Use of electronic anti-fouling technology with filtration to prevent fouling in a heat exchanger

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Abstract

An innovative technology to control fouling in heat exchangers was developed, based on a combined use of electronic anti-fouling (EAF) technology and filtration. To validate the concept, the present study conducted a series of accelerated fouling tests with an artificial hard water of a hardness of 1000 mg l^{-1}. The pressure drop across a heat transfer test tube and the overall heat transfer coefficient were measured as a function of time. The pressure drop obtained with the combined use of the EAF treatment and filter showed almost no change from the initial value. Furthermore, the overall heat transfer coefficient obtained with the combined use of the EAF treatment and filter decreased by 6% from the initial value, whereas the U value dropped by 29% without any treatment. © 1998 Elsevier Science Ltd. All rights reserved.

Nomenclature

A interior surface area of heating tube
A   cross-sectional area vector
B   magnetic field strength vector
C_p heat capacity
E   induced electric field intensity vector
$\dot{m}$ mass flow rate
q'' heat flux
R_f fouling factor
s   line vector along the circumferential direction
T temperature
t time
U overall heat transfer coefficient.

Subscripts
b   bulk
clean   clean tube
fouled   fouled tube
in   inlet
out   outlet
o   initial state
s   surface
w   tube wall.

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1. Introduction

The scale problem originates in the use of hard water. When hard water is heated (or cooled) inside heat transfer equipment, the solubility of dissolved mineral ions often decreases [1]. When conditions such as temperature, pressure, and pH change in a flow system such that the solubility of a mineral ion decreases, the mineral ions precipitate to form crystals. This phenomenon usually happens on the heat transfer surface, because the water temperature suddenly changes as water makes contact with the heat transfer surface. When scales deposit on a heat exchanger surface, it is traditionally called 'fouling'.

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 [2]. Many variables control the fouling in a heat exchanger, including water characteristics (i.e., pH, hardness, alkalinity, suspended solids, fluid temperature variation), heat exchanger surface temperature, pressure, flow velocity, flow separation and recirculation, etc.

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. The solubility characteristics of these scale-

causing mineral ions with temperature are given in Linke [1] and Fan [3]. One of the most common forms of scales is calcium carbonate ($CaCO_3$), 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.

Once scales build up on 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. 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 [4]. Ion exchange and reverse osmosis are also used to reduce water hardness, alkalinity, and silica level [4]. However, these methods are expensive at the industrial level, and require heavy maintenance for proper operation. Once fouling occurs in a heat exchanger, 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, hydro-blasting, sand blasting, metal or nylon brushing are used—operations which incur downtime and repair costs.

The objective of the present study is to examine the feasibility of a new method to control fouling in a heat exchanger: a combined use of an electronic anti-fouling (EAF) technology and filtration. With this technology, one can significantly reduce or prevent fouling in the heat exchanger, thus maintaining the initial peak performance of the heat exchanger indefinitely. Furthermore, one can discontinue the use of scale-inhibiting or scale-removing chemicals, thus preserving a clean environment.

2. Operating principle of the electornic anti-fouling technique

Figure 1 shows a schematic diagram of the operation of an electronic anti-fouling (EAF) technology, and the concept of a combined use of EAF technology and filtration. A wire is wrapped around a feed pipe to a heat exchanger, forming a solenoid. The two ends of the wire are connected to the EAF control unit. The EAF 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 Faraday's law [5]:

$$\int \mathbf{E} \cdot \mathbf{ds} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot \mathbf{dA} \qquad (1)$$

where $\mathbf{E}$ is an induced electric field intensity vector, $\mathbf{s}$ is a line vector along the circumferential direction, $\mathbf{B}$ is a magnetic field strength vector, and $\mathbf{A}$ is the cross sectional area vector. In order to maximize the induction, a pulsing current having a square-wave signal is used. The current and frequency of the square-wave signal used in the present study were 0.2 A and 500 Hz, respectively. The frequency was optimized at 500 Hz to minimize the self-induction caused by the solenoid coil. The impedance from the self-induction also increases with the diameter of the solenoid, a phenomenon which significantly reduces the magnitude of the square-wave current signal in large diameter pipes. In order to mitigate this drawback occurring in large pipes, a newly improved circuit with a constant-current source has been recently introduced [6]. More detailed descriptions on the operating principle of the electronic anti-fouling device can be found elsewhere [3, 7-10].

