International Communications in Heat and Mass Transfer 38 (2011) 1008–1013

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

# Benefit of filtration in physical water treatment for the mitigation of mineral fouling in heat exchangers[☆]

Wontae Kim [1], Young I. Cho [*]

*Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19104, USA*

ARTICLE INFO

Available online 19 May 2011

*Keywords:*
Fouling
Physical water treatment
Filtration
Heat exchanger
Fouling prevention
Mineral scale

ABSTRACT

The objective of the present study was to investigate the benefit of filtration in the physical water treatment used to mitigate mineral scale build-up in heat exchangers. Two types of filters were used: a 5-μm cartridge fabric filter and a sand filter with 20-μm pores, both of which were used at a side-stream loop in a laboratory cooling tower. Heat transfer fouling experiments were conducted using a double-pipe heat exchanger with cooling water at 5 and 8 cycles of concentration with a make-up water hardness of 200–240 ppm. The test results demonstrated that the filtration enhanced the performance of the PWT synergistically, resulting in a near initial peak heat transfer performance in the double-pipe heat exchanger.

## 1. Introduction

Fouling in general can be described as the formation of unwanted deposits on a heat transfer surface. Mineral fouling or the formation of scales such as calcium carbonate is common in cooling-water applications, where pure water evaporates to remove heat gained from condenser [1]. Hence, circulating cooling water quickly becomes supersaturated even if make-up water is soft. As the supersaturated cooling water is heated inside condenser, the calcium ions precipitate due to the inverse solubility characteristics of $CaCO_3$ salt. A number of studies [2–9] have been conducted to better understand mineral fouling process and its mitigation.

Since the scale deposits have very low thermal conductivities and thus behave as an insulating layer, the heat transfer rate is diminished at the heat exchanger with scale deposits [2]. As the deposits grow on the heat transfer surface, the opening inside the heat exchanger becomes smaller, increasing the pressure drop. Subsequently, more pumping power is needed to maintain flow, which will result in higher energy consumption. Currently, industry-standard practices for preventing mineral fouling call for the addition of scale-inhibiting chemicals to circulating cooling water [1]. The use of such chemicals contributes to fresh water pollution, a major environmental concern.

Several physical water treatment (PWT) methods [10–13] have been introduced in recent years as alternatives to standard chemical water treatment; some of the best results have been documented using solenoid-type PWT technologies using oscillating fields. PWT means any non-chemical methods that are utilized for the mitigation of mineral fouling. The present study utilized a solenoid-coil device with a square-wave pulsing current to create time-varying magnetic fields, which in turn produced an induced pulsating electric field in the circulating water, a process known as Faraday's law [14]. Excess mineral ions such as calcium and magnesium in cooling water precipitate in the form of mineral salts, providing nucleation sites for other dissolved mineral ions [12]. As the cooling water is continuously circulated, the precipitated seed crystals grow into larger particles. Thus, it is hypothesized that if the large particles could be removed from the cooling water, fouling at the heat exchanger could be prevented or significantly mitigated. Furthermore, the amount of blowdown could be reduced, thus increasing the cycle of concentration (COC) with substantial water savings.

The objective of the present study was to investigate the benefit of filtration used in conjunction with PWT by conducting fouling heat transfer experiments in a laboratory cooling-tower system at two different COC levels of 5 and 8 with a make-up water hardness of 200–240 ppm.

## 2. Experimental facility and methods

Fig. 1 shows a schematic diagram of the present experimental set-up. It consisted of a laboratory cooling tower, a double-pipe heat transfer test section, an automatic blowdown system based on electric conductivity measurement, four thermocouples, a flow meter, a pump, a data acquisition system (DAS), a PWT unit using a solenoid coil and power supply, and a side-stream filtration.

The detail view of the heat transfer test section is shown in Fig. 2, which was made of two concentric circular tubes: a copper tube at the inside and a quartz tube at the outside for visual inspection. The inner tube was a typical copper tube used in industrial chillers manufactured by companies like York, Carrier, and Trane. The outside diameter of

---

[☆] Communicated by W.J. Minkowycz.

[*] Corresponding author.
E-mail address: choyi@drexel.edu (Y.I. Cho).

[1] Present address, Aritec Corp., Yongin-Si, Gyeonggi-Do, Republic of Korea.

