

Numerical method for heat transfer and fouling analysis of a shell and tube heat exchanger using statistical analysis

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Abstract—Through proper monitoring, problems can be identified and isolated well before the economics of the process are threatened. In contrast to most conventional methods, fouling can be detected when the heat exchanger operates in transient states. Statistical analysis is used to develop a fouling growth model of a heat exchanger subjected to fouling. The statistical analysis was considered for four different types of distributions out of which the lognormal distribution was found to be most suitable. Experiments were conducted with a single pass shell and tube heat exchanger with water both as the hot and cold fluids. The results show that the proposed tool is very effective in detecting critical fouling in a heat exchanger, which can be utilized for predicting the optimal maintenance schedule. Hence, the results of this work can find application in predicting the reduction in heat transfer efficiency due to fouling in heat exchangers that are in operation and assist the exchanger operators to plan cleaning schedules.

Key words: Shell and Tube Heat Exchanger, Threshold Fouling, Fouling Resistance, Cumulative Distribution Function, Reliability

INTRODUCTION

The accumulation of scale, organic matter, corrosion products, coke, particulates or other deposits on a heat transfer surface is a phenomenon called fouling that costs the process industries heavily. These deposits degrade heat exchanger performance over time compared with “clean” conditions at start up. The fouling layer is a conductive resistance to heat transfer that must be accounted for in the design heat transfer coefficient. Fouling thickness and thermal conductivity both contribute to the resistance. Simultaneously reduced cross sectional flow area also increases pressure drop in the fouled region.

Several researchers have worked on theoretical modeling of the fouling behavior in different kind heat exchangers under different operating conditions. Polley et al. presented a logical framework for analyzing chronic fouling problems in refinery pre-heat trains [1,2] and introduced the concept of threshold fouling. Muller-Steinhagen [3,4] give a complete review of the state of the art in the area of fouling mitigation by various techniques. Watkinson and Wilson [5] do a comprehensive review of the chemical reaction fouling due to organic fluids. A new model has been proposed by Nasr and Givi [6] that includes terms for fouling formation and removal. This model has also reported the fouling behavior and drawn threshold curves to identify fouling and no fouling formation zones. Negrao et al. [7] have shown prediction of heat exchanger effectiveness from classical literature relations as a function of NTU and heat capacity ratio.

To enforce compliance with critical pressure and operational criteria, heat exchangers must be cleaned often according to a regular maintenance schedule [8]. The scheduling of cleaning interventions

can be based on the prior knowledge of the time behavior of the thermal resistance deposits in the individual exchanger [9,10]. As fouling is usually not visible from outside the industrial processing equipment, a direct method of measurement of the fouling developed on the heat transfer surfaces of a heat exchange device is almost impossible. This can only be ascertained and quantified from its effects on various performance parameters of a heat exchanger [11,12].

The classical detection methods are based on study of the heat transfer coefficient or the effectiveness, temperature measurements, ultrasonic or electrical measurements and weighing of heat exchanger pipes [13,14]. But to get accurate results, these methods require the system to present successive steady states, which is far too restrictive or costly.

The drawback of these techniques is mainly due to limited number of sensors which can detect only localized fouling. Although these temperatures can be useful for trending, there are many factors that can affect this calculation, including variable process heat loads, different temperature levels in different seasons, and even the accuracy of thermocouples used. Because this method involves subtraction of two large numbers, accurate measurement techniques and equipment are also critical.

The aim of this paper is to alert the user before a significant degradation of the heat exchanger occurs. This gives an indication when the preventive maintenance can be carried out so that the life time of the device can be increased efficiently. When fouling cannot be avoided, it can be monitored. A good service program can monitor several critical heat exchangers in a system to prove the performance of a heat exchanger. Through proper monitoring, problems can be identified and isolated long before the economics of the process are threatened. This work introduces the statistical approach to develop fouling growth models which can be used for optimal maintenance schedule of the exchangers.

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MODELING OF FOULING PROCESS

Fouling can be determined by measuring the increase in overall heat transfer resistance, which is the major concern in heat exchangers. The overall heat transfer resistance is the sum of conductive and convective heat transfer resistance. For a clean tube, at time $t=0$, the conductive resistance of the deposit is zero so that the convective resistance is equal to the overall heat transfer resistance. At any time, $t>0$, the relative contribution of conductive and convective resistance to overall heat transfer resistance will depend on the type of deposit accumulated on the heat transfer surface.

