Surface Temperature Effect on Surface Erosion in Heat Exchangers

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ABSTRACT: A theoretical approach showing the effect of surface temperature on surface erosion in heat exchangers has been developed. This approach is based on the basic fouling deposition and removal processes. As a result this study, for each working condition, there was a specific surface temperature, defined as **critical surface temperature**. Below this critical temperature, i.e. the working temperature is less than the critical one, the fouling rate increases with increasing surface temperature and it has the maximum value nearest the critical temperature. Above the critical temperature, i.e. the working temperature is greater than critical one, the fouling rate has a negative sign, and it means that some erosion of the heat transfer surface will be occurred. This erosion has maximum value nearest the critical temperature and decreases with surface temperature. At the critical temperature no fouling and no erosion will be occurred. A new formula describing the critical surface temperature in such process with the concealing affecting parameters has been presented.
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1. Introduction

Erosion of heat transfer surfaces may be occurred due to mechanical, chemical, electrical or thermal effects. In the present study, the thermal effects are considered. The present theoretical approach is deduced from the fouling phenomenon point of view. Fouling is defined as the accumulation of unwanted material on the heat transfer surface and hence increases the surface thickness where erosion eroded the surface and hence decreases its thickness. That is means that fouling and erosion are two faces for one coin but each phenomenon is the inverse of the other. Therefore the parameters that affecting one phenomenon could be affect the other one.

Many investigators have studied both the fouling and erosion phenomena theoretically and experimentally. Kern and Seaton [1, 2] and Kern [3], made the groundwork of the fouling studies. Mostafa *et al.,* [4], experimentally studied the effect of surface temperature on both the precipitation fouling and particulate fouling. They found that the fouling resistance increases with surface temperature in the case of precipitation fouling, where it decreases with increasing surface temperature in the case of particulate fouling. Mostafa [5], in his book chapter, presented a very comprehensive review for the fouling phenomenon. Mostafa [6] introduced a very successful and useful method to overcome the fouling effects in heat exchanger networks (HEN). Recently, Yang *et al.,* [7] constructed a model for the fouling induction period. They found that the shorter induction periods are dealing with higher surface temperature.

During the past years, many achievements have been obtained on deposition and removal models to predict particulate fouling on heating surfaces under inertial impaction. Thornton and Ning [8], and Konstandopoulos [9] studied deposition criteria for particle inertial collision with the tube wall. Feng *et al.,* [10] researched the effect of influence parameters on particle-wall inertial collision deposition. Abd-Elhady *et al.,* [11] proposed that inertial impact speed is the main parameter of collision deposition for particles with a powdery layer. Van *et al.,* [12] developed a two-body collision deposition mechanism for particle impaction with a powdery layer. Huang *et al.,* [13] developed a numerical model for the deposition rate using macro probability statistics.

Fouling removal is another important process of the fouling growth. Rodriguez *et al.,* [14] reported that fouling removal is mostly depended upon gas flow velocity. Abd-Elhady *et al.,* [15] found that fouling removal is related to the impact speed or the contact time of the incident particles. Polley *et al.,* [16] concluded that fouling removal rate is proportional to the 0.8 power of the Reynolds number. Previous research in fouling mechanism has respectively focused on the process of particulate deposition or removal.

Fouling growth on heating surfaces is determined by the difference between the deposition and removal of particles on and from the fouling layer. Particulate fouling is mainly influenced by physicochemical properties and transport mechanisms of suspended particles, such as particulate size, transport forces arising from the

gradients of density, temperature and velocity in the flow field. An integrated fouling model was developed by Yadi *et al.,* [17] by considering the combined suspended particles deposition and the fouling removal processes.

Some examples of using Fluent code for predicting fouling phenomena occurring at heating surfaces can be found in publications [18, 19]. Particulate fouling of convective heat-transfer surfaces is usually assessed by empirical correlations. Nevertheless, constant progress in numerical calculation methods allows for predicting fouling phenomena occurring at heating surfaces, Wacławiak and Kalisz [20].

