

Prediction of Thickness and Fouling Rate in Plate Heat Exchanger of MTR Reactor

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Abstract: Heat exchangers are important and essential components in nuclear reactors and power plants. In this context, studying the performance of heat exchanger under normal and abnormal operational conditions is of great importance relevant to the economic and operational safety in power plants. Fouling and scale formation in heat exchangers could have serious impacts on the operating conditions of the nuclear reactors. This study aims at the simulation of fouling crystallization process in plate-type heat exchanger in MTR reactor by developing an Engineering Equation Solver (EES) Program. The finding of this work would enable us to evaluate the thickness and fouling rate in plate-type heat exchanger in MTR reactor. The crystallization fouling of calcium sulphate (CaSO_4) in plate heat exchanger was also investigated. Also, the effect of fluid velocity on fouling resistance and the rate of deposit thickness were studied in each of primary and secondary circuits.

[A.A. Fahmy, M.M. EL Fawal, and B.M. Taher **Prediction of Thickness and Fouling Rate in Plate Heat Exchanger of MTR Reactor**. Journal of American Science 2012; 8(3): 377-383].(ISSN: 1545-1003).
<http://www.americanscience.org>. 50

Keywords: Fouling; Heat exchanger; Fouling Resistance; Calcium Sulphate.

1. Introduction

Plate type heat exchangers (PHEs) are one of the most efficient types of heat transfer equipment. This equipment is much more compact, requires much less materials for production, much smaller footprint, than conventional shell and tube unit. PHEs have a number of advantages, such as compactness, low total cost, less fouling, flexibility in changing the heat transfer area, accessibility and energy saving. PHE consists of a set of corrugated heat transfer plates clamped together. In multi pass PHE plates are arranged in such way, that they are forming groups of parallel channels. Such group is corresponding to one pass and the stream is going consequently through the passes, as shown in Fig. (1), which presents the main components of a gasket plate heat exchanger. Nowadays, PHEs are used worldwide in all industries such as petroleum industry, food industry, pharmaceutical, nuclear reactors and material industry by replacing shell and tube heat exchangers. PHE is a type of heat exchanger that uses metal plates to transfer heat between two fluids. This has a major advantage over a conventional heat exchanger in that the fluids are exposed to a much larger surface area because the fluids spread out over the plates. This facilitates the transfer of heat, and greatly increases the speed of the temperature change. It is not as common to see plate heat exchangers because they need well-sealed gaskets to prevent the fluids from escaping, although modern manufacturing processes have made them feasible. Plate-type heat exchangers also have higher heat

transfer efficiency; this feature enables smaller plate-type heat exchangers to have the same heat transfer capability as larger shell and tube devices. However, the slow progress made in developing a dependable method of sealing the gaskets located between the plates limits its use for high-pressure applications. Therefore, plate-type heat exchangers work only for low-pressure systems. Improvements in the seal technology do allow for the replacement of older shell and tube exchangers for more efficient plate models.

The advantages of plate heat exchangers are: higher thermal conductivity, higher accuracy of temperature control, lower of contact time, lower construction area, and easier for cleaning than shell and tube heaters [1]. However, disadvantage of plate heat exchangers is fouling formed by CaCO_3 at high operating temperature that caused by flow pattern in plate heat exchanger. Fouling is defined as the accumulation of unwanted materials on the surface of heat exchanger. It has a lot of problems in design and operation such as the low thermal conductivity due to fouling layer and, the reduction of cross-sectional area as deposition occurs, that causes an increase in pressure drop. Particulate fouling has a major problem when sea water and under ground water that contain high amount of calcium ion were used [2-4]. Epstein N. [2] classifies fouling into six types:

