Investigation of Fouling and its Impact in Heat Exchangers

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Abstract

As heat transfer device, heat exchanger has gained wide applications across different areas of domestic and industrial set-ups. Various studies have been carried out to analyze and predict its performance. However, one major problem that limits heat exchanger performance is fouling effect. Based on this, different studies and approaches have been employed by different researchers on reduction and mitigation of fouling. The following review paper furnishes the different major analysis carried out by different researchers on the effect of fouling of shell and tube type of heat exchanger. The study found that despite of the existing models developed towards understanding fouling, there is no single model that has provided an accurate prediction of fouling in tube and shell type heat exchangers. Further to this, majority of the study results only pointed to small scale laboratory test schemes and there is absence of sufficient data that predicts actual (real life) service performance.

Key words: Heat Exchanger, Heat Transfer, Energy System, Fouling model, Mitigation

I.   Introduction

The fouling of heat exchangers may be defined as the accumulation of unwanted deposits on heat transfer surfaces. The layer of foulant formed on heat transfer surface offers an additional resistance to heat transfer. It also results in the reduction of the flow area which increases the flow velocity for a given volumetric flow rate. Moreover, the deposit is usually hydro-dynamically rough and offers additional resistance to the flow of the fluid across the deposit surface. Therefore, the effects of fouling are, in general, a reduction in exchanger efficiency and excessive pressure drop across the exchanger including other associated operating problems. In recent years that the problem of heat exchanger fouling has attracted scientific and theoretical treatment and many aspects remain to be investigated. In some heat exchangers fouling occurs rapidly, in others the equipment may operate for long

periods, perhaps several years, before a problem becomes apparent. Much depends on the particular fluid and the conditions under which the exchanger operates. The nature of deposits is extremely variable. In some examples, deposits are hard and difficult to remove and in other accumulations are soft and removal. It is usual to find that deposits are made up of different components. The deposit associated with cooling water, for instance, may include: corrosion products, particulate matter, crystals and living biological material. The extent of each of the components in the deposit will depend on many factors including the origin of the water, its treatment and the processing conditions. It is possible that one component is dominant, e.g., scales formation or corrosion. Because of this extremely variable quality of deposits, it has become common practice to consider different fouling mechanisms in the development of techniques to mitigate the problem.

II. Different mechanisms of fouling

There are six different mechanisms have been identified that give rise to fouling problems in heat exchangers. They include:

1. Crystallization or precipitation fouling is generally occurred by the deposition of dissolved salts from saturated solutions (such as $CaCO_3$, $CaSO_4$, or Na_2SO_4 in water) due to changes in solubility with temperature on a heated surface. The deposition of inverse solubility salts (e.g., $CaCO_3$, $Mg_2(SO_4)$) on heated surfaces is known as scaling and the deposited layer is hard and tenacious. On the other hand the deposition of normal solubility salts (e.g., $NaCl$ or Na_2SO_4) on cooled surfaces forms porous layers and it is called sludge or powdery deposit.

2. Particulate fouling is defined as the collection of solid particles suspended in a fluid onto a heat transfer surface. Particles may be small (i.e., < 1 μm) or may be large (i.e., several mm). Particulate fouling is common in both liquid and gas systems.

3. Biological   fouling is   the   accumulation   of microorganisms, plants, algae, or animals on heat exchanger surfaces. The phenomenon usually associated with water systems, e.g., cooling water, contains both microorganisms and macro organisms. The former may include bacteria, yeasts, fungi or algae, while the latter includes mussels and barnacles.

4. In case of chemical reaction fouling a heat exchanger's surface can also become cluttered with unwanted deposits due to fouling from chemical reactions in the fluid stream. The effect of heat on a process fluid, as it passes through the exchanger, may accelerate chemical reactions, e.g. cracking or polymerization reactions that can give rise to deposition on the surface. In some cases the metallic surface of the heat exchanger acts as a catalyst thereby accelerating the fouling process. Systems in petroleum processing and food processing are particularly prone to chemical fouling. Chemical reaction fouling is usually associated with liquids but it may also occur in vapour or gas streams.