Mostafa [21] investigated that, the flow velocity has a strong effect on both the fouling rate and the asymptotic fouling factor; where the flow velocity affects on both the deposition and removal processes. Increasing flow velocity results in decreasing both of the fouling rate and asymptotic values. Comparing the obtained theoretical results with available experimental ones showed good agreement between them. The developed model can be used as a very useful tool in the design and operation of the heat transfer equipment by controlling the parameters affecting fouling processes. Also, Mostafa [22] has been developed a new theoretical approach based on the basic fouling processes for investigation the effect of surface temperature on surface particulate fouling. On the light of his results, all contrary conclusions presented in literatures which concluded that; *"the increase in surface temperature may lead to increase, decrease or have no effect on the amount of material depositing at a surface"* are right conclusions. He investigated this phenomena that, it depends on the working temperature is below, equal or above the critical surface temperature. A new formula describing the critical surface temperature with the affecting parameters has been deduced.

Xie [23] studied the erosion of heat exchanger tubes in the convective section of an industrial boiler by products of coal combustion. The experiments have been carried out under high surface temperatures, at 450, 550 and 650 K. It concluded that the rate of metal loss by erosion was lowest at low temperature, regardless of the oxygen concentration and the erosion was most rapid at high temperature in the presence of very low oxygen concentration. The erosion rate was increased by increasing the gas velocity. Ranjbar [24] investigated the effect of flow induced corrosion and erosion on failure of a tubular heat exchanger and concluded that the main reason of the exchanger failure is due to the very low velocity of water, causing accumulation of deposits, reduction of diameter and sometimes complete blockage of tubes besides of the surface

erosion caused by impingement attack. Kuźnicka [25] studied the Erosion-corrosion of heat exchanger tubes. It found that the tube damage was caused by erosion-corrosion induced by two factors: disturbed flow of water containing suspended solid particles and chemical composition of water rich in chlorides that resulted in loss of stability of protective cuprous oxide layer. Klenowicz *et al.,* [26] investigated the Corrosion-erosion damage of heat exchanger tubes by desalted crude oil flowing at shell side. They concluded that the reason of the damage may be cavitation corrosion at the ways of crude slow vortex flow at which temperature was high enough to allow explosions of low volatile components. Martinella *et al.,* [27] studied experimentally the High-temperature erosion tests on materials for fluidized bed combustor heat-exchanger tubes. They concluded that the erosion rate is increased as surface temperature is increased.

There are many parameters which affecting the erosion process and according to many investigators, [28-32] the most important ones are the particle concentration, particle size, surface material, fluid flow velocity and surface temperature. Up to now, the effect of surface temperature on the surface erosion is not well known, where the effect of flow velocity is well known in which the most studies indicated that the erosion rate increases with increasing flow velocity. The effect of the surface temperature on the erosion rate has been mentioned in several studies. These studies indicated that the role of surface temperature is not well understood. This lack of understanding was the motivation of the present work to improve our conception of this problem.

2. Theoretical Approach

As it is known from the previous theoretical studies, the particulate fouling process is consisting of two sub-processes which are deposition process and removal process. Therefore the fouling rate is given by

Accumulation rate = deposition rate − removal rate, or

$$\frac{dm_f}{d\theta} = \phi_d - \phi_r \qquad (1)$$

2.1. Deposition Rate (φ_d)

In this model, it will consider only the colloidal particles i.e. $d_p < 50$ μm, where the gravity has no effect on deposition or removal processes.

The increasing rate of the fouling layer thickness (x_f) is given by

$$\left(\frac{dx_f}{d\theta}\right)_d = \frac{S \cdot N}{\rho_f A_s} \qquad (2)$$

Where the stickability (S) is given by the Arrhenius equation as

$$S = k_s \exp\left(- E/R_g T_s\right) \le 1 \qquad (3)$$

Where k_s is constant, known as sticking coefficient
As shown in Fig. (1), the particle flow rate toward the surface (N) is represented as

$$N \propto \Delta C \cdot \dot{M}$$
$$= k_1 (C_s - C_b) \cdot \dot{M} \qquad (4)$$