Regardless of the type of fouling process, the net fouling rate is the difference between the foulant deposit rate m_d and the foulant reentrainment rate m_r . Hence the mass of foulant deposited on the heat transfer surface over a given period of time can be expressed as [15]

$$\frac{\partial m(s,t)}{\partial t} = m_d(s,t) - m_r(s,t) \tag{1}$$

Eq. (1) can be reformulated in terms of mass per unit heat transfer area for a uniform spatial distribution of deposit.

$$\frac{dM}{dt} = M_d - M_r \tag{2}$$

Furthermore, mass per unit heat transfer area considering uniform distribution of fouling along the heat transfer surface can be expressed as

$$M_d = \rho_f \delta_f = \rho_f k_f R_f \tag{3}$$

The fouling resistance R_f represents the thermal resistance of the foulant layer deposited for a unit area of the heat transfer surface. Consequently, fouling rate can be specified as

$$\frac{dM_d}{dt} = \rho_f \frac{d\delta_f}{dt} = \rho_f k_f \frac{dR_f}{dt} \tag{4}$$

It is assumed that both the mass density and the thermal conductivity are invariant with time. Hence the Eq. (4) becomes

$$\frac{dR_f}{dt} = R_{d,r} - R_r \tag{5}$$

Where $R_{d,r} = M_{d,r} / \rho_f k_f$ represents the fouling resistance rate for deposition while $R_r = M_{r,r} / \rho_f k_f$ represents the fouling resistance rate for removal.

The relationship between overall heat transfer coefficient based on tube outside surface area and thermal resistance for a clean heat exchanger can be defined as

$$\frac{1}{U_c} = \frac{1}{h_{o,c}} + R_w \frac{A_o}{A_w} + \frac{1}{h_i A_i} \tag{6}$$

Similarly, for a fouled heat transfer surface the above relation is defined as

$$\frac{1}{U_f} = \frac{1}{h_{o,f}} + R_f + R_w \frac{A_o}{A_w} + \frac{1}{h_i A_i} \tag{7}$$

The model is idealized with the assumptions that $h_{o,c} = h_{o,f}$ and $h_{i,c} = h_{i,f}$ to calculate the overall thermal resistance due to fouling [15].

$$R_f = \frac{1}{U_f} - \frac{1}{U_c} \tag{8}$$

STATISTICAL ANALYSIS

Much of the research in engineering, basic science and industry is empirical and makes extensive use of experimentation. Statistical analysis can greatly increase the efficiency of these experiments and often strengthen the conclusion so obtained [16,17]. The objective of this work is to estimate the time required to reach a threshold level of fouling in a heat exchanger. The threshold fouling [18] can be characterized by the operating conditions and requirements of the application. In this study a statistical analysis is developed to formulate the fouling model of a shell and tube heat exchanger. Analyzing the fouling data over a period of observation, the K-S statistics is utilized to develop the fouling growth model.

For the time required to reach critical fouling level, the cumulative distributive function (CDF) can be given as [19,20]

$$F(t_i) = \frac{i}{N_f + 1} \tag{9}$$

Where $i=1, 2, \dots, N_f$ for the i^{th} event of time to reach the critical level of fouling and $F(t_i)$ is the cumulative value of $F(t)$ at $t=t_i$.

The probability of -ree operation of the exchanger can be expressed in terms of the probability function $R(t)$ defined as

$$R(t) = 1 - F(t) \tag{10}$$

The degree of cumulative damage to the heat exchanger can be expressed in terms of cumulative hazard function $H(t)$ [19,20]

