

Influence of Surface Temperature on Surface Fouling–Theoretical Approach

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Abstract: A theoretical approach for investigation the effect of surface temperature on surface particulate fouling has been developed. This approach is based on the basic fouling processes. As a result of this study, for each working condition, there was a specific surface temperature, defined as **critical surface temperature**. Below this temperature, i.e. the working temperature is less than the critical one, the fouling rate will increase by 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 temperature. At the critical temperature no fouling will be built up. On the light of these 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. This 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.

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1. Introduction

Fouling of heat transfer surface is defined as the accumulation of unwanted material on the heat transfer surface. This accumulation deteriorates the ability of the surface to transfer heat besides to the increase of the pressure drop through the heat transfer apparatus. Many investigators have studied the fouling phenomenon theoretically and experimentally. **Kern and Seaton** [1, 2] and **Ken** [3], made the groundwork of the fouling studies. Recently, **Nesta and Bennett** [4] introduced a new design of heat exchangers. They concluded that minimize wall temperature and maximize the flow velocity tends to minimize fouling; they also found that the heat exchanger material has a pronounced effect on fouling particularly when biological fouling is a concern. **Yang et al.**, [5] constructed a model for the fouling induction period. They found that the shorter induction periods are dealing with higher surface temperature. **Subbarao et al.**, [6] studied particulate fouling of glass particles under high temperatures. They concluded that the fouling layer formation is strongly dependent on the gas phase temperature and gas phase velocity and once the deposit has formed, increasing gas velocity hasn't any effect on removal of particles from the deposited layer. **Mostafa et al.**, [7], studied experimentally the effect of surface temperature on both the precipitation fouling and particulate fouling. They found that the fouling resistance increases with temperature in the case of precipitation fouling, where it decreases with temperature in the case of particulate fouling.

Fouling is influenced by a great number of affecting parameters, on the one hand by physical ones

such as; flow velocity, temperature and the chemical nature and surface finish of the wall. On the other hand, the chemical concentration of the different compounds (solute, solvent, impurities) has to be taken into account. The great number of these parameters and their interdependence explain the difficulties encountered when predicting fouling by a theoretical approach. That is the reason why this phenomenon is essentially represented by empirical laws for each particular case. This allows optimal operating conditions and technical solutions to be obtained which avoid, or at least reduce, fouling, for a specific process. According to many previous researchers; the most important ones are the flow velocity and the surface temperature.

The effect of flow velocity is well known in which the most studies such as **Mostafa et al.**, [8], **Dunqi et al.**, [26], and **Knudsen et al.**, [27], indicated that the fouling rate decreases with increasing flow velocity.

Through the years many efforts have also been made on probing the phenomenon of the particulate fouling on heating surfaces. Some examples of using Fluent code for predicting fouling phenomena occurring at heating surfaces can be found in publications [9-10]. 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, **Waclawiak and Kalisz** [11].

Also, many achievements have been obtained on deposition and removal models to predict particulate

fouling on heating surfaces under inertial impaction. **Thornton and Ning** [12], and **Konstandopoulos** [13] studied deposition criteria for particle inertial collision with the tube wall. **Feng et al.**, [14] researched the effect of influence parameters on particle-wall inertial collision deposition. **Abd-Elhady et al.**, [15] proposed that inertial impact speed is the main parameter of collision deposition for particles with a powdery layer. **Van et al.**, [16] developed a two-body collision deposition mechanism for particle impaction with a powdery layer. **Huang et al.**, [17] 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.**, [18] reported that fouling removal is mostly depended upon gas flow velocity. **Abd-Elhady et al.**, [19] found that fouling removal is related to the impact speed or the contact time of the incident particles. **Polley et al.**, [20] 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 fouling 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 **Pan et al.**, [21] by considering the combined suspended particles deposition and the fouling removal processes.

From the above literature review it was shown that, the effect of the surface temperature on the fouling rate has been mentioned in several studies however, these studies indicated that the role of surface temperature is not well understood and much more research needs to be carried out on the effect of surface temperature. Up to now, the effect of surface temperature on the surface fouling is not well known, where some literatures show that; the increase in surface temperature may lead to increase [6, 22], decrease [4, 23], or have no effect on the fouling rate [24]. The motivation of the present work is to improve our understanding of this problem and to provide solutions to reduce and control fouling.

