



Velocity effect on electronic-antifouling technology to mitigate mineral fouling in enhanced-tube heat exchanger

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Abstract

The purpose of the present study was to investigate the effect of flow velocity on an electronic-antifouling (EAF) treatment, which was considered to mitigate mineral fouling in a heat exchanger with cooling-tower water. Nine different tests were conducted with no-blowdown: six runs with an in-line EAF treatment and three runs with the EAF treatment at a side-stream loop. The flow velocities tested were 0.6, 1.2, 1.5 and 2.0 m/s. As the flow velocity was increased, the benefit of the in-line EAF treatment decreased. At a flow velocity of 0.6 m/s, the fouling resistance decreased by 80% in the case with the EAF treatment compared with that in the no-treatment case for both in-line and side-stream EAF treatments. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Fouling; Electronic-antifouling; Flow velocity; Enhanced tube; Heat exchanger

1. Introduction

This paper deals with the mitigation of mineral fouling using an electronic-antifouling (EAF) technology [1–9] in a heat exchanger with an enhanced-surface tube. The operational principle of this EAF technology has not yet been fully understood. One of the parameters in question in the use of the EAF technology is the effect of flow velocity through a solenoid, a component of the EAF technology, on overall EAF performance. Intuitively, as the flow velocity at the solenoid coil increases, the time for water molecules to stay inside the coil decreases, thus, the EAF performance is speculated to decrease. Likewise, as the flow velocity decreases, EAF performance is speculated to increase. If this phenomenon can be experimentally validated, one can consider other changes such as the pipe diameter, the frequency of the pulsating current signal, the number of solenoid coils, etc. for further improvement of the EAF technology.

Scale is formed when hard water is heated (or cooled) in heat transfer equipment such as heat exchangers, condensers, evaporators, cooling towers, boilers, and pipe walls. The type of scale differs depending on the mineral content of the available water.

Scale often observed in industry includes calcium carbonate, calcium sulfate, barium sulfate, silica, iron scales, and others. One of the most common forms of scale is calcium carbonate (CaCO_3), which occurs naturally as an ingredient of chalk, limestone, and marble. Acidic water passing over and permeating through the ground dissolves limestone into calcium and bicarbonate ions, thereby making hard water. When the hard water is heated inside heat transfer equipment, the calcium and bicarbonate ions precipitate due to the changes in solubility, forming hard scale on the heat-transfer surfaces, and clogging pipes and manifolds. When scale deposits in a heat exchanger surface, it is traditionally called fouling [10,11].

Many efforts have been made by numerous researchers to understand and control fouling in heat exchangers in the past [12–19]. They have focused on various methods to predict fouling behavior more accurately which in turn helps prevent fouling problems. Numerous researchers have studied fouling phenomena with enhanced-tube heat exchangers to see if the

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Nomenclature

A	total heat transfer area, m^2
c_p	specific heat at constant pressure, J/kg K
D_c	outer diameter of corrugation, cm
ID	inner diameter of acrylic tube, cm
OD	outer diameter of acrylic tube, cm
e	corrugation height, cm
L	total length of outer tube, cm
L_c	corrugation length, cm
\dot{m}	mass flow rate, kg/s
n_s	number of starts
P	corrugation pitch, cm
\dot{Q}	heat transfer rate, W
R_f	fouling resistance, $m^2 \text{ K/W}$

t	time, h
T	temperature, $^\circ\text{C}$
ΔT_{lm}	log mean temperature difference, $^\circ\text{C}$
U	overall heat transfer coefficient, $\text{W/m}^2 \text{ K}$
V	cooling water flow velocity, m/s

Greek symbol

α	helix angle, degree
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Subscripts

f	fouled
c	cooling water side
h	hot water side
i	inlet, clean
o	outlet

enhanced surface reduces fouling as compared with a smooth tube [20–28]. Some published studies [21,26] have reported that lower fouling resistance was obtained by using an internally enhanced tube compared to a plain tube. Others [25,27,28] reported that enhanced tubes were more susceptible to fouling but still provided better heat transfer performance than that of the plain tube under the same fouling conditions. Web and Kim [23] reported that particulate fouling rates obtained from enhanced tubes at laboratory-controlled conditions were almost the same as those obtained from plain tubes. This may be attributed to the fact that the characteristics of the fouling mechanism are very sensitive to fluid velocity in a heat exchanger, surface geometry, water concentration, bulk temperature, and tube material. In spite of the uncertainty related to fouling, enhanced tubes are being used in various heat exchangers, water chillers, and air-conditioning condensers.

Until now, in order to prevent or control mineral fouling, chemical treatment has been used. However, chemical treatment has several drawbacks, including disposal and pollution problems, handling of hazardous chemicals, and cost. If there could be a non-chemical method to effectively prevent or mitigate mineral fouling, such a method would be beneficial, not only to the industry but also to the environment. Little research [1] has been conducted to test the validity of the non-chemical water treatment method particularly in an enhanced-tube heat exchanger.

In a cooling-tower water application, the concentration of dissolved mineral ions is much greater than that in make-up water due to the evaporation of water. In order to maintain a certain level of concentration of mineral ions, a portion of water in the cooling tower has to be discharged (i.e., blowdown), and the same amount of water has to be added in the form of make-up water.