Where k_1 is constant, for steady flow conditions and constant fluid properties, the constant $|k_1| = |k_D|$ where k_D is the mass transfer coefficient.
The particles concentration at the surface (C_s) is given by

$$C_s = \frac{non-stick\ particles}{flow\ rate,\ \dot{M}}$$
$$= \frac{N(1-S)}{\dot{M}} \qquad (5)$$
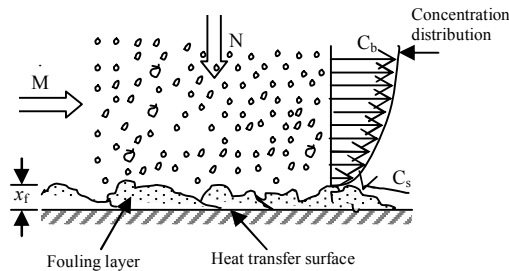
Fig. (1) The deposition process

From Eqns. (4) & (5), the particles mass flux toward the surface is given as

$$N = k_1 \cdot \dot{M}\left[C_b - \frac{N(1-S)}{\dot{M}}\right]$$
$$= \frac{k_1 C_b \dot{M}}{1 + k_1(1-S)} \qquad (6)$$

From Eqns. (2) & (6), it can get

$$\left(\frac{d(x_f)}{d\theta}\right)_d = \frac{S \cdot N}{\rho_f A_s}$$
$$= \frac{k_1 C_b S \cdot \dot{M}}{\rho_f A_s[1 + k_1(1-S)]}$$

but

$$\dot{M} = \rho \cdot u \cdot F$$

Therefore

$$\left(\frac{dx_f}{d\theta}\right)_d = \frac{k_1 C_b S \rho u F}{\rho_f A_s[1 + k_1(1-S)]}$$

And the deposition rate is given as

$$\phi_d = \rho_f \left(\frac{dx_f}{d\theta}\right)_d$$
$$= \frac{k_1 C_b S \rho u F}{A_s[1 + k_1(1-S)]} \qquad (7)$$

2.2. Removal Rate (φ_r)

As shown in Figs. (2) & (3) the decreasing rate in the fouling layer thickness due to removal process $\left(dx_f / d\theta\right)_r$ is proportional to the shear stress (τ), the fouling layer thickness (x_f), and to the inverse of deposit strength (ψ), therefore

$$\left(\frac{dx_f}{d\theta}\right)_r \propto x_f \tau \frac{1}{\psi}$$
$$\left(\frac{dx_f}{d\theta}\right)_r = k_2 x_f \tau \frac{1}{\psi}$$

Where k_2 is constant and the deposit strength (ψ) is represented by the weaker force of the adhesion or cohesion forces.

$$\tau \propto \rho u^2$$
$$= k_3 \rho u^2$$

Where $k_3 = \frac{1}{2} f$, and f is the friction factor, therefore

$$\left(\frac{dx_f}{d\theta}\right)_r = k_2 x_f \frac{k_3 \rho u^2}{\psi}$$
$$= k_4 x_f \frac{\rho u^2}{\psi}$$

Where $k_4 = k_2 k_3$
Therefore the removal rate is given as

$$\phi_r = \rho_f \left(\frac{dx_f}{d\theta}\right)_r$$
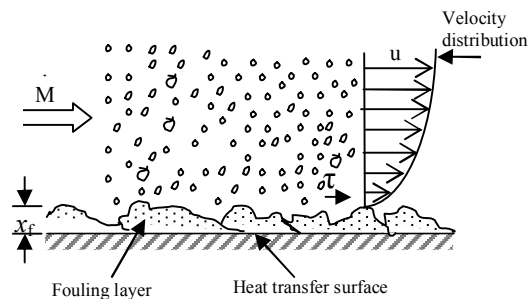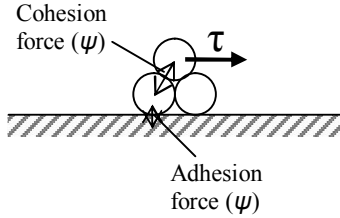$$= k_4 \rho \rho_f x_f \frac{u^2}{\psi} \qquad (8)$$

