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OPTIMISING PERFORMANCE OF HEAT EXCHANGER AGAINST FOULING

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ABSTRACT

Heat Exchangers (HEs) are used widely in industries where transfer of heat between two or more mediums is a necessity. The fouling of a heat exchanger is a natural phenomenon and depends upon various factors like fluid - velocity & composition, working temperatures, material of HE, flow geometry, etc. The various fouling reduction techniques are being used in Industries for increasing the performance of the HE. The present paper utilizes the methodology prescribed in the available literature for prediction of Net Transfer Unit (NTU): clean and fouled values, for predicting corresponding clean and fouled Effectiveness. The predicted fouled and clean values of effectiveness compare to the corresponding measured effectiveness of a heat exchanger. The real time operational parametric trending is taken from the available literature for A unit HE of Urea process plant for Nortore Nigeria Plc. The imbibed parameters were used for predicting "Predicted Clean" and "Predicted Fouled" and calculating "Actual Measured" effectiveness of the HE, for a span of ten weeks before maintenance and, ten weeks after maintenance. Thereafter, using "Predicted Clean", "Predicted Fouled" and "Actual Measured" values of effectiveness, Index of fouling "IF" has been calculated for complete twenty weeks of operation of the unit. The IF values confirmed high fouling for the first ten weeks of operation and therefore heat transfer rate was also lower than the design value. The plant undertook a maintenance post tenth week of operation when the heat transfer rate was minimum i.e. 9778.4 W. The calculated value of fouling index has been found to be the maximum during the tenth week, indicating fouled HE. The trend between the heat transfer rate and IF shows close compliance during both before and after the maintenance period.

KEYWORDS: Heat Exchanger, Fouling

I. INTRODUCTION

(a) HEs are used widely in industrial application where transfer of heat between two or more mediums is a necessity. There are various types of HEs and upcoming challenges and researches tend to modify these HEs towards better performance. The most simple and traditional type of HE that has got wide industrial application is a Shell & Tube type. The basic principle involved in the Heat Exchange between the two working fluids is the principle of conservation of energy, i.e. the heat given by the hot fluid is absorbed by the cold fluid. However, with ageing and continuous operation of the HE, the heat exchange occurring between the two fluids reduces, which may be attributed majorly to deposition of foreign material that absorbs part of heat and thereby causing fouling of the HE. Thermal Fouling (in the presence of temperature gradient) means accumulation of any undesirable deposition of a thermal insulating material (which provides added thermal resistance to heat flow) on a heat transfer surface occurring over a period of time. This solid layer adds an additional thermal resistance to heat flow and also increases hydraulic resistance to fluid flow.

(b) The fouling process is a natural phenomenon that affects the performance of the HE. Therefore, it becomes pertinent to monitor the process of fouling for planning maintenance routines. The actual performance of HE at a given time of operation should be available to the maintenance engineer to enhance economy and safety of the plant and equipment. Additionally, real time monitoring can also indicate the ideal time to stop the operation and undertake maintenance on HE.

(c) The economic loss to HE fouling can go to phenomenally high values and in the case of high hydraulic pressure involved can lead to safety concerns for man and material. In case of refineries heating of large quantities of crude oil is involved. The chemical industries having shell & tube HEs, the crude oil flows through the tubes and various hot fluid flows through the shell side. These fluids are highly fouling and heat transfer coefficient and energy recovery can go down as low as 30% compared to their clean values. The annual Loss attributable to heat exchanger fouling in the US and UK together is of the order of USD 16.5 Billion as per reference [4].

II. MODELLING FOULING OF HE

The various models of the fouling process on a *HE* are based on the principal characteristic feature that the net mass fouling rate is a determinant of the difference between the foulant deposit rate and the foulant retrainment rate. The foulant deposition cause an additional resistance to the heat transfer and is called as fouling resistance. Figure 1 shows four scenarios for the growth of the fouling resistance over a period of time. The duration of time τ_d over which the fouling resistance is negligible is termed as delay period. The four scenarios as depicted in Figure 1 are: -

i. Linear Characteristics. Linear characteristics of fouling indicate a proportional increase of fouling resistance with time and is observed with constant deposition rate and no occurrence of reentrainment of foulant.

ii. Decreasing Deposition rate. In cases where deposition of foulant is decreasing however is always greater than removal rate of foulant. This type of fouling mechanism has been observed in crystallization fouling in a plate exchanger and also in particulate fouling.

iii. Asymptotic behavior. In asymptotic characteristics of fouling the removal of foulant progressively becomes more effective. As the time progresses the resistance due to fouling achieves a constant thickness termed as the asymptotic scale of thickness.

iv. Sawtooth Pattern. This type of fouling is generally associated with sea water corrosion of copper tubes.

