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Modeling and Analysis of Fouling Behaviour in Plate and Frame Heat Exchanger

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***Abstract*—** The fouling of heat exchangers in the oil and gas industry is not only a recurring challenge in refineries but it is also becoming a challenge in crude oil production and treatment facilities where heat exchangers are deployed to cool the crude oil temperature downstream of stabilization system prior to storage. A predictive mitigation approach to addressing fouling in heat exchangers remains the most viable option to avoid production train capacity limitations, unplanned shutdown and attendant loss of revenue. Considerable researches have been carried out which lead to the development of models used for predicting fouling resistances in shell and tube heat exchangers. However, this study focused on evaluation of the performance of a plate and frame heat exchanger utilized in cooling of crude oil prior to storage in a cargo tank for export. It also developed a fouling resistance suitable for forecasting the exchanger performance and predicting the maintenance management scheme. The data employed were continuously measured for three years and employed for the analysis. It found that the lower the hot stream approach temperature, the more the fouling resistance. In addition, the work validates that as the fouling resistance increases with time, the efficiency of the plate and frame heat exchanger diminishes.

Keywords: Fouling Models, Fouling Resistance, Energy System, Heat Exchanger, Scaling

I. Introduction

Heat exchangers are important process equipment utilized in nearly all industries and play key role in the quest for optimal use of energy. They are often deployed to recover heat energy, which otherwise would be wasted. The applications of heat exchanger are significant in various sectors such as power generation, aviation, space heating, refrigeration and air-conditioning systems, chemical process facilities, sewage treatment systems, refineries, cooling and heating.

In the upstream sector of the oil and gas industry, heat exchangers are deployed in oil processing system, gas compression systems and in many utility systems. However, the heat exchangers are frequently restricted by the process-related depositions on the heat transfer surfaces, which often lead to higher operation costs, higher maintenance costs, safety hazards, environmental hazards, throughput limitation and inefficient energy recovery [1]. This deposit known as fouling is one of the biggest challenges facing the efficiency of a heat exchanger. Fouling involves the deposition of material on to a process surface [2]. [3] described fouling as a process where the surfaces separating the fluids in the heat exchanger accumulate deposits as the fluids flow through them. It is the undesirable accumulation of matter on a heat transfer surface resulting in reduced thermal efficiency and increased pressure drop [4]. Fouling rate, also defined as the difference between the material deposition and removal rates on the heat transfer surfaces [5], is an important phenomenon that has capacity to determine the performance of a heat exchanger. Loss of revenue attributed to heat exchanger fouling can be significant. Inadequate heat exchanger performance costs some international oil and gas companies approximately seven hundred and fifty million US dollars ($750 million) per year due to lost throughput and increased fuel and utility consumption, and concurrently exacerbates the environmental footprint [4]. The cost of fouling is connected to energy wastage and associated downtime. Heat exchangers for use in preheat trains of crude oil refineries currently appear to be designed based on pre-specified fouling factors [6]. Fouling has a chronic operational effect that is considered the major unsolved problem in heat transfer technology [7].

Fouling Formation

Like other phenomena, several factors are responsible for fouling formation on a heat transfer surface. [8] performed a study on the fouling features of Crude Oil from Australia and found that surface temperature has a significant effect on fouling rates. An increase of approximately 80oC results in triplicating of the initial fouling rate. [9] posited that in some crude oils, an increase in bulk temperature does not always result in increase in initial fouling rates. The study further proposed a threshold fouling model using the film temperature in the Arrhenius expression after conducting experiments in a high pressure, high temperature recirculation flow pilot-scale fouling test rig with different crude oils at certain operating conditions. The model's accuracy was shown to predict initial fouling rates very close to experimental data. In a combined experimental and modeling study to relate crude oil properties to their intrinsic fouling propensities, [10] observed that the effluent temperatures of crude oil continuously declined due to buildup of thermal insulating foulant on the wall. The study developed a theory that fouling is driven by coking reaction and mass transfer; and mostly influenced by oil's solvency power and the contents of asphaltene, basic nitrogen, and metals which were combined into a fouling propensity index used for developing improved fouling reduction methods. In a related study involving the mixing of crude oil before loading into the test apparatus, [11] observed that different mixing methods can produce different heat transfer coefficients and different fouling rates. [12] expounded a simple, fundamental theory that certain velocity and shear stress thresholds in horizontal flows can be responsible for sedimentation particulate fouling and the values compare favorably with industrial experience. [13] simulated a crude oil fouling process using asphaltene precipitation to study the aging process of the fouling layer and observed that wall shear stress has a high impact on mitigation of fouling as it enables the removal of fouling precursors and thus reduce the deposit formation. Various studies suggest that fouling formation is caused or accelerated by several factors such as wall/bulk temperatures, flow velocities, aging, shear stress and fluid properties.

Modeling of Fouling Behaviour

The threshold fouling approach has become an accepted tool for analyzing fouling data but there has been little activity in the development of quantitative models for the past ten years [14]. [15] studied fluid dynamics and phase behavior of crude-oil fouling in a closed-end heat-exchanger on the basis that the deposition process associated with fouling was due to asphaltene precipitation and a two-step chemical reaction. It predicted phase equilibrium constants used to quantify the asphaltene precipitation rate. The outcome showed that the delicate interplay between heat transfer and fluid dynamics, which accompanies the flow, leads to enhancement and suppression of chemical reaction and precipitation-driven fouling, and an overall rise in the fouling rate. [15] modelled and simulated different crude oil deposit aging scenarios in a crude oil refinery preheat train wherein the transients of fouling and aging as well as the interactions between individual units were captured. Based on this, the deleterious impact of fouling and concomitant aging, quantified in terms of thermal resistances, was significantly reduced by fast aging as opposed to medial, slow, or no aging of the gel deposit. Faster aging rate reflected improved heat recovery and a lesser demand for and lower cost of heat exchanger cleaning. The concomitant higher growth of coke deposit due to aging, however, resulted in greater hydraulic resistance, which is inimical to operations.

