

EXPERIMENTAL VALIDATION OF ELECTRONIC ANTI-FOULING TECHNOLOGY WITH A PLATE HEAT EXCHANGER

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ABSTRACT

The objective of the present study was to investigate the validity of a new electronic anti-fouling (EAF) technology through accelerated fouling tests. The EAF technology has been developed for the purpose of mitigating scales in both plate-and-frame and shell-and-tube heat exchangers. The present test results obtained from the present study demonstrate that the EAF technology can significantly reduce scale deposits both in an accelerated fouling test and in a field study.

INTRODUCTION

Scaling is the accumulation of mineral deposits typically from a liquid stream. If scaling occurs in a heat exchanger, it is often called fouling. Precipitation fouling of dissolved mineral ions is one of the most common and serious fouling problems in heat exchangers (Taborek et al., 1972; Suitor et al., 1977; Knudsen, 1981). Hence, most heat exchangers used in hard water areas need periodic maintenance to remove scales. Reduction or prevention of the precipitation fouling would create huge economic benefits.

Various scale-inhibiting chemicals, such as dispersing or chelating agents, are used to prevent scales (Snoeyink & Jenkins, 1982). Ion exchange and reverse osmosis processes, which require large up front capital investment and rigorous maintenance, are also used in the process industry to reduce water hardness, alkalinity, and silica level. Once scale problems occur, the correction of the scale problems is accomplished by acid cleaning with chemicals such as H_2SO_4 or HCl (Cowan & Weintritt, 1976), scraping, and hydro-blasting or sand blasting. These operations require downtime and incur repair costs. Acid cleaning has been effective in removing existing scales and is a part of routine maintenance for various heat transfer equipment. However, the cost of the chemical treatment is recurring, 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 (Cowan & Weintritt, 1976). 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 (Cowan & Weintritt, 1976).

One of the major problems of these alternative solutions is the lack of understanding of the operating principle. Furthermore, no one knows whether it works or not. Some of the claims made by the companies marketing permanent magnets are incorrect from the principle of fundamental physics and chemistry. Furthermore, most claims are testimonial statements, which do not add much in understanding the theory of the alternative methods.

The present study focuses on an electronic anti-fouling (EAF) technology, which is one of the most recent alternative solutions. The objective of this study is to conduct accelerated fouling tests to validate the EAF technology and to investigate the operating envelop of the EAF technology for the prevention of fouling in heat exchangers.

BACKGROUND

Scales are formed when hard water is heated (or cooled) in heat transfer equipment. Scales often observed in industry include calcium carbonate, calcium sulfate, barium sulfate, silica, iron scales, and others. The most common form of scales is calcium carbonate ($CaCO_3$). Acidic water passing over and permeating through rocks dissolves limestone into calcium and bicarbonate ions, thereby making water hard. When the hard water is 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 (Snoeyink & Jenkins, 1982).

Once scales build up in a heat transfer surface, at least two problems associated with scales occur. First, the performance of the heat transfer equipment significantly decreases. Due to the small thermal conductivity of scales, a thin coating of scales (i.e., even 0.01 or 0.02 in) on the heat transfer surface greatly reduces the overall heat transfer performance (Cowan & Weintritt, 1976; Incropera & DeWitt, 1996). Second, a small change in tube diameter substantially decreases the flow rate across the heat transfer equipment, thus reducing the total heat transfer capacity of the equipment (Munson, 1994).

Fouling problems are of major concern to many industries using water and heat. Examples include process, petroleum, food, utility, marine, mining, air compressor and air separation industries. If one can reduce or prevent fouling in heat transfer equipment in these industries, the savings in energy, maintenance, replacement of equipment, etc. will be truly significant.

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, all of which affect solubility.

The solubility of calcium carbonate decreases with increasing temperature, whereas it decreases with decreasing pressure (Linke, 1958). When conditions such as temperature and pressure change in a flow system such that the solubility of calcium carbonate decreases, calcium and bicarbonate ions in hard water precipitate to form 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. Figure 1 shows a chemical reaction of CaCO_3 precipitation occurring inside a heat exchanger, a phenomenon which is called "uncontrolled precipitation" in the present study (Snoeyink & Jenkins, 1982; Cowan & Weintritt, 1976).