The induced electric field, which oscillates with time, provides the necessary molecular agitation to charged mineral ions such that dissolved mineral ions such as calcium and bicarbonate collide and precipitate. To illustrate the molecular agitation, Fig. 2 shows a sketch of a cross section of a pipe where an induced electric field oscillates with time. For an induced electric field in the clockwise direction, positive ions move clockwise while negative ions move counterclockwise, resulting in collision and precipitation in bulk solution. When the induced electric field changes to the counterclockwise direction, positive ions move counterclockwise while negative ions move clockwise, also resulting in collision and precipitation. The precipitated nuclei and heat exchanger surface compete for dissolved mineral ions inside the heat exchanger. Since the combined surface area of the nuclei can be greater by several orders of magnitude than the surface area of the heat exchanger, the fouling at the heat exchanger surface can be prevented.

Once dissolved ions are converted into insoluble mineral crystals of submicron to several micron size, one can remove them using a filter as shown in Fig. 1. As a proof of the above-mentioned collision and subsequent precipitation, Fan [3, 6] measured the alkalinity of EAF treated solution after the solution was passed through a 2 μm size filter and found that there was approximately 18-24% drop in the alkalinity.

A standard household filter made by Aqua-Pure (Meriden, CT) with pore size ranging from 5-20 μm was used in the present study. Using both the EAF treatment and filter, the level of supersaturation of the water significantly decreases; thus, new scale deposits on the heat transfer surface are significantly reduced or prevented.

3. Experimental methods

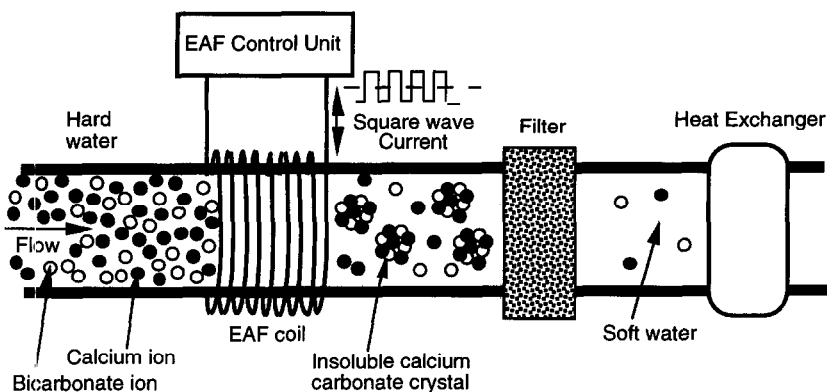The present study reports a fouling experiment conducted under extremely harsh fouling conditions. Figure

Fig. 1. Schematic diagram of the concept of electronic anti-fouling (EAF) technology integrated with filtration. EAF technology uses a solenoid-induced molecular agitation to convert dissolved mineral ions to insoluble particles, whereas filter removes the precipitated particles from water, thus preventing new scale build-up in the heat exchanger.
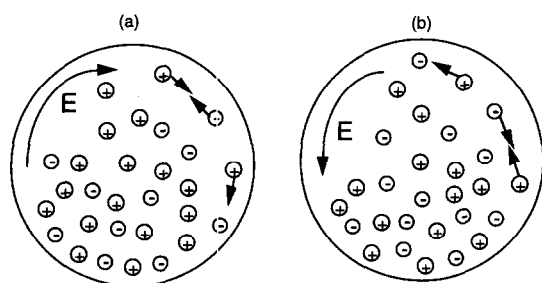