2. Theoretical Approach

From the previous theoretical studies [13-38], 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

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

2.1. Deposition Rate (ϕ_d)

In the present model, only the colloidal particles i.e. $d_p < 50 \mu\text{m}$, where the gravity has no effect on deposition or removal processes, will be considered. For large particles, $d_p \geq 50 \mu\text{m}$ there is another type of fouling mechanism what is known as sedimentation fouling (i.e. deposition occurs under the effect of gravity) which can be often prevented in heat transfer equipment by pre-filtration.

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

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

Where the stick ability (S) is given by the Arrhenius equation as

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

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

$$\begin{aligned} N &\propto \Delta C \cdot \dot{M} \\ &= k_1 (C_s - C_b) \cdot \dot{M} \end{aligned} \quad (4)$$

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

$$\begin{aligned} C_s &= \frac{\text{non-stick particles}}{\text{flowrate}, \dot{M}} \\ &= \frac{N(1-S)}{\dot{M}} \end{aligned} \quad (5)$$

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

$$\begin{aligned} N &= k_1 \cdot \dot{M} \left[C_b - \frac{N(1-S)}{\dot{M}} \right] \\ &= \frac{k_1 C_b \dot{M}}{1 + k_1 (1-S)} \end{aligned} \quad (6)$$

From Eqns. (2) & (6);

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

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

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

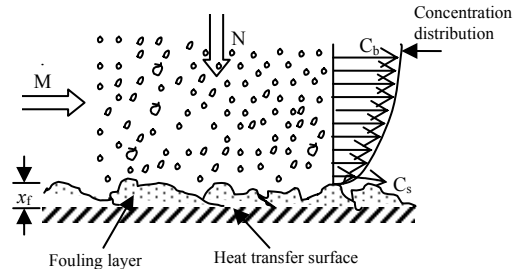


Fig. (1) The deposition process

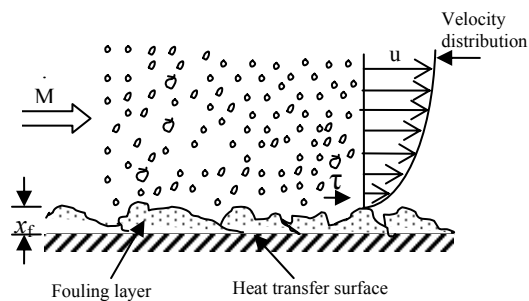
2.2. Removal Rate (ϕ_r)

As shown in Figs. (2) & (3) the decreasing rate in the fouling layer thickness due to removal process $(dx_f / d\theta)_r$ 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 represented by the weaker force of the adhesion or cohesion forces.



(ψ) is

Fig. (2) The removal process

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

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

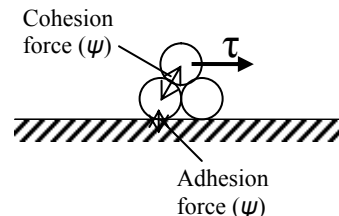


Fig. (3) The removal mechanism

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

Where $k_4 = k_2 k_3$

Therefore the removal rate is given as

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

2.3. Fouling Factor (R_f)

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

$$\begin{aligned} \frac{dm_f}{d\theta} &= \phi_d - \phi_r \\ &= \frac{k_1 C_b S \rho u F}{A_s [1 + k_1 (1 - S)]} - k_4 \rho \rho_f x_f \frac{u^2}{\psi} \end{aligned}$$

But

$$\begin{aligned} m_f &= \rho_f x_f \\ &= \rho_f (\lambda_f R_f) \end{aligned}$$

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

$$\begin{aligned} \frac{dR_f}{d\theta} &= \frac{1}{\rho_f \lambda_f} \left(\frac{dm_f}{d\theta}\right) \\ &= \frac{1}{\rho_f \lambda_f} \left[\frac{k_1 C_b S \rho u F}{A_s [1 + k_1 (1 - S)]} - k_4 \rho \rho_f x_f \frac{u^2}{\psi} \right] \\ &= \frac{k_1 C_b S \rho u F}{\rho_f \lambda_f A_s [1 + k_1 (1 - S)]} - \frac{k_4 \rho u^2}{\psi} R_f \end{aligned} \tag{9}$$

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

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

And

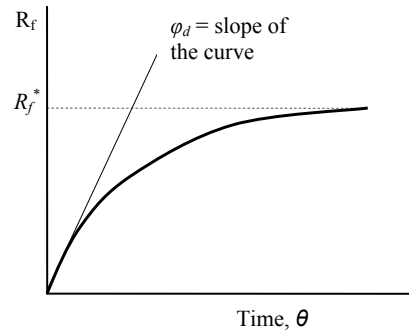


Fig. (4) The fouling curve

$$\left.\frac{dR_f}{d\theta}\right|_{\theta=0} = \frac{k_1 C_b S \rho u F}{\rho_f \lambda_f A_s [1 + k_1 (1 - S)]} = \phi_d \tag{11}$$