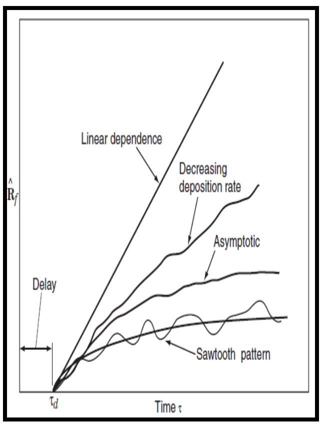

Figure 1: Time Dependence of the Fouling Resistance

III. MONITORING *HE*'S OPERATING PARAMETERS

(a) The operating parameters of an *HE* like inlet/outlet temperatures of the fluid streams, overall heat transfer, mass flow rate of streams are very critical for ascertaining the present status of scale/biofilm formation on heat transfer area of the tubes and shell of the *HE*. [4] Conducted performance analysis of 2650 KW refinery *HE* has Crude oil as the cold fluid and Low Sulfur Waxy Residue (*LSWR*) as the hot fluid. The analysis has been carried out for a period of three years, starting from May 2002, when the *HE* was mechanically cleaned. The parametric analysis carried out was used to model the expected behavior of the fouling process by the use of historical data obtained. The real time monitoring of data is a very crucial tool for planning maintenance of *HE*s.

(b) The system changes like Mass flow rates when incorporated in the theoretical calculations than the results will show high compliance with the practical data. [1] & [5] established an approach that consists of a comparison of the measured effectiveness of an *HE* with that of its predicted counterpart. The data trending has been undertaken on shell and tube *HE*s of a refinery plant having huge crude pre heat trains. [1] Proposed index of fouling using the measured effectiveness and predicted effectiveness that clearly indicates the performance status of the *HE*. [5] utilized the approach to trend the data collected from a crude pre heat train of President Getu´ Leo Vargas Refinery of PETROBRAS located in Arauca´ria-PR, Brazil, over a period of 3 years (approx) post cleaning of the *HE*s. The approach of comparison of the predicted and measured effectiveness has been observed to be an effective tool in performance assessment of the *HE*s.

IV. MATHEMATICAL EQUATIONS

The data to be analyzed for performance trending will differ depending upon process, type of industry, available and fitted sensors on the equipment. However, the analysis should involve least number of variables for ease of handling data. The following equations/relations/standards for the calculation of the predicted & measured effectiveness and index of fouling can be utilized for a **counter flow *HE* has single shell and tube pass**, for carrying out performance analysis: -

(a) Maximum Fouling Resistance: Maximum fouling resistance is a standard design value of thermal resistance for which the *HE* is assumed to be working satisfactorily. These maximum values are available in the T.E.M.A standards and depends upon the working fluid, temperatures velocity and other operating parameters. The maximum thermal resistance for a heat exchanger involves a series of thermal resistances from the hot fluid to the colder fluid, including thermal resistances due to fouling on both fluid sides. ***These standard values in the present work have been obtained from T.E.M.A standards for calculating "fouled overall heat transfer coefficient, "U_f" from corresponding "Clean/Design Overall heat transfer Coefficients, "U_{cl}".***

(b) Measured Effectiveness: Measured effectiveness of *HE* is an on-site value. "ε_m" indicates the actual obtained performance of the *HE*. This can be calculated from the ratio of actual heat transferred rate (Q) from hot fluid to the cold fluid to the maximum thermodynamically permitted heat transfer rate (Q_{max}) that can take place.

$$\varepsilon_m = \frac{\dot{Q}}{Q_{max}} = \frac{(\dot{m}c_p)_h (T_{hi} - T_{ho})}{(\dot{m}c_p)_{min} (T_{hi} - T_{ci})} \quad \textbf{(i)}$$

