

Scaling Growth in Heat Transfer Surfaces and Its Thermohydraulic Effect Upon the Performance of Cooling Systems

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A new theoretical model to predict the build-up of scaling on the heat transfer surface of coolers is developed. Scaling fouling is originated as a layer of crystals of inverse solubility salts such as calcium carbonates present in cooling water, is formed on the heat transfer surface. Even though fouling cannot be fully avoided, its detrimental effect can be minimised by accurate prediction of fouling rates. Most current models for the prediction of scaling are based on a mechanism that considers mass transfer through the laminar layer and the chemical reaction between ions to form the salt. It has been observed that with such models, the velocity of deposition of crystals augments as the fluid velocity increases without a tendency to an asymptotic behaviour. Theoretically, at higher fluid velocities, it is expected that a removal phenomenon to take place with the consequent reduction in the rate of deposition. Besides, even with time, the rate of deposition cannot be maintained since velocity increases as the cross-sectional area of a tube is reduced and the inertial and friction forces tend to maintain the ion species in solution dampening the reaction. In this paper, a new model is proposed to account for the removal term. The model is validated against experimental data and its performance is compared against existing models available in the open literature.

1. Introduction

Scaling is a common type of fouling that takes place in cooling systems and is associated to water hardness. This type of fouling happens as crystals deposits grow on a heat transfer surface becoming a layer that diminish heat transfer. The most common type of scaling is the one formed from calcium carbonates and sulphates. These salts have the characteristic that its solubility decreases at increased temperatures, thus reaching the condition of oversaturation until crystals start to deposit on the surface (Pugh et al, 2007). Scaling is strongly dependent on temperature, velocity, concentration and pH. Once formed it can only be removed on an acidic environment (Bott, 1994). Among the various water dissolved salts that originate fouling, this work focuses on CaCO_3 since it is the compound that is found in the largest proportion in most sources of cooling water (Pääkkonen, 2015). The importance of studying fouling lies in the fact that not only heat exchangers reduce its thermal effectiveness (Zahid et al., 2016) but that the downstream consequences create huge economic losses as reported by Alabrudzinski et al. (2016).

2. Methodology

Hasson et al. (1968) proposed a fouling mechanism based on the laminar layer where mass transfer by diffusion and chemical reaction take place. Mass transfer by diffusion can be expressed by Eq(1) and Eq(2):

$$\dot{m} = \beta([Ca^{2+}]_b - [Ca^{2+}]_i) \quad (1)$$

$$\dot{m} = \beta([CO_3^{2-}]_b - [CO_3^{2-}]_i) \quad (2)$$

Where β is the mass transfer coefficient. As soon as the salt ions reach a surface, the deposition process starts by the chemical combination to form the CaCO_3 molecule which with time, gives birth to a crystal layer. The mass transfer rate can also be expressed as a function of the rate of reaction, the ion concentration at the interface and its solubility:

$$m = k_r ([\text{Ca}^{2+}]_i [\text{CO}_3^{2-}]_i - K_{sp}) \quad (3)$$

Where K_{sp} is the solubility constant of calcium carbonate, k_r is the coefficient of reaction which is determined from the Arrhenius equation.

$$k_r = k_0 e^{-\frac{E}{RT_i}} \quad (4)$$

Where k_0 is the reaction constant, E is the activation energy, R is the gas constant and T_i the temperature at the solid-liquid interface. As a layer of crystals is formed on a heat transfer surface, it creates an additional thermal resistance to heat transfer. The value of this resistance depends on various parameters, such as ion concentration, temperature, and fluid velocity among others. When a theoretical model is used to predict the growth of scaling with time, it is commonly found that its value increases monotonically with time and even exhibiting greater values with velocity. Such behaviour is contrary to theory since higher velocities are associated to turbulent regimes where particles are more likely to be removed impeding reaction and precipitation (Bott, 1994). The need then arises to include the effects of viscosity, fluid density, diameter and roughness on the removal of Ca^{2+} and CO_3^{2-} before they react to form a CaCO_3 molecule. From the Pi (π) Buckingham theorem (Boyling, 1979), it is found that a dimensionless parameter that affects the rate of deposition is the friction factor, f .

$$f = \frac{\tau}{\rho u^2} \quad (5)$$

The friction factor is related to the flow resistance on the surface of the fouling layer. Now, the effect of velocity can be included by means of the inertial forces and viscous forces which are represented by Reynolds number. Thus, a new empirical factor (α) expressed by Eq (6) is used. The correlating parameters a and b are determined from experimental data.

