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Electronic anti-fouling technology to mitigate precipitation fouling in plate-and-frame heat exchangers

YOUNG I. CHO† and BYUNG-GAP CHOI

Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19104, U.S.A.

and

BENNAT J. DRAZNER

Alfa Laval Thermal Inc., Industrial Division, Richmond, VA 23231, U.S.A.

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Abstract—The objective of the present study was to investigate the validity of an electronic anti-fouling (EAF) technology through accelerated fouling tests. A plate-and-frame heat exchanger (with 20 stainless steel plates) was used for the tests, in which pressure drop across the heat exchanger, and the universal heat transfer coefficient were measured over a range of flow rates. In order to accelerate the rate of fouling, artificial hard water of 1000 ppm (as $CaCO_3$) was used in the present study. The test results showed that the EAF technology could significantly reduce new scale deposits even in the accelerated fouling test, which was an extremely harsh fouling environment.

1. INTRODUCTION

Scales are formed when hard water is heated (or cooled) in heat transfer equipment such as heat exchangers, condensers, evaporators, boilers, and pipe walls. The type of scale differs from industry to industry, depending on the mineral content of available water. Scales often observed in industry include calcium carbonate, calcium sulfate, barium sulfate, silica, iron scales, and others [1]. One of the most common forms of scales is calcium carbonate ($CaCO_3$), which occurs naturally as an ingredient of chalk, limestone, and marble. When scales deposit in a heat exchanger surface, it is traditionally called "fouling".

Once scales build up on a heat transfer surface, at least two problems associated with scales occur [2–4]. The first problem is the degradation in the performance of the heat transfer equipment. Due to the small thermal conductivity of scales, a thin coating of scales on the heat transfer surface will greatly reduce the overall heat transfer performance. The second problem is that a small change in tube diameter substantially decreases the flow rate or increases the pressure drop across the heat transfer equipment.

Various scale-inhibiting chemicals such as dispersing or chelating agents are used to prevent scales [1]. Ion exchange and reverse osmosis are also used to reduce water hardness, alkalinity, and silica level. However, these methods are expensive at the industrial level and require heavy maintenance for proper operation. Once fouling occurs in heat exchangers, scales are removed by using acid chemicals, which shorten the life of heat exchanger tubes, thus necessitating premature replacement. When acid cleaning is not desirable, scraping, hydroblasting, sand blasting, metal or nylon brushes are used—operations which incur downtime and repair costs [4].

The present study introduces a new electronic anti-fouling (EAF) technology, which has been developed for the purpose of mitigating new scales in both plate-and-frame and shell-and-tube heat exchangers. If the EAF technology can be used to reduce the maintenance efforts, one can discontinue the use of scale-inhibiting or scale-removing chemicals, thus preserving a clean environment. The primary benefit of the EAF technology, if proven, will be in maintaining the initial peak performance of a heat exchanger indefinitely.

This paper reports the test results obtained with and without a new electronic anti-fouling (EAF) technology. Since detailed descriptions of this new EAF technology were given elsewhere [5–7], we will only briefly explain the operating principle.

2. ELECTRONIC ANTI-FOULING (EAF) TECHNOLOGY

The EAF technology creates induced oscillating electric fields using time-varying magnetic fields gen-

† Author to whom correspondence should be addressed. E-mail: ycho@coe.drexel.edu.

NOMENCLATURE

A, B	empirical constants
D_H	hydraulic diameter of a channel in plate-and-frame heat exchanger
f	friction coefficient
Re	Reynolds number
U	universal heat transfer coefficient
V	average flow velocity in a channel
ΔP	pressure drop across plate-and-frame heat exchanger.

Greek symbols

τ_W	shear stress
β	plate inclination angle
ρ	density of test solution
μ	dynamic viscosity of test solution.

erated in a solenoid wrapped around a feed pipe carrying water—a process that can be described by Faraday's law [8]. Since dissolved ions in water have either positive or negative charges, they are agitated by the oscillating electric field [9]. As a result, the collision among the positive and negative ions increases, facilitating the precipitation of these ions [10] in the feed pipe before water enters heat transfer equipment. Figure 1 illustrates the overall operating principle of the electronic anti-fouling technology.