- **(c) Predicted Effectiveness:** Predicted effectiveness is classified into two types, Fouled Effectiveness "ε_f" and Clean Effectiveness "ε_{cl}" that are obtained from NTU_f and NTU_{cl} values respectively. Additionally, the NTU_f and NTU_{cl} values are calculated by using U_f and U_{cl} values respectively. The working equations are enumerated below: -

$$NTU_p = \frac{(UA)_p}{(\dot{m}c_p)_h} \quad \text{.....} \tag{ii}$$

Additionally, if design details are available to the maintainer than the exact value of NTU_P with varying mass flow rates can be obtained from the following relations: -

$$\frac{(NTU)_P}{(NTU)_D} = \frac{[(\dot{m}c_p)_{min,d}/(\dot{m}c_p)_{min}]^{1-b}}{\{1+(UA/HA)_d[((\dot{m}c_p)_{min,d}/(\dot{m}c_p)_{min})^{a-b}(R/R_d)^a - 1]\}}$$

$$\frac{(NTU)_P}{(NTU)_D} = \frac{[(\dot{m}c_p)_{min,d}/(\dot{m}c_p)_{min}]^{1-a}}{\{1+(UA/HA)_d[((\dot{m}c_p)_{min,d}/(\dot{m}c_p)_{min})^{b-a}(R/R_d)^b - 1]\}} \tag{iii}$$

Post obtaining the NTU_P values the value of predicted effectiveness "ε_p" for a counter flow *HE* can be obtained by the following relation: -

$$\varepsilon_p = \frac{2}{1 + R + \sqrt{(1+R^2)}\,\dfrac{1 + e^{[-NTU_P\sqrt{(1+R^2)}]}}{1 - e^{[-NTU_P\sqrt{(1+R^2)}]}}} \tag{iv}$$

- **(d) Heat Capacity Ratio**: For an *HE* having C_h as C_{min}, R ie Heat capacity ratio for the two stream is given by the relation : -

$$R = \frac{(\dot{m}c_p)_h}{(\dot{m}c_p)_c} = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ho}} \tag{v}$$

- **(e) Index of Fouling (IF):** The Index of Fouling (IF) can be obtained from the values of predicted effectiveness and measured effectiveness values obtained previously. IF is defined as the ration between difference between Clean and measured effectiveness & Clean and Fouled effectiveness.

$$IF = \frac{\varepsilon_{cl} - \varepsilon_m}{\varepsilon_{cl} - \varepsilon_f} \tag{vi}$$

V. CASE STUDY

[8] Entail performance assessment of two similar *HE*s A & B for 10 weeks before maintenance and 10 weeks after maintenance, of *Urea process plant for Nortore Nigeria Plc*. The performance assessment aimed at performance optimization of Marine *HE*s. The maintenance of *HE*s A & B was undertaken prior to "*after maintenance"* assessment, by high pressure jetting and chemical cleaning technique respectively. The *HE*s are counterflow types with hot fluid as *Ammonium Cyanate* and cold fluid as *Water*. ***The performance parameters were imbibed from the before and after maintenance parameter trending for A unit, and were developed for predicting Fouled Effectiveness "ε_f", Clean Effectiveness "ε_{cl}", Measured Effectiveness "ε_m" and Index of Fouling "IF" by using [1] & [5] approach***. The recorded & obtained parameters are tabulated in the table 1.

VI. RESULTS

The ε_{cl}, ε_m, ε_f and IF values for the *HE* has been tabulated. The following can be apprehended from the obtained values of ε_{cl}, ε_m, ε_f and IF for the *HE* during the period of operation/monitoring: -

- **(a)** Prior to maintenance being carried out on the *HE* the value of ε_m is close to ε_f giving high values of IF, indicating high fouling.
- **(b)** The Index of Fouling between week 1 to week 9 has varied between 0.5-0.8, that explains for the less quantity of Total heat transfer (Q) than the design value in this period.
- **(c)** During the week 10 the value of ε_m has exceeded the value of ε_f, thereby giving an IF value of 1.019, (IF=1 indicates fouled *HE*). At this stage of operation, it becomes necessary to undertake maintenance on the *HE*.
- **(d)** Post maintenance the value of ε_m for complete ten weeks of duration has been found to be close to the corresponding ε_{cl}, this explains for the high quantity of total heat transferred during this duration.
- **(e)** The fouling resistance for ammonium cyanate has been assumed on the basis of available values in T.E.M.A standards for the calculation of U_f (and is kept on higher side for increased factor of safety).
- **(f)** During tenth week the ε_m value is equal (approx) to ε_{cl} values indicating a clean HE (IF=0) for clean HE that explains high Total Heat Transfer Rate.