Moreover, [16] stated that crude oil fouling researches should be directed to reflect the fouling behaviour of operating exchangers. Based on this, some studies have been carried out to develop models for predicting fouling rate or fouling initiation time. However, despite the existence of the studies, there has not been any that has developed a model that can be used to generalize or universally analyse fouling behaviour in different kinds of heat exchanger. The models are exchanger specific. In addition, several of the previous studies were done with different fluids (other than crude oil) which have different characteristics. Further to this, most of the existing research endeavors were focused on shell and tube heat exchangers in small laboratory scale test sections such as heated rods and short tubular sections. This does not represent dynamic operating conditions as would be observed on a life process plant. More so, in the studies where crude oil was used, most of them were based on stabilized crude used in the downstream process plants (refineries) and not on that used in the upstream. Thus this study focused on evaluation of the performance of a plate and frame heat exchanger deployed in the oil & gas production/treatment facility of upstream sector with operational data. It also focused on in situ experimental measurement of crude oil flow data in a crude cooler facility belonging to a leading oil and gas firm in Nigeria. The data employed were continuously measured for three years and employed for the analysis. The work led to the development of an empirical model that can predict future fouling potential, hence providing monitoring that can also be used to define the economic incentive for possible modifications or redesign of poor performing heat exchangers.

II. Materials and Methods

Two modes of heat transfer play out in a heat exchanger, namely convection within each fluid molecules and conduction through the wall separating the two fluids [17]. In the analysis of heat exchangers, it is convenient to work with an overall heat transfer coefficient, U, that accounts for the contribution of all these effects on heat transfer. The heat transfer rate, Q, is taken to be a positive quantity and its direction is understood to be from the hot fluid to the cold in accordance with the second law of thermodynamics. The rate of heat transfer in a heat exchanger is expressed as [18].

$$Q = U \times A \times MTD \qquad (1)$$

where: Q=Heat duty, U=Overall heat transfer coefficient, W/ (m2-oC), A=Heat transfer area, m2, MTD = Mean temperature difference, oC.

The plate and frame heat exchanger used for this study was manufactured by TRANTER with a model number GXD-085-M-5-UP-267. The hot liquid employed was stabilized crude oil with water as the cold liquid. The exchanger is in continuous use with a primary purpose being to lower the crude oil temperature to an acceptable range in order to minimize flashing of hydrocarbon light ends in the storage tanks as well as eliminate impact of high temperature on its internal coating. The key design parameters are shown in Table1.

Table 1: Design and Process Parameters

Parameter	Value
Hot Crude Oil Flow Rate	887m3/hr
Cooling Water Flow Rate	457m3/hr
Hot Side Inlet Temperature	81.1^{o}C
Hot Side Outlet Temperature	43.3^{o}C
Cold Side Inlet Temperature	22.2^{o}C
Cold Side Outlet Temperature	48.9^{o}C
Hot Side Velocity	0.613m/s
Cold Side Velocity	0.325m/s
Number of Plates	267
Total Heat Transfer Surface Area	3
Calculated Pressure drop	0.67bar
Duty	14.75MW
Heat Transfer Rate	2325W/m^2-^{o}C
Mean Temperature Difference	26.28^{o}C

The analysis of a heat exchanger can be performed by either the Number of Transfer Units (NTU) method or the log mean temperature difference (LMTD) method [17]. The LMTD method is applied to problems for which the fluid flow rates and inlet temperatures, as well as a desired outlet temperature, are prescribed. Therefore, a heat exchanger modeling application that utilizes the LMTD approach was used.

Data Gathering

The multi-year operation data of the plate and frame heat exchanger employed for the study were sourced from an oil and gas firm in Nigeria. They include the mass flow rate of the hot crude oil, mass flow rate of the cooling water, inlet temperature of the hot crude oil, outlet temperature of the hot crude oil, inlet temperature of the cooling water and pressure drop across the heat exchanger. These operating parameters were utilized with the HTRI Xchanger Suite to generate the cooling water outlet temperature, duty of the plate and frame, overall heat transfer coefficient and fouling resistance at various operating points. The values of the various operating data were detected by various instrumentation devices like the turbine flow meters, temperature transmitters and pressure gauges. The values of some parameters like the flow rates and temperatures are automatically transmitted to a system of record (SoR) called the Exaquantum which both stores the data for several years as well as provides real time values of the operating parameters at any point in time. Some other operating data like the pressure drop across the heat exchanger was manually recorded by operating personnel by reading the pressure gauges on the inlet and exit lines of the unit.

