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# Use of Electronic Descaling Technology to Control Precipitation Fouling in Plate-and-Frame Heat Exchangers

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## ABSTRACT

The objective of the present paper was to investigate the validity of the electronic descaling (ED) technology through accelerated fouling tests. A small plate-and-frame heat exchanger (with 20 stainless steel plates) was used for the tests, where pressure drop and overall heat transfer coefficients were measured over a range of flow rate. In order to accelerate the rate of fouling in a laboratory test, artificial hard water of 1,000 ppm as  $\text{CaCO}_3$  was recirculated at relatively small flow rates. The 1,000 ppm hard water was prepared by adding  $\text{CaCl}_2$  (0.01 M) and  $\text{NaHCO}_3$  (0.02 M) to tap water. The test results depicted that the ED technology could significantly reduce new scale deposits even in the accelerated fouling test, which had an extremely harsh fouling environment. A field test with a much larger plate-and-frame heat exchanger (with 140 titanium plates) demonstrated that the ED technology could keep plate surfaces scale-free, maintaining the initial heat transfer coefficient indefinitely.

## INTRODUCTION

Scales are 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 scales 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. One of the most common forms of scales is calcium carbonate ( $\text{CaCO}_3$ ), which occurs naturally as an ingredient of chalk, limestone, and marble. Acidic water passing over and permeating through rocks dissolves limestone into calcium and bicarbonate ions, thereby making water hard. When the hard water is then pumped into heat transfer equipment, the calcium and bicarbonate ions precipitate due to the changes in the solubility, forming hard scales on the heat transfer surfaces, and clogging pipes and manifolds. When scales deposit in a heat exchanger surface, it is traditionally called "fouling" [1-3].

Once scales build up in a heat transfer surface, at least two problems associated with scales occur. The first problem is the degradation in the performance of the heat transfer equipment. Because the thermal conductivity of scales is much smaller than that of pipe materials, 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.

Several billions of dollars are lost every year due to equipment failure or replacement caused by scale problems. For example, most heat exchangers

used in hard water areas need regular maintenance every three to six months and major overhauls every three to five years. Thus, reduction or prevention of scale deposits would create huge economic benefits.

Various scale-inhibiting chemicals such as dispersing or chelating agents are used to prevent scales [4]. The anionic 'claws' of these agents chemically grip dissolved cations, thus neutralizing them. Ion exchange and reverse osmosis are also used to reduce water hardness, alkalinity, and silica level. Once scale problems occur, the correction of the scale problems is accomplished by acid cleaning, scraping, and hydro-blasting or sand blasting, operations which incur downtime and repair costs. Acid cleaning has been effective in removing existing scales and is a part of routine maintenance for many types of heat transfer equipment. However, the cost of the chemical treatment recurs periodically, and the loss of equipment material due to the repeated acid cleaning and the disposal of the chemicals are of a matter of concern.

There have been a number of alternative solutions to the chemical treatment of water for the purpose of fouling control. History shows that Egyptians used permanent magnets two to three thousand years ago in an attempt to reduce scale deposits in pipes carrying hard water [5]. In the United States, there have been numerous efforts for the past 150 years to introduce permanent magnets or electromagnetic devices as manifested by the long list of patents awarded by the U.S. patent office [5]. More recently, a number of devices using electromagnetic field or sound waves have appeared in the market. Currently a number of companies market different types of non-chemical methods in the world. One of the major problems of these alternative solutions is the lack of understanding of the operating principle (or theory). Recently, Cho et al. [6] presented the theory of an electronic descaling technology, one of the most recent, promising alternative solutions. The objective of this paper is to investigate the validity of the electronic descaling (ED) technology through accelerated fouling tests.

## BACKGROUND

The scale deposition mechanism is often explained by a process that includes the dissolution of minerals, supersaturation, nucleation, precipitation, crystal growth, and, finally, scale deposition. Many variables control the scale deposition mechanism. The three most important variables are temperature, pressure, and pH because the solubility of scale-causing minerals are critically dependent on these three variables.

The solubility of calcium carbonate decreases with increasing temperature and pH, whereas it decreases with decreasing pressure [7]. When conditions such as temperature, pressure, and pH change in a flow system such that the solubility of calcium carbonate decreases, calcium and bicarbonate ions in hard water precipitate to form  $\text{CaCO}_3$  crystals. This happens usually on heat transfer surfaces because water temperature suddenly changes as the water makes contact with the heat transfer surfaces. Furthermore, the heat transfer surfaces are negatively-charged (i.e., in a solution whose pH is greater than 7.0); thus, positively-charged ions such as calcium and magnesium line up against the negatively-charged heat transfer surfaces within a distance of 10-30 angstrom, a phenomenon known as "electric double layer" [8].