The conservation of fresh water, coupled with maintaining the maximum efficiency of a heat exchanger in the cooling-water system, is one of the major issues related to the fouling and cooling-water treatment.

Although Cho et al. studied the feasibility of EAF technology to mitigate mineral fouling in various heat exchangers [2–6], the effect of flow velocity through the solenoid coil used in the EAF technology on the performance of the technology was not investigated. The purpose of the present study was to investigate the effect of the flow velocity at the solenoid-coil on the performance of the EAF treatment using an enhanced tube.

2. Experimental method

Fig. 1 shows a schematic diagram of the present test facility, which consists of a water-circulating loop, an electronic-antifouling device, a cooling tower, a pump, a concentric-tube test section, and a floating-ball valve for automatic feeding of make-up water. In the study, the EAF treatment was applied first in the main flow loop and later in a side-stream loop. In the first case, as the flow velocity varied in the solenoid coil installed in the main loop, the flow velocity also varied in the enhanced tube. In the second case, when the flow velocity varied at the solenoid coil installed in the side-stream loop, the flow velocity at the enhanced tube was unchanged during the test. For both cases, high heat-flux conditions were employed in order to accelerate fouling at laboratory. These high heat-flux conditions will be discussed in further detail.

Fig. 2 shows a schematic diagram of the main heat-transfer test section, including detail dimensions and the actual photograph of the enhanced tube. The main heat-transfer test section was composed of two concentric

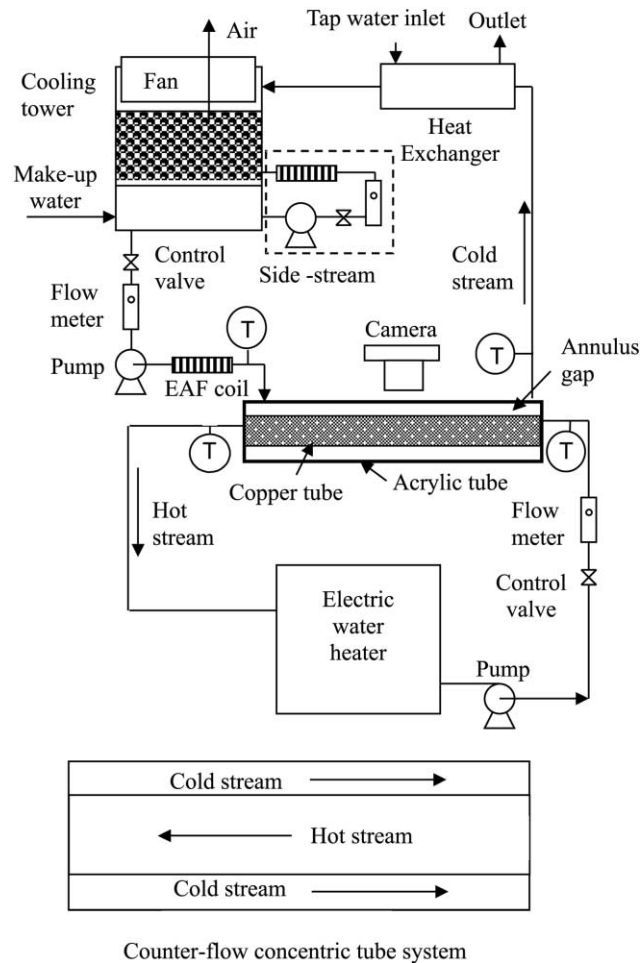


Fig. 1. Schematic diagram of a scale-deposit test facility with a simulated cooling tower.

tubes: the inner one was made of an enhanced copper tube, and the outer one was made of an acrylic tube. The dimensions of the outer tube were 2.54 cm \times 1.91 cm \times 20.4 cm (OD \times ID \times L). The dimensions of the inner enhanced tube are given in Fig. 2(b). Fig. 2(c) shows the photograph of the two tubes (i.e., enhanced copper tube as the inner tube and acrylic tube as the outer tube). The two tubes were connected with compression fittings at both ends of the inner and outer tubes. The cooling water moved in the annulus gap between the two tubes, whereas hot water moved inside the inner tube (see Fig. 1 for details). The flow directions of the hot and cold water were opposite to each other, thus forming a counter-flow heat exchanger.

The flow rate of the cooling water varied from 0.769×10^{-4} m³/s (i.e., 1.22 gpm) to 2.019×10^{-4} m³/s (i.e., 3.2 gpm). The flow velocity corresponding to 1.22 gpm was 0.6 m/s (i.e., 2 ft/s) in the cooling channel,

where fouling occurred. Such a relatively small flow velocity often occurs in a water chiller running at a reduced load. Note that the annulus gap was changing locally but the cross-sectional area of the enhanced tube at any axial location was constant with the cross-sectional area of 0.000129 m², based on which the mean flow velocity was estimated. The Reynolds number in the cooling channel was 9275 based on the hydraulic diameter of the test section. The flow velocities and Reynolds numbers for the case of 1.577×10^{-4} m³/s (i.e., 2.5 gpm) were 1.2 m/s (i.e., 4 ft/s) and 17,325 respectively, whereas those for a flow rate of 2.019×10^{-4} m³/s (i.e., 3.2 gpm) were 1.5 m/s (i.e., 5 ft/s) and 22,176, respectively.

