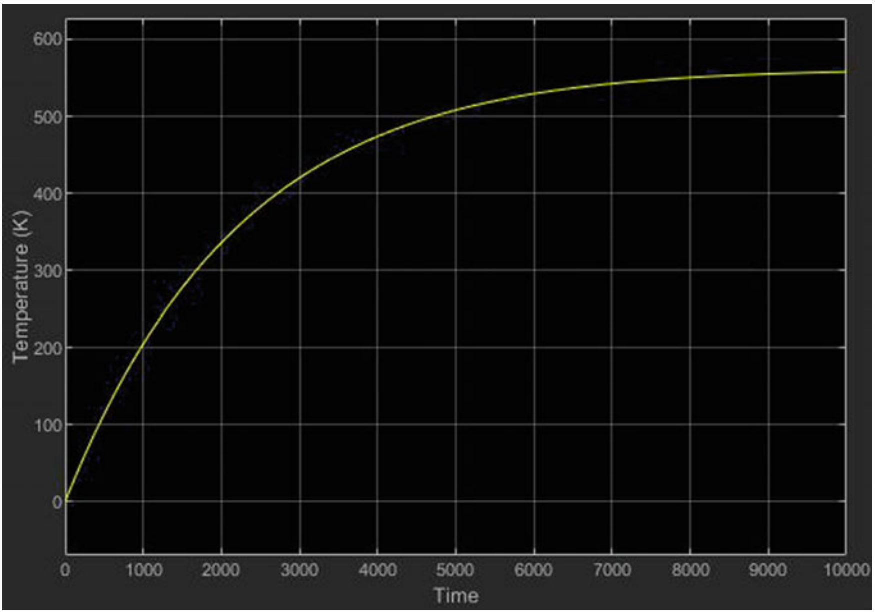


**Fig. 5** Crude oil final outlet temperature

passes through all four heat exchanger in the heat exchanger network with the output temperature of 557.78 K. It increases drastically with time until it reaches 5000 min (83.33 h). The gradient of the curve before 5000 min is approximately 0.1. After 5000 min, the gradient of the curve is approximately 0.01. This indicates that the crude oil temperature is increasing lesser as compared to the first 5000 min as the crude tends to be thermally saturated.

In addition, Fig. 6, shows the total heat flow through the four heat exchangers. It can be seen that the heat flow is decreasing over time. For the first 5000 min, the

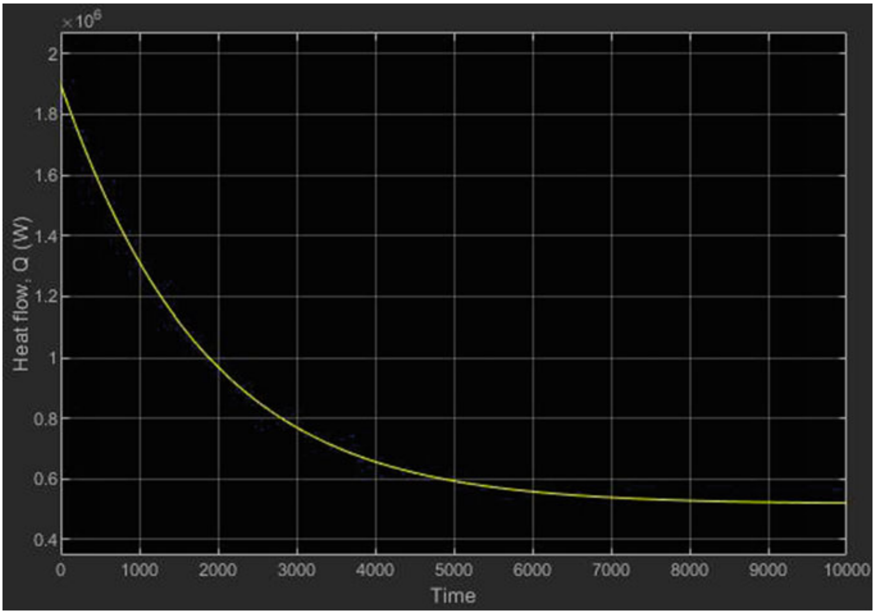


**Fig. 6** Total heat flow

heat flow decreases drastically with a gradient of −261.14. This means that a large amount of heat exchange is happening for the first 5000 min. However, for the last 5000 min the gradient of the graph is −14.61. As compared to the first 5000 min, the final 5000 min have lesser heat transfer.

