

Mathematical Modelling and Simulation of Fouling of Nigerian Crude Oil Equipment Installations

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Abstract

The aim of this research work was to develop Mathematical Model to Predict the Fouling of Nigeria Oil Equipment Installation. The term fouling can be defined as the deposition of unwanted material on heat transfer equipment, which results in an increase in thermal resistance to heat transfer and subsequent loss of equipment thermal efficiency. The modelling equation formulated was based on the principle of fouling process being in unsteady state condition. That is, the rate of deposition is not equal to the rate of removal. In other words, there is an accumulation. The final mathematical model developed representing the fouling of Nigeria Oil equipment was

obtained as:
$$\frac{d}{dt}R_f = C_1C_2 \exp\left(\frac{-E}{R_g T_s}\right) (C_r)^r - \frac{C_3 \cdot C_4}{\rho_f \cdot R_b} \left(\frac{W}{A_0}\right)^2$$
. The correlation

between the experimental and simulated result obtained using Average Absolute Deviation (A.A.D) was between 0.0131 - 0.0201. The fluid temperature of 43°C and 63°C and wire temperature 200°C, 250°C and 300°C were the operating conditions for the investigation and prediction. The model was simulated using VISUAL BASIC 6.0 to predict the fouling behaviour. The results obtained showed that refinery Naptha fouls very heavily and this fouling decreases with increasing fluid and wire temperature. Fouling was very severe for wire temperature 200°C and fluid temperature 46°C. The main mechanism of fouling for refinery Naptha was chemical polymerization.

Keywords

Fouling rate, Mathematical model, Visual Basic Programme, Crude oil, Average Absolute Deviation, Fluid Temperature, Wire Temperature

Introduction

The term fouling is defined as the deposition of unwanted material on heat transfer equipment, which results in an increase in thermal resistance to heat transfer and subsequent loss of equipment thermal efficiency. [Bott, 1995]. This deposition includes organic reaction products, high molecular weight process stream components, coke and inorganic salts, involving the transfer of heat either from a fluid to the solid or vice versa.

Crude oil fouling is generally believed to be caused by impurities present in the crude oil such as corrosion product (iron sulphide and rust), water and salt [sodium chloride, calcium chloride and magnesium chloride] by asphaltenes exceeding their solubility limits, or by thermal decomposition or autoxidation of reactive constituents in the oil. Asphaltene precipitation is considered to be a major cause of crude unit fouling [Murphy and Campbell, 1992].

At the same time, reactive constituents in oil may undergo thermal decomposition, polymerization, or autoxidation reaction to produce fouling precursors.

Dickakian (1997) has shown the role of asphaltenes and polar molecules in fouling at elevated temperature where coke is produced following phase separation. At lower temperatures, asphaltene precipitation occurs due to changes in solvent nature via blending or pressure change.

Fouling leads to reduced heat transfer, increased pressure drop, blocked process pipes, and these effects are costly. The cost factors include higher heat exchanger requirements, increased fuel consumption, reduced throughput and increased maintenance. In addition to the operational losses, fouling forces significant capital expenditure, so fouling factors are taken into consideration.

Fouling phenomenon can also be experienced in gas-solid processes, such as deposition of carbonaceous particles, oil and incombustibles on the exhaust pipes of automobiles, fuel-powered engines and chimneys. Liquid-solid fouling also is found in

obnoxious particle deposition in process flow lines, public water supply pipes, and the fouling of domestic cooking. Fouling on utensils e.g kettles, make fouling a menace not only to the petroleum industry but also at home pots and pans had been a domestic nuisance which at times need such drastic measure like scrapping off the deposit with knife edges.

Mathematical modelling is a comprehensive method of representing a physical phenomenon, in terms of mathematical equation while computer simulation is the use of computer to generate solution to a problem or the behaviour of a system. [Meyer, 1992]. The utilization of basic laws of physics and chemistry are used to describe mathematically the operations of a reactor. The mathematical model developed, generally consist of a set of differential equations that are frequent too complex, that they become impossible to solve by analytical methods. However, the solution of the mathematical model derived, can often be accomplished by simulation of the model with an analogue or a digital computer. The success of the approach is governed not only by the completeness and reliability of the mathematical model but also by the amount and accuracy of the basic experimental data [Perry and green 1997]. The objective of this paper is to develop a model equation to predict fouling rate of Nigerian crude oil equipment installations. The fouling characteristics of oil equipment installation are influenced by such fouling factor as rate of fouling, effect of certain process variable such as flow rate, temperature of bulk and surface, oxygen concentrations on the rate or degree of fouling. This process variable will be incorporated in the development of the final model.