To calculate the fouling resistance, temperatures were measured at four different positions: cooling-water inlet and outlet, and hot-water inlet and outlet, see Fig. 1. The cooling water entered the test section at a constant

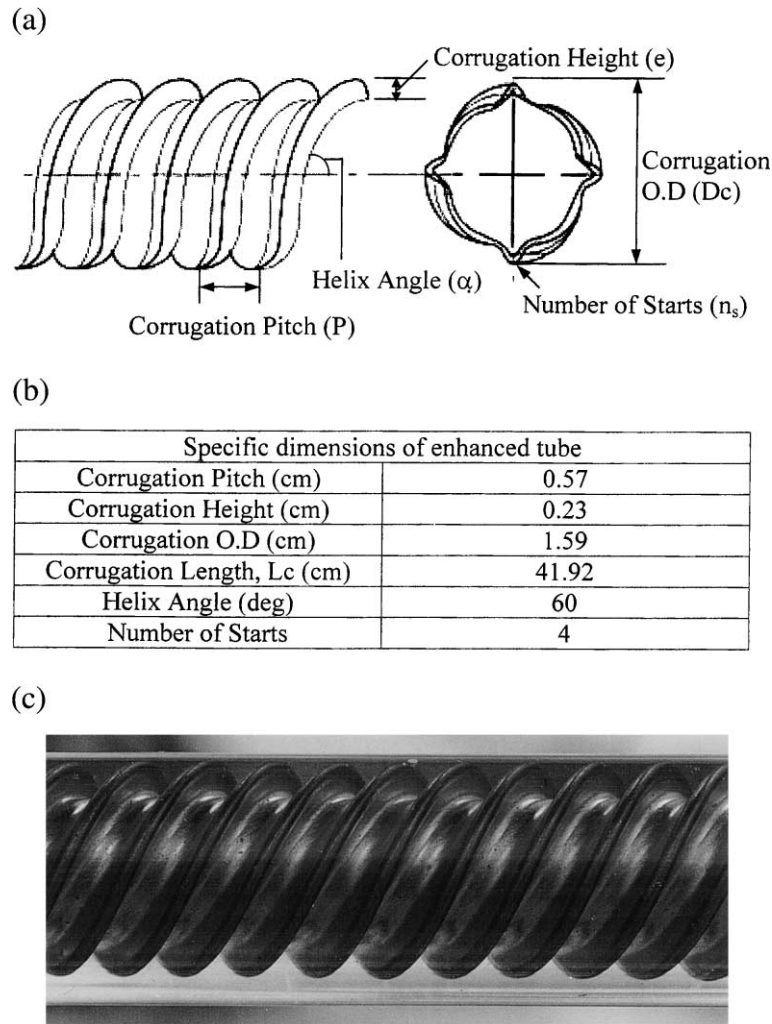


Fig. 2. Schematic diagram of an enhanced-surface tube and actual dimensions.

temperature of 25 ± 0.5 °C and heated to 39, 31, and 30 °C in the three flow-velocity cases (i.e., 0.6, 1.2, and 1.5 m/s, respectively). The hot water entered the test section at a constant temperature of 95 ± 0.5 °C and cooled to 78, 80, and 82 ± 0.5 °C in the above three cases during the test.

After the cooling water past the heat-transfer test section, it was first sent to a small shell-and-tube heat exchanger to reject heat and then sent to the cooling tower, where the water was further cooled by evaporation. The small shell-and-tube heat exchanger prior to the cooling tower was necessary to maintain the inlet temperature of cooling water prior to heat-transfer test section at 25 °C. The tap water supplied by the City of Philadelphia (see Table 1 for water properties) was used as the make-up water, which was introduced by an automatic floating-valve. To avoid biological fouling in the

test section, 1 ppm of tide detergent and 2.5 ppm of Clorox bleach were added to the make-up water as

Table 1
Analysis of Philadelphia tap water that was used as make-up water

	Minimum	Average	Maximum
Conductivity ($\mu\text{S}/\text{cm}$)	389	520	652
pH	7.3	7.5	7.6
Total hardness (mg/l)	150	190	247
Alkalinity (mg/l)	54	74	93
Chloride (mg/l)	56	75	149
Sulfate (mg/l)	37	61	89
Silica (mg/l)	3	5.8	7.8
Phosphate (mg/l)	0.2	0.25	0.3

The data were provided by the City of Philadelphia.

biocide, as recommended by a local chemical water treatment company.

As the number of cycles of concentration increased, the amount of mineral ions in the cooling-tower water increased accordingly. The cycle of concentration (COC) is defined as the ratio of the concentration of dissolved ions in the circulating cooling-tower water to that in the make-up water. At the completion of each test, the cycle of concentration was determined to be 10.5–10.7, based on the chloride concentration in the circulating water (see Table 2). Note that the COC was estimated using the chloride concentration in the present study because the amount of chloride ions was independent of the fouling process. Since only 0.85 ml of Clorox bleach was added to total 340 l of the make-up water, the effect of the Clorox bleach on the chloride concentration of the circulating cooling-tower water was negligible.