Table 1. Distribution models and their transformation

Model	Probability function	CDF F(t)	X	Y	Parameters
Normal	$\frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{t-\mu c}{\sigma}\right)^2\right]$	$\int_{-\infty}^t f(t) dt = \Phi\left(\frac{t-\mu c}{\sigma}\right)$	t	$\Phi^{-1}[F(t)]$	$\mu_c = -\left(\frac{b}{a}\right)$ $\sigma = 1/a$
Log-normal	$\frac{1}{\sqrt{2\pi}\omega t} \exp\left[-\frac{1}{2\omega^2} \ln\left(\frac{t}{t_0}\right)^2\right]$	$\Phi\left[\frac{1}{\omega} \ln\left(\frac{t}{t_0}\right)\right]$	$\ln(t)$	$\Phi^{-1}[F(t)]$	$t_0 = \exp\left[-\left(\frac{b}{a}\right)\right]$
Exponential	$\lambda e^{-\lambda t} = \frac{1}{\theta} e^{-t/\theta}$	$1 - e^{-\lambda t}$	t	$\ln\left[\frac{1}{1-F(t)}\right]$	$\lambda = \frac{1}{\theta} = a, b = 0$
Weibull	$\frac{m}{\theta}\left(\frac{t}{\theta}\right)^{m-1} \exp\left[-\left(\frac{t}{\theta}\right)^m\right]$	$1 - \exp\left[-\left(\frac{t}{\theta}\right)^m\right]$	$\ln(t)$	$\ln\left[\ln\left[\frac{1}{1-F(t)}\right]\right]$	$m = a, \theta = \exp[-(b/a)]$

$$H(t) = -\ln R(t) \tag{11}$$

Several distributions have been postulated to describe the time required to reach the critical level of fouling in a heat exchanger by probability plotting, parameters estimation or distribution model's validation. This study transforms the equation for the CDF to a form that can be plotted as

$$Y = aX + b \tag{12}$$

The parameters for various distributions can be found by the above transformation. The slope, a, and the intercept, b, of the regression model for various distribution are summarized in Table 1 [19,20].

The coefficient of determination (R^2) is used to determine the ability of a model to interpret the data. It can be expressed as

$$R^2 = \frac{(\overline{XY} - \overline{X}\overline{Y})^2}{(\overline{X^2} - \overline{X}^2)(\overline{Y^2} - \overline{Y}^2)} \tag{13}$$

where $\overline{X} = \frac{1}{N} \sum_{i=1}^N X_i$, $\overline{Y} = \frac{1}{N} \sum_{i=1}^N Y_i$

The various distribution methods are characterized as follows [21].

(i) Exponential distribution:

$$\mu_c = \frac{1}{\lambda} = \theta$$

$$\sigma^2 = \frac{1}{\lambda^2} = \theta^2$$

$$\theta^\pm = \hat{\theta} \exp[\pm 1.018 |Z_{\alpha/2}| N^{-1/2}]$$

For different confidence limits, the value of $|Z_{\alpha/2}|$ takes different values.

Confidence limit	80%	90%	95%	99%
$ Z_{\alpha/2} $	1.28	1.648	1.96	2.58

(ii) Weibull distribution:

$$\mu_c = \theta \left[\left(1 + \frac{1}{m} \right) \right]$$

$$\sigma^2 = \theta^2 \left\{ \left[\left(1 + \frac{2}{m} \right) \right] - \left[\left(1 + \frac{1}{m} \right) \right]^2 \right\}$$

$$\theta^\pm = \hat{\theta} \exp[\pm 1.018 |Z_{\alpha/2}| N^{-1/2}]$$

$$m^\pm = \hat{m} \exp[\pm 1.018 |Z_{\alpha/2}| N^{-1/2}]$$

(iii) Normal distribution:

$$\mu_c^\pm = \hat{\mu}_c \pm |Z_{\alpha/2}| \frac{\hat{\sigma}}{\sqrt{2N}}$$

$$\sigma^\pm = \hat{\sigma} \pm |Z_{\alpha/2}| \frac{\hat{\sigma}}{\sqrt{2(n-1)}}$$

(iv) Lognormal distribution:

$$\mu_c = t_0 \exp\left\{ \frac{w^2}{2} \right\}$$

$$\sigma^2 = t_0^2 \exp(w^2) [\exp(w^2) - 1]$$

$$t_0^\pm = t_0 \exp[\pm |Z_{\alpha/2}| \hat{\omega} N^{-1/2}]$$

$$\omega^\pm = \hat{\omega} \pm |Z_{\alpha/2}| \frac{\hat{\omega}}{\sqrt{2(n-1)}}$$

Using the results of the optimum distribution with its parameters, the fouling growth model can be developed by calculating the critical fouling level from thermal analysis of the heat exchanger performance. The thermal analysis of a heat exchanger provides a mathematical relationship linking the heat exchanger performance with the extent of fouling. This provides a practical approach of generating appropriate fouling growth curves in order to adjust the operational parameters for optimal cleaning schedule of a heat exchanger.