1. Particulate fouling,
2. Reaction fouling,
3. Corrosion fouling,

4. Precipitation fouling,
5. Biological fouling and
6. Solidification fouling.

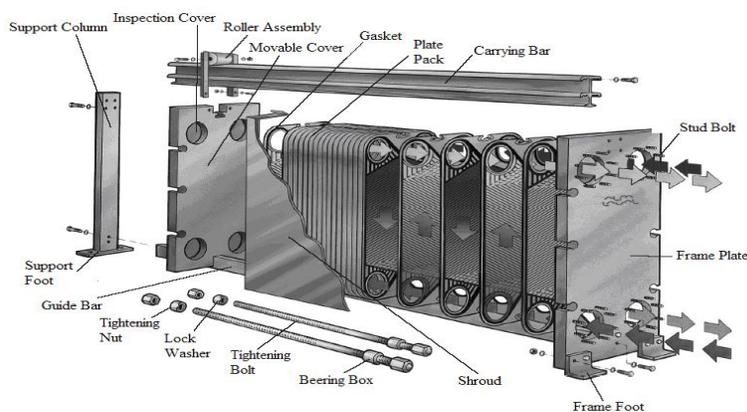


Fig. 1: Main components of gasket plate and frame heat exchanger.

Fouling accumulation on heat transfer impedes the heat transfer and increases the resistance to fluid flow, resulting in higher pressure drop. Industrial heat exchangers rarely operate with non fouling fluids. The growth of deposits causes the thermo-hydraulic performance of heat exchanger to degrade with time. Fouling affects the energy consumption of industrial process, and it can also decide the amount of extra material required to provide extra heat transfer surfaces employed in heat exchanger to compensate for the effects of fouling. In addition, where the heat flux is high, fouling can lead to local hot spots and ultimately it may result in mechanical failure of the heat transfer surfaces. So designers of heat exchanger have to take into account fouling effect and select fouling coefficient in the

current heat exchanger design. Since the fouling on heat transfer surface can significantly deteriorate the performance of any heat exchanger, it should be correctly predicted in calculation of required surface area at the design stage. This is even more important for PHEs with enhanced heat transfer which as a rule have much high film heat transfer coefficients than conventional shell and tube units. Analysis of data available in literature has shown that thermal resistance of Fouling in PHEs is up to ten times lower than recommended by Tubular Exchanger Manufacturers Association (TEMA) for shell and tubes working at same conditions as shown in Table 1[1 and 5].

Table 1: Liquid-Side Fouling Resistances for PHEs vs. TEMA Values [1]

Process Fluid	R_p ($m^2 \cdot K/kW$)	
	PHEs	TEMA
Cooling tower water	0.044	0.18 – 0.35
Steam (oil bearing)	0.009	0.18
Seawater	0.026	0.18 – 0.35
River water	0.044	0.35 – 0.53
Lube oil	0.053	0.36
Organic solvents	0.018 – 0.053	0.36
Soft water	0.018	0.18 – 0.35

1.2 Performance data

As mentioned above, fouling has many effects on the heat exchanger performance. It decreases the exchanger thermal capacity and increases the pressure drop through the exchanger as shown in Fig. (2) [6]. From the figure, it is clear

that the total resistance to heat transfer is decreased during the first stages of fouling due to the surface roughness resulting from initial deposition. After that and with deposits building up, the thermal resistance returns to increase again.

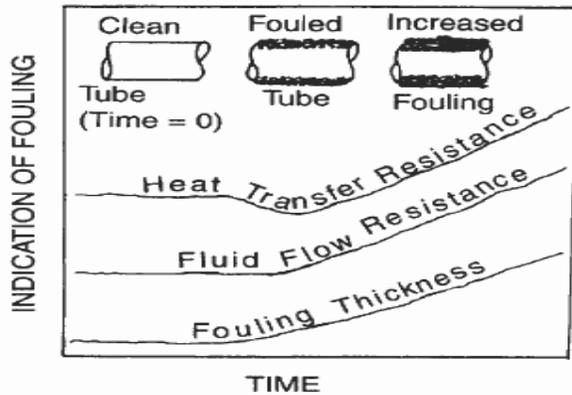


Fig. 2: Fouling effects on exchanger performance [6]

In order to model and predict the industrial processes fouling problems it is first necessary to understand what is happening and what are the causes and effects of fouling. To achieve this, it is necessary to carefully examine and evaluate all the data and operating conditions at various plants in order to understand what the variables which are effective on fouling and what are the mechanisms of such phenomena. The possibility of whether the fouling material is a part of the feed to the system or it is a product of reaction / aggregation / flocculation in the system must be clarified. The role of various operating conditions such as pressures, temperatures, compositions, flow rates, etc. and their variations in the system on fouling must be understood and quantified. Only with appropriate modeling considering all the possible driving forces and mechanisms of fouling one may be able to predict the nature of fouling in each case and develop mitigation techniques to combat that.