$$\alpha = a(f \times \text{Re})^b \quad (6)$$

Incorporating this correction factor into Eq (3) results:

$$\dot{m}_d = \alpha k_r ([\text{Ca}]_i [\text{CO}_3]_i - [K_{sp}]^2) \quad (7)$$

Where \dot{m}_d is the mass deposition rate. The convenience of using a correction factor such as the one given by Eq (6) is that any other type of salt can be analysed or even any combination of salts present in the cooling water can be analysed provided the experimental data exists for the system under consideration.

2.1 Theoretical model

The fully developed model to predict the rate of mass deposition including the diffusion and reaction steps is represented by Eq(8).

$$\dot{m}_d = \frac{\beta}{2} \left(\frac{\beta}{\alpha k_r} + (C_1 + C_2) - \sqrt{\frac{(\beta + (C_1 + C_2)\alpha k_r)^2 + 4\alpha^2 k_r^2 (K_{sp} - [C_1][C_2])}{\alpha^2 k_r^2}} \right) \quad (8)$$

Where C_1 y C_2 are the Ca^{2+} and CO_3^{2-} concentrations. The thermal resistance due to fouling is expressed by:

$$\frac{dR_f}{dt} = \frac{\dot{m}_d - \dot{m}_r}{\rho_f \lambda_f} \quad (9)$$

Where ρ_f and λ_f are the density and thermal conductivity of the salt; \dot{m}_d is the mass deposited and \dot{m}_r is the mass rate removal from the surface (Quan et al., 2008).

3. Results

For validation purposes, predicted fouling values are compared to typical published fouling resistances in Table 1. Also, results are compared with values reported by other authors using their own theoretical models. The aim is to demonstrate that the new model can produce reliable results. For the purposes of the analysis, the data reported on Tables 2 and 3 are used to determine the fouling rate. Treated water with low hardness consisting solely of CaCO_3 flowing through a smooth copper pipe was considered.

Table 1: Typical fouling resistance factors (Bott, 1994)

Fluid type	R_f ($\text{m}^2\text{K/W}$)
River water below 50°C	0.0021-0.001
Cooling water (treated)	0.0002-0.00035
Cooling water (untreated)	0.0005-0.0009

Table 2: Data for CaCO_3 fouling rate calculation

Ca^{2+} (mol/l)	CO_3^{2-} (mol/l)	pH	P (kg/m^3)	μ (kgm/s)	R (J/mol K)
0.0034	0.00514	8.2	1,000	0.001	8.314

Table 3: Data for CaCO_3 fouling rate calculation (continued)

ρ_f (kg/m^3)	λ_f (mol/l)	D_h (m)	K_0 ($\text{m}^4/\text{kg s}$)	E (kJ/kmol)	D_{if} (m^2/s)
2,700	1.5	0.0254	2.05E15	115E3	7.90E-10

Experimental data published in the open literature are used to validate the model. Figure 1 shows the new model plotted against mass deposited measured experimentally by Pääkköken (2015) and in Figure 2, the new model is plotted against the experimental fouling resistances determined by Wu and Cremaschi (2013). Figures 1 and 2 show that the new model has good agreement with the experimental data. In the case of Figure 2, it can be observed that the thermal resistance increases with time and reduces with velocity. The results confirm that the new model accurately describes the real phenomenon.

