Impact of Flow velocity on Surface Particulate Fouling - Theoretical Approach

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Abstract: The objective of this research is to study the effect of flow velocity on surface fouling. A new theoretical approach showing the effect of flow velocity on the particulate fouling has been developed. This approach is based on the basic fouling deposition and removal processes. The present results show that, the flow velocity has a strong effect on both the fouling rate and the asymptotic fouling factor; where the flow velocity affects 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.

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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. Therefore fouling tends to decrease the heat exchangers performance and can lead to operation failure. Transport and capture of particles on heat transfer surfaces are functions of the size of particles, the chemical and physical properties of the transported particles and operating conditions. Fouling can lead to increase capital and maintenance costs and major production and energy losses in many energy-intensive industries. Many investigators have studied the fouling phenomenon theoretically and experimentally. **Kern and Seaton** [1, 2] and **Kern** [3], made the groundwork of the fouling studies. Recently, **Yang *et al.,*** [4] constructed a model for the fouling induction period. They found that the shorter induction periods are dealing with higher surface temperature. **Nesta and Bennett** [5] 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. **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], experimentally studied the effect of flow velocity on both of the fouling resistance and the asymptotic values. They found that the fouling resistance and the asymptotic values are decreased by increasing the flow velocity. They also found that the asymptotic fouling factor is very sensitive to the flow velocity especially at low flow velocities where this sensitivity decreases with increasing flow velocity.

There are many parameters which affecting the fouling process, and according to many investigators the most important ones are the flow velocity and the surface temperature. Many efforts have been made by numerous researchers to study the affecting parameters on the fouling phenomenon in heat exchangers. They have focused on various methods to predict fouling behavior more accurately which in turn helps prevent fouling problems. **Lee and Cho** [8] experimentally studied the velocity effect on electronic anti fouling technology to mitigate mineral fouling in enhanced-tube heat exchanger. They concluded that the characteristics of the fouling mechanism are very sensitive to fluid velocity in a heat exchanger, surface geometry, particle concentration, bulk temperature, and tube material. **Abd-Elhady *et al.,*** [9] concluded that as the flow speed in the heat exchanger increases, the thickness and the surface area of the fouling layer deposited over the heat exchanger tube are reduced. There is a limiting flow speed above which fouling is avoided. This limiting speed is related to the critical flow velocity required to roll a particle resting on a flat surface. **Li** [10] concluded that the asymptotic fouling factor increases as the particle concentration increases and Reynolds number decreases.

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** [11], and **Konstandopoulos** [12] studied deposition criteria for particle inertial collision with the tube wall. **Feng *et al.,*** [13] researched the effect of influence parameters on particle-wall inertial collision deposition. Abd-**Elhady**

et al., [14] proposed that inertial impact speed is the main parameter of collision deposition for particles with a powdery layer. **Van *et al.,*** [15] developed a two-body collision deposition mechanism for particle impaction with a powdery layer. **Huang *et al.,*** [16] 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.,*** [17] reported that fouling removal is mostly depended upon gas flow velocity. **Abd-Elhady *et al.,*** [18] found that fouling removal is related to the impact speed or the contact time of the incident particles. **Polley *et al.,*** [19] 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.,*** [20] 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 [21, 22]. 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** [23]. Much more research needs to be carried out on the effect of velocity because its effect is much more complex than that of surface temperature, **Yang *et al.,*** [4].

Up to now, there is a lack in literatures which theoretically investigates the effect of flow velocity on the surface fouling. This lack of theoretical studies was the motivation of the present work to improve our understanding of this problem.

2. Theoretical Approach

From the previous theoretical studies [1-3, 25-38], it is known that 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

$$\frac{dm_f}{d\theta} = \phi_d - \phi_r \tag{1}$$

2.1. Deposition Rate (φ_d)

In the present model, only the colloidal particles i.e. $d_p < 50$ µm will be considered, where for large particles, $d_p \geq 50$ µm, there is another type of fouling mechanism which is known as sedimentation fouling (i.e. deposition occurs under the effect of gravity). Sedimentation fouling can be often prevented in heat transfer equipment by pre-filtration.