It means that the slope of the fouling curve at time zero represents the deposition rate (Φ_d), as shown in figure (4)

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

$$R_f^* = R_f \Big|_{\theta=\infty} = \frac{k_1 C_b S F \psi}{k_4 u \rho_f \lambda_f A_s [1 + k_1 (1 - S)]} \tag{12}$$

From Eqns. (10) and (12), the fouling factor can be written as

$$R_f = R_f^* \left[1 - \exp\left(-\frac{k_4 \rho u^2}{\psi} \theta\right) \right] \tag{13}$$

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

$$R_f = \frac{e^{-E/R_g T_s}}{u \left[\frac{k_4 \rho_f \lambda_f A_s (1+k_1)}{k_1 K_s C_b F \psi} - \frac{k_4 \rho_f \lambda_f A_s}{C_b F \psi} e^{-E/R_g T_s} \right]} \left(1 - e^{-\frac{k_4 \rho_f \lambda_f \theta}{\psi}} \right) \quad (14)$$

This equation can be rewritten in the following form

$$R_f = \frac{e^{-E/R_g T_s}}{u [A' - B' e^{-E/R_g T_s}]} (1 - e^{-D' u^2 \theta}) \quad (15)$$

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

$$\begin{aligned} A' &= \frac{(1+k_1)k_4 \rho_f \lambda_f A_s}{k_1 K_s C_b F \psi} \\ B' &= \frac{k_4 \rho_f \lambda_f A_s}{C_b F \psi} \\ D' &= \frac{k_4 \rho}{\psi} \end{aligned} \quad (16)$$

These parameters can be drawn from the experimental data.

From Eqns. (12) and (16);

$$R_f^* = \frac{e^{-E/R_g T_s}}{u [A' - B' e^{-E/R_g T_s}]} \quad (17)$$

And

$$\frac{R_f}{R_f^*} = 1 - e^{-D' u^2 \theta} \quad (18)$$

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 (5 - 7), 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). As shown in all figures and at $T_s = T_{sc}$, the fouling factor, $R_f = 0$ i.e., there is no fouling. For all the illustrated cases, R_f increases with time, θ , for constant T_s and constant flow velocity, u

2.4. Critical Surface Temperature (T_{sc})

Differentiating Eqn. (15) and equating to zero, the critical surface temperature, T_{sc} , can given as

$$T_{sc} = \frac{-E/R_g}{\ln(A'/B')} \quad (19)$$

Substituting from Eqn. (16) by values of A' and B' , the critical surface temperature can be expressed as

$$T_{sc} = \frac{-E/R_g}{\ln\left(\frac{1+k_1}{k_1 \cdot k_s}\right)} \quad (20)$$

From Eqn. (20), it can be seen that the critical surface temperature, T_{sc} , depends mainly on the activation energy, E , the constant k_l 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 the fouling factor, 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 [7, 27, 28, 32, 33 and 35], and used in Eqns. (15) and (17).

3.1. Effect of Surface Temperature on Fouling Factor

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 $R_f - \theta$ curves have been drawn and illustrated for each case in Figs. (5 - 7) for different values of surface temperature.

3.2. Effect of Surface Temperature on Asymptotic Fouling Factor

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. (8 - 10). As shown in these figures, it is clear that the asymptotic fouling factor, R_f^* is increased by increasing the surface temperature until the critical surface temperature, T_{sc} , in which at this T_{sc} the asymptotic factor is zero and above T_{sc} the asymptotic factor has negative values. This phenomenon satisfies the mentioned conclusion in literature, Gudmundsson [28] which dealing with the effect of surface temperature on fouling rate and stated that "increase in surface temperature may increase,

decrease or have no effect on the amount of material depositing at a surface". According to Eqn. (19) 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.