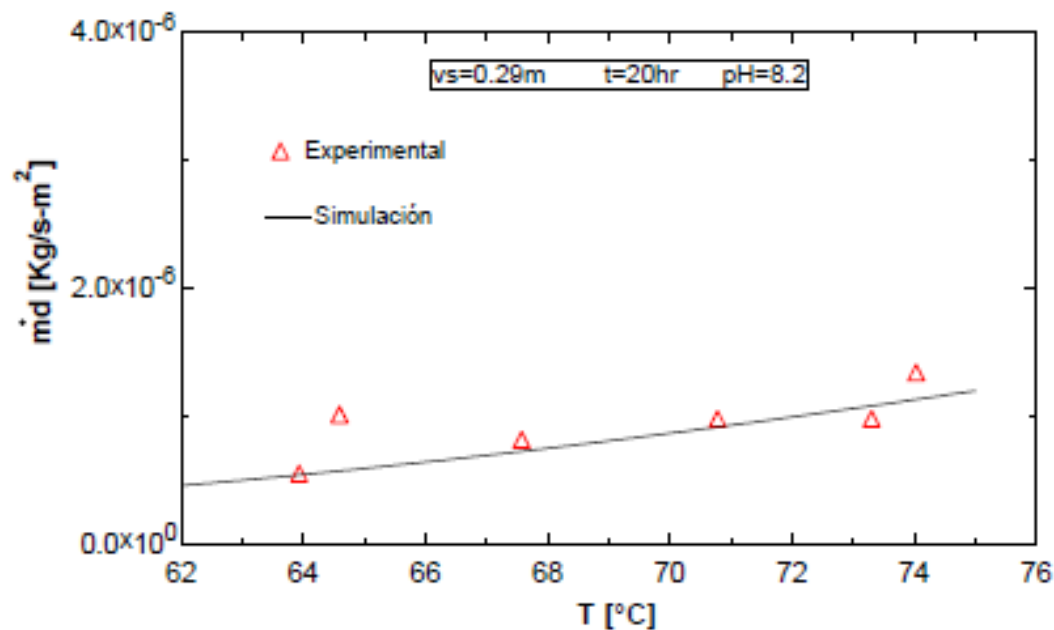


Figure 1: Comparison between experimental data (Pääkköken, 2015) and the modified model for CaCO_3 deposition.

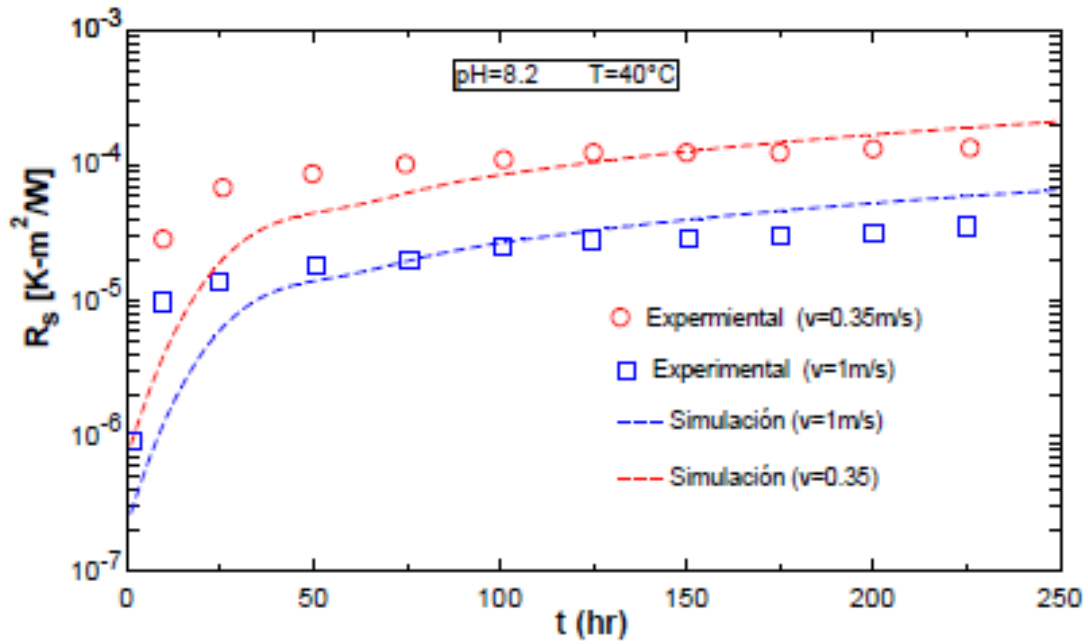


Figure 2: Comparison between the new theoretical model and experimental data (40°C) by Wu and Cremaschi (2013).

3.1 Model performance

In this section, the new model is used for the prediction of the thermal resistance with temperature, velocity and time. The results are compared with the models reported by Pääkkönen (2015) in Figure 3 and Wu and Cremaschi (2013) and Figure 4.