Fig. (2) The removal process

Fig. (3) The removal mechanism

2.3. Fouling Factor (R_f)

From Eqn. (1), the fouling rate is given by

$$\frac{dm_f}{d\theta} = \phi_d - \phi_r$$

$$= \frac{k_1 C_b S \rho u F}{A_s[1 + k_1(1-S)]} - k_4 \rho \rho_f x_f \frac{u^2}{\psi}$$

But

$$m_f = \rho_f x_f$$

$$= \rho_f\left(\lambda_f R_f\right)$$

Where λ_f is the thermal conductivity of the fouling layer, and R_f is the fouling factor, therefore

$$\frac{dR_f}{d\theta} = \frac{1}{\rho_f \lambda_f}\left(\frac{dm_f}{d\theta}\right)$$

$$= \frac{1}{\rho_f \lambda_f}\left[\frac{k_1 C_b S \rho u F}{A_s[1 + k_1(1-S)]} - k_4 \rho \rho_f x_f \frac{u^2}{\psi}\right]$$

$$= \frac{k_1 C_b S \rho u F}{\rho_f \lambda_f A_s[1 + k_1(1-S)]} - \frac{k_4 \rho u^2}{\psi} R_f$$

(9)

Integrating this equation with a boundary condition; ($R_f = 0$ at $\theta = 0$), gives that

$$R_f = \frac{k_1 C_b S F \psi}{k_4 u \rho_f \lambda_f A_s[1 + k_1(1-S)]}\left[1 - \exp\left(-\frac{k_4 \rho u^2}{\psi}\theta\right)\right] (10)$$

And at $\theta = \infty$, the asymptotic fouling factor (R^*_f) is given by

$$R^*_f = R_f\big|_{\theta=\infty} = \frac{k_1 C_b S F \psi}{k_4 u \rho_f \lambda_f A_s[1 + k_1(1-S)]} \quad (11)$$

From Eqns. (10) and (11), the fouling factor can be represented as

$$R_f = R^*_f\left[1 - \exp\left(-\frac{k_4 \rho u^2}{\psi}\theta\right)\right] \quad (12)$$

Substituting by S from Eqn. (3) into Eqn. (10), the fouling factor (R_f) can be written as

$$R_f = \frac{e^{-E/R_g T_s}}{u\left[\frac{k_4 \rho_f \lambda_f A_s(1+k_1)}{k_1 K_s C_b F \psi} - \frac{k_4 \rho_f \lambda_f A_s}{C_b F \psi}e^{-E/R_g T_s}\right]}\left(1 - e^{-\frac{k_4 \rho u^2}{\psi}\theta}\right) (13)$$

This equation can be rewritten in the following form

$$R_f = \frac{e^{-E/R_g T_s}}{u\left[A' - B'e^{-E/R_g T_s}\right]}\left(1 - e^{-D'u^2\theta}\right) \quad (14)$$

Where A', B' and D' are lumped parameters which are given as

$$A' = \frac{(1+k_1)k_4 \rho_f \lambda_f A_s}{k_1 K_s C_b F \psi}$$

$$B' = \frac{k_4 \rho_f \lambda_f A_s}{C_b F \psi} \quad (15)$$

$$D' = \frac{k_4 \rho}{\psi}$$

These parameters can be drawn from the experimental data.

From Eqns. (11) and (15), it can get that

$$R^*_f = \frac{e^{-E/R_g T_s}}{u\left[A' - B'e^{-E/R_g T_s}\right]} \quad (16)$$

2.4. Critical Surface Temperature (T_{sc})

Differentiating Eqn. (14) and equating to zero, the critical surface temperature, T_{sc}, can given as

$$T_{sc} = \frac{-E/R_g}{\ln(A'/B')} \quad (17)$$

Substituting from Eqn. (15) by values of A' and B', the critical surface temperature can be expressed as

$$T_{sc} = \frac{-E/R_g}{\ln\left(\frac{1+k_1}{k_1 \cdot k_s}\right)} \quad (18)$$

From Eqn. (18), it can be seen that the critical surface temperature, T_{sc}, depends manly on the activation energy, E, the constant k_1 which can be represented by mass transfer coefficient, k_D, and the sticking coefficient, k_s.