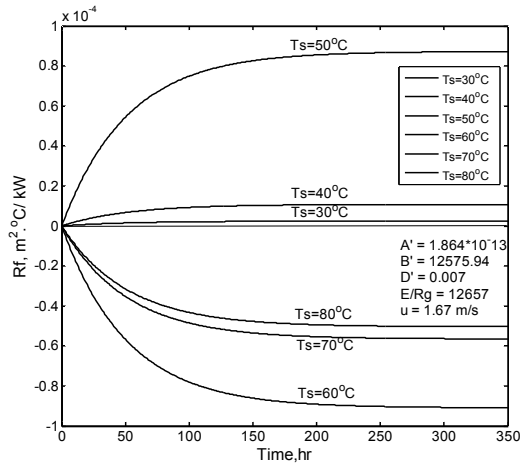


Fig. (5) R_f - θ curves for case 1

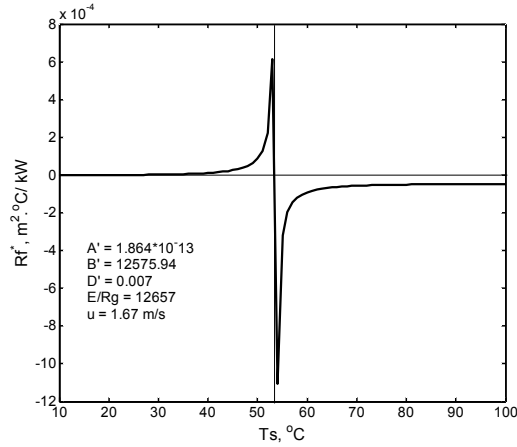


Fig. (8) R_f^* - T_s curves for case 1

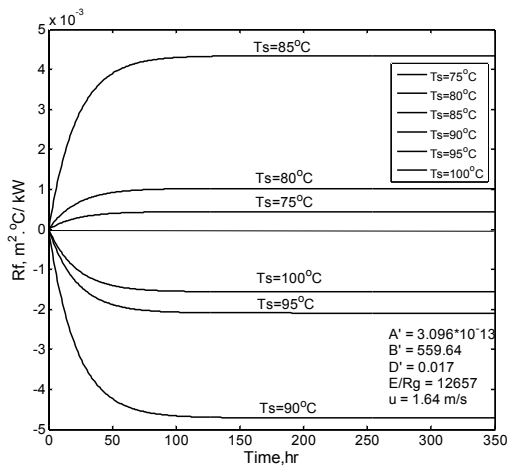


Fig. (6) R_f - θ curves for case 2

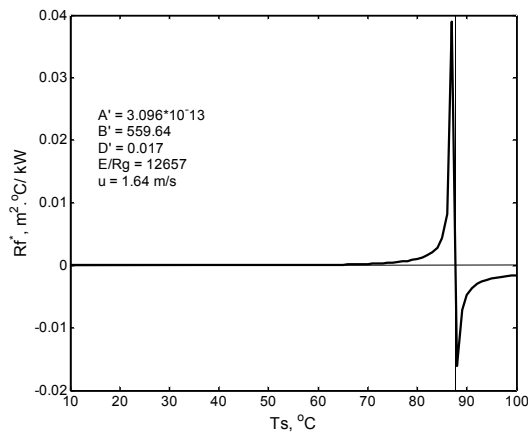


Fig. (9) R_f^* - T_s curves for case 2

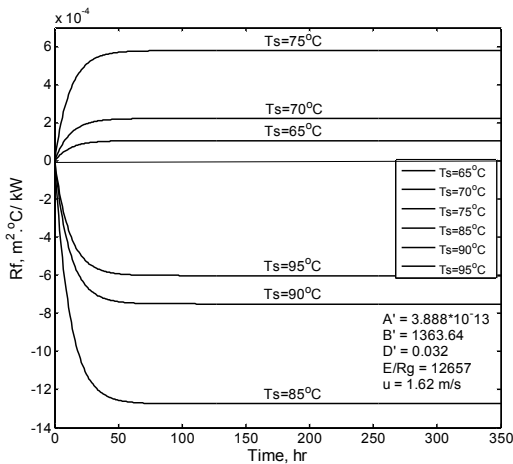


Fig. (7) R_f - θ curves for case 3

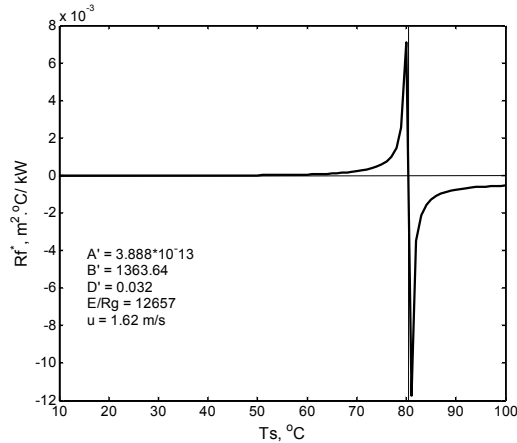


Fig. (10) R_f^* - T_s curves for case 3

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

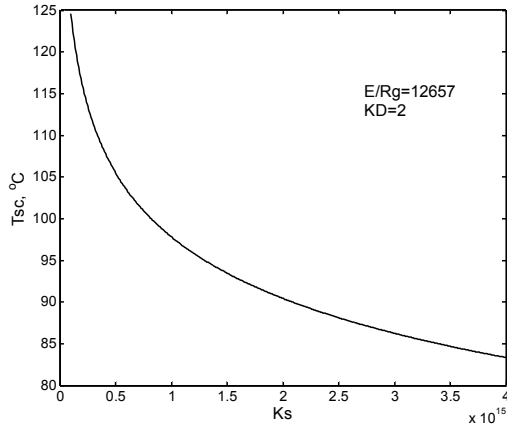


Fig. (11) Effect of sticking coefficient, k_s on the critical surface temperature, T_{sc}

example, the case 2 in Table (1), $t_{sc} = 80.61^\circ\text{C}$, it means that the sites of the heat transfer surface which have a temperature of 80°C or less will face a high rate of fouling while the sites which have a temperature of 81°C or higher will face some erosion.

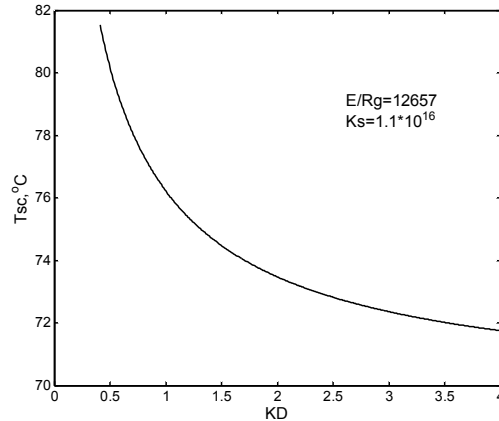


Fig. (12) Effect of mass transfer coefficient, k_D on temperature, T_{sc}

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. (20) and drawn in Figs. (11, 12). From these figures, it can be seen that the critical surface temperature, T_{sc} , exponentially decreases 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 .

Conclusions And Recommendations

A new theoretical model for investigation the effect of surface temperature on both the fouling rate and asymptotic fouling factor for particulate fouling was 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 leads to increase the fouling rate with increasing surface temperature where working above this temperature leads to exist some erosion of the heat transfer surface which is decreased by increasing surface temperature. To