0735-1933/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2011.05.008

## Nomenclature

| | |
|---|---|
| $A_o$ | Outside surface area of copper tube ($m^2$) |
| $c_p$ | Specific heat of water (J/kg K) |
| d | Diameter of copper tube (mm) |
| $\dot{m}$ | Mass flow rate of water (kg/s) |
| $Q$ | Heat transfer rate (W) |
| $R_f$ | Fouling resistance ($m^2K/W$) |
| $T_i$ | Inlet temperature (°C) |
| $T_o$ | Outlet temperature (°C) |
| $\Delta T_{LMTD}$ | Log-mean-temperature difference (°C) |
| $U$ | Overall heat transfer coefficient ($W/m^2$ K) |

*Subscripts*

| | |
|---|---|
| *c* | Cold side |
| *f* | Fouled state |
| *h* | Hot side |
| *i* | Initial clean state |

the copper tube was 1.27 cm, whereas the inside diameter of the quartz tube was 1.76 cm. Hot water moved inside the copper tube, while the cold water moved outside the copper tube, i.e., through the annulus gap made by the two tubes. The hot and cold water were flowing in the opposite directions, forming a counter-flow heat exchanger. The inlet temperatures at the hot and cold sides were maintained at 95 °C and 27 °C, respectively, while the outlet temperatures at the hot and cold sides were at approximately 88 °C and 36 °C, respectively. The volume flow rate of the cold water was $9.5 \times 10^{-5}$ $m^3/s$ (1.5 gpm), with the corresponding flow velocity at the heat transfer test section of 0.81 m/s (Re = 4000). The durations for the fouling tests were 90 and 140 h for the cases of COCs of 5 and 8, respectively.

The fouling tests were conducted using a relatively high heat flux of 90–110 $kW/m^2$ in order to accelerate the fouling process, a practice which was common for fouling researches. Table 1 shows the test conditions of the previous fouling studies [2–8], which used high levels of heat flux as in the present study. The heat transfer rates at the hot and cold water sides were calculated as follows [15]:

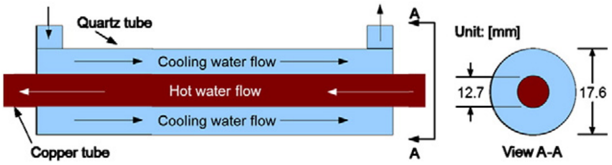

**Fig. 2.** Sketch of the heat transfer test section.

$$Q_h = \dot{m}_h c_{p_h} \Delta T_h \quad \text{(hot water side)} \tag{1}$$

$$Q_c = \dot{m}_c c_{p_c} \Delta T_c \quad \text{(cold water side)} \tag{2}$$

The specific heat $c_p$ was based on the average values of the inlet and outlet temperatures for both hot and cold water. The overall heat transfer coefficient $U$ was calculated as [15]

$$U = \frac{Q_c}{A_o \Delta T_{LMTD}} \tag{3}$$

The heat transfer surface area $A_o$ was calculated by $A_o = \pi d_o L_e$, where $d_o$ is the outer diameter of the copper tube and $L_e$ is the effective heat transfer length. The log-mean-temperature-difference $\Delta T_{LMTD}$ was determined by the following equation [15]:

$$\Delta T_{LMTD} = \frac{\left(T_{h,o} - T_{c,i}\right) - \left(T_{h,i} - T_{c,o}\right)}{\ln\left[\frac{\left(T_{h,o} - T_{c,i}\right)}{\left(T_{h,i} - T_{c,o}\right)}\right]} \tag{4}$$

The fouling resistance was calculated using the universal heat transfer coefficients $U_f$ and $U_i$ corresponding to the fouled and initial states, respectively as

$$R_f = \frac{1}{U_f} - \frac{1}{U_i} \tag{5}$$

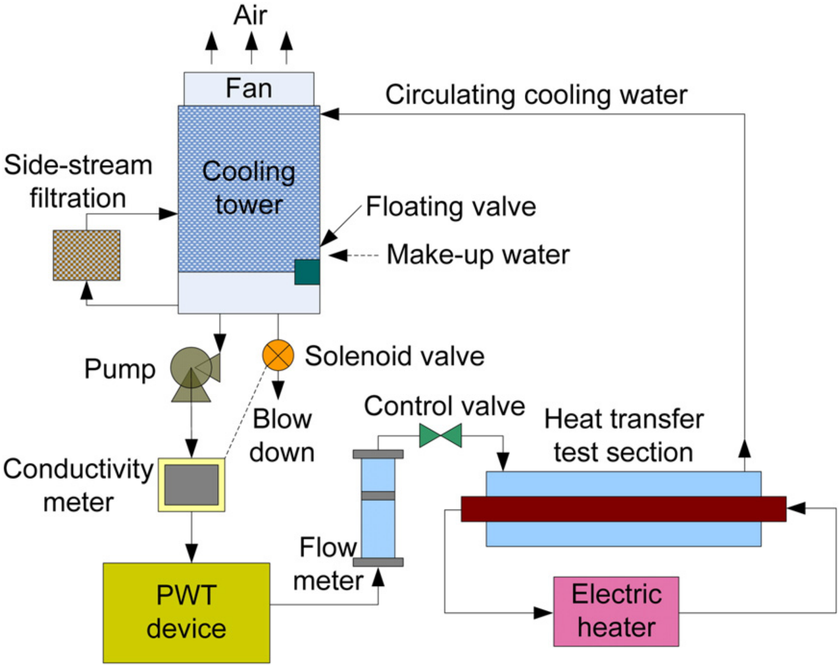

**Fig. 1.** Schematic diagram of the fouling test facility in the present study.