3. Results and Discussion

To show the effect of surface temperature, T_s, on both of the fouling rate, R_f, and the asymptotic factor, R^*_f, the values of the lumped parameters, A', B', D' and E/R_g have been drawn from the available experimental and computational data [23, 24, 29, 33, 34 and 36], and used in Eqns. (14) and (16).

3.1. Effect of Surface Temperature on Erosion Rate

From the drawn values, three cases have been selected and listed in Table (1). Using these selected values of the lumped parameters and by the aid of

Eqn. (15), the R_f-θ curves have been drawn and illustrated for each case in Figs. (4-6) at different values of surface temperature.

Table (1) Selected values of the lumped parameters

Case	A'	B'	D'	u, m/s	R_g/T_s
1	$1.864*10^{-13}$	12575.94	0.007	1.67	12657
2	$3.096*10^{-13}$	559.64	0.017	1.64	12657
3	$3.888*10^{-13}$	1363.64	0.032	1.62	12657

From figures (4 - 6), it can be seen that the fouling factor, R_f, is increased by increasing the surface temperature, T_s, until a specific value of T_s, above this specific temperature R_f has a negative values i. e., some erosion of the heat transfer surface will be occurred. This specific value of T_s is called the *critical surface temperature*, T_{sc}, which depends on the activation energy, E, the mass transfer coefficient, k_D, and the sticking coefficient, k_s, as discussed above and it is given by Eqn. (20). The erosion rate has its maximum value nearest the critical surface temperature and decreases with increasing surface temperature. As shown in all figures and at $T_s = T_{sc}$, the fouling factor, $R_f = 0$ i.e., there is no fouling or erosion. For all the illustrated cases, for constant surface temperature and constant flow velocity, the fouling or erosion rates are increased by the time, θ, until they reach their asymptotic values.

3.2. Effect of Surface Temperature on Asymptotic Values

By using the listed values in Table (1) and by the aid of Eqn. (17), the relation between R_f^* and T_s is illustrated in Figs. (7-9), as shown in these figures, it is clear that th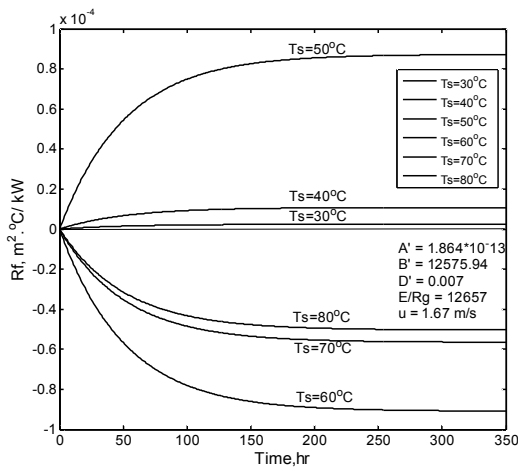e asymptotic fouling factor, R_f^* is increased by increasing the surface temperature until the critical surface temperature, T_{sc}, in which at this temperature the asymptotic factor is zero. Above T_{sc}, the erosion of the heat transfer surface will be occurred and the asymptotic erosion value is decreased by increasing the surface temperature. According to Eqn. (17) and from the above figures, the critical surface temperatures for the three cases listed in Table (1) are 53.63, 80.61 and 87.29 °C respectively. The temperatures are plotted in Celsius scale instead of the Kelvin scale to be more readable.