Depending on the distribution methods, the fouling growth models can be different. For the lognormal distribution, the fouling growth model is given as

$$R_f(t) = R_f(1) t^\beta \tag{14}$$

where, $R_f(t)$ is the fouling resistance at any instant of time t (day), $R_f(1)$ is the fouling resistance at the start of operation of the heat exchanger corresponding to clean condition and β is the constant assumed for this model.

Fig. 1 [21] shows the algorithm for statistical analysis of a heat exchanger subjected to fouling. The input data of the analysis includes the critical level of fouling, which can be determined by the operating engineers either from thermal analysis, previous experience or some specific standards.

MATERIALS AND METHODS

1. Experimental Set-up

Experiments were conducted on a laboratory scale with a 1-1

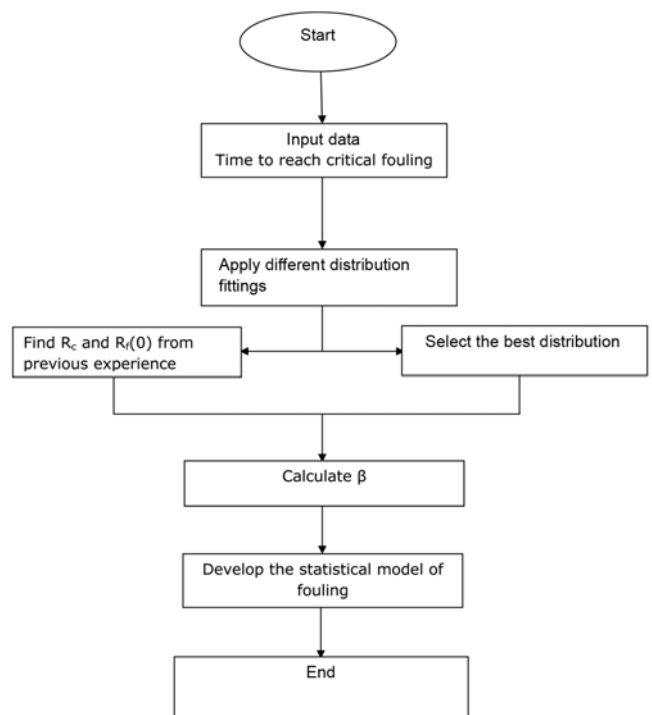


Fig. 1. Statistical evaluation of fouling.

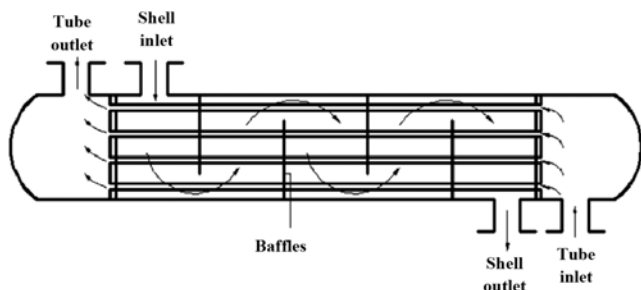


Fig. 2. 1-1 Shell and tube heat exchanger.

shell and tube heat exchanger. Fig. 2 shows the schematic diagram of a 1-1 shell and tube heat exchanger [22]. Fig. 3 shows the complete heat exchanger system including the various measuring instruments used for measurement of different parameters such as temperature and flow rate. The shell and tube heat exchanger consists of a shell of internal diameter 300 mm and 55 copper tubes having internal diameter 9.6 mm and outer diameter 12 mm. The effective tube length is 800 mm. The exchanger consists of four single segmental baffles with 22.5% baffle cut. The data acquisition unit records the inlet and outlet temperatures of the tube and the shell. The cold water is allowed to flow through the tubes while the hot water in the annular area between the shell and the tubes. The water source is common tap water. The flow of the two liquids is counter-current. The second component is the operating program Lab View. Lab View sets the hot and cold water flow rates in liter per hour, and monitors the cold and hot inlet and outlet temperatures.