A total of over seventeen thousand data points covering the periods between 2013 and 2015 were collated from the datasheet for each of the operating parameters making it a total of 68000 data points. In addition, 1200 manually recorded data points were also used. Upon reviewing the data, some data were found to be incomplete for various reasons which included instrumentation (device) malfunction, human errors, measurement error and emergency shutdown of the facility. Based on this, the data were treated in two ways namely:

i. Incomplete data: This results when the system did not capture the values of all the key operating parameters at certain days. Due to the criticality of data completeness, days with incomplete data were removed.

ii. Outliers: Some data were provided but were found to be significantly distant from other measurements recorded and so were excluded from data set. The outliers were evaluated statistically using the Three Sigma Method denoted by equation (2) and this represented 0.07% of the overall data.

$$\alpha \pm 3\sigma \qquad (2)$$

Development of the Heat Exchanger Model

The model development was carried out using the Heat Transfer Research Inc (HTRI) Xchanger Suite and Parametric Study Spreadsheet. The performance parameters such as the ratio of service overall heat transfer coefficient, U_s, to clean overall heat transfer coefficient, U_{cl}, (U_s/U_{cl}) and the Fouling Resistance (R_f) were monitored. Variations in U_s/U_{cl} defines the change in heat transfer capacity with time and hence the heat transfer efficiency. It was noted that tracking U_s/U_{cl} alone can be misleading, because it is a hyperbolic function and hence was more reliable to monitor the fouling resistance, R_f, directly using the equation:

$$R_f = \left(\frac{1}{U_s}\right) - \left(\frac{1}{U_{cl}}\right) \quad (m^2\ °C/W) \qquad (3)$$

Heat Transfer Efficiency

The heat exchanger performance is typically measured in terms of heat transfer efficiency and hydraulic capacity [18]. In this work, the heat transfer efficiencies of the heat exchanger over a period was determined, according to [18], as the ratio of service overall heat transfer coefficient, U_s, to clean overall heat transfer coefficient, U_{cl}, both of which are defined in equations 4 and 5

$$U_s = Q/(A \times EMTD) \qquad (4)$$

$$U_{cl} = \frac{1}{\left[\left(\frac{1}{h_i}\right)\times\left(\frac{D_o}{D_i}\right)+\left(\frac{1}{h_o}\right)+R_w\right]} \qquad (5)$$

where: U_s = Service overall heat transfer coefficient, (W/m^2 °C), Q = Rate of heat transferred, (W), A = Outside area of tubes, (m^2), EMTD = Effective mean temperature difference, (°C), U_{cl} = Clean overall heat transfer coefficient, (W/m^2 °C), h_i = Inside film heat transfer coefficient based on inside area, (W/m^2 °C), D_o = Outside diameter of tubes,(m^2), D_i = Inside diameter of tubes, (m^2), h_o = Outside film heat transfer coefficient based on outside area, (W/m^2 °C), R_w = Wall resistance, (m^2 °C/W)

Modeling the Phenomenon of Fouling Resistance

A multivariate regression method was employed to model the fouling resistance in the plate and frame heat exchanger based on the input parameters. The model shows the relationship between the fouling resistance, the crude oil mass flow rate (kg/s), crude oil inlet temperature (oC), crude oil outlet temperature (oC) and cooling water inlet temperature (oC). To predict the accuracy of the models created and subsequently determine the best performing model, the Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Percentage Error (MPE), Mean Absolute Percentage Error (MAPE), Mean Absolute Bias Error (MABE) and the Nash-Sutcliffe Coefficient of Efficiency (COE) were employed. These equations are presented as equations 4 – 9 respectively:

$$RMSE = \sqrt{\left(\sum_{i=1}^{n} (H_m - H_{cal})^2 \right) / k} \qquad (6)$$

$$MBE = \left(\sum_{i=1}^{n} (H_m - H_{cal}) \right) / k \qquad (7)$$

$$MPE = \frac{\left[\sum_{i=1}^{k} \left(\frac{H_m - H_{cal}}{H_m} \right) \times 100 \right]}{k} \qquad (8)$$

$$COE = 1 - \frac{\sum_{i=1}^{k} \left(H_{cal} - H_m \right)^2}{\sum_{i=1}^{k} \left(H_{cal} - \bar{H}_m \right)^2} \qquad (9)$$

$$MAPE = \frac{\left[\sum_{i=1}^{k} \left| \left(\frac{H_m - H_{cal}}{H_m} \right) \right| \times 100 \right]}{k} \qquad (10)$$

$$MABE = \left(\sum_{i=1}^{n} \left| H_m - H_{cal} \right| \right) / k \qquad (11)$$

Where: k = number of data points, $\bar{H}_m$ = mean of all the fouling resistance obtained from experiment.

III. Results and Analysis

Performance of the Heat Exchanger

The accuracy of the modeling and simulation carried out using the HTRI was first determined by checking the convergence of the results to the original design parameters for the plate and frame heat exchanger. The comparison of the results from the HTRI to that of the manufacturer's design parameters are displayed in Table 2. The Table shows that the results from HTRI are very close to those of manufacturer's datasheet of the in-service plate and frame heat exchanger employed for the study. The degree of accuracy of the results therefore provides the basis for the subsequently performance study using the HTRI.

Table 2: Comparison of results from simulation with that from manufacturer's datasheet

S/No.	Parameter	Data Sheet Value	Modelling results
1	Actual Heat Transfer Coefficient	2325W/m^2-k	2204.8W/m^2-k
2	Required Heat Transfer Coefficient	2627W/m^2-K	2282.4W/m^2-k
3	Duty	14.7MW	14.53MW
4	Area	241.14m^2	241.27m^2
5	Effective Mean Transfer Difference	26.28^{o}C	26.4^{o}C
6	Quantity of Plates	267	267

The heat exchanger and the Frame in series representation are shown in Figures 1 and 2.