Calcite and Aragonite

There are two types of calcium carbonates, CaCO_3 : calcite and aragonite (Cowan & Weintritt, 1976). Calcite is a calcium carbonate which is formed at room temperature (i.e., below 30°C), easily removable with weak HCl acid, less-adherent than aragonite, having a hexagonal crystal shape and a specific gravity of 2.71. Aragonite, also a calcium carbonate, is formed at high temperature (i.e., above 30°C) and is difficult to remove, having an orthorhombic crystal shape, and a specific gravity of 2.94. Specifically, the aragonite is a more troublesome form of calcium carbonate than calcite because it forms a harder and denser deposit than calcite in boilers and other heat transfer equipment (Cowan & Weintritt, 1976). When calcium carbonate is formed at temperature above 30°C , both aragonite (~80%) and calcite (~20%) are formed.

When hard water is heated inside heat transfer equipment, the aragonite type of calcium carbonate is formed due to elevated temperature, thus adhering to heat transfer surfaces (Atkins, 1986). Therefore, if one can precipitate calcium carbonate to form the calcite type of calcium carbonate before the hard water enters heat transfer equipment, one may expect

to reduce or prevent scale deposits. This is the key concept of the electronic anti-fouling technology.

DESCRIPTION OF EAF TECHNOLOGY

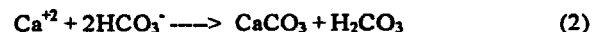
Figure 2 shows a schematic diagram of the operation of an electronic anti-fouling unit. A 18 gauge single stranded wire is wrapped around a feed pipe prior to a heat exchanger, forming a solenoid. Two ends of the solenoid coil are connected to the electronic anti-fouling control unit. The EAF unit produces a pulsing current to create a time-varying magnetic field 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 (Serway, 1990):

$$\oint \mathbf{E} \cdot d\mathbf{s} = - \frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{A} \quad (1)$$

where \mathbf{E} is an induced electric field 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 of solenoid. 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 improve this drawback occurring in large pipes, a circuit with a constant-current source was used for the field test to be discussed later.

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 with the help of impurities in water such as submicron size iron oxide particles.



The precipitated nucleates and heat exchanger surface compete for dissolved mineral ions inside the heat exchanger. Since the combined surface area of the nucleates 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. More detailed descriptions on the operating principle of the electronic anti-fouling device can be found elsewhere (Cho et al., 1997).

Hard water as the Culprit of Fouling

Hard water has excess dissolved mineral ions well above the saturation limit of each dissolved ion, and hence the water becomes unstable (Snoeyink & Jenkins, 1982). If one leaves the supersaturated water in the atmosphere for one or two days, most excess mineral ions precipitate, and the level of supersaturation decreases accordingly (Snoeyink & Jenkins, 1982). However, since the natural precipitation process takes place very slowly, it can not be used in most heat transfer systems.

It is this supersaturated and unstable nature of hard water that causes fouling in a heat exchanger. Fouling also occurs with saturated water because the saturated water becomes locally supersaturated when it makes contact with a heat transfer surface. In this case, the fouling problems occur over a period of years.

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. When one has supersaturated water with a supersaturation level of, for example, six (i.e., hardness of approximately 350 ppm as CaCO_3) (Linke, 1958), the level of supersaturation further increases inside the heat exchanger as the water makes contact with heat transfer surfaces. The supersaturation level (or similarly the Langelier index) of water is the key factor which determines how fast scaling takes place (Snoeyink & Jenkins, 1982).

Hypothesis of the EAF Technology

Electronic anti-fouling (EAF) technology takes advantage of the unstable nature of the hard water. The induced electric field which oscillates with time provides necessary molecular agitation to charged mineral ions, such that dissolved mineral ions (calcium and bicarbonate) collide and precipitate. Once dissolved ions are converted to insoluble mineral crystals, the level of supersaturation of the water significantly decreases; thus new scale deposits on the heat transfer surface are reduced or prevented. The critical issue here is the nucleation and crystallization mechanism of calcium carbonate, which was discussed in detail by Mullin (1993) and Cho et al. (1997).