Subsequently, the electrostatic Coulombic attraction force between the dissolved mineral ions

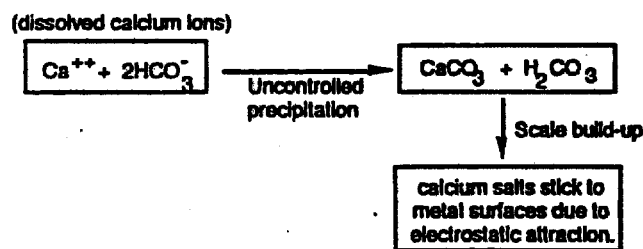


Fig. 1 Block diagram showing uncontrolled precipitation of calcium and bicarbonate ions and subsequent adhesion of  $\text{CaCO}_3$  crystals to heat transfer surface.

and heat transfer surfaces makes these mineral ions adhere to the surfaces as  $\text{CaCO}_3$  crystals precipitate. This is why scale deposits are unavoidable when hard water is used in heat transfer equipment. Figure 1 shows a chemical reaction of  $\text{CaCO}_3$  precipitation occurring inside a heat exchanger, a phenomenon which is called "uncontrolled precipitation" in the present study.

### THE OPERATING PRINCIPLE OF ELECTRONIC DESCALING TECHNOLOGY

Figure 2 shows a schematic diagram of the operation of an electronic descaling unit. A 18 gauge single stranded wire is wrapped around a feed pipe to a heat exchanger. Two ends of the wire are connected to the electronic descaling control unit. The ED unit produces a pulsing current to create time-varying magnetic fields inside the pipe. Subsequently, the time-varying magnetic field creates an induced electric field inside the pipe, a phenomenon which can be described by the following Faraday's law [9]:

$$\int \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{A}$$

where  $\mathbf{E}$  is an induced electric field vector,  $s$  is a line vector along the circumferential direction,  $\mathbf{B}$  is

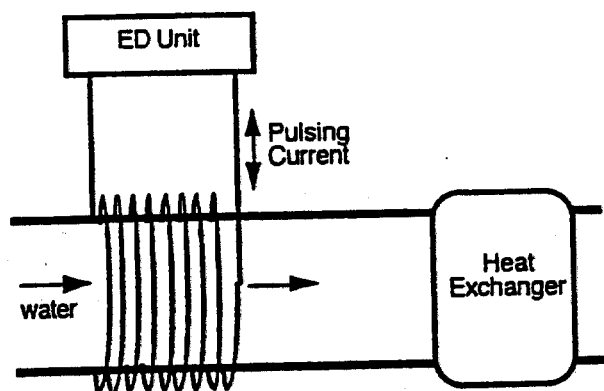


Fig. 2 Schematic diagram of the operation of an electronic descaling unit.

a magnetic field strength vector, and  $A$  is the cross sectional area of pipe. In order to maximize the induction, a pulsing current having a square-wave signal was used.

Figure 3 shows how the electronic descaling technology works. Hard water has excess dissolved mineral ions well above the saturation limit of each dissolved ion, and hence the water becomes unstable. It is this supersaturated and unstable nature of hard water that causes severe fouling in a heat exchanger. Fouling can occur with saturated water because the saturated water becomes locally supersaturated when it makes contact with a heat transfer surface. However, the fouling problems caused by an saturated water occur over a period of years, and this type of slow fouling is not the fouling problem of our concern. The fouling problems of the present interest occur in a time period of weeks or months, which can be attributed to the use of supersaturated water from the beginning.