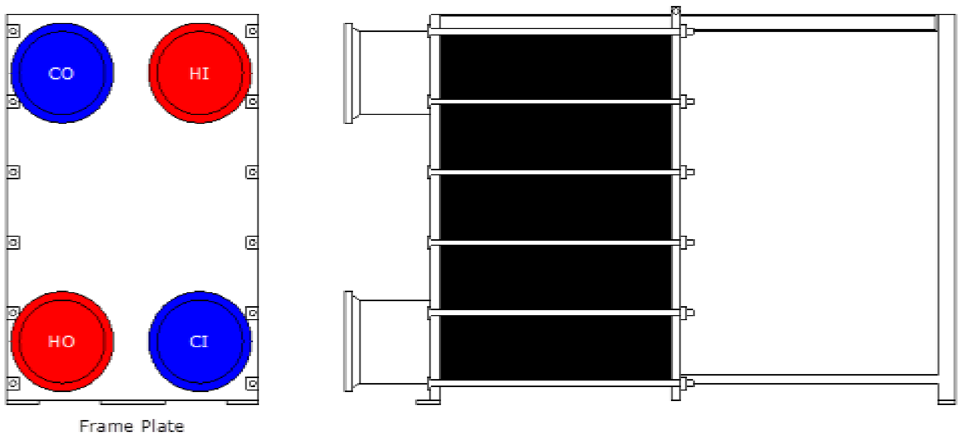

Figure 1: Heat Exchanger Drawing Showing Flow Ports

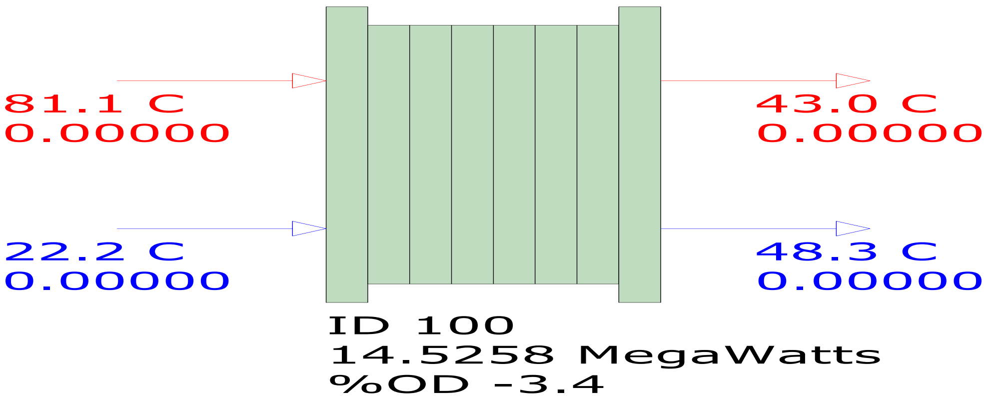

Figure 2: Frame in Series Representation of Heat Exchanger

The variations of the heat transfer efficiency over time are shown in figure 3 (a-c)

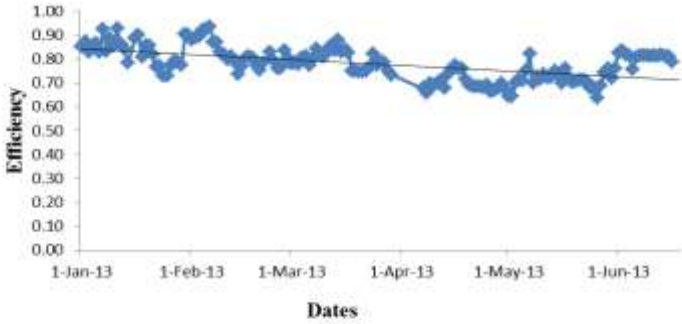

Figure 3a: Heat Transfer Efficiency of the heat exchanger (January - December 2013)

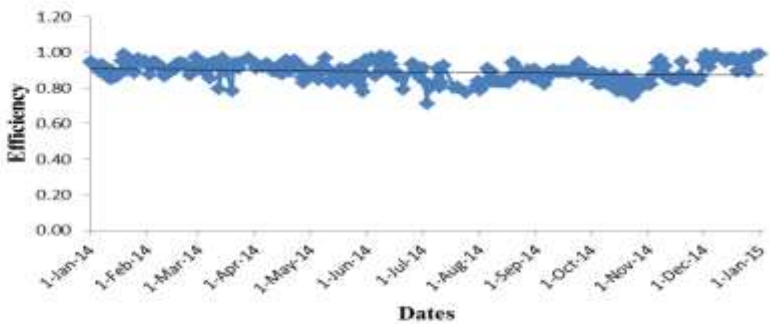

Figure 3b: Heat Transfer Efficiency of the heat exchanger (January - December 2014)

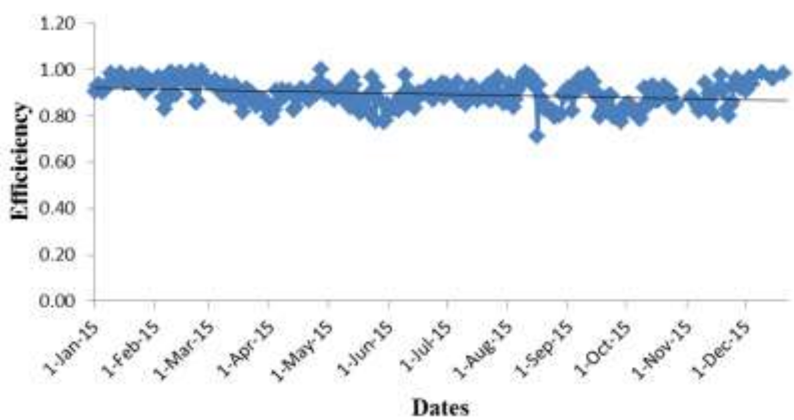

Figure 3c: Heat Transfer Efficiency of the heat exchanger (January - December 2015)