There are essentially two hypotheses which need to be verified in order to establish the principle of the EAF technology: one is the hypothesis of improved collision that results in precipitation of mineral salts, and the other is that when dissolved ions are converted into particles in a feed pipe, new scales can significantly be reduced in a heat exchanger. In order to verify the first hypothesis, the size and number of the crystals of mineral ions in water under various test conditions were measured using a microscope as the water droplet evaporated on a glass slide [5, 11]. The untreated water sample showed a large number of small crystals within a range from 1 μm to 10 μm in diameter, whereas the treated water sample by the EAFT showed large crystals ranging from 10 μm to 20 μm in diameter. The purpose of the present paper was to examine the validity of the second hypothesis by conducting accelerated fouling tests using a plate-and-frame heat exchanger with and without the EAF treatment.

3. EXPERIMENTAL METHOD

Figure 2 schematically shows a flow loop which consists of a reservoir tank, a pump, an electronic anti-fouling (EAF) unit, a flow meter, the main heat transfer test section made of a plate-and-frame heat exchanger (Alfa Laval M3), and a shell-and-tube heat exchanger to maintain the test solution at a constant temperature. The plate-and-frame heat exchanger was made of 20 stainless steel plates: 9 channels were used for steam and 10 channels were used for the test solution. Steam provided by the Philadelphia city steam network was used for testing in the present study.

Since the hardness of tap water available in Philadelphia is approximately 170 ppm as $CaCO_3$, it is not suitable for accelerated fouling experiments. Therefore, hard water was prepared in our laboratory. The test solution was prepared by adding 0.01 M calcium chloride ($CaCl_2$) and 0.02 M sodium bicarbonate

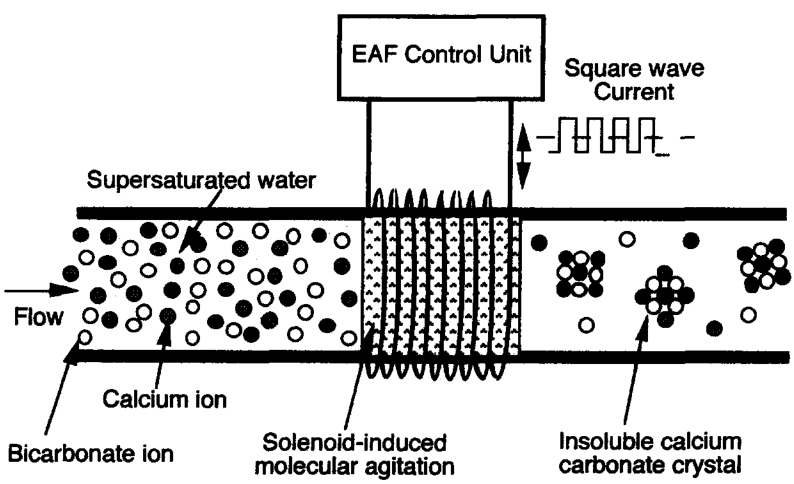

Fig. 1. Illustration of the operating principle of electronic anti-fouling (EAF) technology.