Experimental Procedure

All the bolts, elbows and seals were checked for any leaking points. The 2.5 gallon tank was filled with Naphtha fluid heated up by an immersion heater. The fluid temperature in the tank was measured by mercury in glass thermometer. The fluid was pumped via a back-mix with value V_2 and V_4 closed while V_1 and V_3 were opened as obvious from figure 1. This was allowed to operate for 20 minutes while at the same time adjusting the cooling water valve to ensure that a constant temperature desired was achieved in the tank. When the temperature is fairly constant indicated by the thermometer reading valve V_3 was shut while valve V_2 and V_4

were opened. The variance switch was put on and adjusted to the current that gives the desired wire temperature.

The fluctuation in the wire resistance was basically due to move touching the pipe. This was being read corresponded to that which gave the same power dissipated. This was achieved by measuring the wire resistance from (V/I) and evaluating the power (I^2R) to see whether it is within the operating power range, the system was allowed to equilibrate to steady state by allowing 15 minutes to elapse prior commencement of measurement. After 15 minutes, the inlet and outlet potentiometer reading was taken.

The manometer and gauge reading were noted. The ambient temperature was also taken. Subsequent readings were taken after one hour voltage reading was checked at interval for any fluctuations. Stirring was done manually and the fluid temperature was basically controlled by the cooling water into the heat exchanger and intermittently switching on and off of the immersion heater.

Conceptualization of Modelling Technique -DIAGRAM

Taking for instance that there is a channel (pipe) through which oil is flowing, assuming that the inner part of the pipe is open as shown in figure 1 below, the fouling process that takes in the pipe can be depicted as given below.

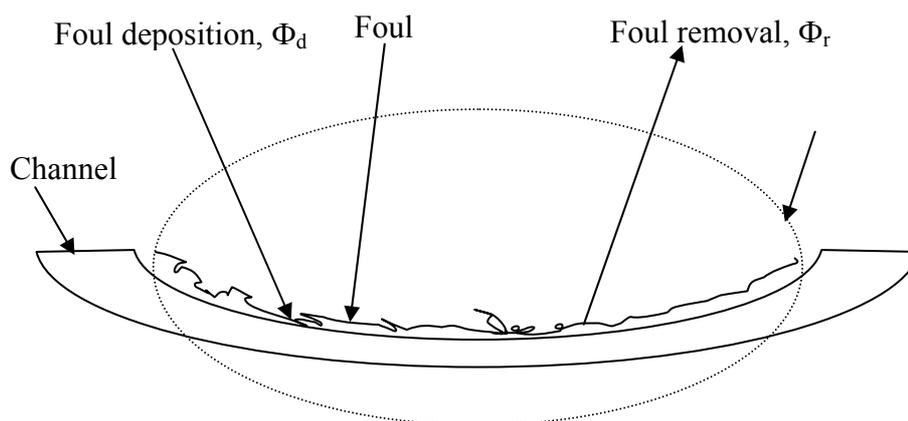


Figure 1. Schematic representation of fouling process

Assumptions

In the course of modelling of the fouling characteristics of Nigerian crude oils, the assumptions made include:

- (i) The fouling process is an unsteady one. That is, the rate of deposition is not equal to the rate of removal. In other words, there is accumulation.
- (ii) The deposition is reaction rate controlled.
- (iii) The flow rate of the liquid (crude oil) is constant.

Model formulation

Starting from the basic principle of mass balances which states that

$$\text{Input} = \text{Output} + \text{Accumulation} \quad (1)$$

That is, Rate of deposition = rate of removal + foul accumulation

Mathematically:

$$\text{Rate of deposition} = d$$

$$\text{Rate of removal} = r$$

Foul accumulation is given as the rate of change of foul and is denoted, mathematically, as

Considering equation 1 (Rate of deposition = Rate of removal + Foul accumulation rate), substituting the various terms yields:

$$\phi_d = \phi_r + \frac{d}{dt} R_f \quad (2)$$

Making the accumulation term the subject of the formula gives:

$$\frac{d}{dt} R_f = \phi_d - \phi_r \quad (3)$$

Taborek *et al* (1972), from their numerous observations, found out that some typical behaviour patterns can be rationalized. In principle, the net fouling rate of crude oil can be expressed as the difference between a deposition and a removal rate equation described by the mathematical relation given below as:

$$\frac{d}{dt} R_f = \phi_d - \phi_r \quad (4)$$

where R_f is the net fouling rate, ϕ_d is the rate of deposition, and ϕ_r is the rate of removal.