Because fouling resistance varies with operation conditions and time, it is needed to know the fouling trends of heat transfer surfaces to determine feasible periodic cleaning of the heat exchanger. Design engineers become more interested in theoretical study of prediction of the fouling process in certain conditions [7]. So some simple and practical models have emerged to estimate the effect of fouling on heat exchanger [8-20]. Most of the existing models only give the initial fouling rate. Clear guidelines and correlations to predict the exact value of fouling in PHE on designing stage are absent. So the aim of this work was to simulate the crystallization fouling process in plate heat exchanger in MTR reactor by developing an Engineering Equation Solver (EES) Program. Also the fouling in PHEs working with water as both heating and cooling media was investigated. The crystallization fouling of calcium sulphate (CaSO_4) in plate heat exchanger and the effect of fluid velocity on fouling

resistance and the rate of deposit thickness were also studied in each of primary and secondary circuits.

2. Fouling Modeling

Fouling is usually considered to be the net result of two simultaneous processes: a deposition process and a removal process. The net rate of fouling can be expressed in terms of the rate of deposition of fouling mass (\dot{m}_d) and the rate of removal (\dot{m}_r) from the heat transfer surface. Thus,

$$\frac{dm_f}{dt} = \dot{m}_d - \dot{m}_r \quad (1)$$

One of the earliest models of fouling was that by Kern and Seaton [11]. In this model, it was assumed that (\dot{m}_d) remained constant with time (t) but (\dot{m}_r) was proportional to (m_f) and therefore increased with time to approach (\dot{m}_d) asymptotically.

$$\dot{m}_d = \beta \times m_f \quad (2)$$

Then integration of Eq. (1) from the initial condition $m_f = 0$ at $t = 0$ gives

$$m_f = m_f^* (1 - e^{-\beta t}) \quad (3)$$

Where m_f^* is the asymptotic value and $\beta = \frac{1}{t_c}$.

The time constant t_c represents the average residence time for an element of fouling material at the heating surface. Equation (3) can be expressed in terms of fouling resistance R_f at time (t) in terms of the asymptotic value R_f^* by:

$$R_f = R_f^* (1 - e^{-\beta t}) \quad (4)$$

Where,

R_f is the fouling resistance ($\text{m}^2 \cdot \text{C/W}$).

R_f^* is the asymptotic fouling resistance. ($\text{m}^2 \cdot \text{C/W}$).

t is the duration time of deposit.

t_c is the time constant, (hr) and is given by.

$$t_c = \psi / \tau \quad k_2 \lambda_f \quad (5)$$

Where,

k_2 is the removal constant.

τ is the fluid shear stress exerted on the deposit surface.

ψ is the strength or toughness of the deposit layer.

The fouling resistance is not usually measured directly, but must be determined from the degradation of the overall heat transfer coefficient.

The fouling factor R_f could be expressed as:

$$R_f = \left(\frac{x_f}{\lambda_f}\right) \quad (6)$$

or

$$R_f = \frac{1}{U_c} - \frac{1}{U_f} \quad (7)$$

From the deposition – removal model, which was first presented by Kern and Seaton [11], the overall heat transfer coefficient of the fouled surface, may be given as:

$$U_f = \frac{U_c}{1 + U_c \times R_f} \quad (8)$$

Then,

$$U_f = \frac{1}{\frac{1}{U_c} + R_f^* \times \left(1 - e^{-\frac{-t}{\tau c}}\right)} \quad (9)$$

The rate of heat transfer in a heat exchanger under clean and fouled conditions is given by the

$$q = U_c \times A_c \times \Delta T_m = U_f \times A_f \times \Delta T_m \quad (10)$$