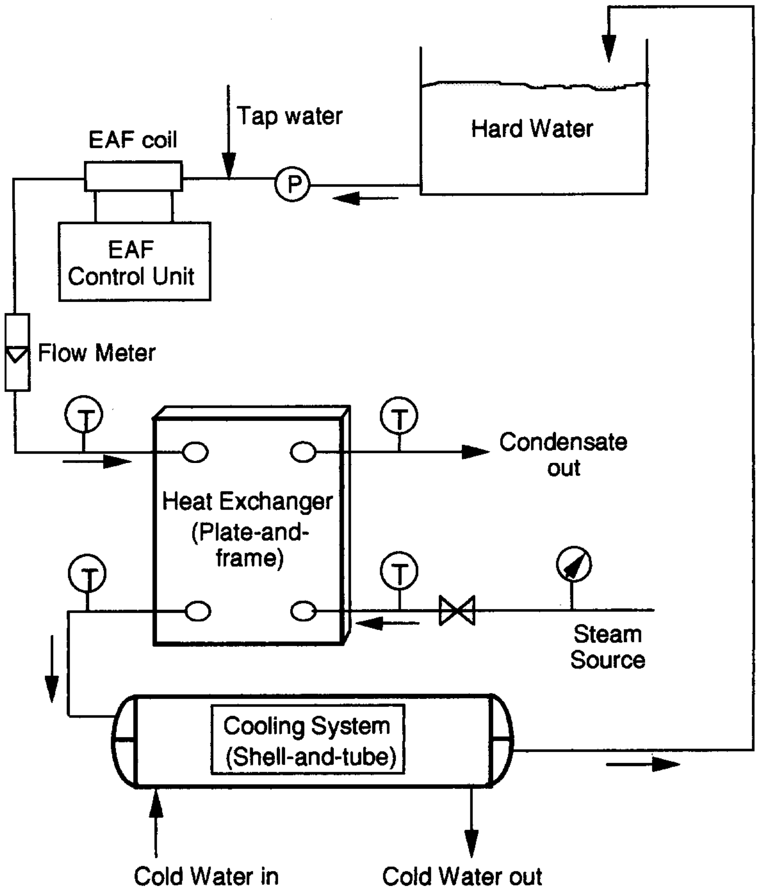

Fig. 2. Schematic diagram of recirculating flow loop with a plate-and-frame heat exchanger as the main test section. The EAF coil for electronic anti-fouling treatment is used in a feed pipe to the heat exchanger.

($NaHCO_3$) to tap water such that the hardness of the test solution was equivalent to 1000 ppm as $CaCO_3$. As we circulated the test solution, the hardness decreased because calcium ions interacted with bicarbonate ions due to temperature changes and agitation by pump. Solid forms of $CaCO_3$ precipitated out from the test solution, adhering to the walls of the plate-and-frame heat exchanger or settling at the bottom of the reservoir tank. Therefore, we replaced the test solution after 4 h of circulation.

The amount of the test solution prepared each time was 180 l (47.5 gallons). Since the artificial hard water was recirculated at a flow rate of 1.5 gpm, the test solution passed through the main test section approximately eight times during the 4 h period. The inlet temperature of the hard water entering the plate-and-frame heat exchanger was maintained at 26°C, whereas the outlet temperature of the water leaving the heat exchanger was maintained at 80±2°C throughout the test. These inlet and outlet temperatures were maintained by adjusting both the flow rate of cooling water in a shell-and-tube heat exchanger and steam pressure. The thermocouples used in the present study were Omega model TMTSS-125G-6 (grounded copper-constantan T type). Calibration was carried out at zero and 100°C, confirming the manufacturer's claim of an accuracy of ±0.1°C. Flow rate was measured using a floating-ball flow meter made by Omega. The flow meter reading was calibrated using a direct weighing method.

The Reynolds number was calculated at the inlet and outlet of a channel of the plate-and-frame heat exchanger as follows:

$$Re = \frac{\rho V D_H}{\mu}$$

where D_H is the hydraulic diameter of a channel in the plate-and-frame heat exchanger, and ρ and μ are the values of density and viscosity of the test solution at inlet or outlet temperature. Of note is that the gap between the two plates was 0.241 cm, and the channel width was 7.06 cm, resulting in the hydraulic diameter of 0.482 cm. Since we used ten channels at 1.5 gpm, the average flow velocity in a channel became 5.36 cm s^{-1}. Since the viscosity of the test solution significantly changed from the inlet to the outlet, the Reynolds numbers corresponding to 1.5 gpm at the inlet and outlet of the plate-and-frame heat exchanger became 302 and 734, respectively. Since the critical Reynolds number from laminar to turbulent flow is approximately 80 for this type of plate-and-frame heat exchanger, the accelerated fouling test was in the turbulent flow regime.

The shear stress in a plate-and-frame heat exchanger is calculated as follows:

$$\tau_W = \frac{\text{gap}}{2 \times \text{channel length}} \Delta P$$

where the channel length was 35.7 cm for the plate-and-frame heat exchanger used in the present study. The pressure drop measured from the clean plate-and-frame heat exchanger was 52 mm H_2O at 1.5 gpm. Hence, the corresponding shear stress was 1.71 Pa. Considering that this type of plate-and-frame heat exchanger is designed to operate at τ_W of 50 Pa, the present accelerated fouling test was conducted well below the design limit.

At the end of 8 hours of circulation of the artificial hard water, we measured the pressure drop across the plate-and-frame heat exchanger over a range of flow rate from 1 to 10 gpm and compared them with the pressure drop data obtained before the accelerated fouling test (i.e., at clean initial state). A Validyne pressure transducer which was calibrated using a U-tube manometer was used for pressure drop measurements. In addition, inlet and outlet temperatures of the test solution, steam temperature and pressure were measured for the estimation of the universal heat transfer coefficient.