Using the reaction controlled deposition, according to assumption No. 2, Taborek *et al* (1972) has proposed that:

$$\phi_d = C_1 R_1 (C_r)^r \quad (5)$$

where C_r is the concentration of the material undergoing the reaction, r is the reaction order

R_r is the reaction rate constant defined as (Rectfer, 1964):

$$R_r = C_2 \cdot e^{[-E/(R_g T_g)]} \quad (6)$$

where C_2 is the proportionality constant, E is the activation energy, and R_g is the universal gas constant.

It should be noted that the exponential temperature relationship of this type of deposition mechanism requires careful attention to the effect of design wall temperatures on deposition rates and eventually maintenance costs.

Substituting the relationship of the R_r into the equation of Φ_d gives:

$$\phi_d = C_1 \cdot \left[C_2 \cdot e^{\left(\frac{-E}{R_g T_g}\right)} \right] \cdot (Cr)^r \quad (7)$$

Further, the rate of removal is given as:

$$\phi_r = C_3 \frac{\tau_s}{R_b} \quad (8)$$

where τ_s and R_b are the fluid shear and deposition bond resistance respectively, and C_3 is a constant.

In addition, τ_s is given as (Brawn & Hansler, 1976):

$$\tau_s = C_4 \frac{1}{\rho_f} \left(\frac{W}{A_o} \right)^2 \quad (9)$$

It should be noted that C_4 is also a constant. Now, substituting equation (9) into (8)

$$\phi_r = C_3 \frac{C_4 \frac{1}{\rho_f} \left(\frac{W}{A_o} \right)^2}{R_b} \quad (10)$$

which is the same as:

$$\phi_r = C_3 \frac{C_4 \left(\frac{W}{A_o} \right)^2}{\rho_f R_b} \quad (11)$$

where W is the flow rate of liquid which is constant (according to assumption No. 3), A_o is the cross sectional area of the flow of the crude, and ρ_f is the density of the crude oil.

Now, the net fouling rate which was originally given as:

$$\frac{d}{dt} R_f = \phi_d - \phi_r \quad (12)$$

can now be written as, after substituting the relationships of Φ_d and Φ_r :

$$\frac{d}{dt}R_f = C_1 \cdot \left[C_2 \cdot e^{\left(\frac{-E}{R_g T_g}\right)} \right] \cdot (C_r)^r - C_3 \frac{C_4 \left(\frac{W}{A_o}\right)^2}{\rho_f R_b} \quad (13)$$

In other words,

$$\frac{d}{dt}R_f = C_1 \cdot C_2 \cdot e^{\left(\frac{-E}{R_g T_g}\right)} \cdot (C_r)^r - \frac{C_3 C_4 \left(\frac{W}{A_o}\right)^2}{\rho_f R_b} \quad (14)$$

$$\frac{d}{dt}R_f = C_1 \cdot C_2 \cdot e^{\left(\frac{-E}{R_g T_g}\right)} \cdot (C_r)^r - \frac{C_3 C_4 \left(\frac{W}{A_o}\right)^2}{\rho_f R_b} \quad (15)$$

The equation above is the model for the fouling rate of Nigerian crude oils.

Results and Discussion

Experimental and simulated results obtained for the Run 1-5 modelling express as fouling rates for, errors and standard deviations according with the time are in table 1-5, and graphical represented in figures 2-5.