5. In some applications heat exchange materials of construction are subject to corrosion due to the aggressive nature of the fluids or impurities in the fluids in contact with the surface. Due to the corrosion process there is formation of a thick corrosion layer. Corrosion fouling may be observed in both liquid and gas systems.

6. Freezing fouling occurs in cooling operations. Freezing of a liquid at the cold surface of the heat exchanger is known as freezing fouling. The frozen layer represents a resistance to heat transfer. For instance, freezing fouling may occur during the production of chilled water.

3. Effects of fouling:

The presence of a deposit on the surfaces of a heat exchanger gives rise to different problems. The efficiency of the heat exchanger is reduced in respect of heat transfer due to the thermal resistance of the deposit. In general, the thermal conductivity of deposits is very much lower than metals so that even a thin layer can result in significant increase of thermal resistance. Generally the surface of the foulant layer is rough compared to the original metal surface. Rough surface increases the heat transfer rate due to the increased turbulence generated by the roughness elements and also offsets the effects of increased thermal resistance across the heat exchanger to some extent. However, the benefits, due to the presence of rough fouling layer, are relatively small in comparison with the restrictions to heat flow offered by the insulating properties of the foulant. These deposits reduce the heat recovery and can restrict fluid flow in the exchanger by narrowing the flow area. For the same flow rate across the heat exchanger fouling results in increasing the flow velocity due to reduction in flow area. Increase in flow velocity causes significant pressure drop in heat exchanger. The flow velocity has a strong influence on the fouling rate where it has direct effects on both the deposition and removal rates through the hydrodynamic effects such as the eddies and shear stress at the surface. It is also well established that, increasing the flow velocity tends to increase the thermal performance of the exchanger and decrease the fouling rate. Uniform and constant flow of process fluids past the heat transfer surface favours less fouling. Foulants suspended in the process fluids will deposit in low-velocity regions, particularly where the velocity changes quickly, as in heat exchanger water boxes and on the shell side. Higher shear stress promotes dislodging of deposits from surfaces. It is possible to reduce the tendency of sedimentation and accumulation of deposits onto a heat transfer surface by maintaining relatively uniform velocities across the heat exchanger.

Reduced heat transfer and increased pressure drop under fouled conditions can have significant implications for energy utilization on the process plant. Fouling effects have huge implications in terms of cost of operation. The economic penalties of heat exchanger fouling on the financial performance are due to the presence of deposits that may not always be recognized at the design stage, or during subsequent operation. Fouling can be controlled but cannot be prevented.

Controlling of fouling is costly and time consuming. Considering fouling in an idealized way four different curves may be obtained if R_f (fouling resistance) is plotted against time as shown in Fig 1 [X].
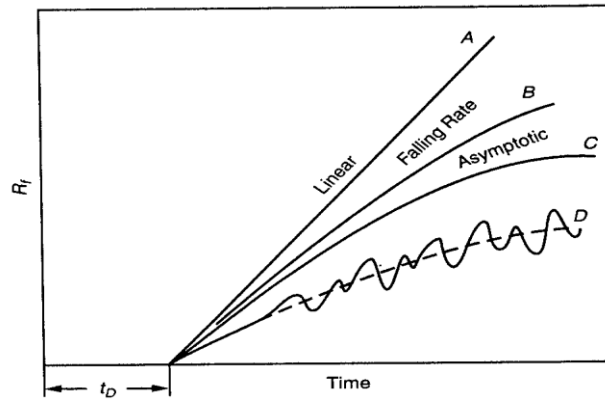
Fig 1: Typical Fouling resistance vs. time curve

The delay time, t_D indicates initial delay period during which no fouling occurs. Slope of the curve is given by the equation (1).