The test results are presented in the form of pressure drop, ΔP, across the plate-and-frame heat exchanger and the universal heat transfer coefficient, U. Due to the condensation of steam inside the plate-and-frame heat exchanger a simple method of using the log-mean-temperature-difference could not be used to calculate U. Hence, the universal heat transfer coefficient was calculated using a two-phase flow computer program at Alfa Laval Thermal, Richmond. Temperature, flow rate, and steam pressure data obtained from the present fouling study were compared with "standardized" laboratory correlations developed by Alfa Laval Thermal for plate heat exchangers. These correlations relate resulting Nusselt number with corresponding Reynolds number as well as friction factor. In presence of inert gases the film coefficient is broken into a film condensation resistance component, mass transfer resistance component, and subcooling zone liquid film resistance component. An iteration between actual temperatures realized and amount of subcooling required to consume "oversurfacing" established the reported clean versus actual service overall heat transfer coefficients.

4. RESULTS AND DISCUSSION

As a plate-and-frame heat exchanger fouls, the pressure drop across the plate-and-frame heat exchanger increases. Figure 3 shows the changes in the pressure drop due to fouling during eight hours of circulation of 1000 ppm hard water.

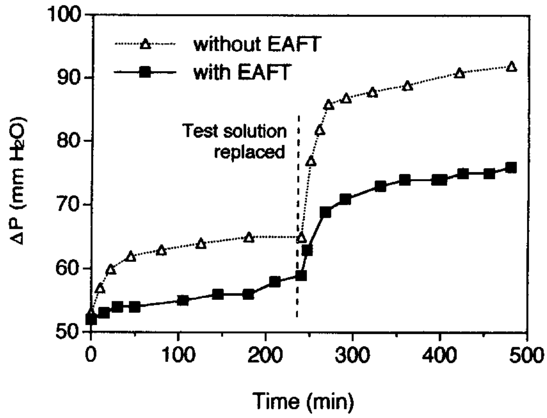

Fig. 3. Variation of pressure drop across plate-and-frame heat exchanger with and without electronic anti-fouling (EAF) treatment with 1000 ppm hard water at 1.5 gpm.

For the case without the EAF treatment, ΔP increased from the initial value of 52 to 62.5 mm H_2O at $t = 50$ min and then reached an asymptotic value of 65 mm H_2O at the end of the first 4 h of circulation. Since the test solution passed through the main test section twice for the first 50 min, it resembled a once-through flow system during the first 50 min. When we started the second half of the accelerated fouling test with a fresh 1000 ppm hard water, the pressure drop across the plate-and-frame heat exchanger dramatically increased from 65 to 86 mm H_2O in the next 30 min, a 32% increase in ΔP. After this initial rapid increase in ΔP, the pressure drop increased gradually to 92 mm H_2O at the end of an 8 h run.

For the case with the EAF treatment, ΔP increased from the initial value of 52–54 mm H_2O at $t = 50$ min and then reached a value of 59 mm H_2O at the end of the first 4 h of circulation of the hard water. In the second half of the accelerated fouling test, the pressure drop across the plate-and-frame heat exchanger increased from 59 to 71 mm H_2O in the next 30 min, a 20% increase in ΔP. After this initial rapid increase in ΔP, the pressure drop increased gradually to 74 mm H_2O at the end of an 8 h run. Although the EAF technology did not completely prevent fouling inside the plate-and-frame heat exchanger, the results shown in Fig.3 dramatically demonstrate the benefit of using the EAF treatment in a plate-and-frame heat exchanger.

The pressure drop results shown in Fig. 3 depict an interesting phenomenon on the rate of fouling. When we compare the rate of fouling at the beginning of the first 4 h operation (i.e., at $t = 0$) and that at the beginning of the second 4 h operation (i.e., at $t = 240$ min), the latter is significantly greater than the former. The former represents the rate of fouling from pristine clean plates, whereas the latter represents that from already-fouled plates. Hence, we conclude that the rate of fouling at a fouled plate is significantly greater than that at a clean plate. Furthermore, the rate of fouling without the EAFT was consistently greater than that obtained with the EAFT.

The results in Fig. 3 also show that the pressure drop increases very gradually after the initial rapid increase. This is due to the fact that in a recirculation experiment the hardness of the test solution continues to decrease. Subsequently, the pressure drop approaches as asymptotic value.

Figure 4 shows pressure drop, ΔP, as a function of flow rate measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different cases: clean initial state, tests without the electronic anti-fouling treatment (EAFT) and with the EAFT. ΔP increased by 250–290% depending on flow rates when the EAF treatment was not used, whereas when the EAF treatment was applied during the recirculation ΔP increased by 150–165% depending on flow rates. The results from Fig. 4 clearly indicate that the EAF treatment significantly reduced fouling inside the plate-and-frame heat exchanger.