Therefore,

$$\frac{A_f}{A_c} = \frac{U_c}{U_f} \quad (11)$$

Combining Eqs. (5) and (7), then

$$\frac{A_f}{A_c} = U_c \times R_f + 1 \quad (12)$$

Another important factor which is related to the fouling resistance is the cleanliness factor, CF which is given as:

$$CF = \frac{U_f}{U_c} = \frac{1}{(U_c \times R_f) + 1} \quad (13)$$

Watkinson [12] reported the effect of fluid velocity on the asymptotic fouling resistance in the case of calcium sulphate scaling as follows:

$$R_f^* = \frac{0.101}{v^{1.33} \times D^{0.23}} \quad (14)$$

Where,

v is the fluid velocity.

Sand deposition from water may be calculated as follows:

$$R_f^* = \frac{0.015}{v^{1.2}} \quad (15)$$

Program has been composed using the above equations to calculate the deposit weight and the variation of deposit thickness and fouling resistance with time for both primary and secondary cooling circuits of MTR reactor. Also the variation of fluid shear stress with fluid velocity for primary and secondary circuits is also investigated. The effect of time and velocity on asymptotic fouling resistance has been also investigated. The obtained results are shown below.

3. Results and Discussion

A new heat mass transfer model was developed to predict the fouling process of calcium carbonate on heat transfer surface based on Kern - Seaton model. The present model took into account the effect of operating parameters like, time, concentration and fluid velocity on the scale formation of calcium sulphate. Also the effect of concentration on calcium sulphate deposition has been studied. The obtained results show that the deposition weight of calcium sulphate increases with the increase of concentration due to the increase of fluid particles stickiness probability with flow surface as shown in Fig. (3). Figs. (4 and 5) illustrate the variation of deposit thickness with time for secondary and primary circuits of the heat exchanger, it is clear from these figures that fouling is a time dependent process; hence the deposit thickness increases with increasing time due to the increase of deposit weight of the foulant. Also the calculated results show that fouling resistance of primary side increases with time as shown in Fig. (6). This could be attributed to the accumulation of the suspended particles on the

flowing surface. Hence the thickness of the foulant increases, so its resistance increases.

Figs. (7 and 8) show that the fluid (water) shear stress increases with increasing of fluid velocity in the primary and secondary sides. As the fouling deposit builds up, the cross-sectional area for flow decreases, thus causing an increase in the average velocity of the fluid for a constant mass flow rate and increasing the shear stress. Higher shear stress promotes dislodging of deposits from surface. No doubt that, the fluid velocity is an important parameter in the scale formation process. It can either enhance the diffusion of the foulant species towards the heating surface or accelerate the removal of scale deposit from it. The variation of the asymptotic fouling resistance of calcium sulphate with time for different flowing velocities was investigated and shown in Fig. (9). It was found that foulants suspended in the process fluids will deposit in low velocity regions hence, at low velocity the foulants suspended in the fluid tend to stick with heat transfer area, so the fouling thickness increase with decreasing fluid velocity, hence increasing the fouling resistance. The asymptotic fouling resistance for primary and secondary circuits was studied with respect to the velocity variation. It was found that the increase of flow velocity tends to increase the thermal performance of the exchanger and decrease the fouling rate. The asymptotic fouling resistance value decreases with the increase of velocity till about $0.21 \text{ m}^2 \cdot \text{C} / \text{W}$ at 1.8 m/s for primary side and till about $0.002 \text{ m}^2 \cdot \text{C} / \text{W}$ at 6 m/s for secondary side as shown in Figs. (10 and 11) respectively.

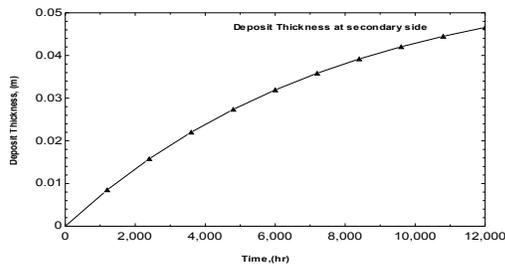


Fig. 3: Variation of deposit weight with concentration.