$$\frac{dR_f}{dt} = \phi_d - \phi_r \qquad (1)$$

Where Φ_d and Φ_r represents deposition rate and removal rate respectively. If both deposition rate Φd is constant and removal rate is negligible, $\Phi_r \approx 0$ or difference between deposition and removal rate is constant ($\Phi_d - \Phi_r =$ constant) then fouling resistance vs time curve results in a straight line (A). Falling rate curve (B) may result from decreasing deposition rate (Φ_d) with constant or decreasing removal rate (Φ_r). Asymptotic fouling curve (C) may result from a constant deposition rate (Φ_d) and the removal rate (Φ_r) being directly proportional to the deposit thickness until $\Phi_{d=}\Phi_r$ at t asymptote. Periodic change in operating condition results in the sawtooth configuration shown in curve D.

III.   Literature Review:

Fouling in tube and shell heat exchangers has been the subject of intensive research by different groups of researchers. Therefore many mathematical models to represent fouling have been developed to predict the fouling rates as a function of key design and operational parameters. Kern et al. [XI] suggested that the net fouling rate is the difference between the rates of deposition and removal. The basic differences between various models reported in literature are in the description of the deposition and removal rate terms. The rate of deposition is described either by a transport-reaction model or reaction model while the rate of removal is described either by shear-related or mass transfer related expressions. In general, transport-reaction models are more rigorous than the reaction models. Watkinson et al. [XXIII] described the fouling results from experiments in gas oil fouling and developed a model for gas oil fouling. The model focused on the deposition of particles on the

heat transfer surfaces in two-step process (1) transport then (2) adhesion. It was observed by them that the deposition rate was proportional to both the mass flux and the adhering probability. They have suggested a modification by defining the mass flux as a mass convection equation considering the concentration of foulant on the surface of deposit. Ruckenstein et al. [XIX] in their study described a model that separates the resistance of the transport and attachment for deposition of particles for turbulent flow considering both momentum and molecular diffusion step. The objective of their study was to develop a model that could predict the deposition rate of colloidal particles by considering the effects of diffusion, convection, and interaction forces. The attachment model considered the effect of surface particle interactions and the forces required by the particle to overcome the resultant forces acting on it to attach. The result of this model was two separated resistances, one for each process. This model attempted to quantify the actual forces rather than just expressing the resulting interactions as a probability term. Crittenden et al. [III] developed a transport-reaction model by considering chemical reaction as well as the transport of fouling precursor to and from the heated surface. They further modified their model which included a back-diffusion term [IV]. The modified model described the transport of precursor mass flux to the heat transfer surface as

$$N_r = \rho_f \, \lambda_f \frac{dR_f}{dt} + C_3 \frac{\tau}{\chi} R_f \qquad (2)$$

Where ρf and λf are the deposit constant and thermal conductivity respectively, τ is the shear stress, χ is the deposit strength and C3 is a constant. They carried out tests in a circulation system where the crude oil is circulated through an annular test section at different velocities ranging from 0.91 to 3.1 m sec-1and at two temperatures of 149 and 204°C. But they were unable to justify the reason behind the requirement of finite concentration of foulant at the surface for back diffusion to occur.

Epstein et al. [VIII] developed another model for initial chemical reaction fouling at the heat transfer surface considering fouling rate to be proportional to the time of residence of the surface attachment at the fluid surface. The greater the residence time, the greater would be the opportunity for chemical reaction to occur. The mathematical relationship for initial fouling rate and the mass flux is given as.

$$\left[\frac{dR_f}{dt}\right]_{t=0} = \frac{m\emptyset}{k_f \rho_f} \qquad (3)$$

Where m is the stoichiometric factor, ρ_f is the foulant density and k_f is the thermal conductivity of the foulant and Φ is the deposition mass flux.The driving force for the mass transfer from the bulk fluid to the surface of foulant precursor was expressed as the difference between its bulk and surface concentrations, C_b and Cs, respectively.

$$\varphi = \frac{C_b}{\frac{kSc^{2/3}}{uf^{1/2}} + \frac{k\prime\rho u^2 f}{\mu \exp{(-E/RT_S)}C_s^{n-1}}}$$