Hot water was produced by an electric water-heater and circulated at a flow rate of $6.309 \times 10^{-5} \text{ m}^3/\text{s}$ (i.e., 1.0 gpm). The water heater had a heating element of 4.2 kW, and its temperature was controlled using a thermostat (Omega Engineering, Inc.). The heat flux used in the present study was 211, 216, and 227 kW/m² (i.e., 67,000, 68,000, and 71,000 Btu/h ft²) at flow velocities of 0.6, 1.2 and 1.5 m/s, respectively. Note that the majority of water chillers manufactured today are designed to operate with a full-load condenser heat flux in the range of 18.9–31.5 kW/m² (i.e., 6000–10,000 Btu/h ft²). In the present study, a much higher heat flux was used to accelerate the fouling so that each run could be completed in one week.

Table 3 shows magnitudes of heat flux, flow velocity, and hardness of water used in previous laboratory fouling studies. As indicated in Table 3, previous re-

searchers also used certain test conditions to accelerate fouling in their laboratory tests so that they could complete fouling tests in a reasonable time. For example, both Helalizadeh et al. [30] and Morse and Knudsen [22] used much larger heat fluxes than those used in the present study. Kim and Webb [23] used a relatively low heat flux of 13 kW/m², but used an extremely large hardness of water, 1500 mg/l. Hasson et al. [11] used relatively moderate heat flux and hardness of water, but used an extremely high surface temperature of 85 °C to accelerate fouling.

The first test was conducted without any treatment at a flow velocity of 0.6 m/s, and the second test was carried out with an EAF treatment at the same flow velocity. As shown in Fig. 1, the EAF treatment of the cooling water was done before the cooling water entered the test section. In other words, the EAF coil for the EAF treatment was installed in-line with the heat-transfer test section. The EAF coil used in the present study was 25.4 cm long (i.e., 80 turns), which was made of a 14-gauge single stranded wire.

The EAF treatment uses a square-wave pulsing current at 500 Hz to create time-varying magnetic fields, which in turn produces an induced pulsating electric field in the circulating water. Excess mineral ions such as calcium and magnesium in the circulating water are believed to precipitate into mineral salts, forming nucleates for later crystal growth. Details of the operating principle of the EAF treatment can be found elsewhere [1–9]. Similar tests were repeated at flow velocities of 1.2 and 1.5 m/s with and without the EAF treatment.

At the completion of the above six experiments with the in-line EAF treatment, three additional tests were performed to study the effect of the EAF-treatment time

Table 2

Analysis of make-up water and circulating water measured at $t = 0$ and at the end of $t = 150$ -h tests, respectively

	Make-up water/initial state	Circulating water					
		No-treatment, flow velocity (m/s)			In-line EAF-treatment, flow velocity (m/s)		
		0.6	1.2	1.5	0.6	1.2	1.5
Conductivity ($\mu\text{S}/\text{cm}$)	610/1000	4021	4041	4055	4024	4035	4052
pH	7.4/7.6	8.2	8.2	8.2	8.2	8.2	8.2
Total hardness (mg/l)	220/320	1400	1410	1440	1395	1410	1440
Ca ⁺ hardness (mg/l)	150/230	1050	1087	1120	1095	1100	1120
Total alkalinity (mg/l)	85/136	329	328	332	325	328	333
Chloride (mg/l)	81/174	850	856	860	848	851	864
		(10.5) ^a	(10.6) ^a	(10.6) ^a	(10.5) ^a	(10.5) ^a	(10.7) ^a
LSI ^b	−0.04/0.67	2.16	2.17	2.19	2.17	2.18	2.19
LSI ^c	−0.04/1.15	2.62	2.63	2.64	2.63	2.64	2.65
R_f (m ² K/W) ^d		4.98	3.90	1.22	0.97	1.31	1.06

^a () represents the cycle of concentration at $t = 150$ h.

^b LSI at sump water temperature (25 °C).

^c LSI at the surface temperature of enhanced tube (60 °C).

^d R_f , fouling resistance at the end of 150-h test ($\times 10^{-5}$).

Table 3
Investigations of heat flux and flow velocity fouling experiment as lab test

References	Heat flux (kW/m ²)	Flow velocity (m/s)	Concentration (ppm)	Foulant
[11]	1.6	0.25–0.82	110–575	Calcium
[23]	13	0.8–1.82	1500	Aluminum oxide (or Ferric oxide)
[26]	28–52	0.9–1.0 1.4–1.5	2500	MgO
[29]	137	1–1.98	300–450	Calcium
[21]	120–220	0.3–0.8	603–700	Calcium
[22]	276	1.0	490–650	TDS
[30]	100–400	0.5–2.0	1.0–2.5/0.25–1.0	Calcium sulphate/calcium carbonate
Present study	211–227	0.6, 1.2, 1.5	230–1120	Calcium carbonate

on the mitigation of fouling by varying the EAF-treatment time in a side-stream circulation loop, while the flow velocity in the heat-transfer test section was fixed at 1.2 m/s. In order to vary the EAF-treatment time, the flow velocity in the side-stream loop where the EAF coil was installed (see Fig. 1) varied from 0.6 to 2.0 m/s.