Figures 5 and 6 are correlated. As the temperature gradient is smaller, this indicates that the heat flow is slower and thus the heat energy in both liquids is almost equilibrium. After 5000 min, the temperature gradient is approximately 0.01 and the heat transfer gradient is −14.61 which both parameter's gradient is lesser than the first 5000 min. However, the fouling factor of each individual heat exchanger is shown in Fig. 7. It can be seen that the heat exchanger with the product Automotive Gas Oil (AGO) will undergo fouling first at approximately 2933 min. It would take until 6933 min until the Rf value reaches 0.000292. The Rf value will continue to rise till it reaches 0.000306 at approximately 9682 min. For the Rf of kerosene, the starting point would be close to the Rf of AGO. The final Rf after a series of time would also be close to the Rf of the AGO. The only difference between the two graph is the initial steepness of the graph. This is because the temperature difference for kerosene is smaller than the temperature difference in AGO. This also applies to the Rf of the light oil and the Rf of diesel. Both Rf begins at almost the same time but portraying different graph. This is also caused by the light oil heat exchanger have higher temperature difference of the crude inlet and the outlet as compared to the diesel heat exchanger.

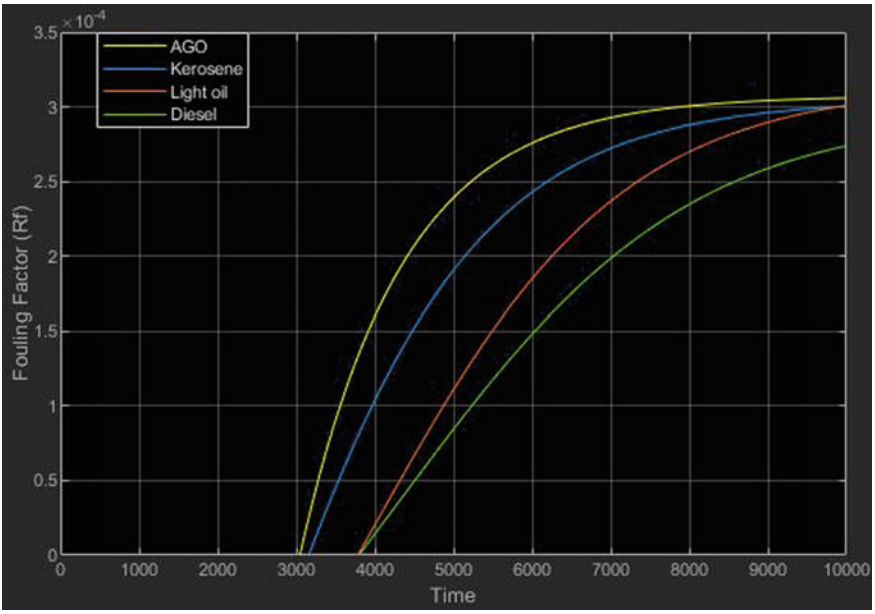


**Fig. 7** Graph of fouling factor (Rf) against time

(b) Varying Mass Flow Rate of Products to 1.6 kg/s

The simulation was conducted also to see the effect of mass flow rate variation of the products into the individual heat exchanger at 1.6 kg/s. The graph of the fouling rate against time were computed and reported as shown in Fig. 8. The fouling factor for the crude passing through the heat exchanger with AGO starts from 3212 min (53.5 h). It increases drastically with time until it reaches 8000 min. After 8000 min, the Rf value tends to be a constant value of 0.000306. The final Rf value for the heat exchanger with AGO, kerosene and light oil are very close to each other. The final Rf value for these three are 0.000306, 0.00029985 and 0.0002993. The only difference that is visible from these 3 Rf curve is the time it starts and the time for it to reach its maximum value. The heat exchanger with kerosene will start fouling at approximately 3362 min and for the heat exchanger with light oil, the fouling will start at 3993 min. For the heat exchanger with diesel, the graph is still increasing but with the simulation run time of 10,000 min, the final Rf value of the heat exchanger is 0.00027. The heat exchanger with diesel will start fouling at 4032 min.

(c) Varying Mass Flow Rate of Products to 1.8 kg/s

The simulation was run with the mass flow rate of the product into the heat exchanger of 1.8 kg/s and other variables are kept constant. The graph of the fouling factor against time is in Fig. 9. The fouling factor for the crude passing through the heat exchanger with AGO starts from 3212 min. It increases with time until it reaches 8000 min. After 8000 min, the Rf value tends to be a constant value of 0.000306. The