(4)

where, k and k′ are two constants, Sc is Schmidt number, f is the friction factor, ρ is the fluid density, u is fluid velocity, E is activation energy, Ts is the bulk temperature, R is universal gas constant μ is dynamic viscosity of fluid and n is the order of the reaction plus attachment process. It was also able to explain the effects of temperature and velocity. However the order of the reaction term n and Sc are unknown for the crude oil fouling. It is also quite difficult to isolate the key precursors of fouling as the crude oil has complex compositions and this creates difficulty in finding out the concentration of exact precursor and its role in fouling. Therefore this model was not able to be used for describing the crude oil fouling.

Ebert et al. [VII] introduced the concept of threshold fouling models for quantifying and mitigating of fouling in crude oil processing. They reported a model of the fouling process as a rate equation by introducing the theoretical concept of fouling and threshold temperature. The threshold temperature is the temperature at which fouling is minimum. The numerical model allowed to predict operating conditions where the fouling rate would be close to zero termed as fouling threshold. This model was based on three assumptions such as (1) The foulant forming reactions occur in the thermal boundary layer at a mean film temperature (T_f) (2) The foulant is transported by diffusion and turbulence eddies from the boundary layer to the bulk flow (3) The net rate of deposition is the difference between the rate of formation and rate of removal. The semi-empirical model for predicting the linear rate of fouling as a function of film temperature and fluid velocity is given as:

$$\frac{dR_f}{dt} = \propto Re^\beta exp\left[-\frac{E}{RT_f}\right] - \gamma\tau_w$$

(5)

Where α, β, E and γ are constants to be obtained from the experimental data. For crude oil fouling, the constants were found to be β = −0.88, E = 68kJ/mol, α = 8.39 m^2K/J and γ = 4.03×10^{-11} m^2K/J. This model was used to predict the operating conditions where the fouling rate would be close to zero. The model was derived considering the effects of crude oil density and viscosity and ignored the effects of thermal conductivity, specific heat of the crude oil. Panchal et al. [XVII] modified the model by incorporating the Prandtl number. The revised model was given as

$$\frac{dR_f}{d_t} = Re^\beta P_r^{-0.33}\left(\exp\frac{-E}{RT_f}\right) - \gamma\tau_w$$

(6)

The value of β was assumed to be -0.66 and the film temperature T_f, was determined in terms of surface temperature (Ts) and bulk temperature (Tb) as

$$T_{f=} \ T_b + 0.55 \ (T_s - T_b) \tag{7}$$

Polley et al. [XVIII] developed another threshold models for crude oil fouling. This model incorporated simple modifications to the model developed by Ebert et al. [VII] considering wall temperature instead of film temperature in the reaction term and retained the dependency of velocity in form of Reynolds number in the generation term. In this model they considered the removal term based on the wall shear stress and suggested a physical mechanism to remove deposit from the tube wall. They also suggested that prior to deposit formation, the mechanism for opposing fouling is associated with a mass transfer process rather than one associated with wall shear stress. The presented model was given as

$$\frac{dR_f}{d_t} = \alpha Re^{-0.8} P_r^{-0.33} \left(exp \frac{-E}{RT_w} \right) - \gamma Re^{0.8} \tag{8}$$

Considering laboratory crude oil fouling data of a refinery preheat train, the constants of this model were found out to be $\alpha = 10^6 m^2 K/Wh$, $\gamma = 1.5 \times 10^9 m^2 K/Wh$ and $E = 48 kJ/mol$.