Table 1. Fouling Rates (cal/hr cm² °C) for Run 1

Time (hr)	Experimental	Simulated	Error	Std. Dev.
0	0.00	0.00	0.00	0.0000
1	33.27	33.26	0.01	0.0071
2	223.84	223.81	0.03	0.0212
3	44.38	44.39	-0.01	0.0071
4	95.55	95.55	0.00	0.0000
5	172.68	172.84	-0.16	0.1131
6	286.07	286.10	-0.03	0.0212
7	290.15	290.10	0.05	0.0354
8	442.77	442.79	-0.02	0.0141
9	712.95	712.96	-0.01	0.0071
10	1285.78	1285.76	0.02	0.0141
11	1226.41	1226.42	-0.01	0.0071
12	2774.12	2774.10	0.02	0.0141
Average Absolute Deviation =				0.0201

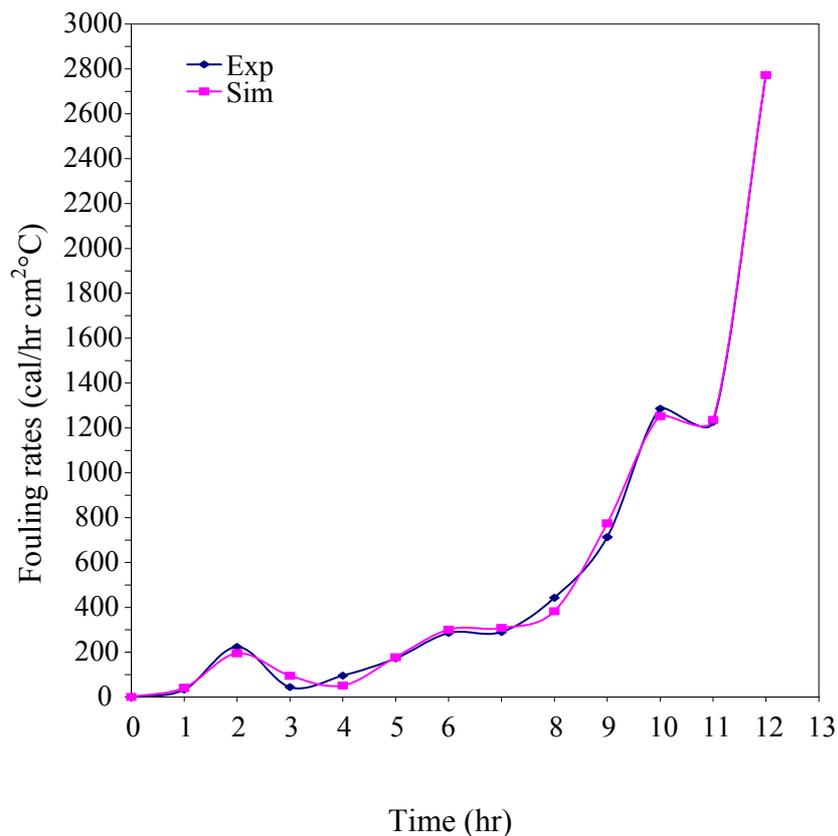


Figure 2. Graphs of experimental and simulated fouling rates for Run 1 using statistical method ($T_{FL} = 46^{\circ}\text{C}$, $T_w = 200^{\circ}\text{C}$)

Table 2. Fouling Rates (cal/hr cm² °C) for Run 2

Time (hr)	Experimental	Simulated	Error	Std. Dev.
0	0.00	0.00	0.00	0.0000
1	0.00	0.00	0.00	0.0000
2	0.00	0.01	-0.01	0.0071
3	2.59	2.57	0.02	0.0141
4	32.40	32.41	-0.01	0.0071
5	42.21	42.23	-0.02	0.0141
6	89.44	89.42	0.02	0.0141
7	151.81	151.84	-0.03	0.0212
8	241.40	241.38	0.02	0.0141
9	358.41	358.31	0.10	0.0707
10	89.44	89.46	-0.02	0.0141
11	531.85	531.89	-0.04	0.0283
12	1131.53	1131.55	-0.02	0.0141
Average Absolute Deviation =				0.0169