From Figure 3 (a – c), the heat transfer efficiency for each year studied tends to reduce over time. The downward trend of the heat transfer efficiency can be extrapolated to estimate when the efficiency drop would become a concern, hence facilitating early planning for possible maintenance action. The decline in heat transfer efficiency was more pronouced in 2013 than in 2014 and 2015. Based on the field data,the heat transfer efficiency was 85% as at the beginning of 2013; but it dropped to 72% by the end of the year. In 2014, the heat transfer efficiency dropped from 92% at the beginning of the year to 84% at the end of the year while in 2015 it was 92% at the beginning of the year and declined to 83% at the end of the year. The dynamic nature of the fluid properties and the process is essentially responsible for the behaviour of the efficiencies from year to year. The temperature difference was noted as responsible for the disparity in heat transfer efficiency behaviour over the years of study. The approach temperature (~average of 55^{o}C) of the crude was lowest in 2013 due to the then reservoir conditions unlike those of 2014 (~average of 58^{o}C) and 2015 (~average of 62^{o}C). Lower crude approach temperature imply lower temperature difference between the crude and cooling water and vice versa.

Moreoever, the changes in the fouling resistance R_f over time are presented in figure 4 (a-c):

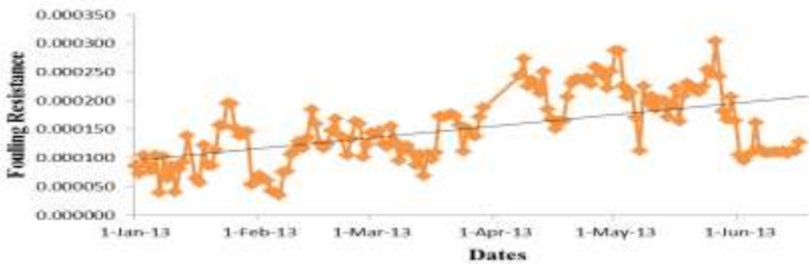

Figure 4a: Progression Fouling Resistance of the heat exchanger for the period of January to December 2013

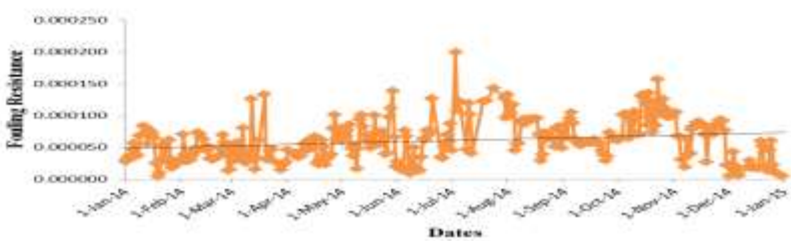

Figure 4b: Progression Fouling Resistance of the heat exchanger for the period of January to December 2014

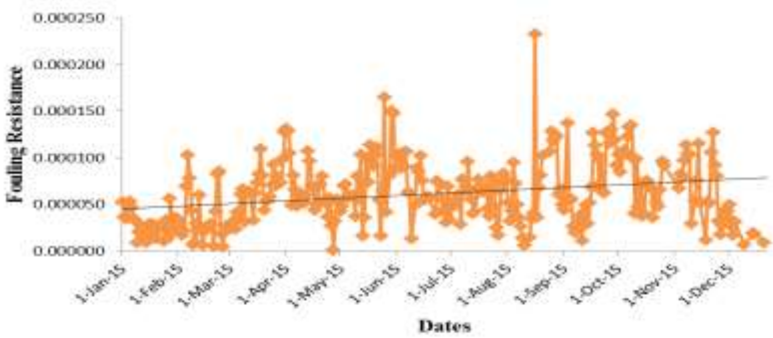

Figure 4c: Progression Fouling Resistance of the heat exchanger for the period of January to December 2015

The figure 4 (a – c) shows the fouling resistances were seen to increase over time for each year. The dynamics of the operating conditions such as changes in flow rate and variations in feed temperature were responsible for the fluctuations in data points. According to [19], fouling of heat transfer surfaces is a complex process which involves many parameters with poorly understood interactions. Hence, it could result in highly unstable processes with frequent significant fluctuation, if the variation of the heat transfer coefficient or fouling resistance was observed with time. The increase in fouling resistance over time was more in 2013 than in 2014 and 2015 respectively. In 2013, the fouling resistance ranged from 0.000035 m^2-K/W at 61°C to 0.000320 m^2-K/W at 54°C. In 2014, the fouling resistance ranged from 0.000005 m^2-K/W at 63°C to 0.00020 m^2-K/W at 59°C. In 2015, it ranged from 0.000005m2-K/W at 62°C to 0.000165 m2-K/W at 56°C. Hence, it was observed that fouling resistance tends to increase with lower feed temperature in a plate and frame heat exchanger used for crude oil services. However, an understanding of the performance of the heat exchanger in relation to its fouling resistance is essential in order to forecast its impact on the performance and ascertain the best maintenance on the unit. This will require the development of a predictive model that explains the phenomenon of fouling resistance with input parameters. Figures 5a and 5b show the trends of the combined heat transfer efficiency and fouling resistance with time respectively.

