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Model for seawater fouling and effects of temperature, flow velocity and surface free energy on seawater fouling[☆]

Dazhang Yang¹, Jianhua Liu^{1,2,*}, Xiaoxue E¹, Linlin Jiang¹¹ School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China² Shanghai Key Laboratory of Multi-phase Flow and Heat Transfer, Shanghai 200093, China

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ABSTRACT

A kinetic model was proposed to predict the seawater fouling process in the seawater heat exchangers. The new model adopted an expression combining depositional and removal behaviors for seawater fouling based on the Kern–Seaton model. The present model parameters include the integrated kinetic rate of deposition (k_d) and the integrated kinetic rate of removal (k_r), which have clear physical significance. A seawater-fouling monitoring device was established to validate the model. The experimental data were well fitted to the model, and the parameters were obtained in different conditions. SEM and EDX analyses were performed after the experiments, and the results show that the main components of seawater fouling are magnesium hydroxide and aluminum hydroxide. The effects of surface temperature, flow velocity and surface free energy were assessed by the model and the experimental data. The results indicate that the seawater fouling becomes aggravated as the surface temperature increased in a certain range, and the seawater fouling resistance reduced as the flow velocity of seawater increased. Furthermore, the effect of the surface free energy of metals was analyzed, showing that the lower surface free energy mitigates the seawater fouling accumulation.

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1. Introduction

The coastal plants such as petrochemical engineering and power stations use seawater as cooling water for saving fresh water and operation cost. A statistic shows that 42% of power stations use seawater as cooling water in USA [1]. The cooling seawater for a 500 MW nuclear power station is about $30 \text{ m}^3 \cdot \text{s}^{-1}$ [2].

However, the heat exchangers using seawater is easy to get fouled. Firstly, there are a lot of inorganic salts in seawater such as Mg^{2+} , Al^{3+} , and pH of seawater is between 7.2 and 8.6, which results in crystallization fouling in heat exchangers. The electrical conductivity of seawater is $4.788 \text{ s} \cdot \text{m}^{-1}$, while drinking water's is $0.0005\text{--}0.05 \text{ s} \cdot \text{m}^{-1}$. The higher electrical conductivity of seawater causes more corrosion fouling in seawater. Besides, the surface layer of ocean has high BOD (biochemical oxygen demand) and COD (chemical oxygen demand). In some places near the sewage draining exit, the BOD reaches $200 \text{ mg} \cdot \text{L}^{-1}$ [3], so the bio-fouling can be easily formed in seawater. Rubio *et al.* [4] found that the nature of the seawater fouling was predominantly inorganic, containing over 70% of total fouling.

The seawater fouling decreases the heat transfer efficiency and increases the pressure drop of heat exchangers [5,6]. The designing and the operation of heat exchangers have to contemplate redundancy area and equipment cleaning. According to statistics, the condenser fouling of a 550 MW coal-fired power station can cause a loss of 0.4–2.2 million U.S. dollars every year because of the additional fuel and reduced productivity [7]. The economic loss due to fouling in heat exchangers is about 0.25% of GDP in the industrial developed countries [1].

For all the above reasons, people must estimate the fouling process to clean heat exchangers and design anti-fouling methods. Therefore, an accurate and practical kinetic model is important for predicting the fouling process of seawater heat exchangers. Several models for fouling deposition in fresh water were proposed in the literature [8]. However, most of them are not appropriate for seawater heat exchangers. Hasson *et al.* [9,10] proposed a diffusion model for calcium carbonate deposition without removal behavior. According to our investigation, the seawater fouling is quite different from common fouling in fresh water. The main composition of seawater crystallization fouling is not calcium carbonate but rather magnesium hydroxide. Nebot *et al.* [11] proposed a model for fouling on power plant steam condensers cooled with seawater. The model has two parameters ($R_{f\infty}$ and $t_{0.5}$) to describe the fouling process, but the model cannot distinguish the effects between deposition and detachment.

In this paper, a kinetic model for seawater fouling was proposed based on the Kern–Seaton model [12] with deposition rate refined

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* Corresponding author.

E-mail address: lwnlwn_liu@163.com (J. Liu).

using an Arrhenius equation. The experimental setup was built for application and validation of the model. Based on the model and the experiments, the effects of temperature, flow velocity and surface free energy on fouling process were investigated. The fouling model can be efficiently helpful to improve the coefficient of heat exchangers and reduce operating consumption. The study helps for industrial operation using seawater as cooling medium.

