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Integrated experimental investigation of seawater composite fouling effect on the 90/10 Cu/Ni tube

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ABSTRACT

The fouling effect of seawater samples collected from three New Hampshire beaches on a 90/10 Cu/Ni commercial heat exchanger tube was investigated. A fouling monitoring device, designed on the basis of fouling thermal resistance, was used for this experimental study. The filtered seawater samples were circulated through the closed loop experimental setup for durations of seven and 14 days and the fouling thermal resistance was measured continuously. Analytical microscopy was performed on the tube surface before and after the experiments to see the effect of seawater fouling on the tube surface. The results show different fouling behavior for the seawater samples. This different behavior is confirmed by the different composition of the samples. Fouling monitoring experiments reveal a higher fouling thermal resistance for one of the seawater samples, Hampton seawater, contrary to the results of SEM analysis which show a lower crystallization rate for Hampton sample. Water decomposition analysis shows the lowest sodium content for Hampton seawater compared to the other samples. Accordingly, corrosion of the tube surface occurs with a higher rate for Hampton seawater due to the presence of chlorine ions and a lower concentration of sodium. The high fouling resistance of Hampton seawater can be explained as the result of several simultaneous fouling mechanisms, corrosion and crystallization indicating composite fouling behavior. The results of the current study are critical for the industries which use seawater as the cooling water source.

1. Introduction

Fouling is accumulation of undesirable material (deposits) on heat exchanger surfaces. It is a synergistic consequence of transient mass, momentum, and heat transfer phenomena involved with exchanger fluids and surfaces, and depends significantly on heat exchanger operation conditions. This process influences heat transfer and flow conditions in a heat exchanger. Undesirable material may be crystals, sediments, inorganic salts, biological growth, and corrosion products. Fouling within the heat transfer equipment is often a limiting factor in plant operation. The effects of fouling, which increases pressure drop and decreases the heat transfer efficiency of equipment, are well known [1].

In 1960 Heat Transfer Research Incorporated (HTRI) was organized to conduct applied research in various areas of heat transfer. Fouling was one of the areas selected for investigation by HTRI, and was described as the 'major unsolved problem in heat transfer' [1]. Afterwards, very little research had been done until the late 1970s. However, recent research is beginning to give some insights into this complex industrial problem.

Although environmental pressures are increasingly limiting the application of seawater for cooling purposes it is still one of the main coolants in industry. Seawater is used as a coolant in the power generation industry. According to Knees [2], the US power industry used around 6700 m^3/s (106 million US gallons per minute) which was 80% of all industrial cooling water or a third of the water usage for all purposes in the USA in 70s. An estimation of the global water distribution done by Gleick [3] is listed in Table 1. Based on the data presented in Table 1 cooling with seawater, when it is locally available, is considered the primary resource of water.

The most important forms of fouling occurring in systems using seawater are as follows [4]:

- *Crystallization fouling*: this includes the deposition of calcium carbonate, calcium sulfate, and other salts with inverse solubility behavior. Inverse solubility means lower solubility in higher temperatures. An under-saturated solution becomes

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Table 1
Global water distribution [3].

Water source	Percentage (%)
Oceans, seas, and bays	96.5379
Icecaps, glaciers, and permafrost	1.7579
Ground water	1.6883
Surface water	0.0150
Atmosphere	0.0009

super-saturated by increasing the solution temperature and this causes formation of crystals near the hot surface where the solubility is locally lower compared to the bulk solution.

- *Corrosion fouling*: presence of chlorine and sulfur in seawater accelerates the corrosion process of most metallic surfaces including copper and its alloys. An insulating layer forms on the surface by oxidation of the tube. The combination of chlorine and sulfur is known to accelerate corrosion appreciably in copper–nickel alloys.
- *Biofouling*: a whole range of biological growth form on heat exchanger tubes in seawater including micro-organisms to macro-organisms.
- *Particulate fouling*: great amount of suspended particles exist in seawater including silt, mud, sand, and other finely divided particles. Even filtering cannot completely eliminate all suspended particles. In most fouling mechanisms some aspect of particulate fouling is involved. For instance, corrosion products can be removed from the surface by the flow and deposit on the surface in the other parts of the heat exchanger by particulate fouling. In crystallization, the deposition is dependent on the transport of solid crystallites across the boundary.

Accordingly, seawater has a composite fouling behavior. Composite fouling is a form of fouling process involving more than one type of fouling species or mechanism, which might interact with each other to produce the final deposit [5]. Despite the practical significance not much effort have been devoted to investigate composite fouling and to date conventional study on fouling mechanisms has been restricted to single-component systems. Oliveira et al. [6] reviewed the basic mechanisms of fouling and reported that synergistic phenomena (positive or negative) seem to occur when two or more types of foulant are presented in the fluid. Sheikholeslami et al. [7], and Sudmalis and Sheikholeslami [8] also studied the effect of interfering species on the fouling process.