Fig. 2. Sketch of cross section of a pipe where induced electric field oscillates with time. (a) For E field in the clockwise direction, positive ions move clockwise while negative ions move counterclockwise, resulting in collision and precipitation in bulk solution and (b) for E field in the counterclockwise direction, positive ions move counterclockwise while negative ions move clockwise.
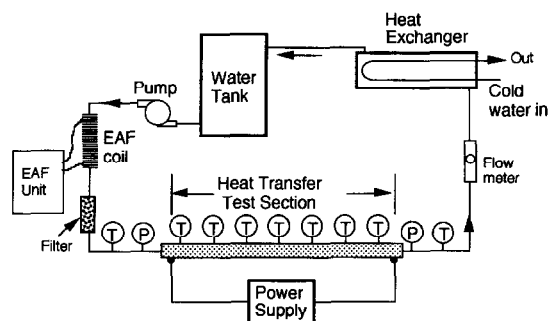

Fig. 3. Schematic diagram of recirculating flow loop where accelerated fouling tests were conducted. Both electronic anti-fouling (EAF) coil and filter are located between pump and the inlet of the main heat transfer test section.

3 schematically shows a flow loop used in the present study which consists of a reservoir tank, a pump, a flow meter, an electronic anti-fouling unit, the main heat transfer test section, and a heat exchanger. The main test section (with an inside diameter of 0.0191 m and a length of 4.74 m) was heated electrically using a DC power supply such that a constant heat flux boundary condition could be maintained at the pipe surface. The total heat gained by the test solution was obtained from the measurement of the temperature difference between the inlet and outlet of the test solution and the mass flow rate.

A flow rate of 2.84×10^{-5} m^3 s^{-1} (i.e., average velocity of 0.1 m s^{-1}) was used in the recirculating loop, resulting in an average Reynolds number of 3476 based on the mean bulk temperature. This small flow rate 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 25°C throughout the experiment. The outlet temperature downstream of the test section was in a range of 78–80°C. A typical power input for the present test at a velocity of 0.1 m s^{-1} was 4.8 kW.

Since the hardness of tap water available in Philadelphia is approximately 150 mg l^{-1} as CaCO$_3$, it is not suitable for the 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 (NaHCO$_3$) to tap water such that the hardness of the test solution was equivalent to 1000 mg l^{-1} as CaCO$_3$. The values of pH, alkalinity, TDS, and electric conductivity were 7.9, 1000 mg l^{-1} as CaCO$_3$, 2800 mg l^{-1}, and 3950 μS cm^{-1}, respectively.

As we recirculated the test fluid, calcium and bicarbonate ions deposited on the heat transfer test tube,

reducing the hardness of the test solution. Therefore, the test fluid had to be replaced every 4 h with a fresh test fluid of 1000 mg l^{-1}. Since a typical run took approximately 40 h, we replaced the test solution ten times for each run.

During the test, the pressure drop across the main heat transfer test section was measured as a function of time using a pressure transducer (Validyne DP 103) which was calibrated using a U-tube manometer. In addition, the inlet and outlet temperatures of the circulating hard water were measured using thermocouples, Omega model TMTSS-125G-6 (grounded copper–constantan T type). In order to obtain the overall heat transfer coefficient, U, we measured the outer wall temperature along the test section using T-type thermocouples cemented on the outer wall. Calibration was carried out at zero and 100°C, confirming the manufacturer's claim of the accuracy of ± 0.1°C. Details of the thermocouple locations and mounting method can be found in Fan [3].