The above results could interpret the phenomena of existing a very thick fouling layer at some sites of the surface of an electrical heating element which used to heat water and there is no fouling at other sites of the same surface or may be there is some erosion, this may be due to the variation of temperature over the surface. For example, the case 2 in Table (1), $t_{sc} = 80.61$ °C, it means that the sites of the heat transfer surface which have a temperature of 80 °C or less will faced a high rate of fouling while the sites which have a temperature of 81 °C or higher will faced a high rate of surface erosion which decreased with surface temperature.
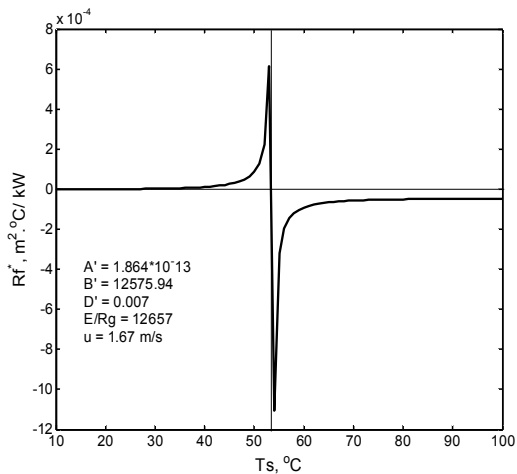

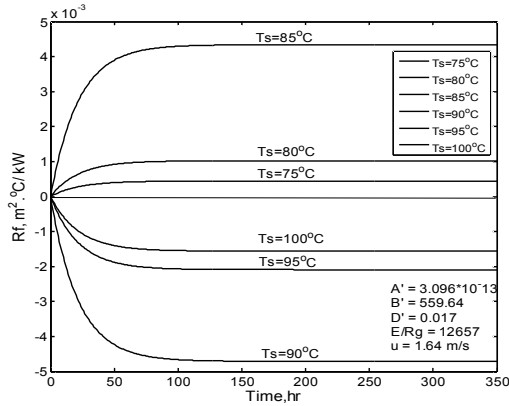Fig. (4) R_f-θ curves for case 1

Fig. (7) R_f^*-T_s curves for case 1

Fig. (5) R_f-θ curves for case 2
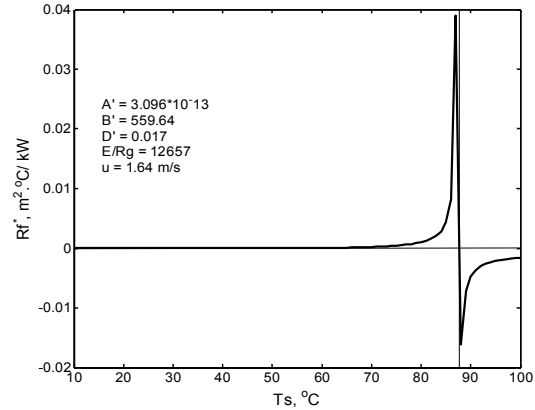

Fig. (8) R_f^*-T_s curves for case 2

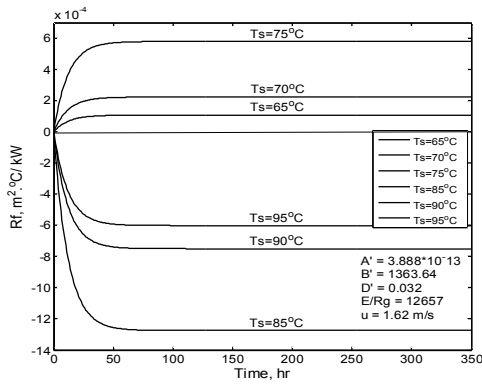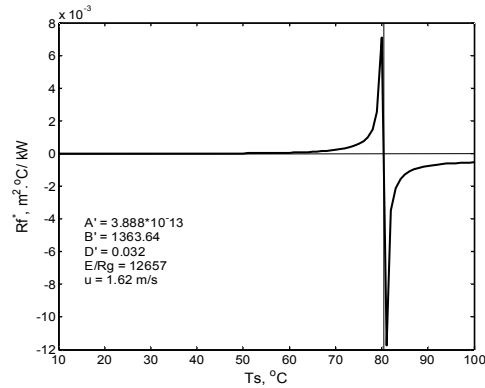
Fig. (6) R_f-θ curves for case 3