avoid the high rate of fouling or high rate of surface erosion, it must to work with a temperature as far as possible from the critical surface temperature. And, 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 therefore, the working far from the critical temperature is recommended. In the design of heat transfer equipments and knowing the sticking coefficient and mass transfer coefficient, the critical surface temperature can be determined and controlled.

Nomenclature

A_s	heat transfer surface area, m^2	R_g	universal gas constant, $J/mol\ K$
A'	lumped parameter, defined by Eqn. (16)	R_f	fouling factor (fouling resistance), m^2K/W
B'	lumped parameter, defined by Eqn. (16)	R_f^*	asymptotic fouling factor, m^2K/W
C	concentration of fouling material, kg_p/kg_{fl}	S	stickability, -
C_b	concentration of fouling material at fluid bulk, kg_p/kg_{fl}	T_s	heat transfer surface temperature, K
C_s	concentration of fouling material at surface, kg_p/kg_{fl}	T_{sc}	heat transfer critical surface temperature, K
D'	lumped parameter, defined by Eqn. (16)	u	fluid flow velocity, m/s
E	activation energy, J/mol	x_f	thickness of fouling layer, m
f	friction factor, -	Greek Letters	
F	fluid flow cross-sectional area, m^2	ϕ_d	deposition rate, kg/m^2s
k_D	mass transfer coefficient, m/s	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

k_s	sticking coefficient, -	layer, kg_f/m^3
k_l	proportional constant, -, defined by Eqn. (4)	τ fluid shear stress, N/m^2
k_d	proportional constant, s^{-1} , defined by Eqn. (7)	ψ strength of fouling layer, N/m^2
m_f	mass of deposited material, kg_p/m^2	Subscripts
M'	fluid flow rate, kg_p/s	d deposition
N	particles mass flux toward the surface, kg_p/s	f fouling
		fl fluid
		p particle
		r removal

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