The test results in the present study are presented in the form of pressure drop, ΔP, and the overall heat transfer coefficient, U. The U value was calculated as follows: since the heat flux, q'', can be obtained from the following equation:

$$q'' = \dot{m}C_p[T_{b,out} - T_{b,in}]\frac{1}{A} \tag{2}$$

the fouling factor, R_f, can be estimated as

$$R_f = [T_{w,fouled} - T_{w,clean}]\frac{1}{q''}. \tag{3}$$

This method of estimating the fouling factor as shown in equation (3) was first introduced by Fischer et al. [11] and later by Müller-Steinhagen et al. [12]. Once the fouling factor is determined, the overall heat transfer coefficient can be calculated using the following definition of U:

$$U = \frac{1}{R_f + \frac{1}{U_0}}. \tag{4}$$

The errors estimated from the uncertainty analysis for q'', R_f, U_0, and U, were 1.9, 1.7, 6.4, and 4.6%, respectively.

4. Results and discussion

Figure 4 shows pressure drop, ΔP, as a function of time for four different cases: no treatment, filter only, EAF treatment only, and combined use of EAF treatment and filter. For the case without any treatment, ΔP increased gradually from its initial value of 249 Pa to a plateau value of 580 Pa near the end of the test (i.e., $t = 40$ h), an increase of 132% from the initial state. For the case with the EAF treatment, ΔP gradually increased from the initial value of 249–435 Pa, an increase of approximately 75% from the initial state.
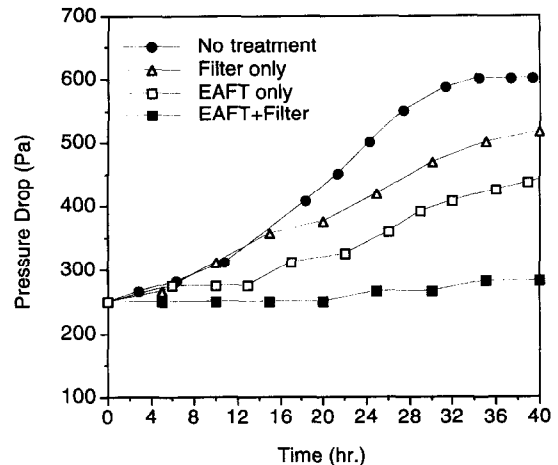

Fig. 4. Pressure drop across the test section vs. time for four different cases: no treatment, filter only, EAF treatment only and EAF treatment with a filter.

When the EAF technology and a filter were used together, ΔP almost remained unchanged, validating the concept of the combined use of EAF technology and filtration to prevent fouling. Obviously, when EAF technology and filtration were used together, scale-causing mineral ions and particles were removed from water, thus reducing the hardness.

Figure 4 also shows the pressure drop obtained with a filter. ΔP increased gradually from its initial value of 249–515 Pa by the end of the test, approximately 107% increase from the initial state. A filter with pore size of 5–20 μm cannot remove any dissolved ions. However, in a recirculating flow system, the pump creates enough disturbance for the ions to collide and cause precipitation. In a supersaturated solution, heterogeneous nucleation will occur throughout the bulk fluid as well as on the wall. Hence, a filter helps reducing fouling in a heat exchanger in the recirculating loop. It is of note that as the precipitated crystals were collected in the filter, the flow rate was found to be unchanged during the 40 h operation.

Figures 5 and 6 show the fouling factor, R_f, and the overall heat transfer coefficient, U, respectively, as a function of time for four different cases: no treatment, filter only, EAF treatment only, and combined use of EAF treatment and filter. The fouling factor increased from zero at the initial state to 0.00024 m^2 K W^{-1} at the end of the 40 h test for the case without any treatment. The overall heat transfer coefficient decreased from 1730–1221 W m^{-2} K^{-1}, a decrease of 29% from the initial peak value.