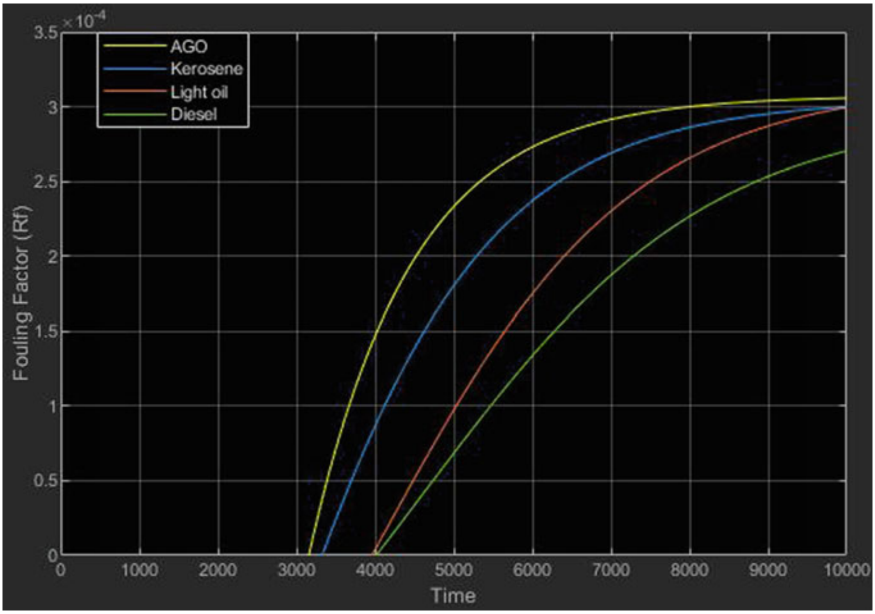


**Fig. 8** Graph of fouling factor against time for $\dot{m}_{product} = 1.6\,\text{kg/s}$

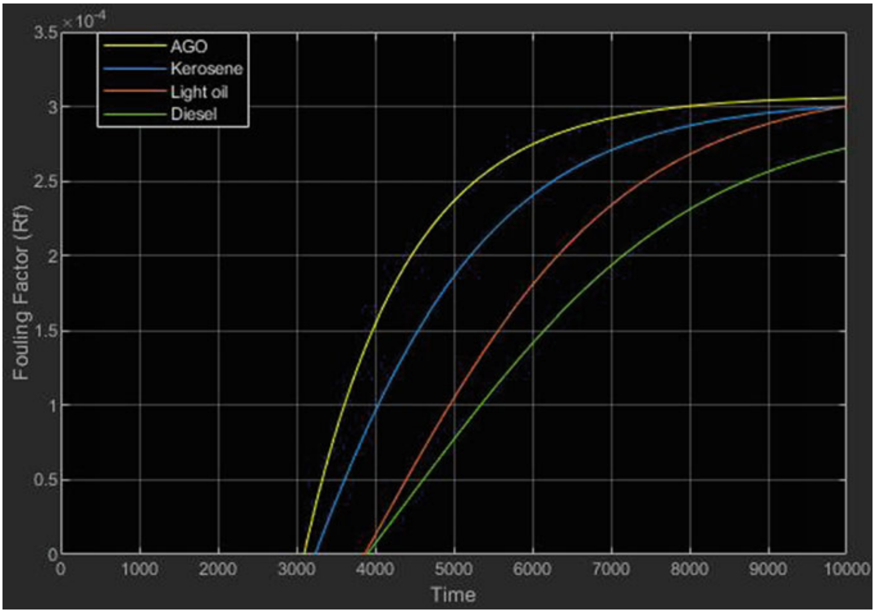


**Fig. 9** Graph of fouling factor against time for $\dot{m}_{product} = 1.8$ kg/s

final Rf value for the heat exchanger with AGO, kerosene and light oil are close to each other. The final Rf value for these three are 0.000306, 0.0003 and 0.0003. The only difference that is visible from these 3 Rf curve is the start time of the fouling that is 3212 min for AGO, 3272 min for kerosene and 3892 for Light oil. For the heat exchanger with diesel, the graph is still increasing but with the simulation run time of 10,000 min, the final Rf value of the heat exchanger is 0.000272. The heat exchanger with diesel will start fouling at 3912 min.

(d) Varying Mass Flow Rate of Products to 2.2 kg/s

The mass flow rate of the product is changed to 2.2 kg/s with all other variables remains unchanged. The graph of the fouling factor against time is shown in Fig. 10. For the heat exchanger with AGO flowing through, the fouling will start at 3062 min. It then increases till 7082 min and the Rf value slowly increases with time till it reaches its maximum of 0.000306. The maximum Rf value for heat exchanger with kerosene and heat exchanger with light oil is slightly lower than AGO but both the Rf values are the same. The maximum Rf value of kerosene and light oil is 0.000301. The time for fouling to occur for kerosene is 3122 min and for light oil is 3742 min. However, for the heat exchanger with diesel as the product, the fouling would start at 3732 min and would have a maximum of 0.000275.