Fig. (9) R_f^*-T_s curves for case 3

3.3. The Critical Surface Temperature

To show the relation between the critical surface temperature, T_{sc}, and the working parameters, the selected values listed in Table (1) have been exploited and used in Eqn. (18) and drawn in Figs. (10, 11). From these figures, it can be seen that the critical surface temperature, T_{sc}, decreases

exponentially with both of k_s and k_D coefficients. This means that by determining the sticking coefficient, k_s and the mass transfer coefficient, k_D, and controlling them, the critical surface temperature, T_{sc}, can be controlled for a specific value of the activation energy, E.
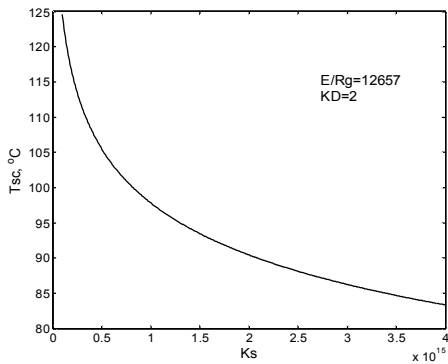

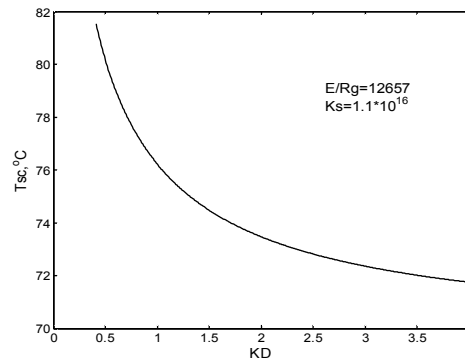Fig. (10) Effect of sticking coefficient, k_s on the critical surface temperature, T_{sc}

Fig. (11) Effect of mass transfer coefficient, k_D on temperature, T_{sc}

Conclusions and Recommendations

A new theoretical model for predicting the effect of surface temperature on both the fouling rate and on the surface erosion has been developed. The present results show that, each operating condition has its own critical surface temperature which can be predicted by the aid of the present model. Working below this temperature, there is no erosion and fouling rate increases with increasing surface temperature where working above this temperature, there is no fouling and the erosion of heat transfer surface will be occurred and it decreases with increasing surface temperature. To avoid the high rate of fouling or high rate of surface erosion, it must work as far as possible from the critical surface temperature. To work without fouling or surface erosion, it must work exactly at the critical surface temperature, and as it is known that doing this is very difficult or say it is impossible, the working far from the critical temperature is recommended. In the design of heat transfer equipment and knowing the sticking coefficient and mass transfer coefficient, the critical surface temperature can be determined and controlled.

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Nomenclature

A_s heat transfer surface area, m^2
A' lumped parameter, *defined by Eqn. (16)*
B' lumped parameter, *defined by Eqn. (16)*
C concentration of fouling material, kg_p/kg_{fl}
C_b concentration of fouling material at fluid bulk, kg_p/kg_{fl}
C_s concentration of fouling material at surface, kg_p/kg_{fl}
D' lumped parameter, *defined by Eqn. (16)*
E activation energy, *J/mol*
f friction factor, -
F fluid flow cross-sectional area, m^2
k_D mass transfer coefficient, *m/s*
k_s sticking coefficient, -
k_1 proportional constant, -, *defined by Eqn. (4)*
k_4 proportional constant, s^{-1}, *defined by Eqn. (7)*
m_f mass of deposited material, kg_p/m^2
M' fluid flow rate, kg_{fl}/s
N particles mass flux toward the surface, kg_p/s
R_g universal gas constant, *J/mol K*
R_f fouling factor (fouling resistance), m^2K/W
R_f^* asymptotic fouling factor, m^2K/W
S stickability, -
T_s heat transfer surface temperature, K
T_{sc} heat transfer critical surface temperature, K
u fluid flow velocity, *m/s*
x_f thickness of fouling layer, *m*

Greek Letters

φ_d deposition rate, kg/m^2s
φ_r removal rate, kg/m^2s
λ_f thermal conductivity of the fouling layer, *W/mK*
θ time, *s*
ρ density of working fluid, kg_p/m^3
ρ_f density of fouling layer, kg_{fl}/m^3
τ fluid shear stress, N/m^2
ψ strength of fouling layer, N/m^2

Subscripts

d deposition
f fouling
fl fluid
p particle
r removal