The hot water used for the experiments was produced by using a geyser with a cut-off temperature of 100°C. Hot water from the geyser flows through the shell via a rotameter which measures the flow rate. The hot water is pumped through the annular area by means of a 0.25 hp pump. The attached rotameter measures the cold water flow rate. The inlet and outlet temperatures for both the hot and cold

fluid are measured with thermocouples and read from a digital temperature indicator.

2. Experimental Procedure

The experiments were conducted with normal tap water both as the cold fluid while the hot fluid was hard water having hardness within a range of 500 to 550 ppm of NaOH. The geyser used for heating the water was set with a cut-off temperature of 100°C. For every set of data we waited until steady state was reached. At the steady state the inlet and outlet temperatures of both the hot and cold fluids do not change for a particular flow rate. The experimentation involved four major steps.

First, the operating boundaries of the heat exchanger were determined. Then the heat exchanger was operated at various combinations of cold and hot water flow rates ranging from 1200LPH to 5000LPH. An operating space was determined, taking into account the hot water temperature corresponding to various hot water flow rates. In a further step, initial trials were conducted keeping the hot water flow rate constant while varying the cold water flow rates. After each increase in cold water flow rate, we waited until the flow rates reached steady state. Then in the next time, step 2 was repeated except the cold water flow rate was maintained constant and the hot water flow rate was varied. The procedure of steps 2 and 3 were repeated a few times to achieve steady state and to ensure that the data was reproducible. The experimental data includes the temperatures measured at the inlet and outlet of both hot and cold water flow corresponding to various flow rates of both the hot and cold water.

RESULTS AND DISCUSSION

The statistical analysis method is considered in this study for the prediction of fouling in case of the above-mentioned shell and tube heat exchanger. The result of the experimental work was analyzed by statistical approach for prediction of the time required to reach critical level of fouling. The results of the statistical analysis are

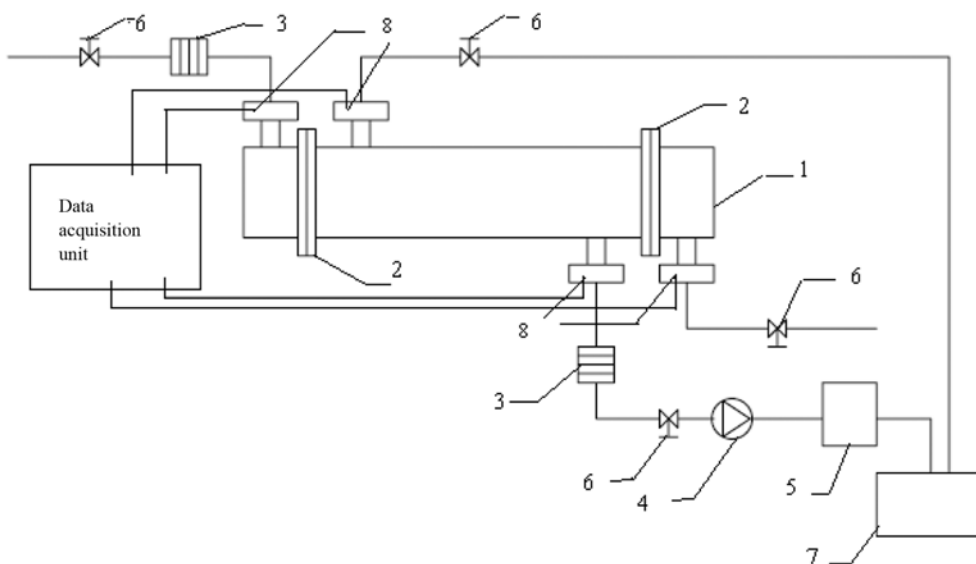


Fig. 3. Schematic diagram of experimental set-up.