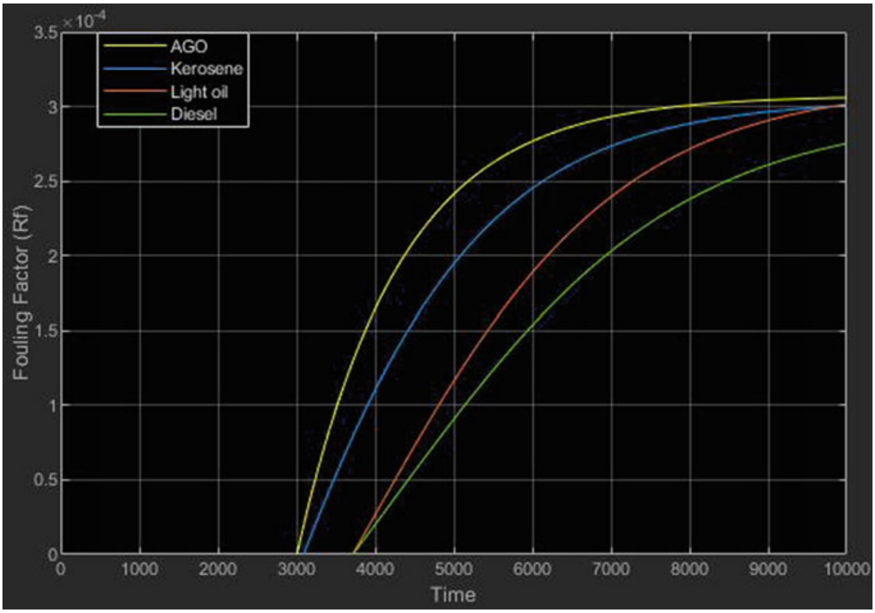


**Fig. 10** Graph of fouling factor against time for $\dot{m}_{product} = 2.2\,\text{kg/s}$

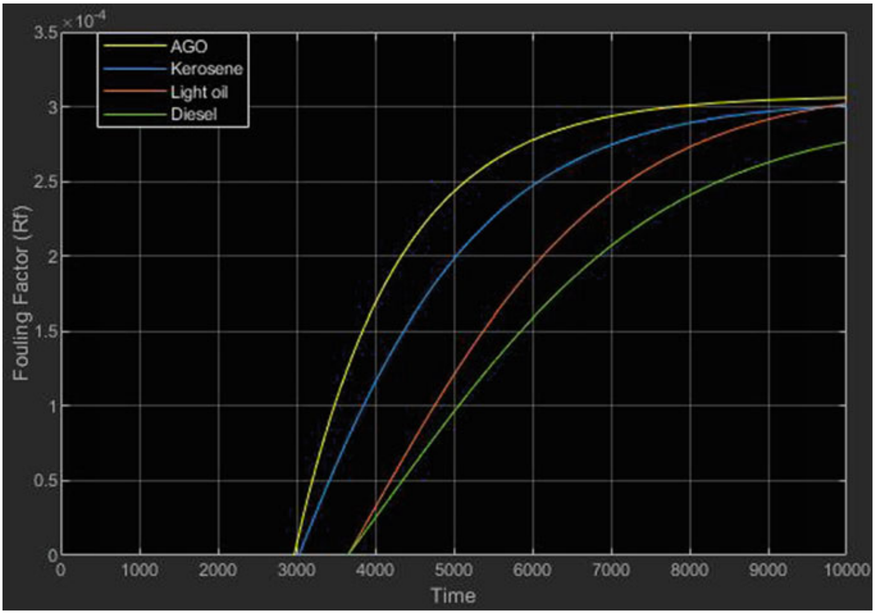


**Fig. 11** Graph of fouling factor against time for $\dot{m}_{product} = 2.4\,\text{kg/s}$

(e) Varying Mass Flow Rate of Products to 2.4 kg/s

The mass flow rate of the product is set to 2.4 kg/s and all other variables remain a constant. The graph of the fouling factor against time is shown in Fig. 11. For the heat exchanger with AGO flowing through, the fouling will start at 3032 min. It then increases until approximately 7500 min and the Rf value slowly increases with time till it reaches its maximum of 0.000306. The maximum Rf value for kerosene and light oil is slightly lower than AGO but both the Rf values are the close to each other. The maximum Rf value of the heat exchanger with kerosene 0.000301 and for the heat exchanger with light oil 0.000302. The time for fouling to occur for kerosene is 3062 min and for light oil is 3682 min. However, for the heat exchanger with diesel as the product, the fouling would start at 3662 min and would have a maximum of 0.000276.

## 4 Conclusions

This research indicates that fouling crude oil in the heat exchanger at the inlet temperature of 303.15 K will start at 3052 min. It will then increase with time until the maximum fouling factor for the entire heat exchanger network to be 0.000306. This will also give an output temperature of 577.78 K while maintaining at a very low fouling factor. The increase in the inlet temperature of the crude will cause the fouling factor to reduce and also the time for fouling to start will be slower. This is because the temperature between the crude and the product in which flows through the heat exchanger will be smaller. The mass flow rate of the product supplying heat to the crude also plays a very important role. As the mass flow rate of the product increases, the fouling factor increases. This is because the temperature of the product does not change much as the mass flow rate increases. The products are run through the heat exchanger faster causing the temperature of the product in the heat exchanger to be a constant. This will intern increase the temperature difference in the heat exchanger to be higher and thus increase the fouling factor. It is also noticeable that the time for fouling to occur at a lower mass flow rate of the product is slower as compared to the higher mass flow rate. Further research on crude oil fouling with respect to temperature and mass flow rate must be done by taking into consideration other factors and other different type of heat exchanger that is use in the industry.

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