Electronic descaling (ED) technology takes advantage of the unstable nature of the supersaturated water. The induced electric field which oscillates with time provides necessary molecular agitation to charged mineral ions such that calcium and bicarbonate ions collide each other and precipitate. Once dissolved ions are converted to insoluble mineral crystals, the level of

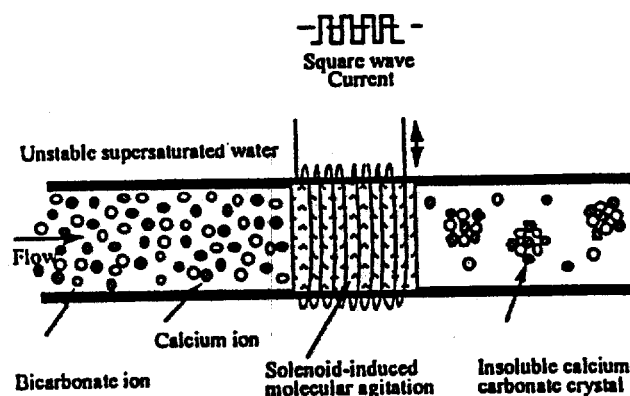


Fig. 3 Schematic diagram of controlled precipitation through electronic descaling technology.

supersaturation of the water significantly decreases; thus new scale deposits on the heat transfer surface are prevented. The critical issue is the nucleation and crystallization mechanism of calcium carbonate, which was addressed by Cho et al. [6] and will not be repeated here.

## METHODS

Figure 4 schematically shows a flow loop used in the present study which consists of a reservoir tank, a pump, an electronic descaling (ED) 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 recirculating test solution at a constant temperature. The plate-and-frame heat exchanger was made of 20 stainless steel plates, where 10 channels were used for steam and 9 channels were used for cooling water. Steam provided by Philadelphia city steam network was used for testing.

Since the hardness of tap water available in Philadelphia is approximately 170 ppm as  $\text{CaCO}_3$ , it is not suitable for accelerated fouling experiments. Therefore, artificial hard water was prepared in our laboratory. The test fluid was prepared by adding 0.01 M calcium chloride  $\text{CaCl}_2$  and 0.02 M sodium bicarbonate  $\text{NaHCO}_3$  to tap water such that the hardness of the test solution was equivalent to 1,000 ppm as  $\text{CaCO}_3$ . As we recirculated the test fluid, the hardness decreased because calcium ions interacted with bicarbonate ions. Solid forms of  $\text{CaCO}_3$  precipitated out from the test solution and settled at the bottom of the reservoir tank. Therefore, the test fluid had to be replaced every four hours by draining the water from both the reservoir tank and flow loop, and fresh test fluid of 1,000 ppm hardness was thereafter refilled in the reservoir tank. Since a typical run took approximately eight hours, we replaced the test solution twice for each run. The amount of the test solution prepared each time was 180 liters (47.5 gallons).

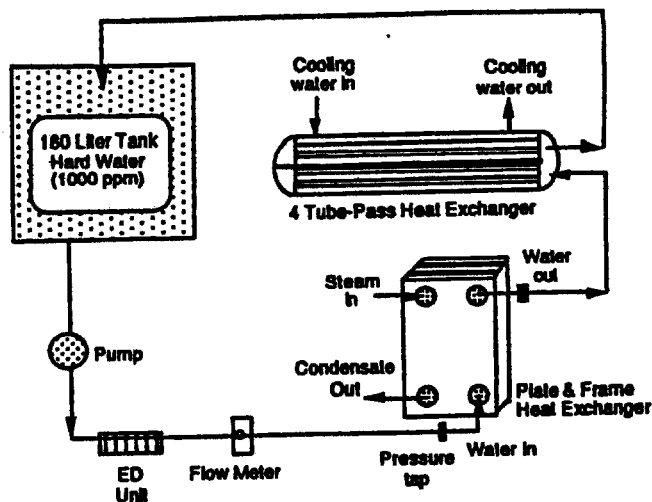


Fig. 4 Schematic diagram of recirculating flow loop, where accelerated fouling tests were conducted.

For accelerated fouling tests, the hard water (i.e., 1,000 ppm) was recirculated at a flow rate of 1.0 gpm for eight hours. The test solution was passing through the main test section approximately five times for four hours.

The small flow rate of 1.0 gpm was selected to accelerate fouling in a laboratory. A shell-and-tube heat exchanger was used to remove heat gained by the test solution so that the temperature of the test solution at the entrance of the test section could be maintained at  $26 \pm 0.5^\circ\text{C}$  throughout the experiment. The outlet temperature downstream of the test section was maintained at approximately  $80 \pm 2^\circ\text{C}$  by adjusting steam pressure throughout the test. At the end of 8 hours' operation, we measured the pressure drop across cooling water side while we varied the flow rate from 1 to 10 gpm. Four temperatures (i.e., inlet and outlet temperatures of water side and steam side) at each flow rate were recorded for the evaluation of heat transfer behavior. Similar test was conducted at a flow rate of 1.5 gpm for comparison.