The fouling resistance was often calculated using the following equation [31]:

$$R_f = \frac{1}{U_f} - \frac{1}{U_i} \quad (1)$$

where U_f is an overall heat transfer coefficient from a heat exchanger experiencing fouling, and U_i is the overall heat transfer coefficient from a clean heat exchanger. The overall heat transfer coefficients were calculated from the following equation:

$$U = \frac{\dot{Q}}{A\Delta T_{lm}} \quad (2)$$

where ΔT_{lm} is a log-mean-temperature difference, which can be described as [31]

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln \left[\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})} \right]} \quad (3)$$

The heat transfer rate, \dot{Q} , was estimated from both the heating and cooling channels as

$$\dot{Q} = [\dot{m}c_p(T_i - T_o)]_h = [\dot{m}c_p(T_o - T_i)]_c \quad (4)$$

The heat transfer rate estimated from the hot-water side, \dot{Q}_h , was consistently bigger by 6% than that of the cooling-water side, \dot{Q}_c , a phenomenon which may be attributed to the heat loss to the surroundings via the acrylic tube. The heat transfer rate in the cooling-water side, \dot{Q}_c , was used to calculate the overall heat transfer coefficient in the present study. To reduce the heat loss the hot-water side components were insulated. However, the main heat-transfer test section was not insulated, in order to observe and photographically record scale growth on the heat-transfer surface as a function of time during the test.

3. Results and discussion

Table 2 presents the results of water analyses of the make-up water and the circulating water at $t = 0$ (initial state) and 150 h (at the end of the tests). Water properties of total six samples (i.e., no treatment and EAF treatment in three different flow velocities) were measured. The water property data of the make-up water were in agreement with the results reported by the city of Philadelphia given in Table 1. In the present study, water properties at the initial state (i.e., $t = 0$) were different from those of the make-up water. The make-up water was circulated and concentrated by the cooling tower without heat. When the electric conductivity of the circulating water reached 1000 $\mu\text{S}/\text{cm}$, heat-transfer tests started, and this was the beginning of each run, i.e., $t = 0$. Thus, the initial state in each experiment had the exactly same water condition.

All six experiments were conducted for a period of 150 h, and the water property data of the six samples measured at the end of each test together with fouling resistances are given in Table 2. The values of the electric conductivity, pH, total hardness, calcium hardness, total alkalinity, chloride, and Langelier saturation index (LSI) for the above six cases were similar to each other, yet the fouling resistances at the end of 150-h tests were distinctly different, a phenomenon that will be discussed later in detail.

When the LSI is greater than 0.5, the water is considered as scale forming. In general, positive LSI indicates a tendency of calcium carbonate scaling, whereas negative LSI indicates a tendency of corrosion. LSI for each case was calculated at two different temperatures: one at cooling-water inlet temperature and the other at the surface temperature of the enhanced tube.

The surface temperature was calculated with a modified Dittus and Boelter's equation for the heat transfer coefficient at turbulent annular flow [32]. Since this equation is for a plain tube, not for an enhanced tube, the surface temperature estimated using this equation tends to be overestimated. Based on the modified Dittus and Boelter's equation, the surface temper-

ature was about 60 °C considering that $A_{\text{enhanced}} = 1.4 \times A_{\text{plain}}$.

In practice, LSI values are calculated based on the surface temperature because scale deposition happens on the heat exchanger surface. In the present experiment, the surface temperature of 60 °C was much greater than that of a typical industrial case (i.e., approximately 40 °C), and thus the LSI values estimated from the surface temperature may be too big. Alternatively, LSI values calculated based on the bulk-water temperature (i.e., 25 °C) are also given in Table 2 for comparison.

In the case of calcium hardness, a small difference was found among the six water samples. The calcium

hardness for the no-treatment case was less than that for the EAF treatment case for the flow velocities of 0.6 and 1.2 m/s. This result can be explained as follows: the EAF treatment caused the precipitation of calcium ions in the bulk solution, thus keeping calcium salts in the circulating water, whereas for the case of no treatment calcium ions were reduced from the circulating water as the calcium ions deposited on the test section as scale.

Fig. 3 shows three sets of photographs of fouled heat-transfer surfaces taken at the end of the 150-h tests with no treatment and the in-line EAF treatment. First, in the case of no treatment with a flow velocity of 0.6 m/s, heavy scale almost uniformly deposited on the entire