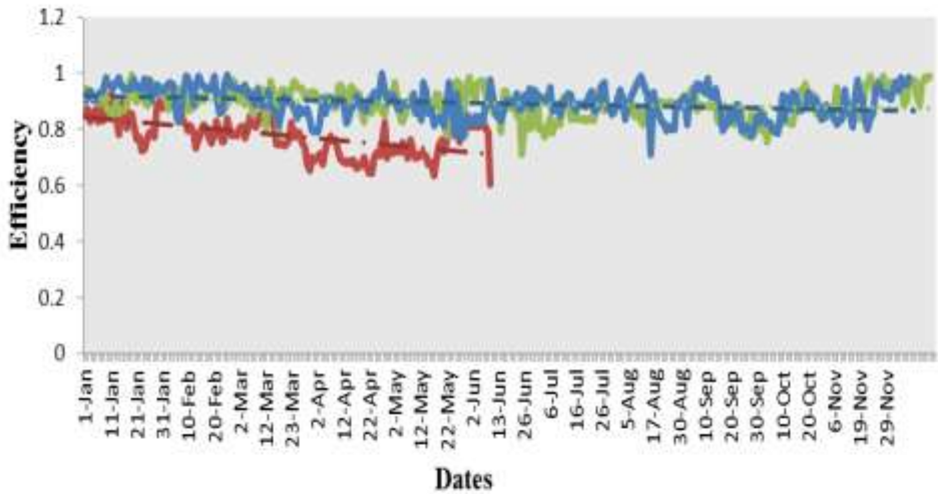

Figure 5a: Progression of Combined (Multi-Year) Heat Transfer Efficiency

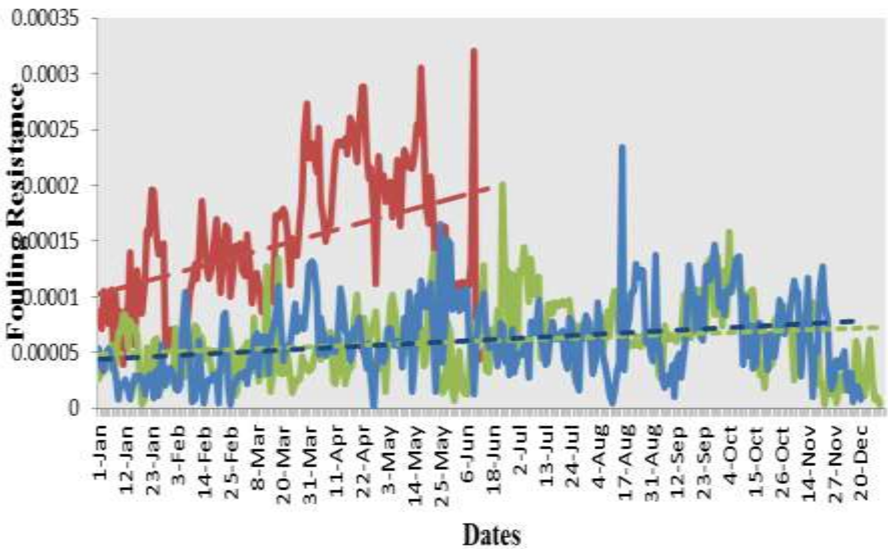

Figure 5b: Progression of Combined (Multi-Year) Fouling Resistance

Regression Model Analysis of the Heat Exchanger Fouling Resistance (R_f)

The multivariate regression models were developed using the eight hundred and eleven historical data set for the fouling resistance over time. The following modelling equations (12-16) were gotten

$$R_f = aTw_i + bTo_o + cTo_i + dM_0 + et + f \quad (12)$$

$$R_f = aTw_i + bTo_i + cM_o + dt + e \quad (13)$$

$$R_f = aM_o + bt + c \quad (14)$$

$$R_f = aTw_i + bTo_o + cTo_i + dM_o + et^2 + ft + g \quad (15)$$

$$R_f = aTw_i + bTo_o + cTo_i + dM_o^2 - et + f \quad (16)$$

where: Tw_i = Cooling Water Inlet Temperature (^{0}C), To_i = Crude Oil Inlet Temperature (^{0}C), To_o = Crude Oil Outlet Temperature (^{0}C), M_o = Crude Oil Mass Flow rate (kg/s), t = Precise Day of Operation within a specified period (day), R_f = Fouling Resistance (m^2-K/^{o}C), and a, b, c, d, e, f, g are correlation coefficients. The values of the correlation coefficients as determined from Eqs. 12 to 16 are shown in Table 3, while those of the error and performance analysis for the different models are shown in Table 4.

Table 3: Regression Model Constants

Coefficients	MODEL 1	MODEL 2	MODEL 3	MODEL 4	MODEL 5
a	-2.9563E-05	-1.49156E-05	-2.7E-06	-2.955E-05	-3E-05
b	4.83066E-05	-4.42831E-06	-9.1E-08	4.82E-05	4.8E-05
c	-1.96825E-05	-2.57434E-06	0.00058	-1.965E-05	-2E-05
d	-3.26233E-06	-5.62769E-08	0	-3.243E-06	-9.8E-09
e	-2.00747E-09	0.001100191	0	8.186E-12	-1E-09
f	0.000682127	0	0	-8.819E-09	0.000424
g	0	0	0	0.0006811	0

Table 4: Regression Model Error and Performance Analysis

Error Term	MODEL 1	MODEL 2	MODEL 3	MODEL 4	MODEL 5	Minimum	Maximum
RMSE	0.8892744	2.0813766	3.7159727	0.8929542	0.87362	0.8736199	3.7159727
MBE	-0.0780832	0.4920447	0.6525238	-0.078055	-0.074976	-0.0780832	0.6525238
MABE	0.1537614	0.832592	0.9672618	0.1529291	0.158822	0.1529291	0.9672618
MPE(%)	-7.8083234	49.204468	65.252375	-7.8055016	-7.497631	-7.8083234	65.252375
MAPE (%)	0.7908089	4.3321284	13.808453	0.7973673	0.763212	0.7632117	13.808453
COE	0.9855844	0.6273876	0.4975269	0.9856152	0.983878	0.4975269	0.9856152
Multiple R (%)	99.072	72.272	59.653	99.074	98.961	59.653	99.074
R-Squared (%)	98.152	52.232	35.585	98.156	97.933	35.585	98.156

From the results of Tables 3 and 4, it is observed that “MODEL 4” is the best model with the coefficient of performance of 98.6% for predicting the fouling resistance of the heat exchanger. “MODEL 1” with a coefficient of performance of 98.5%" & "MODEL 5 with a coefficient of performance of 98.3 are also dependable models. Further to this, comparisons between the measured and calculated fouling resistances using each of the developed models are shown in the figures 6 (a – e).