Table 1: IF Calculation 'Urea Process Plant for Nortore Nigeria Plc Obtained Parameters [8]

Weeks	Temp Cold		Temp Hot		Heat Transfer Coeff. (W/m²degC)	LMTD (degC)	Area (m^2)	Total Heat Transfer, Q (W)	R,Heat Capacity Ratio (T_{co}-T_{ci})/ (T_{hi}-T_{ho})	NTU_{cl}	NTU_F	ε_{cl}	ε_m	ε_f	IF
	T_{ci}	T_{co}	T_{hi}	T_{ho}											
Before Maintenance															
1	29	49	100	68	121.067	44.73	2.01	10884.8	0.625	0.896	0.705	0.492	0.450	0.432	0.700
2	29	47	100	65	122.850	43.95	2.01	10852.5	0.514	0.983	0.773	0.533	0.490	0.469	0.670
3	29	41	100	59	125.786	42.88	2.01	10841.3	0.293	1.152	0.906	0.618	0.570	0.546	0.667
4	29	45	100	62	124.378	43.07	2.01	10767.5	0.421	1.075	0.846	0.573	0.535	0.506	0.567
5	29	38	100	56	126.583	42.10	2.01	10711.6	0.205	1.251	0.985	0.664	0.620	0.587	0.571
6	29	52	100	70	119.617	44.41	2.01	10677.5	0.767	0.856	0.673	0.460	0.423	0.407	0.698
7	29	36	100	53	126.903	40.78	2.01	10402.0	0.149	1.377	1.084	0.708	0.662	0.630	0.589
8	29	56	100	72	118.343	43.50	2.01	10347.3	0.964	0.824	0.649	0.430	0.394	0.381	0.735
9	29	33	100	50	125.388	39.65	2.01	10152.4	0.08	1.500	1.181	0.755	0.704	0.675	0.638
10	29	59	100	76	110.742	43.93	2.01	9778.4	0.8*	0.935	0.736	0.477	0.423	0.424	1.019
After Maintenance															
1	29	32	100	63.5	147.493	49.37	2.01	14563.46	0.082	0.764	0.600	0.526	0.514	0.442	0.143
2	29	31	100	61.5	150.150	48.48	2.01	14558.54	0.052	0.806	0.634	0.552	0.542	0.464	0.114
3	29	31	100	62	149.701	48.61	2.01	14553.93	0.052	0.796	0.626	0.541	0.535	0.460	0.074
4	29	34	100	64	146.843	48.87	2.01	14352.43	0.139	0.763	0.601	0.514	0.507	0.438	0.092
5	29	36	100	65	146.198	48.66	2.01	14229.99	0.200	0.749	0.590	0.500	0.492	0.426	0.108
6	29	38	100	66	144.092	48.43	2.01	13956.751	0.265	0.742	0.584	0.488	0.479	0.418	0.129
7	29	40	100	69	140.647	49.33	2.01	13876.230	0.355	0.680	0.536	0.452	0.437	0.386	0.227
8	29	39	100	67.5	141.643	48.89	2.01	13849.853	0.308	0.715	0.563	0.472	0.458	0.403	0.203
9	29	42	100	70	133.689	49.01	2.01	13104.200	0.433	0.698	0.549	0.451	0.423	0.386	0.431
10	29	45	100	71	126.167	48.21	2.01	12165.022	0.552	0.727	0.572	0.396	0.408	0.347	-0.25

VII. CONCLUSIONS

The IF calculated using [1] and [5] was found to be more than one during the tenth week of operation before maintenance. During that week the total heat transfer rate is also found to be the least of all the weeks, indicating high fouling. Additionally, it can be observed by seeing the trend of the IF values that the *HE* entails cleaning/maintenance at an early date. The trending between measured values and predicted values of effectiveness show analogy between the heat transfer rate and corresponding IF. It has been observed that when the heat transfer rate reduces due to fouling, the ε_m values tend to shift towards the ε_f values and when the heat transfer rate is high/closer to design values than the ε_m value tend to shift towards the ε_{cl} value showing optimum performance (as is evident from the heat transfer rate trending post maintenance period). It is envisaged that the present approach may be extended to different types of *HE* post minor alteration in the equation of effectiveness, and therefore can serve as a powerful tool in predicting the fouling rate and mitigation of fouling by scheduling maintenance of the *HE* at the initial or predetermined stage of fouling.

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