The test results are presented in the form of pressure drop,  $\Delta P$ , and overall heat transfer

coefficient,  $U$ . The former was measured by a Validyne pressure transducer which was calibrated using an U-tube manometer. The overall heat transfer coefficient,  $U$ , was calculated from the measured inlet and outlet temperatures of water, the inlet temperature of steam, and the outlet temperature of condensates.

## RESULTS AND DISCUSSION

Figures 5 and 6 show pressure drop,  $\Delta P$ , as a function of flow rate measured after 8 hours' operation at a flow rate of 1.0 and 1.5 gpm, respectively. Square symbols represent  $\Delta P$  corresponding to clean initial state. Triangles indicate the  $\Delta P$  results obtained after the heat exchanger was used for 8 hours without ED treatment, whereas circles indicate those obtained with the ED treatment. For the case of 1.0 gpm shown in Fig. 5,  $\Delta P$  increased by 700 - 1,100% depending on flow rate when the ED treatment was not used during the 8 hours' operation. On the other hand, when the ED treatment was applied during the recirculation,  $\Delta P$  increased only by 150 - 220% depending on flow rate. For the case of 1.5

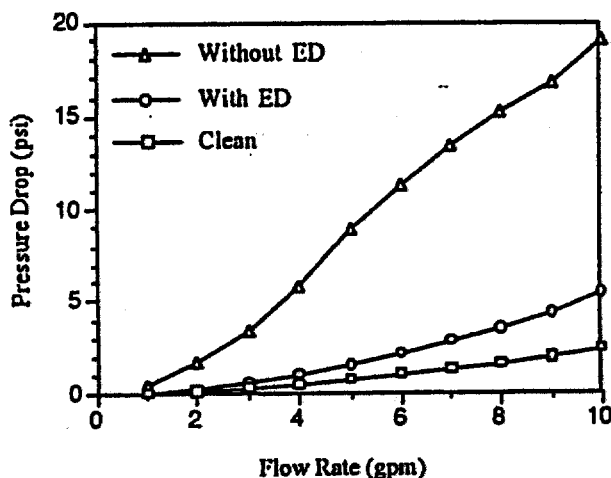


Fig. 5 Changes in pressure drop across cooling water side vs. flow rate. Accelerated fouling was done by circulating 1,000 ppm hard water for 8 hours at 1.0 gpm.

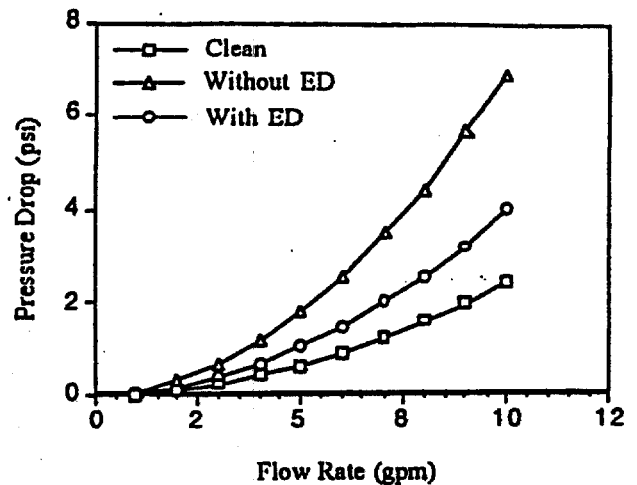


Fig. 6 Changes in pressure drop across cooling water side vs. flow rate. Accelerated fouling was done by circulating 1,000 ppm hard water for 8 hours at 1.5 gpm.

gpm shown in Fig. 6,  $\Delta P$  increased by 250 - 290% depending on flow rate when the ED treatment was not used, whereas when the ED treatment was applied during the recirculation,  $\Delta P$  increased by 150 - 165% depending on flow rate. The results from both figures clearly indicate that the ED treatment significantly reduced fouling inside the plate-and-frame heat exchanger.

Figure 7 shows changes in pressure drop across water side during the initial 50 minutes. Since the test solution passed through the main test section twice for the first 50 min., it was almost like a once-through flow system. For the case without the ED treatment,  $\Delta P$  increased from 5.2 cm H<sub>2</sub>O at  $t=0$  to 62.5 cm H<sub>2</sub>O at  $t=50$  min. whereas for the case with the ED treatment,  $\Delta P$  increased from 5.2 cm H<sub>2</sub>O to 54.0 cm H<sub>2</sub>O at  $t=50$  min. It is of note that since the magnitude of  $\Delta P$  was relatively small, we used a U-tube manometer for the measurement of  $\Delta P$  changes with time. The results shown in Fig. 7 dramatically demonstrate the benefit of using ED treatment in a plate-and-frame heat exchanger.