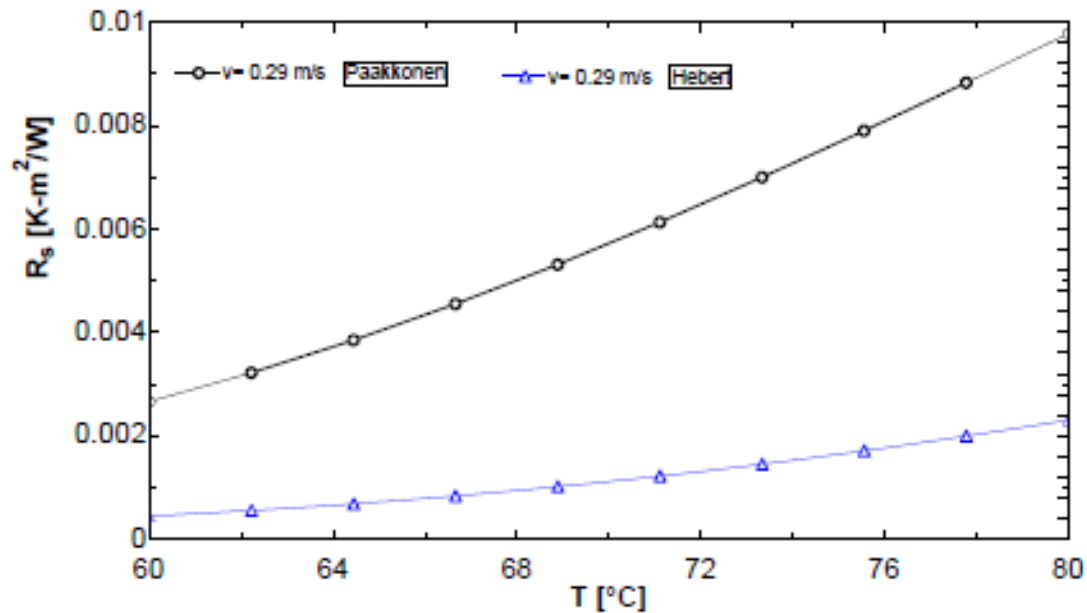


Figure 3: Prediction of thermal resistance due to fouling. Comparison between new model and Pääkkönen (2015).

Figure 3 shows the comparison with the model proposed by Pääkkönen (2015). The data reported corresponds to fouling rates as a function of temperature for a velocity of 0.29 m/s. In this case, it is found that the new model produces estimations which are more acceptable compared to what is expected from reported

values. Figure 4 shows further use of the theoretical models to predict the fouling resistance for a 6-month period. Two velocities are considered: 0.35 m/s and 1 m/s using data from Table 2.

Figure 4 shows the comparison for a temperature of 80°C. The thermal resistance predicted by Wu and Cremaschi (2013) reaches values as high as $2 \times 10^{-2} \text{ m}^2 \text{ K/W}$ which are 10 times greater than reported values. Besides, as the velocity increases, the thermal resistance also increases which is contrary to what it is expected. The new model, on the other hand, exhibits fouling resistances in the range of $2.5 \times 10^{-3} \text{ m}^2 \text{ K/W}$. In this case the behaviour with velocity is as expected; this is, as velocity increases the fouling resistance decreases. Figure 5 shows the use of the new model to predict the fouling thermal resistance in the tube of a cooler in a 6-month operating period. The tube has a length of 2 m; water enters the tube at 20°C and leaves at 60°C.