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

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

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

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

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;

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

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

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

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

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

From Eqns. (2) & (6);

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

but

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

Therefore

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

And the deposition rate is given as

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

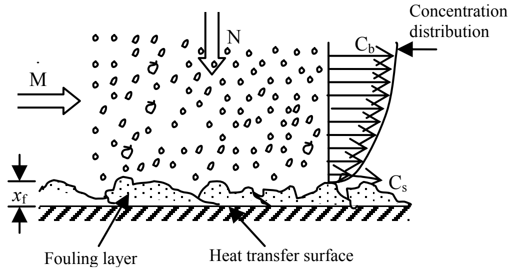

Fig. (1) The deposition process

2.2. Removal Rate (φ_r)

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

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

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

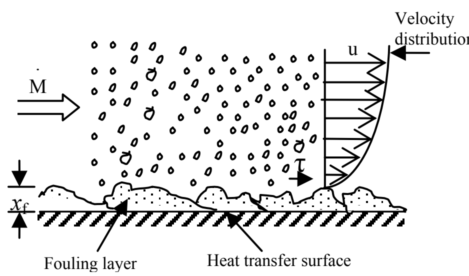

Fig. (2) The removal process

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 $k_3 = ½ f$, 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

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

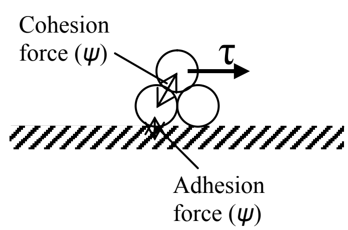

Fig. (3) The removal mechanism

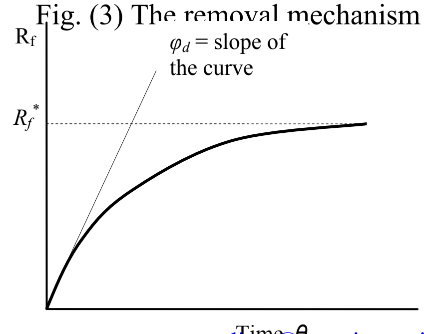

Fig. (4) The fouling curve

2.3. Fouling Factor (R_f)

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

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

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

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

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

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

$$= \frac{k_1 C_b S \rho u F}{\rho_f \lambda_f A_s\left[1 + k_1(1 - S)\right]} - \frac{k_4 \rho u^2}{\psi} R_f \qquad (9)$$

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

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

And

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

It means that the slope of the fouling curve at time zero represents the deposition rate

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

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

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

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

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

$$R_f = \frac{e^{-E/R_g T_s}}{u\left[\frac{k_4 \rho_f \lambda_f A_s (1 + k_1)}{k_1 K_s C_b F \psi} - \frac{k_4 \rho_f \lambda_f A_s}{C_b F \psi} e^{-E/R_g T_s}\right]}\left(1 - e^{\frac{-k_4 \rho u^2}{\psi}\theta}\right) \qquad (14)$$

2.4. Effect of flow velocity (u)

To examine the effect of flow velocity on the surface fouling, equation (10) can be rewritten in the following form

$$R_f = A \cdot \frac{1}{u}\left(1 - e^{-Bu^2\theta}\right) \qquad (15)$$

Where A and B are lumped parameters which are given as

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

$$B = \frac{k_4 \rho}{\psi} \qquad (16)$$

These parameters can be drawn from the experimental data.

From Eqns. (12) and (16),

$$R_f^* = A \cdot \frac{1}{u} \qquad (17)$$

And

$$\frac{R_f}{R_f^*} = 1 - e^{-Bu^2\theta} \qquad (18)$$

Equation (15) can be rewritten in the following form

$$R_f = A \cdot \frac{1}{u}\left(1 - e^{-\theta/\theta_c}\right) \qquad (19)$$

Where θ_c is defined as the time constant and given by

$$\theta_c = \frac{1}{B \cdot u^2} \qquad (20)$$

3. Results and Discussion

To show the effect of flow velocity, u, on both the fouling factor, R_f, and the asymptotic factor, R_f^*, the values of the lumped parameters, A and B have been drawn from the available experimental and computational data [7, 25, 30, 34, 35, 38] and used in Eqns. (15) and (17).

3.1. Effect of Flow velocity 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 - θ curves have been drawn and illustrated for each case in Figs. (5-7), for different values of flow velocities.