In the design of a plate-and-frame heat exchanger, the pressure drop across the plate-and-frame heat exchanger is often estimated from the following empirical correlation of the friction coefficient:

$$f = A\left[\frac{65}{\beta}\right]^{2.22} \times \frac{1}{Re^{B}}$$

where A and B are constants to be determined empirically for a given heat exchanger. β is the plate inclination angle, which is 30° for the M3 type used in the present study.

From the pressure drop results shown in Fig. 4, we calculated the friction coefficients for three different

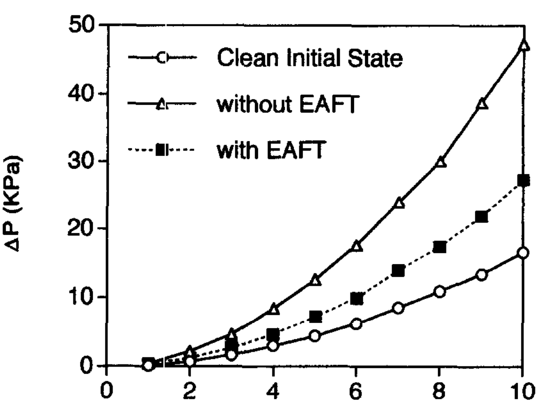

Fig. 4. Pressure drop data across plate-and-frame heat exchanger over a range of flow rates measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

cases, and the results are shown in Fig. 5. For the clean initial case, the friction coefficients gradually decreased with the Reynolds number, i.e., from $f = 0.99$ at $Re = 490$ to $f = 0.82$ at $Re = 4900$.

The friction coefficients calculated after the heat exchanger was used for 8 h without the EAFT were almost constant, i.e., $f = 2.32$. When the plate-and-frame heat exchanger was used with the EAFT for 8 h under identical conditions, the friction coefficients were much smaller than those obtained without EAFT as shown in Fig. 5. The constants A and B can be summarized as follows:

$A = 0.291$ and $B = 0.08$ for clean initial state

$A = 0.42$ and $B = 0.001$ for the case without EAFT

$A = 0.291$ *and* $B = 0.02$ for the case with EAFT

Figure 6 shows universal heat transfer coefficients measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different cases: clean initial state, tests without the electronic anti-fouling treatment (EAFT) and with the EAFT. The U values from clean initial state varied from 2900 to 3200 $Wm^{-2} K^{-1}$ over a range of flow rate. When the plate-and-frame heat exchanger was used for 8 h without the EAFT, the U values dropped from 3248 to 1674 $Wm^{-2} K^{-1}$ at 5 gpm (i.e., almost 50% drop from the initial U value). On the other hand, the U values obtained for the case with the EAFT did not show any decrease as depicted in Fig. 6.

There are two questions one may ask regarding the results shown in Fig. 6. The first question is why the U values for the case without the EAFT increased with increasing flow rate (i.e., see triangles in Fig. 6). Usually, at low flow rates the convective heat transfer coefficient is small, whereas at high flow rates it is large. When the convective heat transfer coefficient is large, the effect of scaling on U values should be large compared with the case having a small convective heat transfer coefficient. When we dis-assembled the plate-and-frame heat exchanger, we observed in the case without the EAFT that approximately 40% of the plates were covered with relatively thick scales around steam inlet port. At high flow rates, for example, above 6 gpm, the plate-and-frame heat exchanger still had enough clean heat transfer surfaces available, resulting in relatively high U values, although the U values were still much smaller than those obtained at the clean initial state.

When one compares the pressure drop data shown in Fig. 3 and the U values shown in Fig. 6, one may ask the second question- why the EAF treatment almost kept the initial U value throughout the test while it did not maintain the initial pressure drop. It may be explained as follows: The pressure drop is very sensitive to surface roughness and the gap between the two plates. Hence, even a thin scale layer can cause a relatively large increase in pressure drop. Without the EAF treatment, both pressure drop and U values showed clear symptoms of fouling because a thick