- 1. Heat exchanger
- 2. Tube sheet
- 3. Rotameter
- 4. Pump
- 5. Electrical heater
- 6. Valve
- 7. Storage tank
- 8. Temperature sensor

Table 2. Statistical functions for the fouling cycles

Fouling cycle	Time (days)	Cumulative distribution function F(t)	Reliability R(t)	Cumulative hazard function H(t)
1	40	0.091	0.909	0.095
2	64	0.182	0.818	0.201
3	87	0.273	0.727	0.318
4	93	0.364	0.636	0.452
5	102	0.455	0.545	0.606
6	129	0.545	0.455	0.788
7	142	0.636	0.364	1.012
8	145	0.727	0.273	1.299
9	148	0.818	0.182	1.705
10	164	0.909	0.091	2.398

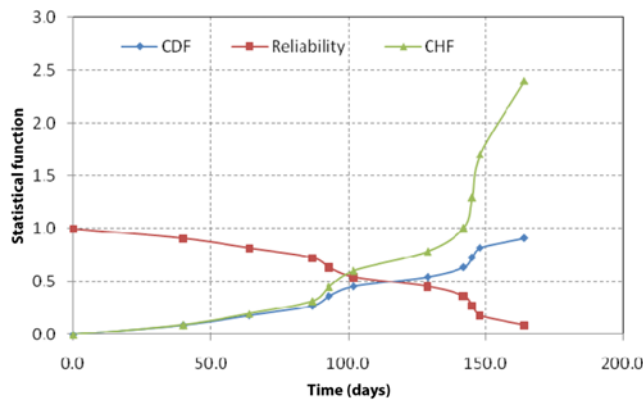


Fig. 4. Statistical functions for the fouling cycles of heat exchanger.

summarized in the Tables 2 and 3. The whole experimentation work is divided into 10 fouling cycles. The statistical functions are represented in Fig. 4, which illustrates the fouling behavior and the possible failure of the exchanger for different kinds of statistical distributions. It can be observed that the efficiency of operation of the exchanger is reduced with progress of time. Simultaneously, the fouling growth increases in a slower rate at the beginning of operation, while it improves rapidly after a certain period of time.

The statistical data for different distributions are illustrated in Fig.

Table 3. Statistical distributions for fouling cycles

Fouling cycle	Time (days)	F(t)	Normal distribution		Log-normal distribution		Exponential distribution		Weibull distribution	
			X	Y	X	Y	X	Y	X	Y
1	40	0.091	40	-1.54	3.69	-2.12	40	0.1	3.69	-1.54
2	64	0.182	64	-1.16	4.15	-1.66	64	0.22	4.15	-1.16
3	87	0.273	87	-0.69	4.46	-1.17	87	0.36	4.46	-0.69
4	93	0.364	93	-0.44	4.53	-0.84	93	0.54	4.53	-0.44
5	102	0.455	102	-0.12	4.62	-0.46	102	0.77	4.62	-0.12
6	129	0.545	129	0.12	4.85	-0.12	129	0.98	4.85	0.12
7	142	0.636	142	0.44	4.96	0.14	142	1.24	4.96	0.44
8	145	0.727	145	0.69	4.98	0.37	145	1.68	4.98	0.69
9	148	0.818	148	1.16	5.0	0.52	148	2.46	5.0	1.16
10	164	0.909	164	1.54	5.1	0.84	164	3.62	5.1	1.54

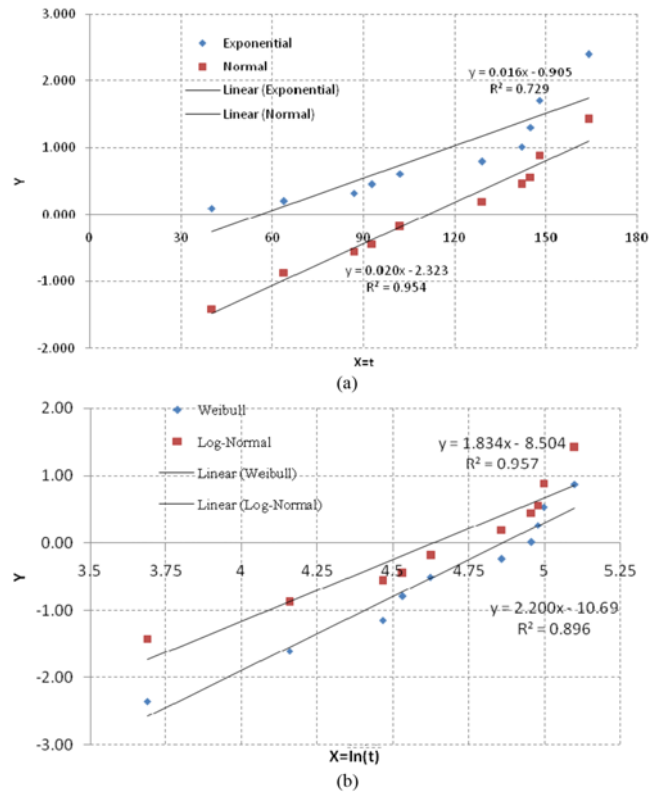


Fig. 5. (a) Exponential and normal distribution for fouling. (b) Weibull and log-normal distribution for fouling.

