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Experimental study of composition and influence factors on fouling of stainless steel and copper in seawater

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ABSTRACT

Metals and alloys are easily fouled in marine environment. It is a big problem for heat exchangers using cooling seawater in power plants or ships. In the paper, a seawater-fouling dynamic test device was built to investigate the composition and influence factors on fouling of stainless steel and copper in the cooling seawater system. Moreover, the static trials were performed to study the fouling and corrosion of stainless steel and copper in marine environment. The experimental results show that the seawater fouling of stainless steel is crystallization fouling, and the main elements of fouling are magnesium and aluminum. In addition, the results show that the seawater fouling of copper is corrosion fouling. In the dynamic experiments, the effects of heat flux and Reynolds number on stainless steel fouling were studied. The results show that higher heat flux and higher Reynolds number of seawater lead to the accumulation of seawater fouling.

1. Introduction

The water resources on the earth are $1.36 \times 10^{18}\ m^3$ (Steinhagen et al., 1993), and 97.2% of water resources is oceans (Pugh et al., 2005). The seawater is frequently used as the cooling water in the coastal power plants. The once-through seawater system gives lower available temperature to improve thermal efficiency. According to Keens (Keens, 1977), the US power industry used around $6700\ m^3{\cdot}s^{-1}$ cooling water which was 80% of all industry water in 1970s. Keens estimated the 42% of power stations use seawater as cooling water in USA. The flow of once-through seawater is quite high (ranging between 10 and $50\ m^3{\cdot}s^{-1}$) (Bott, 1998). For instance, the cooling seawater for a 500 MW nuclear power station is about $30\ m^3{\cdot}s^{-1}$ (Satpathy et al., 2010).

In marine environment, the fouling easily forms on the surface of metals. The fouling mechanism of seawater interacts with the metal materials. The main forms of seawater fouling in cooling system are usually considered: crystallization, corrosion, bio-fouling and particulate fouling (Izadi et al., 2011a; Nebot et al., 2007; Rubio et al., 2014). The accumulation of seawater fouling was considered as the result of several physical, chemical, biological and their interaction processes (Marshal et al., 1994; Eguía et al., 2008). Crystallization is a common fouling in marine environment. Because a lot of inorganic salts are in seawater such as Mg^{2+} and Ca^{2+}, they become crystallization fouling in weak alkaline environment. In addition, corrosion fouling is usually found in seawater. Metal materials such as Ferrous are easily oxidized and corroded in seawater.

Copper alloys, stainless steel and titanium alloys are proposed to use in the seawater cooling system. Fairhurst (1984) studied the developments of stainless steels which exposed in seawater. He manufactured the stainless steel with low carbon and low nitrogen to seawater cooled condensers. Compared with stainless steel, the copper alloys have better anti-fouling ability than the stainless steel. The antifouling ability of copper alloys correlation with exfoliation effect, which is the result of interaction between stain layer adhesion and spalling force of the attachments (Ma et al., 2009).

In the seawater cooling system, the fouling could decrease the thermal efficiency and increase the pressure drop (Nebot et al., 2007; Rubio et al., 2014). Drake (1979) indicated that the fouling thermal resistance of cooling system accounted for 72% of the overall thermal resistance. The crystallization fouling was 33% and the bio-fouling was 39% including the overall thermal resistance. The thermal resistance of fouling for plate and frame heat exchangers in coastal seawater was taken for $0.000043\ m^2{\cdot}k{\cdot}W^{-1}$ (Pugh et al., 2005). As the changes of marine climate, the fouling

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Nomenclature

A	total heat transfer area, m^2
I	current of heating rod, A
m	fouling mass, kg
$\overline{m}$	fouling mass on unit heat transfer surface, $kg{\cdot}m^{-2}$
M	metal mass, kg
q	heat flux, $W{\cdot}m^{-2}$
R_f	Fouling thermal resistance, $m^2{\cdot}K{\cdot}W^{-1}$
R_r	resistance of heating rod, Ω
T_{in}	inlet temperature, K
ΔT	temperature difference, K
U	overall heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
λ_f	seawater fouling thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
ρ_f	seawater fouling density, $kg{\cdot}m^{-3}$

Subscripts

c	clean condition
i	inlet
f	fouled condition
o	outlet

in heat exchanger is periodically changed. In a power plant surface condenser, the highest fouling thermal resistance of 0.0025–0.003 $m^2{\cdot}k{\cdot}W^{-1}$ occurs in September to October every year (Ritter and Suitor, 1975).