Figure 8 shows field test results obtained from a much large plate-and-frame heat exchanger (Alfa Laval M30). The plate and frame heat

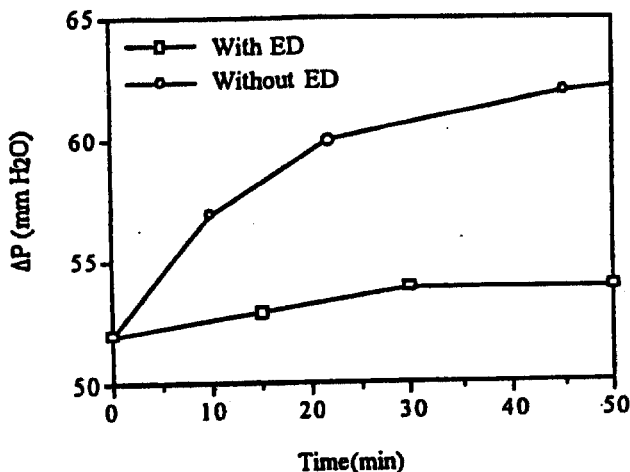


Fig. 7 Changes in pressure drop across cooling water side vs. time during accelerated fouling tests. Hard water of 1,000 ppm was circulated at a flow rate of 1.5 gpm.

exchanger having 140 titanium plates with 14" feed (carbon steel) pipes was used to extract heat from a 7% brine solution whose temperature ranged 90 - 100°C and hardness varied from 100 to 400 mg/L. The brine solution was cooled using a fresh river water which was pumped to the other side of the heat exchanger. Scaling occurred in both sides of the heat exchanger, reducing the heat transfer coefficient by 10% every week as shown in Fig. 8 (open circles). Scale build-up would force the plant to acid clean the heat exchanger every 5-6 weeks.

When an ED unit was installed, which was about 5 days after acid cleaning, the percentage performance was approximately 95%. During the next 16 weeks, the heat exchanger ran without having to acid clean, while maintaining the initial 95% performance as shown by closed circles in Fig. 8.

It is of note that the solubility of silicate increases with increasing temperature. In other words, silica has normal-solubility characteristics such that dissolved silica ions precipitate as hard water is cooled. As demonstrated in Fig. 11, the ED technology could prevent fouling from both brine solution and fresh water, indicating

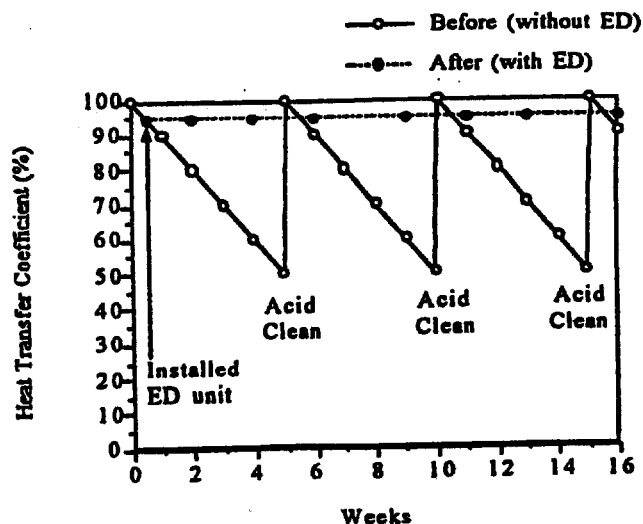


Fig. 8 Results from a field test with a large plate-and-frame heat exchanger. High temperature 7% brine solution was cooling in one side and fresh river water was being heated in the other side. Installation of ED unit was 5 days after acid cleaning.

that the ED technology works not only for inverse-solubility salts (e.g., calcium carbonate) but also for normal-solubility salts (e.g., silica).

## CONCLUSIONS

The present paper investigated the validity of electronic descaling (ED) technology, which was considered as a means to control 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 is very sensitive to fouling. In other words, if fouling occurs in a plate-and-frame heat exchanger in spite of high shear design, the overall heat transfer coefficient will dramatically be reduced. Because of this sensitive relationship between performance and fouling in the plate-and-frame heat exchanger, the ED treatment can be beneficial, if it can prevent or significantly reduce new fouling. The results from both accelerated fouling tests in our laboratory and a field test presented in this study demonstrated that

the ED technology indeed prevents new fouling, thus helping plate-and-frame heat exchangers run at the initial maximum capacity indefinitely.