5(a) and 5(b). All the distributions are fitted with linear functions, and the corresponding fitted equation, coefficient of determination and the goodness of fit test results are summarized in Table 4. The coefficient of distribution for lognormal distribution is highest as compared to the other distributions. As illustrated in the Fig. 5(a) and 5(b), the exponential distribution is weakest, having lowest coefficient of determination 0.729, while the lognormal distribution is having a highest value of coefficient of distribution equal to 0.957. Hence, in this study the lognormal distribution is considered for analysis of the statistical model for fouling formation.

All data taken during the whole period of experimentation is divided into 10 cycles. In the present study, only six cycles are consid-

Table 4. Straight line fit results of statistical distributions

Distribution	Fitted equation	Coefficient of determination (R ²)	K-S modified test statistic
Normal	Y=0.020X-2.323	0.954	0.418
Log-normal	Y=1.834X-8.504	0.957	0.354
Exponential	Y=0.016X-0.905	0.729	0.372
Weibull	Y=2.2X-10.69	0.896	1.024

ered for analysis. The average value of fouling resistance considering the thermal analysis of six fouling cycles is found to be 0.000186 m²·K/W. The critical level of fouling for any particular heat exchanger can be determined depending on the process requirements and operating conditions. In the present equipment studied, the critical level of fouling is taken to be 0.00125 m²·K/W based on previous experience. The mean time required to attain the critical level of fouling based on log-normal distribution is found to be 106.4 days.

The log-normal distribution can be expressed as a power law function $R_f(t)=R_f(1)t^p$ which represents the fouling growth in the present study. The average fouling growth using statistical analysis is derived to be

$$R_f(t)=0.000186t^{0.9206} \quad (15)$$

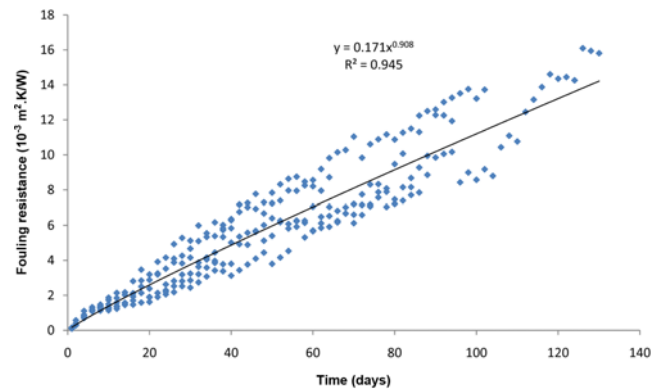
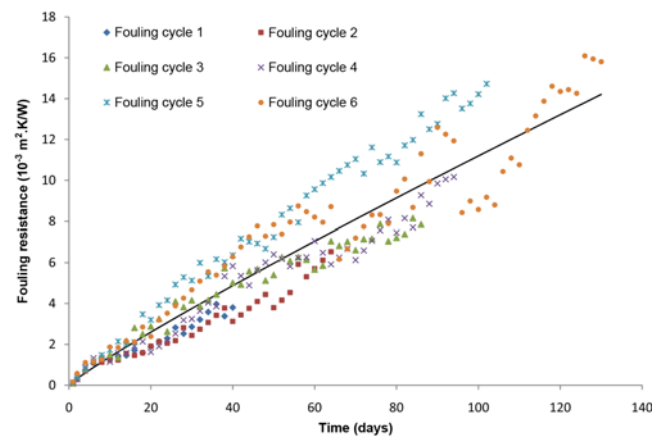
Fig. 6 indicates the thermal analysis of all the fouling cycles under consideration and fitted with a single regression line of power equation law. The coefficient of determination for this distribution is 0.945, which indicates a good accuracy of fitting of the results. The thermal analysis of all the six cycles gives a power distribution law as

$$R_f(t)=0.000171t^{0.908} \quad (16)$$

The comparison between the statistical analysis and the thermal analysis is illustrated in the Table 5. It indicates a variation of maximum 8.7% in the study of fouling growth over a span of 120 days. Hence the accuracy of statistical approach can be considered quite reasonable as compared to the thermal analysis of fouling growth in a heat exchanger. All the data from thermal analysis for the whole 10 cycles are presented in Fig. 6. Fig. 7 illustrates the comparison