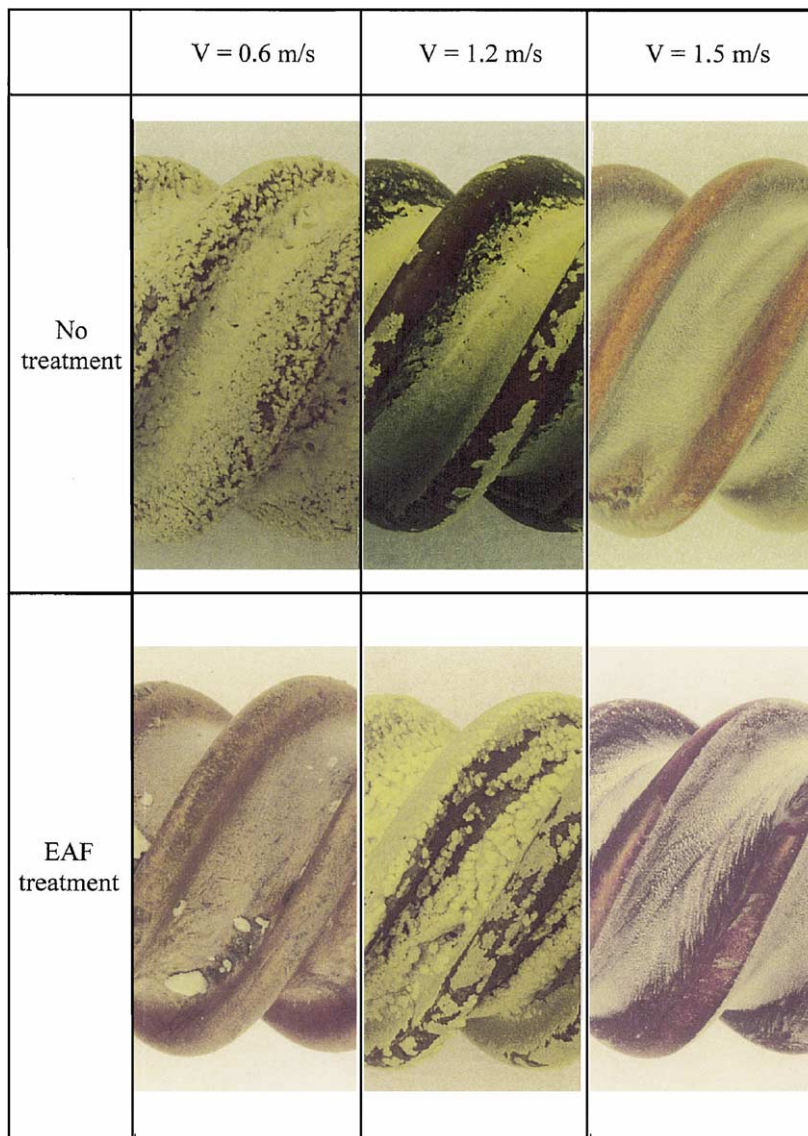


Fig. 3. Photographs of scale layers at the end of tests.

area of the enhanced tube, and the structure of scale looked very brittle. On the contrary, for the EAF treatment case, the heat transfer surface was almost free of scale deposition. Initially, there were very small round-shape scale particles, and they eventually touched adjacent particles, growing up into big particles as fouling continued in the case with a flow velocity of 0.6 m/s.

For the no-treatment case with a flow velocity of 1.2 m/s, the amount of scale deposition was slightly less than for a flow velocity of 0.6 m/s, and the scaled surface looked much smoother, see Fig. 3. In the case of the EAF treatment, a significant amount of scale was observed on the heat-transfer surface but scales appear to be quite loose and ready to fall off.

Fig. 3 also shows that for a flow velocity of 1.5 m/s very tiny particles were scattered uniformly from the trailing edge of the enhanced surface to the valley between fins. From the three cases with the EAF treatment, one can observe that the EAF treatment appears to produce the particulate fouling on the heat-transfer surface.

Fig. 4 shows the results of electric conductivities as a function of time for the six tests. The electric conductivity of the circulating water increased almost linearly with time in all six cases. Since the inlet temperature of the circulating water to the cooling tower was maintained at 28 ± 0.5 °C with the help of a shell-and-tube heat exchanger, the amount of water evaporated and thus the electric conductivity of the circulating cooling-tower water were almost the same in all tests.

Fig. 5 shows fouling resistances as a function of time for all six cases. At a flow velocity of 0.6 m/s the fouling resistances for the in-line EAF-treatment case were 80% less than that for the no-treatment case. This phenom-

enon can be explained as follows: The EAF treatment precipitates mineral ions in the bulk solution. The nuclei grow into large particles, resulting in particulate fouling with soft-sludge type scale deposit [33]. It is speculated that most of the soft scale deposits from the particulate fouling were removed by the shear flow in the annulus gap, thus keeping the heat-transfer surface relatively clean.

When the flow velocity increased to 1.2 m/s, the percentage reduction of the fouling resistance for the EAF-treatment case was smaller than that for 0.6 m/s case. This result can be explained as follows: The higher flow velocity (1.2 m/s) produces a higher shear and a lower surface temperature than for the 0.6 m/s case, thus generally reducing the fouling resistance. The fouling resistance for the 1.2 m/s case with the EAF treatment did not decrease as much as in the case of 0.6 m/s. For example, the percentage reduction of the fouling resistance for the 1.2 m/s case was 65% compared to 80% for the 0.6 m/s case (see Fig. 5).

When the flow velocity was increased to 1.5 m/s, the fouling resistance for the case with no treatment decreased, reaching the smallest value of 1.22×10^{-5} m²/kW among the three cases. When the EAF treatment was applied, the fouling resistance for the 1.5-m/s case dropped by only 13%, compared to 65 and 80% for 1.2 and 0.6 m/s, respectively.

