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Mitigation of scaling in heat exchangers by physical water treatment using zinc and tourmaline

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ABSTRACT

This paper presents a study on the mitigation of calcium carbonate scaling in a double-pipe heat exchanger by physical water treatment (PWT) using zinc and tourmaline as catalytic materials. Artificially-hardened water at 300 mgL^{-1} was utilized as the fluid medium to form fouling deposits. The cooling water (i.e., hard water) velocity was varied from 0.3 to 0.8 ms^{-1}. The inlet temperatures were maintained at $86 \pm 1^\circ$ C and $22 \pm 1^\circ$ C for hot- and cold-water sides, respectively. The results show that in PWT-treatment case, the fouling resistances are 13–50% lower than those in no-treatment case. The SEM image of the deposit shows a blunt shape crystal structure in case of PWT-treatment, while a pointed crystal structure in case of no-treatment. The calcium content of deposits formed in the cases of PWT-treatment is lower by 17–22% than those of the no-treatment, which corresponds to a thinner fouling in case of PWT-treatment.

1. Introduction

Calcium carbonate ($CaCO_3$) fouling or scaling is one of the most common fouling mechanisms found in cooling water applications [1–4]. Scaling occurs when a process uses cooling water supersaturated with mineral salt crystals (i.e., hard water). When these inversely-soluble salt crystals like dissolved calcium ions are exposed to high temperature, they precipitate out of the solution and form deposits on heat transfer surfaces. The buildup of calcium carbonate scales on heat transfer surfaces like heating tubes of an evaporator or other heat exchange systems leads to decreased operating efficiency due to increase in tube wall temperature [5], and increased energy consumption [6–17]. The increase in tube wall temperature is mainly due to the very low thermal conductivity of calcium carbonate (i.e., 2.9 Wm^{-1} K^{-1} [3]) as compared to the thermal conductivity of the metal tube, like copper (i.e., 401 Wm^{-1} K^{-1}) [18].

To mitigate scaling in heat transfer surfaces, chemical additives are often used, but chemicals are expensive and pose problems to the environment [2,19]. Physical water treatment (PWT), a non-chemical method is a good alternative for a safe, and efficient fouling mitigation method. Examples of PWT include permanent magnets, solenoid coil devices, and catalytic materials and alloys [20–26]. In the present study, we used catalytic alloys as PWT method to mitigate calcium carbonate fouling in a double-pipe heat exchanger. A lot of research work has been carried out on the efficacy of catalytic alloys and dosing of metallic ion impurities for controlling the scale. Tang et al. [27] studied the effects of copper-based alloys on the nucleation and growth of calcium carbonate scales on steel plates. Their results showed a decrease in surface tension and oxidation–reduction potential of an artificially-made hard water solution, and there was a longer induction period after the hard water was exposed to copper-based alloys. In separate studies by Tai and Chien [28], and Tao et al. [29], they found that the presence of magnesium ions in the solution could prolong the induction period. Several studies [20,30–32] compared the effect of metal ions like zinc, copper, and iron, which are usually released by PWT on calcium carbonate scaling. Yang [32] in his research showed a significant decrease in calcium carbonate scaling of a reverse osmosis system when a 2 mgL^{-1} dose of zinc was

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Nomenclature

A_o	outer surface area of copper tube (m^2)
d	diameter of copper tube (m)
D	diameter of quartz crystal (m)
L	length (m)
Q	heat transfer rate (W)
R_f	Fouling resistance ($m^2\ KW^{-1}$)
ΔT_{lmtd}	log-mean-temperature difference (°C)
U	overall heat transfer coefficient ($Wm^{-2}\ K^{-1}$)

Subscripts

c	cold-side
fouled	fouled state
initial	initial clean state
i	inner
o	outer
q	quartz crystal
t	tube (copper)

supplied. Macadam and Parsons [30] investigated the effect of dosing iron, copper and zinc in calcium carbonate precipitation. Their results showed zinc as the most effective inhibitor, where a 5 mgL^{-1} zinc dose resulted to a 35% scale reduction. Coetzee et al. [20] also found that zinc was way more effective than copper and magnesium in the reduction of scaling in their study. On the contrary, Wenjun et al. [31] concluded that copper ion was a more effective inhibitor than zinc ion.