Table 5. Comparison of statistical and thermal analysis

Time (days)	R _f (t) from statistical analysis	R _f (t) from thermal analysis	% Difference
1	0.000186	0.000171	8.77193
10	0.001484	0.001384	7.279523
20	0.002774	0.002596	6.834286
30	0.003998	0.003752	6.574697
40	0.005183	0.004872	6.390898
50	0.006338	0.005966	6.24855
60	0.007471	0.00704	6.132386
70	0.008586	0.008097	6.034269
80	0.009685	0.009141	5.949349
90	0.010771	0.010173	5.874502
100	0.011844	0.011194	5.807593
110	0.012908	0.012206	5.747103

**Fig. 6. Fouling growth results for all cycles.****Fig. 7. Comparison of fouling growth results with model.**

of the results from the present statistical model and those of thermal analysis for the six fouling cycles considered for analysis in this present study.

CONCLUSION

In the present study the statistical analysis is used as an invaluable tool for investigation of performance of a shell and tube heat exchanger under fouling condition. The statistical analysis can be used for optimal cleaning schedule in chemical process industries so that the idle time can be reduced to possible minimum and simultaneously the heat exchanger running with poor performance can be avoided. The statistical analysis gives an indication of the extent of fouling on the heat transfer surface, which cannot be estimated from the outside of the exchanger body. Hence, this can be used for prediction of fouling without opening the exchanger, which is very much a complicated process. Thus systematic statistical analysis provides an effective means for prediction of decrease in heat transfer efficiency for effective preventive maintenance scheduling of the heat exchanger cleaning. This can be used for continuous monitoring of a heat exchanger system and improved maintenance scheduling.

NOMENCLATURE

A_c : heat transfer area under clean operating conditions [m²]

A_f : heat transfer area under fouled conditions [m^2]
 c_p : specific heat of both fluids [$J/kg \cdot ^\circ C$]
 $F(t)$: cumulative distribution function
 $H(t)$: cumulative hazard function
 $h_{i,c}$: heat transfer coefficient of fluid inside the tube under clean condition [$W/m^2 \cdot K$]
 $h_{i,f}$: heat transfer coefficient of fluid inside the tube under fouled condition [$W/m^2 \cdot K$]
 $h_{o,c}$: heat transfer coefficient of fluid outside the tube under clean condition [$W/m^2 \cdot K$]
 $h_{o,f}$: heat transfer coefficient of fluid outside the tube under fouled condition [$W/m^2 \cdot K$]
 K-S : Kolmogorov-Smirnov
 k_f : thermal conductivity of foulant layer [$W/m \cdot ^\circ C$]
 LPH : liter per hour
 m : net mass fouling rate [kg/sec]
 m_d : mass deposit rate of foulant [kg/sec]
 m_r : mass removal rate of foulant [kg/sec]
 m_1 : mass flow rate of hot fluid [kg/sec]
 m_2 : mass flow rate of cold fluid [kg/sec]
 M : mass of foulant per unit heat transfer area [$kg/m^2 \cdot sec$]
 M_d : mass deposit rate of foulant per unit heat transfer area [$kg/m^2 \cdot sec$]
 $R(t)$: reliability function
 R^2 : coefficient of determination
 R_c : clean overall heat transfer resistance [$m^2 \cdot K/W$]
 R_d : rate of fouling deposition rate [$m^2 \cdot K/J$]
 R_f : total fouling resistance [$m^2 \cdot K/W$]
 R_r : rate fouling removal rate [$m^2 \cdot K/J$]
 U_c : overall heat transfer coefficient for clean surface [$W/m^2 \cdot K$]
 U_f : overall heat transfer coefficient for fouled surface [$W/m^2 \cdot K$]
 ρ_f : foulant mass density [kg/m^3]
 δ_f : thickness of foulant layer [m]
 σ^2 : variance of distribution
 β : power of fouling power law model
 μ : mean of distribution

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