#### FINAL REMARKS

The present paper uses calcium carbonate as an example of the mineral scales. However, the electronic descaling technique is not limited to the calcium carbonate scale. The ED treatment utilizes the electrical charges of dissolved ions. Since all the dissolved ions have the electrical charges, the ED treatment is effective for any dissolved inorganic ions, including calcium, magnesium, barium, silica, bicarbonate, sulfate, etc.

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

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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  $\text{CaCO}_3$ ) 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. © 1998 Elsevier Science Ltd. All rights reserved.

## 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 ( $\text{CaCO}_3$ ), 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-

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## NOMENCLATURE

$A, B$	empirical constants	$\Delta P$	pressure drop across plate-and-frame heat exchanger.
$D_h$	hydraulic diameter of a channel in plate-and-frame heat exchanger	Greek symbols	
$f$	friction coefficient	$\tau_w$	shear stress
$Re$	Reynolds number	$\beta$	plate inclination angle
$U$	universal heat transfer coefficient	$\rho$	density of test solution
$V$	average flow velocity in a channel	$\mu$	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  $\mu\text{m}$  to 10  $\mu\text{m}$  in diameter, whereas the treated water sample by the EAFT showed large crystals ranging from 10  $\mu\text{m}$  to

20  $\mu\text{m}$  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  $\text{CaCO}_3$ , 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 ( $\text{CaCl}_2$ ) and 0.02 M sodium bicarbonate

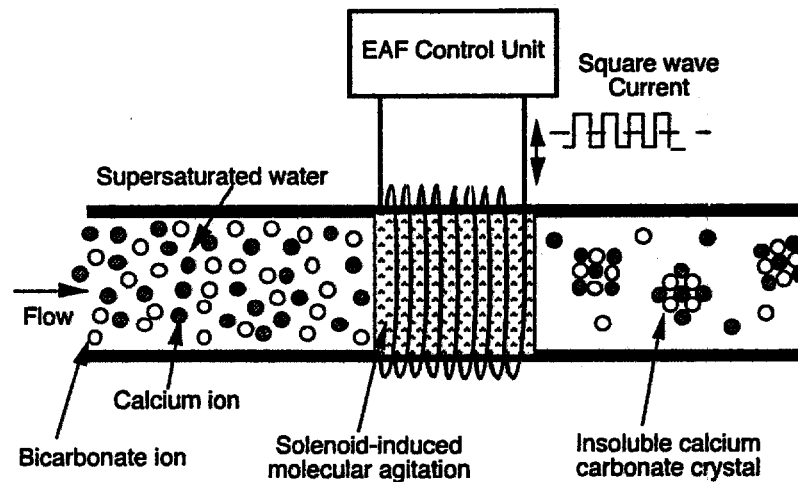


Fig. 1. Illustration of the operating principle of electronic anti-fouling (EAF) technology.