In the present study, PWT using catalytic alloys primarily composed of tourmaline and zinc, was used to mitigate calcium carbonate scaling in a double-pipe, counter-flow heat exchanger. The catalytic materials in the present study are understood to activate heterogeneous nucleation in bulk water. As water goes inside the device, it makes contact with the catalytic materials and a catalytic reaction is believed to take place at the surface of catalytic materials (primarily tourmaline) to dissociate the bicarbonate ions in water, leading to the precipitation of $CaCO_3$ in bulk water. As mineral salt crystals continue to precipitate, they adhere to the already suspended particle in water and grow in size, and adhere to the heat transfer surfaces through gravitational settling and particle transport. The deposits in this case are in the form of soft sludge or particulate fouling, wherein with enough shear forces from the flow of water, could easily be removed [1,4]. The goal of this research was to investigate the efficacy of the present catalytic alloys as PWT in decreasing fouling deposits on heat transfer surfaces.

2. Experimental facility and method

2.1. Facility

Fig. 1 shows the present fouling test set-up. It was divided into the hot and cold water-loops. A double-pipe heat transfer test section was used in the present study. The inner tube was made of copper with dimensions of $d_i = 13.85 \pm 0.05$ mm, $d_o = 16 \pm 0.05$ mm, and $L_t = 631 \pm 1.0$ mm, while the outer tube was made of quartz crystal with $D_o = 28.1 \pm 0.05$ mm, $D_i = 24.8 \pm 0.05$ mm, and $L_q = 499 \pm 1.0$ mm. The effective heat exchanger length was 600 ± 1.0 mm. The test section was covered with Styrofoam to lessen the heat loss to the surroundings. The whole fouling test system including the test section were grounded to lessen the effect of electrical noise and static electricity on the temperature readings.

The PWT using catalytic materials in the present study is shown in the inset of Fig. 1. The geometrical configuration of the PWT device shows a perforated cage-like casing made of zinc where hollow tourmaline cylindrical rods were placed. The outermost casing was made of aluminum.

2.2. Method

2.2.1. Fouling test

Before each fouling test, leakage test was first performed to the test section. The difference in heat transfer rates between the hot- and cold-water sides was found to be ±8%. Artificial hard water was prepared by mixing 50 g of calcium chloride ($CaCl_2$) and 76 g of sodium bicarbonate ($NaHCO_3$) powders in 150 L distilled water using the following chemical reaction [4]:

$$CaCl_2 + 2NaHCO_3 \rightarrow 2NaCl + CaCO_3 + H_2O + CO_2 \tag{1}$$

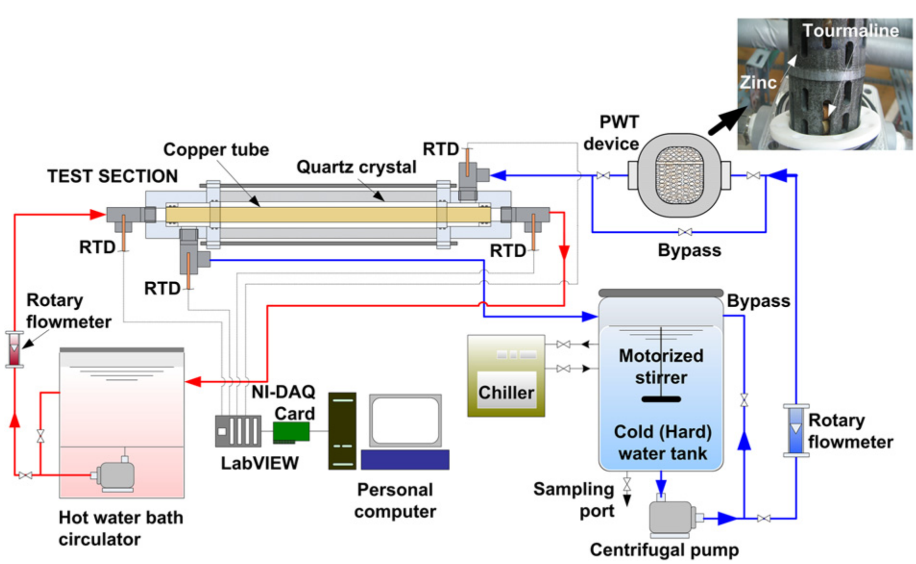

Fig. 1. The schematic drawing of the present fouling test system. It was divided into the hot (in red) and cold-water (in blue) loops. A double-pipe heat transfer test section was used in the present study. The inner tube was made of copper and the outer tube was made of quartz crystal. The inset shows a photo of the present PWT device using zinc and tourmaline.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)