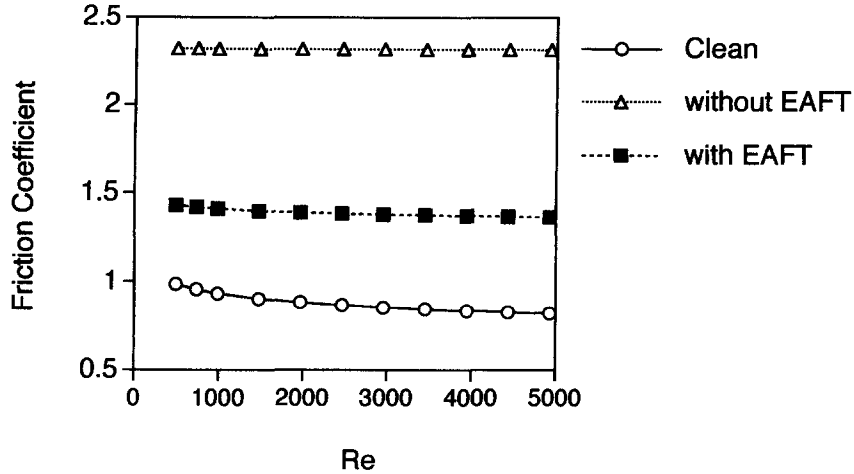

Fig. 5. Friction coefficient vs Reynolds number for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

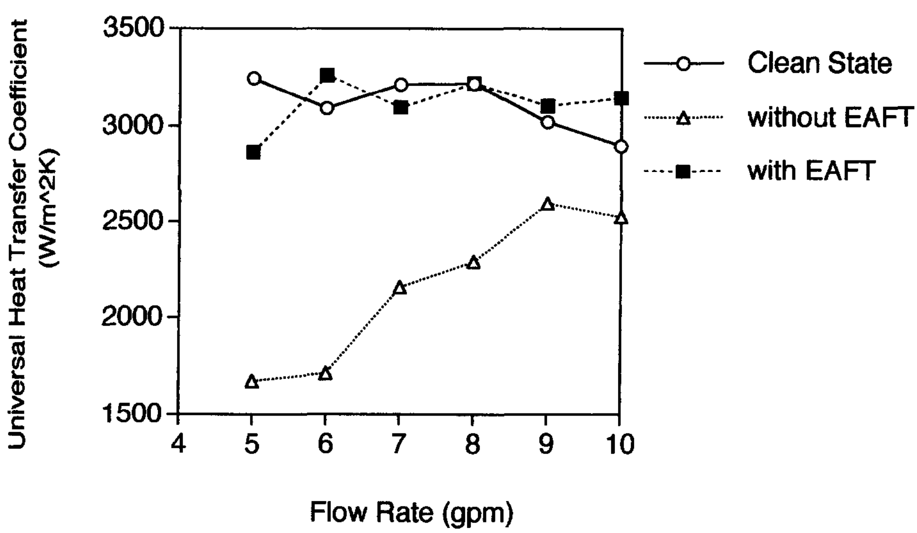

Fig. 6. Universal heat transfer coefficient vs flow rate measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

scale-layer had formed on the plate surface. With the EAF treatment, the scale layer was relatively thin so that one could see the effect of the scale layer only on the pressure drop and not on the U values.

The results in Fig. 6 also show that a higher flow rate (i.e., above 9 gpm) the heat transfer coefficient of the fouled heat exchanger with EAFT tends to be better than the clean state. We speculate that in the fouled heat exchanger the surface roughness can increase the convective heat transfer coefficient at high flow rate, resulting in larger U values. It is not uncommon to observe a negative fouling resistance in the initial period of fouling test, a phenomenon which is often attributed to the increased heat transfer due to increased surface roughness [12].

5. CONCLUSIONS

The present study was conducted in order to investigate the validity of electronic anti-fouling (EAF) technology, which was considered as a means to control new precipitation fouling in a plate-and-frame heat exchanger. The plate-and-frame heat exchanger was chosen in the present study because its thermal performance was very sensitive to fouling.

When we compare the pressure drop results across the heat exchanger for the two cases, (i.e., with and without EAFT), ΔP without the EAF treatment was significantly greater than those with the EAF treatment. Furthermore, the universal heat transfer coefficient results obtained without the EAFT decreased almost 50% in just 8 hours, whereas the U values for the case with the EAFT remained at the initial maximum level. Both ΔP and U values clearly demonstrate the benefit of using the EAF technology to mitigate or prevent fouling inside a plate-and-frame heat exchanger.

Although the present paper uses calcium carbonate as an example of the mineral scales, the electronic anti-fouling technique is not limited to the calcium carbonate scale. This is because the EAF treatment utilizes the electrical charges of dissolved ions to foster collision and precipitation into insoluble crystals.

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