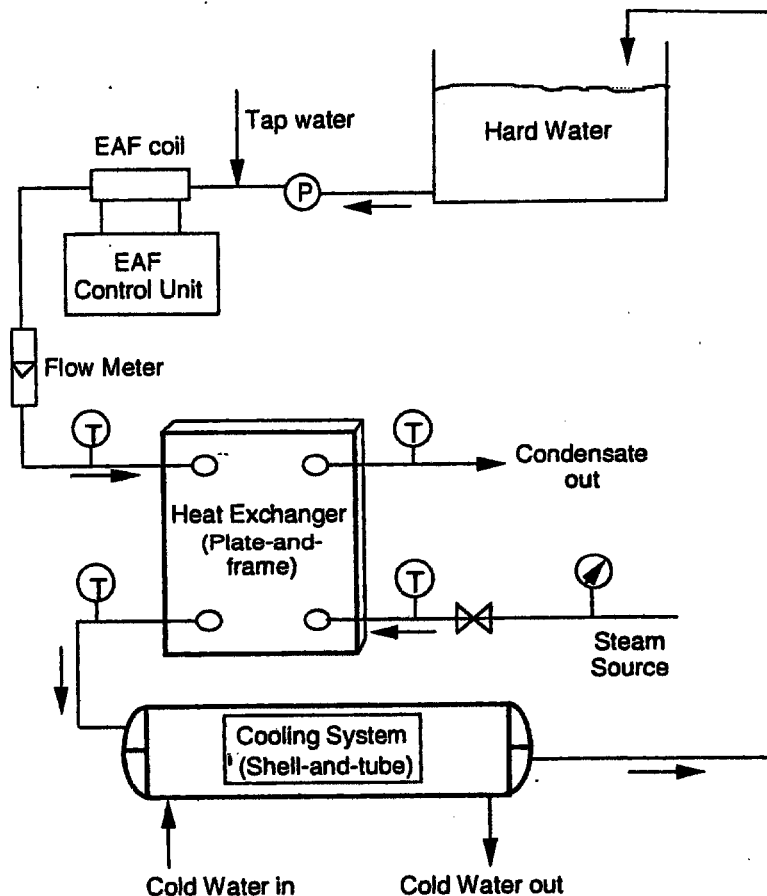


Fig. 2. Schematic diagram of recirculating flow loop with a plate-and-frame heat exchanger as the main test section. The EAF coil for electronic anti-fouling treatment is used in a feed pipe to the heat exchanger.

( $\text{NaHCO}_3$ ) to tap water such that the hardness of the test solution was equivalent to 1000 ppm as  $\text{CaCO}_3$ . 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  $\text{CaCO}_3$  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  $26^\circ\text{C}$ , whereas the outlet temperature of the water leaving the heat exchanger was maintained at  $80 \pm 2^\circ\text{C}$  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). Cali-

bration was carried out at zero and  $100^\circ\text{C}$ , confirming the manufacturer's claim of an accuracy of  $\pm 0.1^\circ\text{C}$ . 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  $\rho$  and  $\mu$  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  $5.36 \text{ cm s}^{-1}$ . 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<sub>2</sub>O 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  $\tau_w$  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,  $\Delta P$ , 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

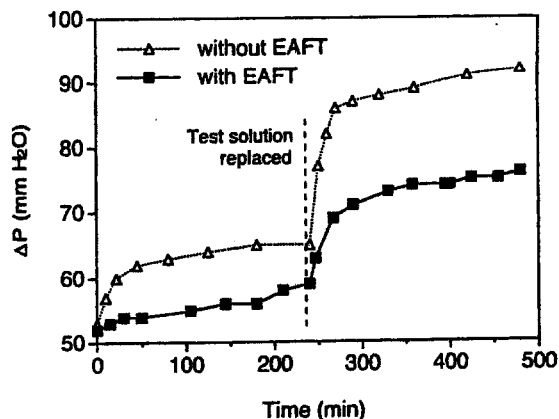


Fig. 3. Variation of pressure drop across plate-and-frame heat exchanger with and without electronic anti-fouling (EAF) treatment with 1000 ppm hard water at 1.5 gpm.

exchanger increases. Figure 3 shows the changes in the pressure drop due to fouling during eight hours of circulation of 1000 ppm hard water.

For the case without the EAF treatment,  $\Delta P$  increased from the initial value of 52 to 62.5 mm H<sub>2</sub>O at  $t = 50$  min and then reached an asymptotic value of 65 mm H<sub>2</sub>O 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<sub>2</sub>O in the next 30 min, a 32% increase in  $\Delta P$ . After this initial rapid increase in  $\Delta P$ , the pressure drop increased gradually to 92 mm H<sub>2</sub>O at the end of an 8 h run.

For the case with the EAF treatment,  $\Delta P$  increased from the initial value of 52–54 mm H<sub>2</sub>O at  $t = 50$  min and then reached a value of 59 mm H<sub>2</sub>O 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<sub>2</sub>O in the next 30 min, a 20% increase in  $\Delta P$ . After this initial rapid increase in  $\Delta P$ , the pressure drop increased gradually to 74 mm H<sub>2</sub>O 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 an asymptotic value.