When the EAF technology was used with a filter, the fouling factor and overall heat transfer coefficient changed very little. The fouling factor increased from zero at
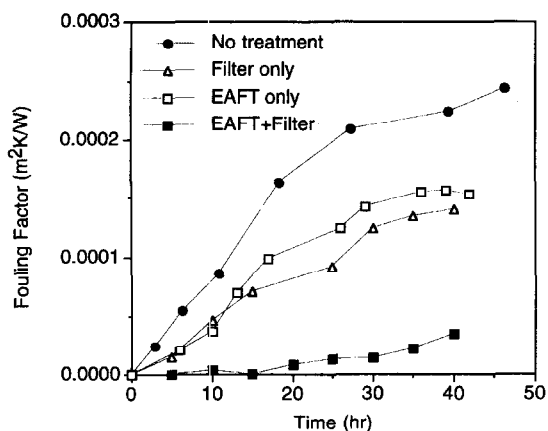
Fig. 5. Fouling factors vs. time for four different cases: no treatment, filter only, EAF treatment only and EAF treatment with a filter.
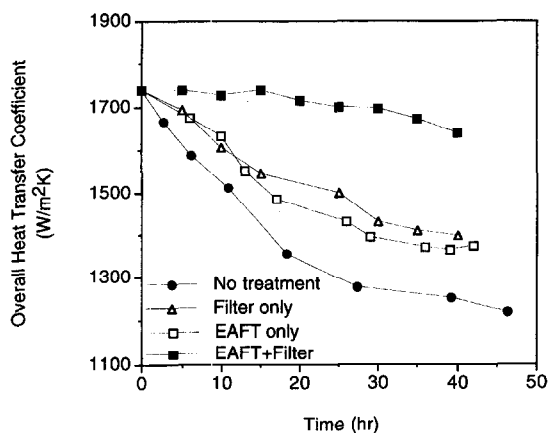

Fig. 6. Overall heat transfer coefficient vs. time for four different cases: no treatment, filter only, EAF treatment only and EAF treatment with a filter.

the initial state to 0.000035 m² K W⁻¹ at the end of the 40 h test. The overall heat transfer coefficient decreased from 1740–1640 W m⁻² K⁻¹, only a 6% decrease from the initial peak value. For the case with the EAF treatment, the overall heat transfer coefficient decreased from 1733–1374 W m⁻² K⁻¹, a 21% decrease from the initial peak value. For the case with the filter, the overall heat transfer coefficient decreased from 1736–1399 W m⁻² K⁻¹, a 19% drop from the initial peak value.

The present study was carried out in order to demonstrate the validity of the combined use of the EAF technology and filtration for the prevention of fouling. In order to accelerate fouling in a relatively short period in a laboratory, we have used artificial hard water of 1000 mg l⁻¹, a small flow velocity of 0.1 m s⁻¹, and an

extremely large temperature rise of 53–55°C across a heat transfer test section. Normally, industrial heat exchangers are not used in such harsh fouling conditions except for evaporators. In order to examine whether or not the EAF technology alone can prevent fouling under normal industrial conditions, i.e., when the flow rate is beyond 1 m s⁻¹, temperature rise is in a range of 10–20°C, and water hardness is in a range of 300–500 mg l⁻¹ as CaCO₃, we have conducted several validation tests. Cho et al. [10, 13] conducted fouling tests with and without the EAF treatment in plate-and-frame heat exchangers and found that the overall heat transfer coefficients obtained without the EAF treatment decreased almost 50% in just 8 h, whereas the U values with the EAF treatment remained at the initial maximum level. Choi [14] studied the effect of the EAF treatment on both fouling factor and initial fouling rate under various flow and thermal conditions. He measured asymptotic fouling resistance in shell-and-tube heat exchangers and found that the EAF treatment generally reduced the fouling resistance by 20–40%. These tests demonstrate that the EAF treatment clearly reduces the precipitation fouling in actual heat exchangers.

There have been a number of other non-chemical methods proposed for the prevention of precipitation fouling in heat exchangers, which include the use of permanent magnets, in-line high voltage electrode, frequency-modulated electronic technique, ozone technique, etc. A comprehensive review paper is under preparation, discussing the validity of these methods and will be available in the future.

5. Conclusions

The present study demonstrated that when the electronic anti-fouling (EAF) technology was used with a filter, precipitation fouling could be significantly reduced in a heat exchanger used in a recirculating loop.

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