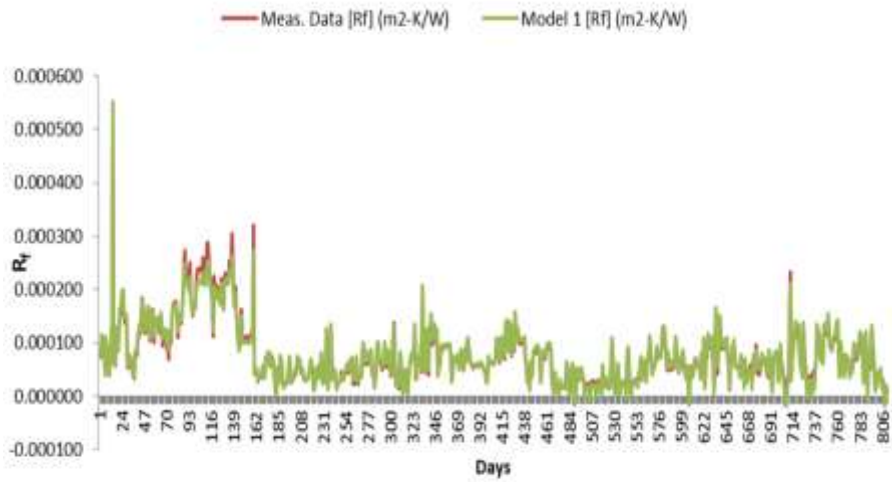

Figure 6a: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (12)

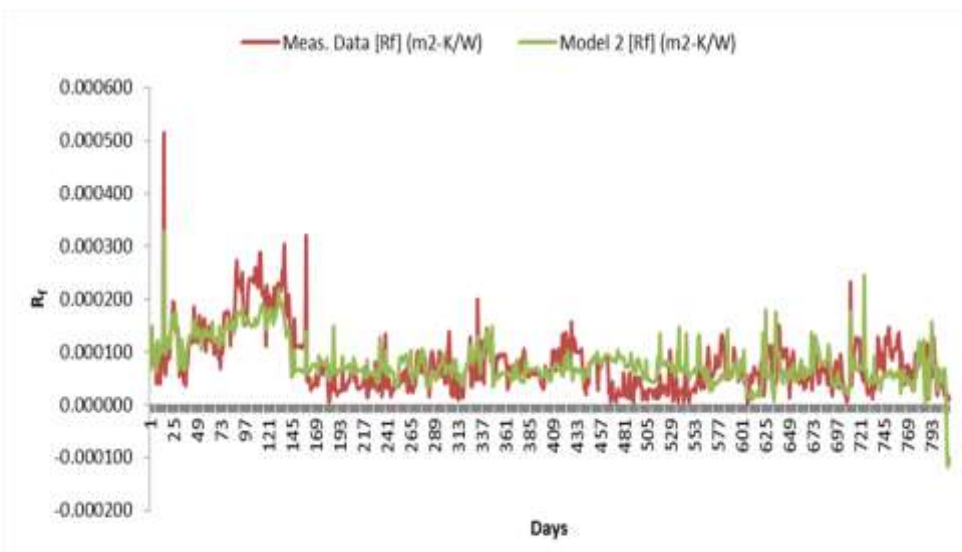

Figure 6b: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (13)

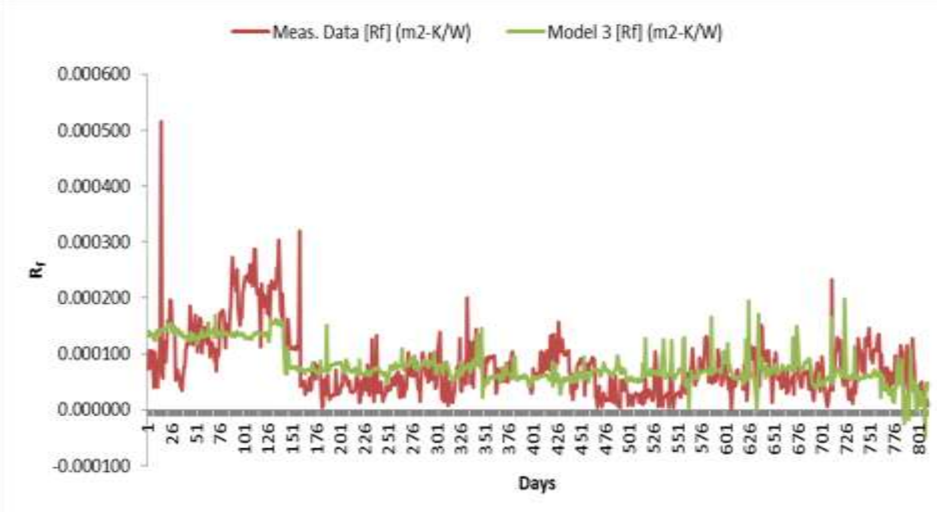

Figure 6c: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (14)