Figure 4 shows pressure drop,  $\Delta P$ , 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.  $\Delta P$  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  $\Delta P$  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.  $\beta$  is the plate inclination angle, which is  $30^\circ$  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

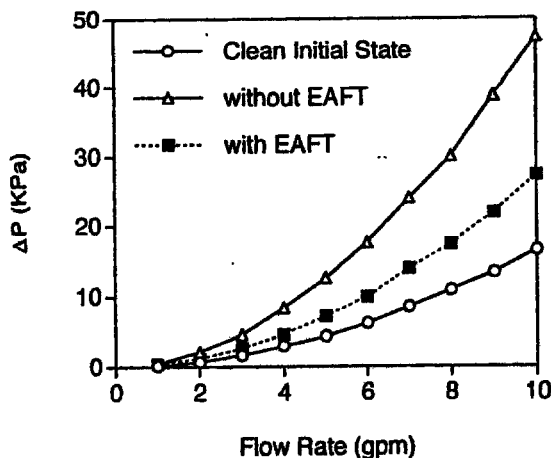


Fig. 4. Pressure drop data across plate-and-frame heat exchanger over a range of flow rates measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

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:

$$A = 0.291 \text{ and } B = 0.08 \text{ for clean initial state}$$

$$A = 0.42 \text{ and } B = 0.001 \text{ for the case without EAFT}$$

$$A = 0.291 \text{ and } B = 0.02 \text{ for the case with EAFT}$$

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  $\text{Wm}^{-2} \text{K}^{-1}$  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  $\text{Wm}^{-2} \text{K}^{-1}$  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

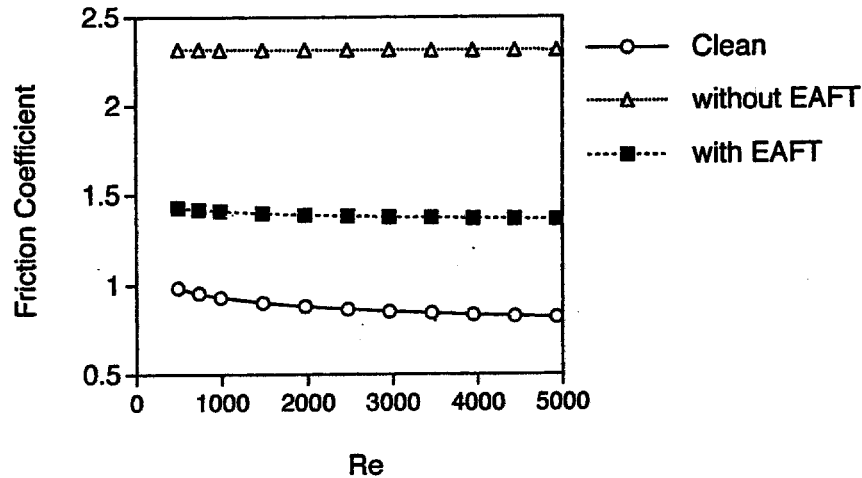


Fig. 5. Friction coefficient vs Reynolds number for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

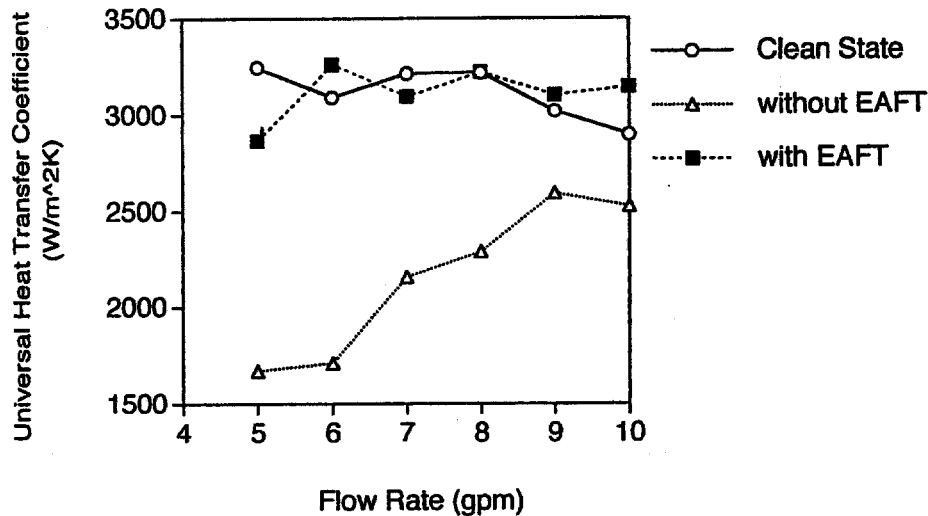


Fig. 6. Universal heat transfer coefficient vs flow rate measured after 8 h of circulation of hard water at a flow rate of 1.5 gpm for three different states: clean initial state, tests without electronic anti-fouling treatment (EAFT) and with EAFT.

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),  $\Delta P$  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  $\Delta P$  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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