The values of LSI were 2.16–2.19 (see Table 2), which were estimated using the bulk temperature of 25 °C at the end of the 150-h tests. These values were much larger than the scale-forming threshold LSI value of 0.5. Accordingly, for the case without the EAF treatment, there was a significant scale build-up as manifested by a large value of the fouling resistance, i.e., 4.98×10^{-5} m²/kW for the case of 0.6-m/s flow velocity (see Table 2).

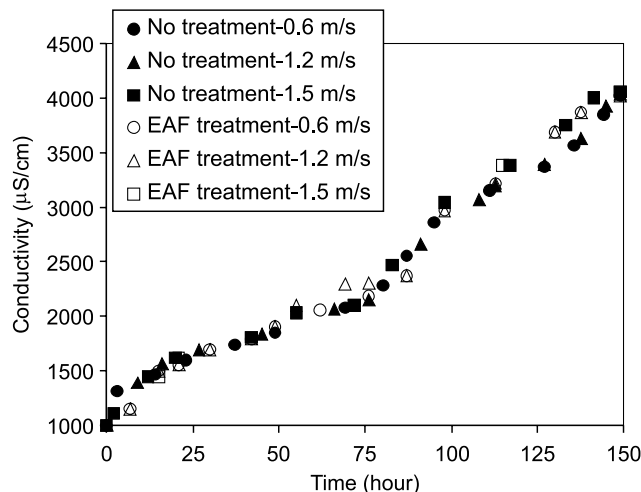


Fig. 4. Electric conductivity vs. time with no blowdown for in-line EAF treatment.

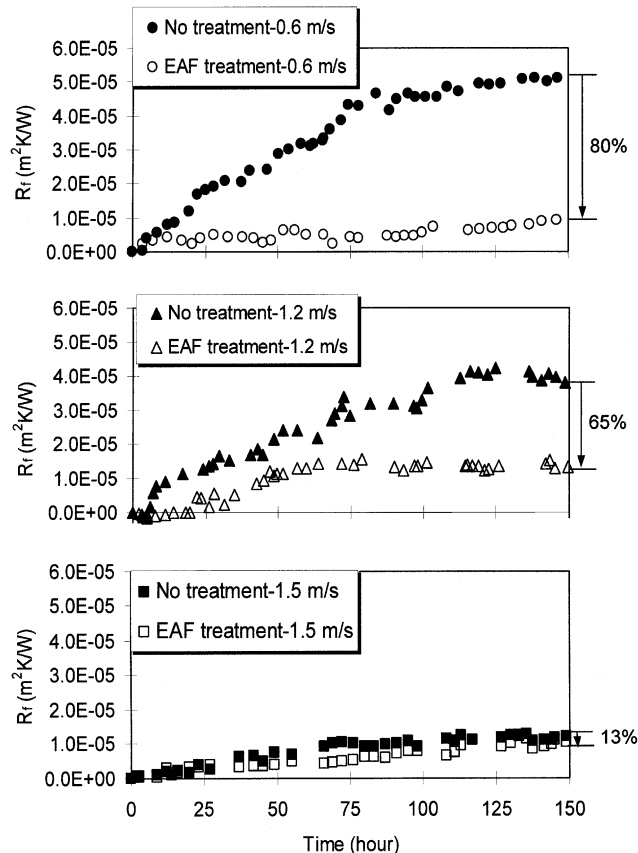


Fig. 5. Fouling resistance vs. time with no blowdown for in-line EAF treatment.

However, at the almost identical LSI of 2.17, the fouling resistance obtained with the EAF treatment at the same velocity was only $0.97 \times 10^{-5} \text{ m}^2/\text{kW}$, indicating that the LSI did not provide any indications for the scaling tendency of cooling-tower water when a non-chemical treatment method like the EAF was used.

In the above six experiments with the in-line EAF treatment, the flow velocity determines two important parameters affecting the outcome of the overall fouling. First, the removal rate of the fouling critically depends on the flow velocity inside the heat exchanger. Second, the EAF-treatment time, which is defined as the residence time of water remaining under the influence of a pulsating electric field, is inversely proportional to the flow velocity. In other words, when the flow velocity is increased, the fouling-removal effect increases but at the same time the effect of the pulsating electric field decreases such that the precipitation of dissolved mineral ions in bulk water occurs less efficiently.

In order to isolate these two effects, the EAF coil was repositioned to a side-stream circulation loop where the flow velocity through the EAF coil could vary independently from the flow velocity at the heat-transfer test

section. Table 4 shows the results of water analyses of the make-up and the circulating measured at $t = 0$ (i.e., the initial state) and 150 h. The water properties show similar trends to those for the in-line EAF treatment. Calcium hardness of the treated water was consistently higher than that for the no-treatment case. As the flow velocity through the EAF coil decreased from 2.0 to 0.6 m/s, the calcium hardness in the circulating water increased from 1100 to 1131 mg/l, suggesting that the precipitation of mineral ions became more effective as the mineral ions were exposed to the pulsating electric field longer at the slow velocity.