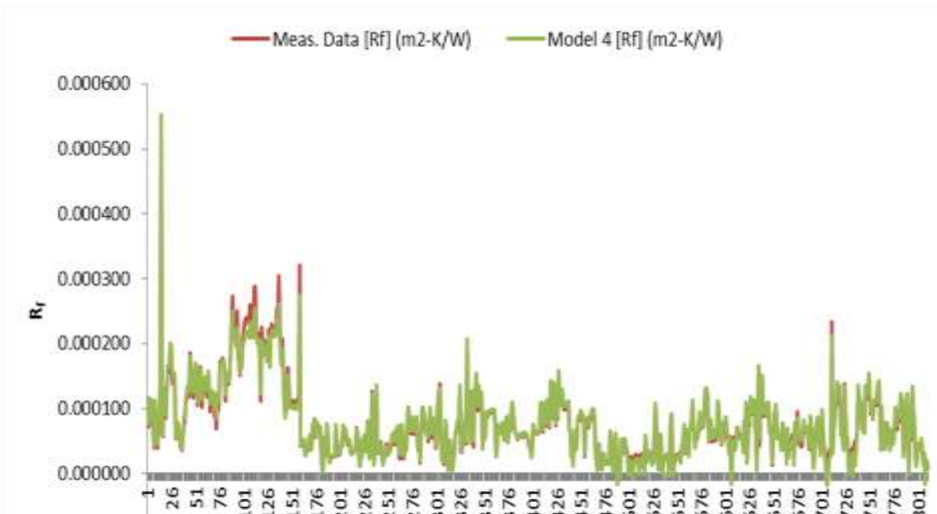

Figure 6d: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (15)

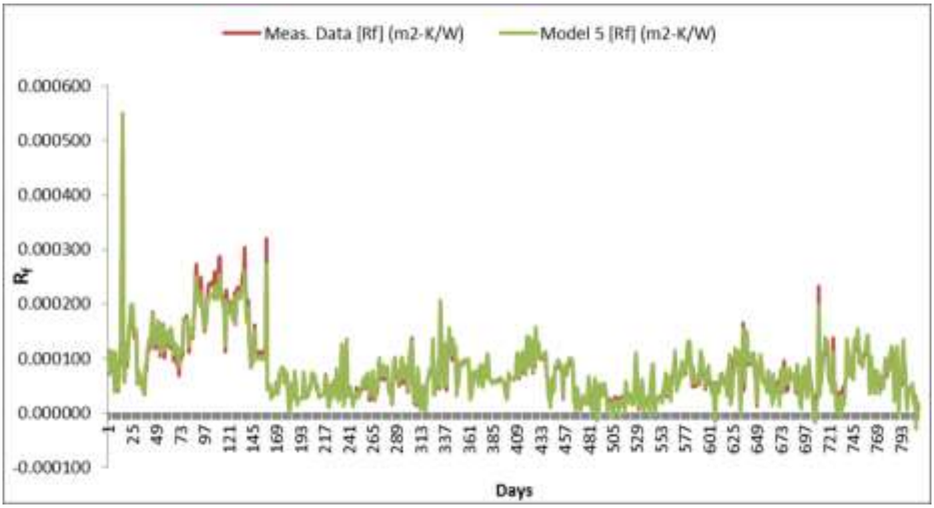

Figure 6e: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (16)

Model Evaluation

Based on the model analysis, equation (17) presents the most accurate model while equation (18) closely followed

$$R_f = \left[4.82T_\infty - 2.96T_{wi} - 1.97To_i - 0.324\ x\ 10^{-1}M_o + 8.19\ x\ 10^{-7}t^2 - 8.82\ X\ 10^{-4}t + 0.0006811\right] \times 10^{-5}$$

(17)

$$R_f = \left[4.83T_\infty - 2.96T_{wi} - 1.97T_{oi} - 0.326\ x\ 10^{-1}M_o - 2.01\ x\ 10^{-4}t + 68.21\right] \times 10^{-5}$$

(18)

Based on the aforementioned, equations (17) and (18) predict the fouling resistance of a plate and frame heat exchanger, enabling the forecast of a time when a maintenance program or any other type of intervention will be required. Table 5 therefore, provides the predicted fouling resistances of a plate and frame heat exchanger for a period (days) using the best model above at operating conditions.

Table 5: Fouling Resistance Predicted by best Regression Model

Time (Days)	Fouling Resistance (m^2 °C/W)
360	5.15E-05
540	5.13E-05
720	5.16E-05
900	5.24E-05
1080	5.37E-05
1260	5.55E-05
1440	5.79E-05
1620	6.09E-05
1800	6.43E-05

1980	6.83E-05
2160	7.28E-05

For instance, if a plate and frame heat exchanger is installed in January 2016, the fouling resistance would have increased to 6.43 x 10-5 m2 °C/W by January 2021. Having this knowledge will enable the operator know that heat transfer efficiency will be impacted in five years' time and then adequate plan can be put in place to clean the heat exchanger or replace with a spare unit.

IV Conclusion

The study focused on investigation of the performance of a plate and frame heat exchanger employed in an oil and gas production/treatment facility of upstream sector with operational data. It developed multivariate regression models that can be used to predict required maintenance plan and forecast the economic implication of fouling on the heat exchanger. Apart from the results already highlighted, the study also found that at a constant cold stream temperature, the lower the hot stream approach temperature, the more the fouling resistance. Hence there is a relationship between the inlet temperature of the hot process stream and the fouling resistance. Moreover, due to the complexity of fouling phenomenon, further work may be required to develop the fouling rate models of plate and frame heat exchangers for various crudes and crude blends with different thermophysical properties and chemical compositions. Furthermore, computational fluid dynamics can be applied to the study to be able to incorporate other fluid properties and also establish the pathway to easy fouling prediction and maintenance set-up programme.

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