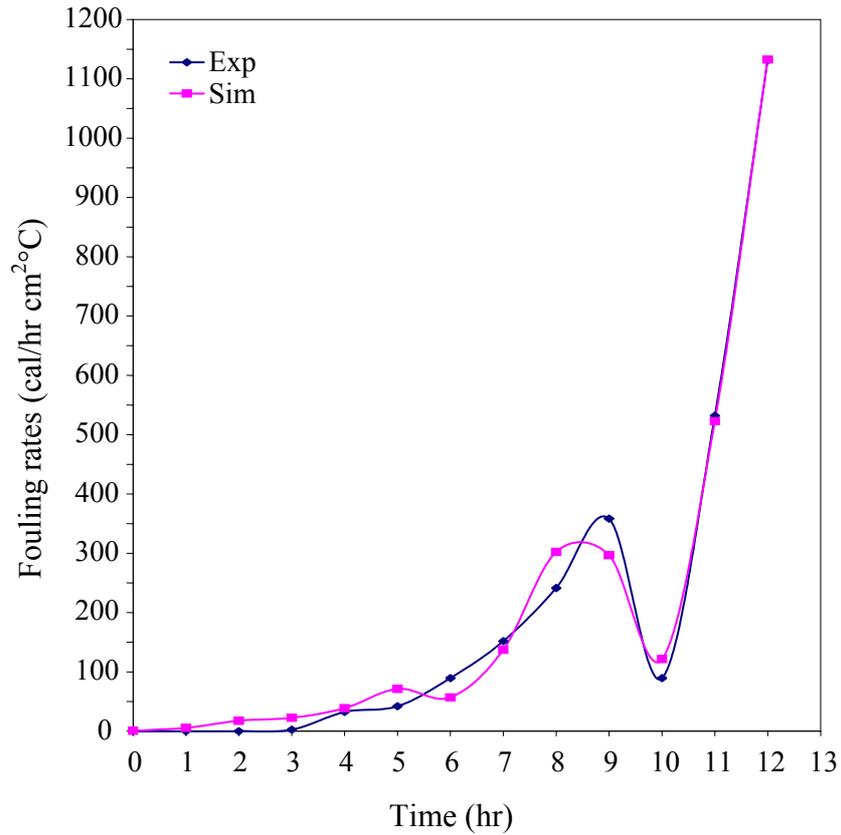


Figure 3. Graphs of experimental and simulated fouling rates for Run 2 using statistical method ($T_{FL} = 46^{\circ}\text{C}$, $T_w = 250^{\circ}\text{C}$)

Table 3. Fouling Rates ($\text{cal/hr cm}^2 \text{ }^{\circ}\text{C}$) for Run 3

Time (hr)	Experimental	Simulated	Error	Std. Dev.
0	0.00	0.00	0.00	0.0000
1	2.55	2.54	0.01	0.0071
2	0.00	0.02	-0.02	0.0141
3	34.75	34.79	-0.04	0.0283
4	34.75	34.74	0.01	0.0071
5	53.96	53.94	0.02	0.0141
6	73.31	73.29	0.02	0.0141
7	77.03	77.05	-0.02	0.0141
8	71.48	71.47	0.01	0.0071
9	120.32	120.34	-0.02	0.0141
10	178.89	178.91	-0.02	0.0141
11	353.35	353.32	0.03	0.0212
12	506.20	506.18	0.02	0.0141
Average Absolute Deviation =				0.0131