2. Kinetic Model

People always hope to design an anti-fouling heat exchanger for seawater and clean them timely with an appropriate method. It is necessary to build a model for seawater, which could supply an estimation of seawater fouling process, so that the optimization of heat exchanger operation can be done easily. The famous model for interpreting the fouling process was proposed by Kern and Seaton [12]. They put forward that fouling proceeds with two mechanisms: deposition and removal. The net mass of fouling is the difference between deposition and removal rates:

$$\frac{dm}{dt} = \frac{dm_d}{dt} - \frac{dm_r}{dt} \quad (1)$$

The Kern and Seaton model is the most popular model of fouling, but it did not propose the definite and appropriate expressions of the deposition and removal rates for different kinds of fouling. Now, most of expressions describing the deposition and removal rates are from data fitting. Our model includes a new expression for the deposition of seawater fouling. We found the seawater fouling is actually a process of crystallization, and the crystallization could be described by the Arrhenius equation. Therefore, we used the Arrhenius equation to express the growth mass rate of depositional fouling:

$$G = k_g \exp\left(-\frac{E}{RT}\right) \Delta C \quad (2)$$

The parameters k_g and E due to the seawater crystallization is determined by seawater and metal surface properties, such as fouling-ion concentration in seawater and the surface free energy of metal.

In the process of seawater fouling, the decreasing mass rate of fouling-ions in seawater is equal to the growth mass rate of depositional fouling in heat exchangers, so Eq. (2) can be expressed as

$$-\frac{dM}{dt} = k_g \exp\left(-\frac{E}{RT}\right) (M-S) \quad (3)$$

Eq. (3) is integrated to get

$$M = \exp\left(\left(-k_g \exp\left(-\frac{E}{RT}\right)t + c\right)\right) + S \quad (4)$$

In the beginning of fouling, the mass of fouling-ions in seawater is assumed as M_0 . Then the mass of depositional fouling is expressed as

$$m_d = (M_0 - M) = M_0 - \exp\left(c - k_g \exp\left(-\frac{E}{RT}\right)t\right) - S \quad (5)$$

In our experiments, we found that the induction period (t_0) was quite short compared to the whole time of fouling, thus the induction period can be ignored. In this case, the constant value (c) is equal to the logarithm of $(M_0 - S)$. The mass of depositional fouling can be expressed as

$$m_d = (M_0 - S) \left(1 - \exp\left(-k_g \exp\left(-\frac{E}{RT}\right)t\right)\right) \quad (6)$$

The differential of the mass rate of depositional fouling can be calculated by

$$\frac{dm_d}{dt} = (M_0 - S) k_g \exp\left(-\frac{E}{RT}\right) \exp\left(-k_g \exp\left(-\frac{E}{RT}\right)t\right) \quad (7)$$

Eq. (7) can also be expressed as

$$\frac{dm_d}{dt} = (M_0 - S) k_d e^{-k_d t} \quad (8)$$

with

$$k_d = k_g \exp\left(-\frac{E}{RT}\right) \quad (9)$$

The detachment of fouling is complex and mutative. Taborek *et al.* [13,14] proposed that the removal rate of fouling has great relevance with flow velocity, fouling mass and intensity, corresponding to the following expression:

$$\frac{dm_r}{dt} = \frac{kv^2 m}{\psi} \quad (10)$$

Combining Eqs. (8) and (10), the differential equation of fouling is obtained:

$$\frac{dm}{dt} = \frac{dm_d}{dt} - \frac{dm_r}{dt} = (M_0 - S) k_d e^{-k_d t} - \frac{kv^2 m}{\psi} \quad (11)$$

Integration of Eq. (11) leads to

$$m = \exp\left(-\frac{kv^2 t}{\psi}\right) \left(c' + (M_0 - S) k_d \int e^{-k_d t} \exp\left(\frac{kv^2 t}{\psi}\right) dt\right) \quad (12)$$

Denoting the removal coefficient $k_r = kv^2/\psi$ and using the initial condition $m(t=0) = 0$, Eq. (12) can be simplified as

$$m = \begin{cases} \frac{(M_0 - S) k_d}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}), & k_r \neq k_d \\ (M_0 - S) k_d t e^{-k_r t}, & k_r = k_d \end{cases} \quad (13)$$

In fact, the integrated kinetic rate of removal is hardly equal to the integrated kinetic rate of deposition. Therefore, we took no account of the situation of $k_r = k_d$. Eq. (13) shows that the process of seawater fouling is a asymptotic curve, which is also proved in experiments.

3. Methods and Experimental Setup

3.1. Experimental methods

In order to obtain the kinetic parameters of the model and validate the new model, a monitoring method for heat exchanger fouling was adopted [15–17]. The fouling resistance was used to represent the fouling on heat transfer surface. As shown in Eq. (14), the amount of fouling is directly related to the heat transfer resistance of fouling on the heat transfer surface [18]:

$$\bar{m} = R_f \rho_f \lambda_f \quad (14)$$

The relationship between R_f and m was linear, as shown by

$$R_f = \frac{\bar{m}}{\rho_f \lambda_f} = \frac{V}{A \rho_f \lambda_f} m \quad (15)$$

Therefore, the mass of seawater fouling could express by the thermal resistance conveniently.

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