Saleh et al. [XX] studied the effect of fluid properties and operating conditions to predict a fouling mitigation strategy. Series of experiments were carried out to examine the effect of operating conditions on the fouling using light crude oil of an Australlian refinery. All these experiments were performed at different operating conditions. The ranges for the operating variables are as follows: velocity 0.25–0.65 m/s, surface temperature 180–260°C, bulk temperature 80–120°C, and pressure from 379– 655 kPa. They reported that the fouling rates were strongly influenced by surface temperature and bulk temperature. It was also reported that the fouling rate was practically independent of pressure and a decrease in the fouling rate was recorded with increase in velocity. They also reported that an increase of 80°C resulted in tripling of initial fouling rate and the average fouling rates for the crude oil were in the range of 2 to 6 × 10^{-7} $m^2 K/kJ$.Nasr et al.[XV] proposed another model ignoring the effect of Prandtl number for fouling as given below in equation (9)

$$\frac{dR_f}{d_t} = \alpha Re^{-\beta} \left(exp \frac{-E}{RT_f} \right) - \gamma Re^{0.4} \tag{9}$$

An investigation carried out using their model using the experimental data recorded by Saleh et al. [XX].The empirical constants were taken as $\alpha = 10.98$ $m^2 K/kJ$, $\beta = -1.547$,$\gamma = 0.96 \times 10 m^2 K/kJ$ and $E = 22.618$ kJ/mol. The proposed model is more empirical than the other earlier models because the numerical value for β has no physical significance. The major disadvantage of this model was that it cannot be used for extrapolation at other operating conditions. Zhenhua et al. [XXV] carried out an experimental study to investigate the fouling process of calcium carbonate in forced convection heat transfer with dynamic monitoring apparatus for fouling resistance. Experiments were carried out using different operating variables such as flow velocity, hardness, alkalinity, solution temperature and heat transfer surface

temperature. They reported to obtain asymptotic fouling curve varying with time. It was also reported by them that decrease in fluid velocity and increase in hardness and alkalinity of the fluid resulted in increased fouling rate.Major mechanisms of fouling were reported to include both crystallization fouling and particulate fouling. Sulaiman et al.[XXII] investigated the effect of fouling on the performance of the shell and tube heat exchanger using the data obtained from operational log book, periodic maintenance data sheet. They reported that the deviation of overall heat transfer coefficient, heat duty, and effectiveness from design values were 24.10%, 26.27%, and 17.17 % respectively in a period of 47 days of operation. Fouling factor was 31.58 % more than the design value. They recommended that periodic maintenance after every 30 days of operation resulted in better performance of the heat exchanger. Mohanty et al. [XIV] in their study used C-factor as a tool to predict the performance of a heat exchanger under fouling condition. C factor was calculated using the recorded data of flow rate and pressure drop. The C-Factor was first calculated throughout cleaning period and then compared with the design value. They suggested that the proposed tool was very effective in predicting the extent of fouling developed and the corresponding reduction in heat transfer efficiency of the heat exchangers and based on these results proper cleaning schedule can also be prepared. Shen et al. [XXI] studied the effects of wastewater velocity and installation location of a shell-and-tube heat exchanger on particle fouling deposited within the heat exchanger. They carried out three long term fouling tests with the heat exchanger installed at the shoot-outlet of a pump with varied wastewater flow rates and one test with the heat exchanger installed at the suction-inlet of a pump at a constant flow rate to study the effect on the heat transfer coefficient and to determine the particle size distribution of the accumulated foulant collected on the heat transfer surface. They reported that the diameters of particles deposited on the tube surfaces were mainly in the range of 1.5–88 μm. The average particle diameter of fouling was 40.8 μm at a velocity of 0.31 m/s (low), 24.4 μm at a velocity of 0.46 m/s (medium), and 18.6 μm at a velocity of 0.69 m/s (high).

In further study Yang et al. [XXIV] studied threshold conditions of crude oil fouling using a batch-stirred cell system (~1litre) at surface temperature of about 400°C and pressure of approximately 30 bar. After substantial fouling on the heat transfer surface, a negative fouling rate was resulted with increase in speed of stirring at a reduced surface temperature as shown in Fig 2.
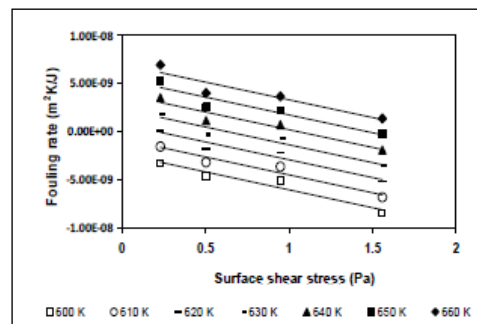