Table (1) selected values of the lumped parameters

Case	1	2	3
A	$1.257*10^{-4}$	$1.963*10^{-4}$	$2.650*10^{-4}$
B	0.085	0.029	0.046

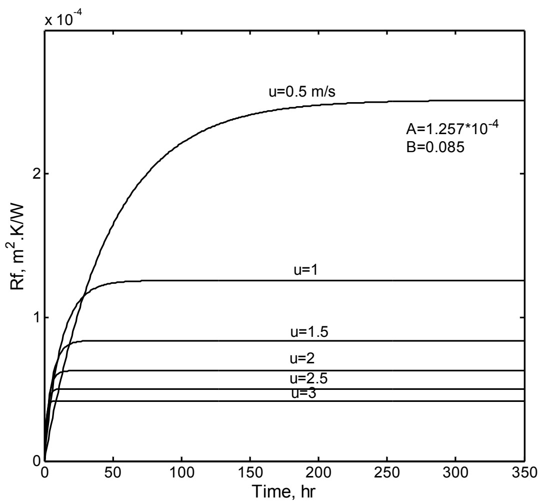

Fig. (5) R_f-θ curves for case 1

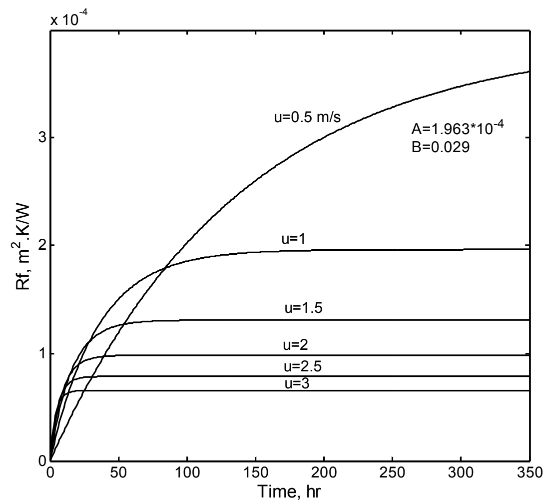

Fig. (6) R_f-θ curves for case 2

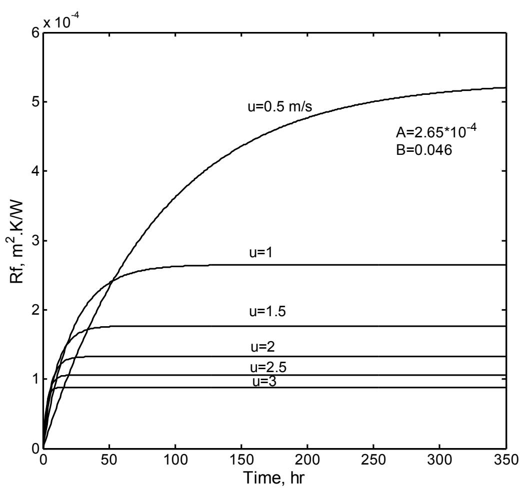

Fig. (7) R_f-θ curves for case 3

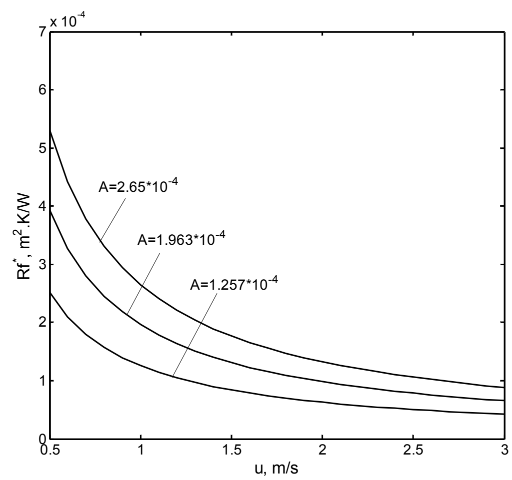

Fig. (8) Effect of flow velocity, u, on the asymptotic fouling factor, R_f^*

From figures (5-7), it can be seen that the fouling factor, R_f, is decreased by increasing the flow velocity, u. The reason of reduction of fouling factor with increasing flow velocity is due the flow velocity affects both the deposition rate, φ_d, [Eqn. (7)] and the removal rate, φ_r, [Eqn. (8)]. In Eqn. (7), the deposition rate is proportional with the flow velocity, u, where in Eqn. (8), the removal rate is proportional with the square of the flow velocity, u^2. As shown from these figures, the fouling factor is very sensitive to the flow velocity at low flow velocities where this sensitivity is decreased by increasing the flow velocity. That is because the time constant, θ_c, $(1/Bu^2)$ decreases with increasing the flow velocity.