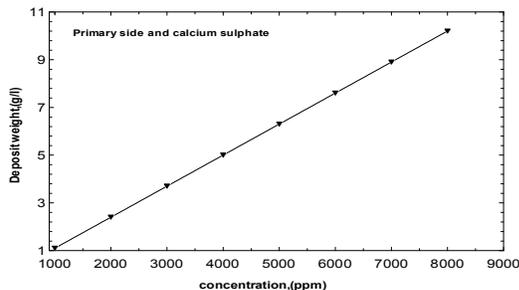


Fig. 4: Variation of deposit thickness with time for secondary circuit.

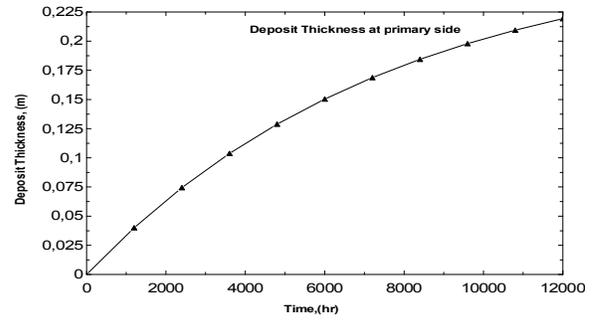


Fig. 5: Variation of deposit thickness with time for primary circuit

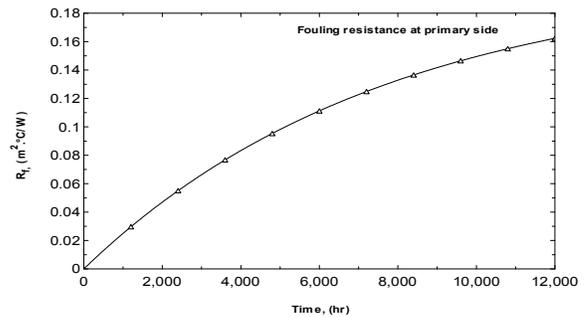


Fig. 6: Variation of fouling resistance for primary side with time.

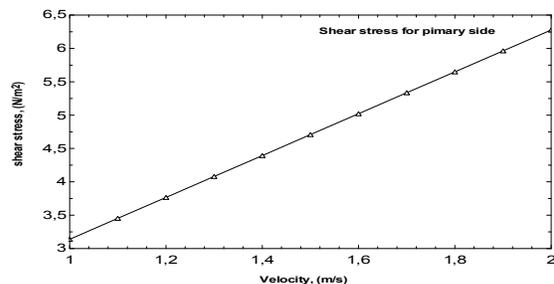


Fig. 7: Variation of fluid shear stress with flowing velocity for primary side.

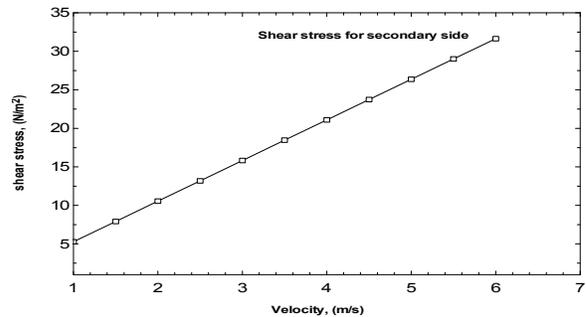


Fig. 8: Variation of fluid shear stress with flowing velocity for secondary side.

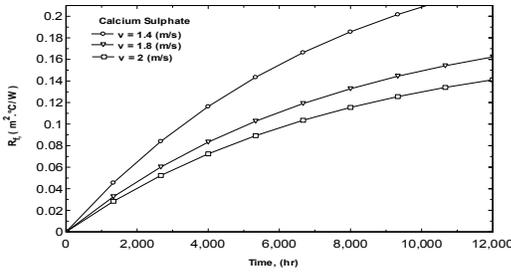


Fig. 9 : Variation of asymptotic fouling resistance with time at different flowing velocity.