Fig 2: Fouling rate against surface shear stress for various initial surface temperatures

Yang et al.[XVII]reported that fouling threshold condition can be predicted with greater accuracy from the data recorded from experiments. This is achieved by the interpolation of the rate of fouling data as shown in Fig. 3.
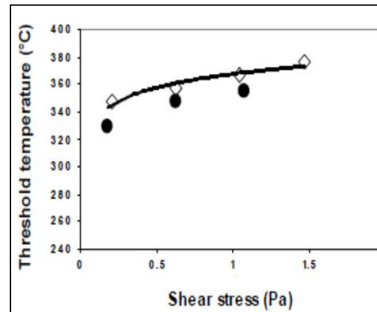

Fig 3 Threshold temperature

IV.   Mitigation of fouling

Cleaning of heat exchangers is one of the simplest strategies used in the industry to address the problem related to fouling. The route is followed only when the cost associated with energy loss due to fouling has become profound. Hence, this becomes a reactive strategy instead of proactive strategy. Nesta et al. [XVI] suggested that in other to mitigate fouling, design of the heat exchanger should maximize shear stress and as well as control wall temperature. In a different approach Klaren *et al*. [XIII] designed a "zero fouling" self-cleaning heat exchanger. A heat exchanger may be defined as "zero fouling" if it works in severe fouling media at both sides of the heat transfer surface and exhibits no measurable decrease in the heat transfer coefficient over a continuous operating period that may last several years. The design was based on the concept that the fouling deposits are removed as they are being formed. Klaren et al. [XII] reported to compare this new zero fouling self-cleaning design with a conventional severe fouling crude oil pre-heater and reported a reduction in required heat transfer surface from 700 m^2 for the conventional exchanger to 229 $m^2$for the newly designed heat exchanger. Benzinger et al. [II] carried out another study to investigate the influence of ultrasound on the fouling of heat exchanger. An electrically heated micro heat exchanger was developed to carry out the experiment. Solution of calcium nitrate/sodium hydrogen carbonate was pumped through the channels of a micro-structured heat exchanger at a mass flow rate of 1.5 kg/h. During flow of the fluid, solid calcium carbonate precipitated of on the surface and which resulted in a reduced heat transfer coefficient. An ultrasonic pulse of 1 min duration was allowed to propagate through the fluid which broke up the fouling layer and the heat transfer coefficient reached again its initial value. Wilson et al. [V] carried out a study to suggest effective cleaning programme for the heat exchanger. They identified the key factors for developing cleaning protocol to mitigate fouling and also highlighted on fouling and cleaning processes for the cases where ageing processes can significantly affect the nature of deposit. Bennett et al. [I]

proposed that fouling mechanisms can be mitigated with proper design strategy. They suggested replacing the fouling factor by additional 20% heat transfer area during design of heat exchanger which will significantly lower capital costs and substantially increase run time between cleanings. In another related study, Ishiyama et al. [IX] reported the development of a highly flexible preheat train simulator constructed in MATLAB/Excel. It was also reported by them that simulation technique can be used successfully for the preparation of cleaning schedules. Demirskiy et al. [VI] reported that fouling mitigation in plate heat exchanger is possible if the wall shear stress can be increased with uniform pressure drop.

V.   Conclusion:

The ultimate desire of any industry where heat exchangers are used is to mitigate the effect of fouling in heat exchangers operating under variable operating conditions. Complete understanding of the concept of fouling and the interactions among various parameters is critical to achieve this. Based on the literatures reviewed, there is no single model that can predict accurately fouling in tube and shell type of heat exchanger.The effective cleaning methodologies and especially self-cleaning methodologies should be investigated further for different types of fluid which can lead to longer operation of a heat exchanger with reduced fouling growth on heat transfer surfaces.

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