Studying the effect of seawater on the metallic alloys received considerable attention in the past few decades. Ritter et al. [9] exposed copper alloy 706 in seawater for 1000 h and measured the fouling resistance. Parry et al. [10] performed a similar analysis on the admiralty brass. Fairhurst [11] studied the developments in stainless steels and their application to seawater cooled condensers. Pugh et al. [12] reviewed fouling effect of seawater as coolant and provided an industrial user guide. Izadi et al. [13] recently investigated the effect of seawater fouling on a 90/10 Cu/Ni commercial heat exchanger tube. A more comprehensive discussion of [13] is presented in this work. It is worth noting that most of the work done on seawater fouling focused on corrosion and little amount of information is available about the composite fouling behavior of seawater.

Seawater fouling was investigated in this paper by conducting prolonged tests with durations of seven and 14 days. The present authors know of no published work investigating seawater fouling in a heat exchanger tube during a period of several days by simulating the on-site conditions of a real heat exchanger. Seawater samples collected from three New Hampshire beaches were used for the current study. An analytical model and an advanced apparatus were used to measure and monitor the variations of the thermal resistance due to seawater fouling. The real operating conditions of a tubular heat exchanger were simulated in the experimental study. Alloy C70600 (referred to as 90/10 Cu/Ni henceforth) was considered as the tube material. Different investigation methods, measurement of fouling resistance, water decomposition analysis, and analytical microscopy of the tube surface were applied for the current study.

The rest of the paper was organized as follows: the mathematical model was developed in Section 2 followed by the description of the monitoring system and experimental procedure in Sections 3 and 4. The results of the experiments were presented and discussed in Section 5. The uncertainty analysis of the experimental results was mentioned in Section 6 followed by the summary and conclusions in Section 7.

2. Mathematical model

The fouling occurring inside the tubes is under investigation and a mathematical model is adapted. First, a model for the fouling resistance is given in terms of the overall heat transfer coefficient and the inside heat transfer coefficient. Next, the latter is determined by heat transfer correlations and geometrical characteristics of the system. The resistance due to fouling is then determined by calculating the difference in heat transfer resistance between fouled and clean conditions.

The notations used in the following sections are defined in the nomenclature provided at the end. The mean of the variable taken over the length of the heat exchanger is indicated by an upper bar. The overall thermal resistance, R_t, for the entire tube wall is given by [14]

$$R_t = \frac{\Delta T}{Q} \tag{1}$$

where ΔT is the temperature difference between hot and cold fluids and Q is the total heat transfer rate. Following it is also defined as [14]

$$R_t = \frac{1}{\overline{U_i}A_i} = \frac{1}{\overline{h_o}A_o} + \frac{1}{2}\ln\left(\frac{D_o}{D_i}\right)\frac{D_o}{k_w A_w} + \frac{1}{\overline{h_i}A_i} + \frac{R_{f,i}}{A_i} \tag{2}$$

where $\overline{U_i}$ is the mean overall heat transfer coefficient with respect to the inside surface area, $\overline{h_i}$ and $\overline{h_o}$ are the mean inside and outside heat transfer coefficients, A_i and A_o are the inside and outside heat transfer areas, D_i and D_o are the inside and outside tube diameters, k_w is the conductivity of the tube material, and $R_{f,i}$ is the thermal resistance due to fouling inside the tube. The effect of any extended surface on the heat transfer has been neglected in Eq. (2). For further simplification and greater accuracy, the resistance due to the outside heat transfer coefficient, $\overline{h_o}$, is neglected because, by applying a heat flux to the outside surface of the tube and insulating the exterior surface by thick thermal insulation, the contribution is negligible. ΔT represents the difference between the temperature of exterior tube wall surface and the temperature of the fluid flows inside the tube. The inside heat transfer coefficient, $\overline{h_i}$, is evaluated from the Gnielinski's semi-empirical correlation [15]

$$\overline{h_i} = \left(\frac{k_i}{D_i}\right)\frac{(\mathrm{Re}_i - 1000)\mathrm{Pr}(z/2)}{1 + 12.7\sqrt{z/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \tag{3}$$

where Re is the Reynolds number of the flow, Pr is the Prandtl number of the flow, and z is calculated as,

$$z = (1.58\ln(\mathrm{Re}_i) - 3.28)^{-2} \tag{4}$$

Then, Eq. (1) in conjunction with Eq. (2) yields,