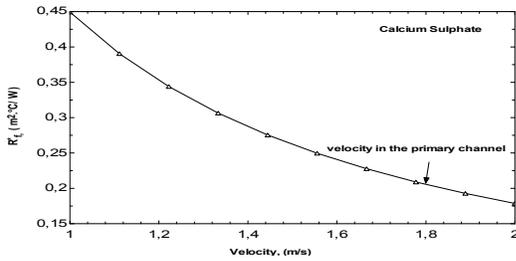


Fig. 10: Variation of asymptotic fouling resistance with flowing velocity for primary side.

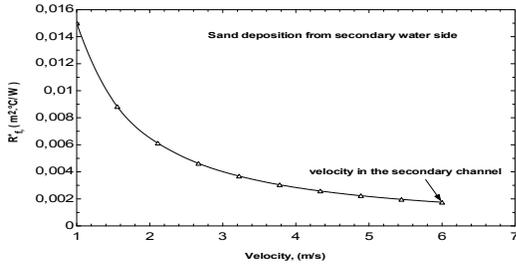


Fig. 11: Variation of asymptotic fouling resistance with flowing velocity for secondary side

Comparisons of the model with experimental data

The variation of the asymptotic fouling resistance with time calculated using the current model was compared with the available experimental data of a typical two pass heat exchanger given by Hasson [16] as shown in Fig. (12). This exchanger had 606 tubes of 19.05 mm outside diameter and 6.1 m. The comparison shows that both calculated and experiment results have the same trend with a deviation which could be attributed to the difference between the exchanger type, the operating condition and also exchanger materials, so the new model could give a good prediction of the fouling process.

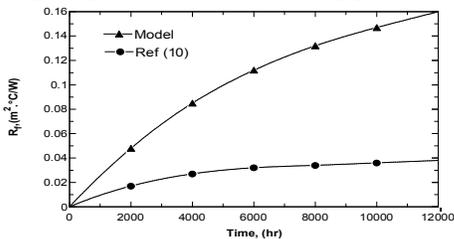


Fig. 12: Comparisons of obtained results of present model and experimental data of ref [10]

4. Conclusion

A new heat mass transfer model was developed to predict the fouling process of calcium carbonate on heat transfer surface based on Kern-Seaton model. The effect of operating parameters like, time, concentration and fluid velocity on the scale formation of calcium sulphate has been taken into consideration in the present model. Also concentration effect on calcium sulphate deposition has been studied. Comparative results of the model with experimental data showed that the present model, has the same trend and in good agreements with results investigated by others, so the new model could be credible to predict the fouling process. Also from the obtained results we could concluded that the scale formation in water is time dependant and has an asymptotic approach.. The velocity of flow can reduce effectively the scale deposit due to the strong effect on the removal mechanism of the scale layer. And with increasing of water velocity in the secondary side the asymptotic value of sand deposition decreases.

Nomenclature:

- A Heat transfer surface area (m²)
- A_C Heat transfer surface area for clean condition (m²)
- A_f Heat transfer surface area for fouled condition (m²)
-
- m_d Deposition (kg/m².s)
-
- m_r Removal rate (kg/m².s)
- m_f Accumulate mass (kg/m²)
- R_f Fouling resistance (m².°C/W)
- R_f^{*} Asymptotic fouling resistance (m².°C/W)
- t Time (s)
- t_c Time constant (s)
- U_C Overall heat transfer coefficient in clean condition (W/m². K)
- U_f Overall heat transfer coefficient in fouled condition (W/m². K)
- v fluid flow velocity (m/s)
- D hydraulic diameter (m)
- x_f fouling layer thickness (m)
- q Heat flux (W/m²)
- ΔT_m Logarithmic mean temperature difference (°C)
- MTR Material Testing Reactor
- Greek letters:**
- β Factor (1/hr)
- λ_f Thermal conductivity of fouling layer (W/m.K)

τ Fluid shear stress (N/m²)
 Ψ Deposition strength factor

Subscripts:

c clean condition.
 d deposition.
 f fouled condition.
 r removal.

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