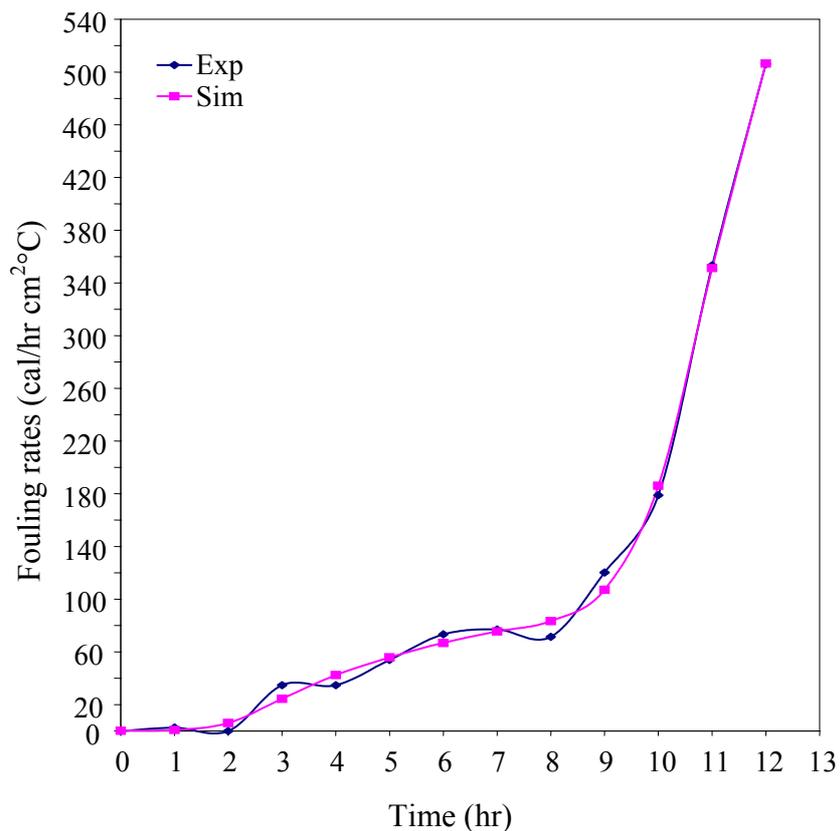


Figure 4. Graphs of experimental and simulated fouling rates for Run 3 using statistical method ($T_{FL} = 46^{\circ}\text{C}$, $T_w = 300^{\circ}\text{C}$)

Table 4. Fouling Rates (cal/hr cm² °C) for Run 4

Time (hr)	Experimental	Simulated	Error	Std. Dev.
0	0.00	0.00	0.00	0.0000
1	3.87	3.86	0.01	0.0071
2	9.16	9.16	0.00	0.0000
3	57.80	57.78	0.02	0.0141
4	27.47	27.46	0.01	0.0071
5	14.60	14.60	0.00	0.0000
6	47.72	47.77	-0.05	0.0354
7	70.21	70.17	0.04	0.0283
8	142.86	142.83	0.03	0.0212
9	145.37	145.38	-0.01	0.0071
10	271.79	271.80	-0.01	0.0071
11	275.77	275.74	0.03	0.0212
12	490.31	490.36	-0.05	0.0354
Average Absolute Deviation =				0.0141

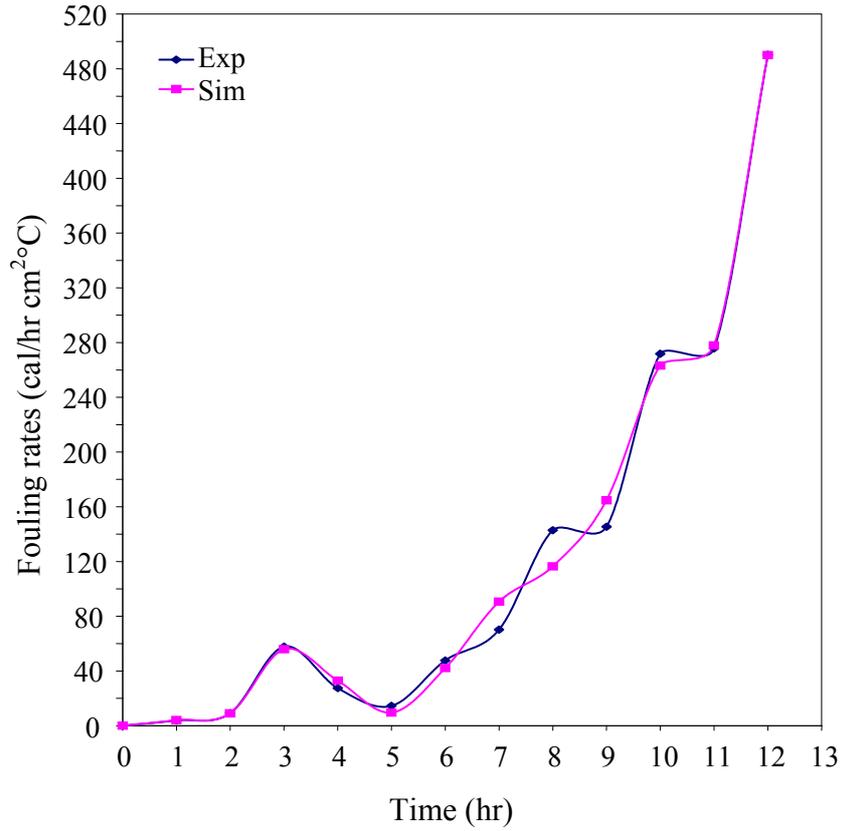


Figure 5. Graphs of experimental and simulated fouling rates for Run 4 using statistical method ($T_{FL} = 63^{\circ}\text{C}$ $T_w = 200^{\circ}\text{C}$)