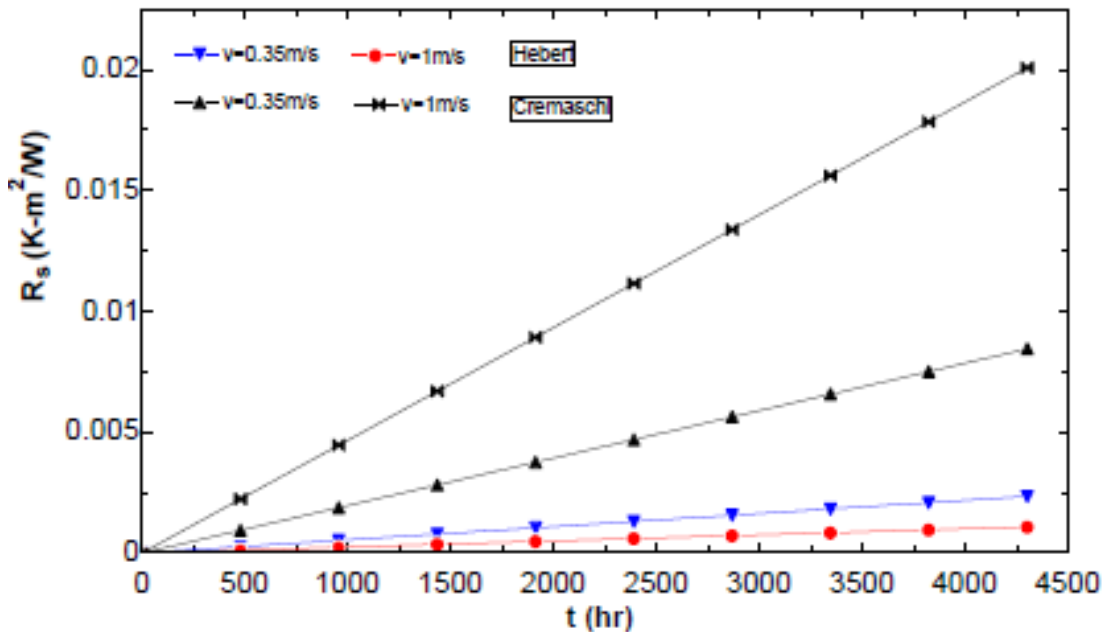


Figure 4: Prediction of thermal resistance due to fouling. Comparison between new model and Wu and Cremaschi model (2013).

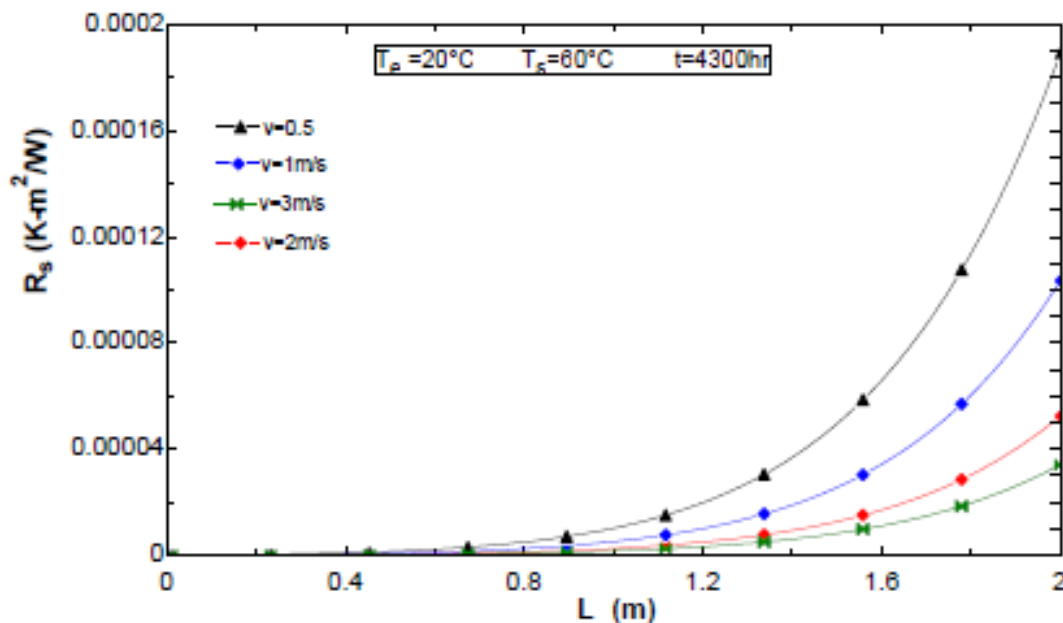


Figure 5: Use of the new model to predict the fouling rate in 2 m long tube for a 6-month operating period. Water inlet and outlet temperatures are 20°C and 60°C.

4. Conclusions

For a given fluid velocity and concentration, fouling resistance due to scaling increases with time. However, at higher velocities, the rate of deposition is expected to show lower values. For a theoretical model to accurately predict such performance inertial and friction forces must be taken into consideration and they should affect the rate of chemical reaction. The rationale behind this is that at higher velocities, the increased turbulence reduces the laminar layer and takes away the Ca^{2+} and CO_3^{2-} preventing them from reacting to form crystals which once formed adhere to the surface creating scaling. A shortcoming of most theoretical models is that when they are used to predict fouling resistances, the predicted values are orders of magnitude greater than the reported values in the literature. Such over prediction renders the use of theoretical models unreliable for design purposes. The model introduced in this work eliminates these shortcomings and can confidently be used for thermal performance analysis leading to design and operating strategies for systems where water is used as a cooling fluid.

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