The heating problem by seawater fouling in cooling system would cause economic loss. In a power plant, the seawater fouling in the condenser leaded to a decrease output power and thermal efficiency of 1.36% and 0.448% respectively (Ibrahim and Attia, 2015). The seawater fouling made the energy loss of 13319.93 kW for a 550 MW nuclear plant. The cost increase of a 550 MW thermoelectric power plant was 0.93 million/yr US dollars, which accounted for 0.88% in the total revenue (Walker et al., 2012). In addition, seawater fouling has a considerable effects on the irreversibility components due to heat transfer and pressure drop in the cooling system (Sahin et al., 2000). The economic loss due to fouling in heat exchangers is about 0.25% of GDP in the industrial developed countries (Pugh et al., 2005). Therefore, people always hope to eliminate or control the seawater fouling, which could improve the heat exchanger coefficient and reduce the operation consumption.

2. Experimental methods and setups

The purpose of the paper is investigation to the fouling of stainless steel and copper in seawater. We designed a dynamic experiment and a static experiment. The dynamic experiment was designed to simulate the fouling process in heat exchangers using seawater. The main experimental setup is a cooling seawater system, where the thermal resistance of fouling was used to monitor fouling. The static experiment was designed to study the effects of metal and seawater temperature on fouling accumulation and corrosion.

In addition, a composition of seawater fouling has a correlation with seawater sample. In our experiments, the seawater samples were collected in the yellow sea of China. The components of seawater were showed in Fig 1. The order of metal elements in seawater are sodium, magnesium, aluminum, followed by calcium.

2.1. The method of dynamic experiment: monitoring the thermal resistance of seawater fouling

It is difficult to directly measure the fouling mass in heat exchangers, so a monitoring method for thermal resistance of fouling was adopted (Quan et al., 2008; Liu and Wang, 1999; Izadi et al. 2011b). In our dynamic experiments, seawater was used to cool the heating rod in order to simulate the heat transfer in heat exchangers. In the process of heat transfer between seawater and heating rod, the fouling forms on the surface gradually, as shown in Fig. 2. As the fouling growing, the temperature difference of heat transfer increases and the heat transfer coefficient becomes lower. The fouling on the surface is the additional thermal resistance over the heating rod. As shown in Eq. (1), the amount of fouling is directly related to the thermal resistance of fouling on the heat transfer surface (Yang et al., 2004). We supposed the λ_f and the ρ_f of seawater fouling were constant, so fouling mass could be represented by the thermal resistance conveniently.

$$R_f = \frac{\overline{m}}{\rho_f \lambda_f} \tag{1}$$

The fouling thermal resistance can be calculated by overall heat transfer coefficients in fouled and cleaning conditions as Eq. (2). In this monitoring method, the fouling thermal resistance could be monitored real-timely and automatically.

$$R_f = \frac{1}{U_f} - \frac{1}{U_c} \tag{2}$$

Based on the thermal balance, the overall heat transfer coefficient between heating rod and seawater can be calculated with

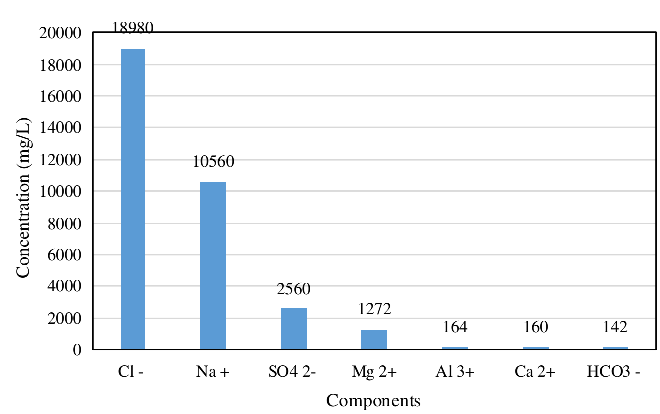

Fig. 1. The components of seawater in the yellow sea of China.

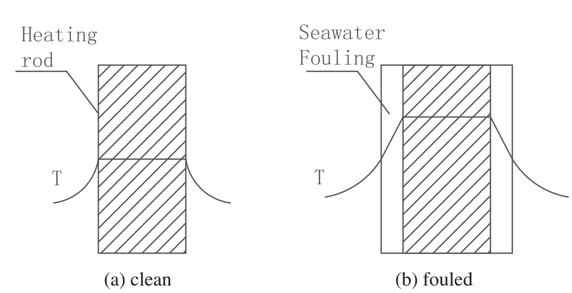

Fig. 2. The thermal resistance of fouling on the surface of heating rod.