Table 5. Fouling Rates (cal/hr cm² °C) for Run 5

Time (hr)	Experimental	Simulated	Error	Std. Dev.
0	0.00	0.00	0.00	0.0000
1	0.00	0.00	0.00	0.0000
2	39.94	39.91	0.03	0.0212
3	1.44	1.45	-0.01	0.0071
4	2.91	2.93	-0.02	0.0141
5	0.00	0.01	-0.01	0.0071
6	45.30	45.26	0.04	0.0283
7	41.71	41.72	-0.01	0.0071
8	107.58	107.56	0.02	0.0141
9	194.49	194.44	0.05	0.0354
10	194.49	194.51	-0.02	0.0141
11	309.43	309.45	-0.02	0.0141
12	309.43	309.44	-0.01	0.0071
Average Absolute Deviation =				0.0131

In the experimentations and simulation result, the Progressive decrease of heat transfer coefficient obviously, shows that fouling had taken place. This trend was not however, uniform, which is expected for chemical-polymerization of fouling of hydrocarbon streams.

This reveals that other mechanisms of fouling superimposed on chemical polymerization fouling. Nevertheless chemical polymerization fouling was observed to take place by the gummy-brown colouration of Nichrome wire. A cross sectional looks in the tank and fluid stream shows chemical reaction taking place. This is obvious since the golden-oil colour of Naptha becomes milky at first which then turns rapidly brown. The lower heat transfer coefficient at the operating run of $T_w = 200^\circ\text{C}$ and $T_{FL} = 46^\circ\text{C}$ compared to subsequent runs of the same fluid but different wall or wire temperature after the 12th hours of run shows severe fouling at this condition. As the wire temperature increases for the same fluid temperature the heat transfer coefficient moves up.

In Figure 3 for wall temperature $T_w = 250^\circ\text{C}$ and $T_{FL} = 46^\circ\text{C}$ after 5 runs shows uniformly decreasing heat transfer coefficient with time, which indicate chemical polymerization fouling for this period. To achieve the same fouling as to when wire temperature was $T_w = 200^\circ\text{C}$ and $T_{FL} = 46^\circ\text{C}$ for higher wire temperature, more time must be allowed. Hence, the amount of fouling that can occur is only in a matter of time, irrespective of the operating condition to give the same problem.

The undulating and oscillatory trend of fouling rate with time for fluid temperature of 63°C obviously shows another fouling behaviour at this temperature which was shown in figure 4 and 5.

The fouling resistance R_f with time is highest for a wire temperature of 200°C and least for wire temperature 300°C after 12 hours. The fouling resistance for the 4hours period of run reveal a situation where the wire temperature is activated for fouling shown in Table 5. The wire temperature of 300°C plot of R_f with time shows creeping trend. Nonetheless the fouling resistance with time after the 4th hour shows a non-uniformly upward increasing tend revealing the unpredictable nature of fouling behaviour.

The induction period is more pronounced in the plot of $\Delta R_f/\Delta t$ with time. The plot from figure 4 shows that for wire temperature of 300°C , the rate of fouling gradually increase almost constantly for the 8 hours of run showing that the rate of fouling at this temperature has decreased.

However, the fouling rate behaviour at $T_w = 200^\circ\text{C}$ shows an unusual trend. The fouling rate decrease non-uniformly with time until after 7 hours of run, after which the fouling resistance rate increases uniformly with time and decreases again (figure 2). The overlapping nature of the curves of wire temperature at 200°C and 250°C (figure 2 and 3)

reveal complex fouling behaviour at this fluid temperature of 63°C. The deposition of particles on the wire was obvious after the end of the experiment. It was observed that the Nichrome wire was covered with fowl of brownish material.

Conclusions

The following conclusions can be made from the discussion and results:

1. The main mechanism of fouling operative in the system is chemical reaction polymerization super imposed with other fouling mechanism.
2. The fouling of refinery Naptha reveals a period of induction to activate the surface for chemical reaction.
3. The fouling is most severe with fluid temperature of 46°C and wire temperature 200°C (figure 5).
4. The fouling rate diminishes for wire temperature above 200°C.
5. At a fluid temperature of 63°C refinery Naptha fouls less and a different fouling behaviour is observed (Figure 2 and 3).
6. The overlapping nature of the curves for fluid temperature of 63°C and wire temperature of 200°C and 250°C for fouling rate with time shows a complex nature of fouling behaviour irrespective of which operating wire temperature (figure 2 and 3).

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