Fig. 6 shows the electric conductivity and the fouling resistance vs. time for the three additional tests. Electric conductivity data show almost the same trend for all cases. In the case of a flow velocity of 0.6 m/s at the side-stream loop, the fouling resistance dropped by 82% from the value obtained with the no-treatment case at the end of the test (i.e., $t = 150 \text{ h}$). For the flow velocity of 2.0 m/s, the fouling resistance reduced only 48%, confirming that as the EAF-treatment time (or residence time) decreased, the effectiveness of the EAF treatment decreased.

Table 4
Analysis of make-up and circulating water measured at $t = 0$ and at the end of $t = 150$ -h tests, respectively for side-stream treatment

	Make-up water/initial state	Circulating water			
		No-treatment, flow velocity (m/s)	Side-stream EAF-treatment, flow velocity (m/s)		
			1.2	0.6	1.2
Conductivity (mS/cm)	610/1000	4041	4040	4041	4040
PH	7.4/7.6	8.2	8.2	8.2	8.2
Total hardness (mg/l)	220/320	1410	1451	1444	1440
Ca ⁺ hardness (mg/l)	150/230	1087	1131	1117	1100
Total alkalinity (mg/l)	85/136	328	326	328	322
Chloride (mg/l)	81/174	856	855	853	856
		(10.6) ^a	(10.6) ^a	(10.5) ^a	(10.6) ^a
LSI ^b	-0.04/0.67	2.17	2.19	2.18	2.17
LSI ^c	-0.04/1.15	2.63	2.65	2.64	2.63
R_f (m ² K/W) ^d		3.90	0.70	1.31	2.03

^a () represents the cycle of concentration at $t = 150$ h.
^b LSI at sump water temperature (25 °C).
^c LSI at the surface temperature of enhanced tube (60 °C).
^d R_f , fouling resistance at the end of 150-h test ($\times 10^{-5}$).

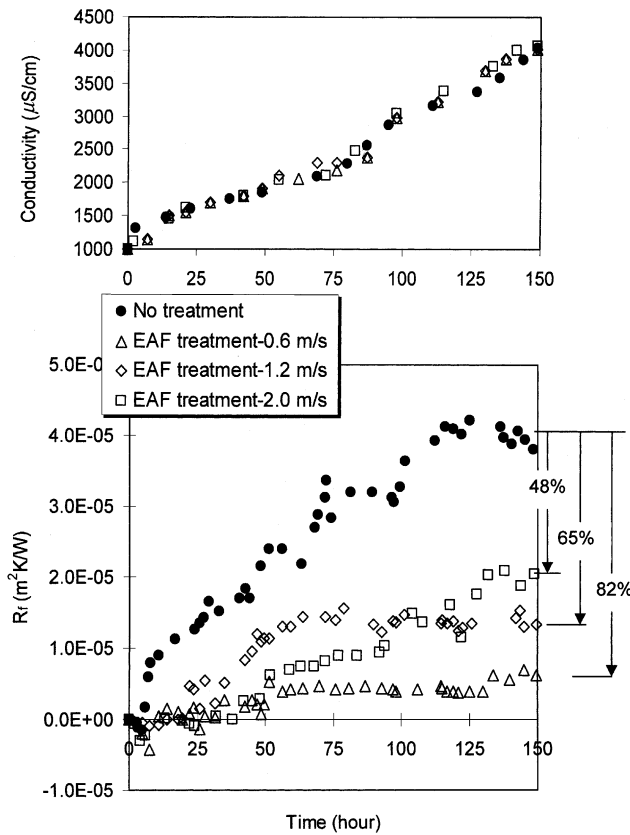


Fig. 6. Electric conductivity and fouling resistance vs. time with no blowdown for side-stream EAF treatment. Velocities are at EAF coil positioned at side-stream loop.

Results given in Fig. 6 may represent typical performance characteristics of any electro-magnetic devices used for cooling-water treatment for the purpose of mineral scale prevention. As water molecules move more slowly through the solenoid coil, the duration of the EAF treatment increases, thus increasing the effectiveness of the treatment. Accordingly, one may consider the use of a large pipe diameter to make water to move slowly where the solenoid coil is installed so that the duration of the EAF treatment can be increased for the maximum benefit of the treatment. Since the frequency of the treatment is reduced in circulating cooling-tower water as the flow velocity at the solenoid coil decreases, one needs to carefully study what the optimum flow velocity should be at the solenoid coil that produces the maximum effectiveness of the EAF treatment. Alternatively, one can consider the possibility of varying the frequency and strength of the pulsating electric field as well as the length of the EAF coil.

4. Conclusions

In the present study, fouling experiments were carried out in order to verify whether EAF treatment could mitigate mineral fouling in an enhanced tube when a high cycle of concentration was used in a cooling-tower water application. In the case of a flow velocity of 0.6 m/s, the fouling resistance for the EAF-treatment case dropped by approximately 80% from that for the no-treatment case. As the flow velocity increased to 1.2, 1.6 and 2.0 m/s, the effectiveness of the EAF treatment was gradually reduced, suggesting that the residence time of the circulating water in a pulsating electric field might play a critical role in the mitigation of mineral fouling in a heat exchanger. The optimum-treatment condition for the EAF treatment should be identified considering parameters such as water hardness, flow velocity, residence time, the frequency and strength of the pulsating electric field, and the length of an EAF coil.

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