3.2. Effect of Flow Velocity 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 u is illustrated in Fig. (8), from this figure, it is clear that the asymptotic fouling factor, R_f^* is reduced by increasing the flow velocity. The reduction in asymptotic fouling resistance due to the increasing of the flow velocity is depending upon the lumped coefficient, A, in which R_f^* is decreased by decreasing this coefficient. It must be noted that the lumped coefficient, A contains many of operating parameters as shown in Eqn. (16).

3.3. Comparison between Theoretical and Experimental Results

To examine the validity of the present model, a comparison between the present theoretical results and the experimental ones [7] has been carried out and illustrated in Figs. (9, 10). As shown in these figures, there is a good agreement between the theoretical and experimental results. It must be noted that in the case of experimental results there is some negative values of R_f at the beginning of operation. That is because of the enhancement of the film heat transfer coefficient due to the roughening of the heat transfer surface caused by the initial deposition of particles on the surface, and the fouling factor is calculated from the resistance of heat transfer point of view, where in the case of the theoretical analysis the fouling factor is calculated from the mass of deposited materials.

Conclusions and Recommendations

A new theoretical model for predicting the effect of flow velocity on both the fouling rate and asymptotic fouling factor for particulate fouling was developed. From this study it can be concluded that, for all operating conditions, both of the fouling rate and the asymptotic fouling factor are reduced by increasing the flow velocity. The asymptotic fouling factor is very sensitive to the flow velocity at low flow velocities; where this sensitivity is decreased by increasing the flow velocity. For example in case 1, Table (1), the asymptotic fouling resistance is reduced by 49.98% when the flow velocity is increased from 0.5 to 1.0 m/s while it is reduced by only 16.67% when the flow velocity is increased from 2.5 to 3.0 m/s. Comparing the obtained theoretical results with experimental ones showed good agreement between them. In the design and operation of heat transfer equipment, the work with high flow velocities as possible is recommended.

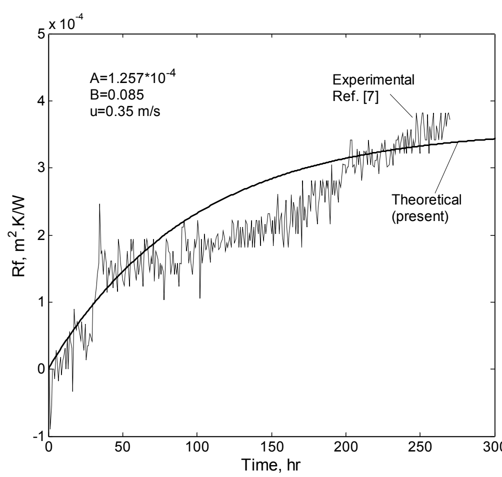

Fig. (9) Comparison between the present theoretical results and experimental results [7] for u=0.35m/s

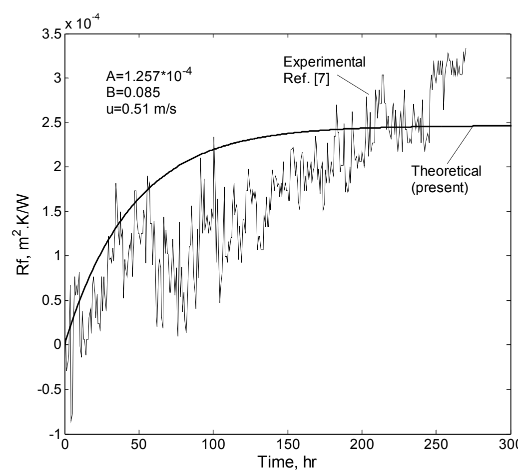

Fig. (10) Comparison between the present theoretical results and experimental results [7] for u=0.51m/s

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}
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*
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

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