If one assumes that the EAF technology converts dissolved calcium and bicarbonate ions to calcium carbonate particles whose size is at the order of $1\ \mu\text{m}$ in diameter, one can calculate how many calcium and bicarbonate ions are converted into the $1\ \mu\text{m}$ size CaCO_3 particle. Based on the molecular weight of CaCO_3 of 100 g/mol, a specific gravity of 2.71 (i.e., calcite), and the Avogadro number, the number of CaCO_3 molecules in a $1\ \mu\text{m}$ size CaCO_3 particle was calculated to be 8.5×10^9 , almost ten billion CaCO_3 molecules (Snoeyink & Jenkins, 1982; Atkins, 1986). In other words, the EAF treatment converts dissolved mineral ions into mineral salt crystals through controlled precipitation at a rate of almost ten billion calcium and bicarbonate ions per $1\ \mu\text{m}$ size CaCO_3 particle. In contrast, a chelating agent or dispersing chemical (i.e., EDTA, HEEDTA or DTPA) has a molecular weight of approximately 400. Since each anionic claw combines with one calcium ion, only 400 calcium ions are neutralized per one chelating molecule. Thus, compared to the chelating agent, the EAF treatment is an efficient way to neutralize the dissolved mineral ions and to prevent them from depositing on the heat transfer surface.

METHOD

Figure 3 schematically shows a once-through flow system used in the present study which consists of two reservoir tanks, two pumps, two flow meters, an electronic anti-fouling (EAF) unit, the main heat transfer test section made of a plate-and-frame heat exchanger (Alfa Laval M3), and another identical plate-and-frame heat exchanger to continuously provide hot water at 87°C . The main plate-and-frame heat

exchanger was made of 20 stainless steel plates, where 10 channels were used for hard water and 9 channels were used for hot water.

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 be dramatically reduced. Because of this sensitive relationship between performance and fouling in the plate-and-frame heat exchanger, the EAF treatment can be beneficial, if it can prevent or significantly reduce new fouling.

The tap water available in Philadelphia had hardness of approximately 150 mg/L as CaCO_3 , hence was not suitable for accelerated fouling experiments. In order to accelerate the rate of fouling in a laboratory test, artificial hard water of 1,000 mg/L as CaCO_3 was used at a flow rate of $6.3 \times 10^{-5}\ \text{m}^3/\text{s}$ (1.0 gpm). In order to prepare a 1,000 mg/L solution, 0.01 M calcium chloride (CaCl_2) was added to tap water in one reservoir tank, and 0.02 M sodium bicarbonate (NaHCO_3) was added to tap water in another reservoir tank. When the two solutions were mixed, the mixed solution had the hardness equivalent to 1,000 mg/L as CaCO_3 . Each reservoir tank had a separate pump and flow meter for flow rate control.

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 $80 \pm 2^\circ\text{C}$ throughout the test. The Reynolds numbers corresponding to $6.3 \times 10^{-5}\ \text{m}^3/\text{s}$ at the inlet and outlet of the plate-and-frame heat exchanger became 201 and 486, respectively. Since the critical Reynolds number from laminar to turbulent flow is believed to be approximately 80 for this vertical flow type of plate-and-frame heat exchanger, the accelerated fouling test was characterized in the turbulent flow regime.

RESULTS AND DISCUSSION

Figure 4a shows the changes in the overall heat transfer coefficient, U , for the 1,000 ppm hard water. When the test was conducted without the EAFT (electronic anti-fouling treatment), the U value decreased from its initial value of 1,630 to 1,052 $\text{W}/\text{m}^2\text{K}$; whereas with the EAFT, it decreased from 1,630 to 1,298 $\text{W}/\text{m}^2\text{K}$. Figure 4b shows the same data in the form of fouling factor vs. time. The fouling factor for the case without the EAFT increased from zero to 0.00034 $\text{m}^2\text{K}/\text{W}$ in 90 min.; whereas for the case with the EAFT, it increased to 0.00016 $\text{m}^2\text{K}/\text{W}$ during the same period.

At the end of the 90 min. accelerated fouling test with 1,000 mg/L hard water, the pressure drop across the plate-and-frame heat exchanger was measured over a range of flow rate from 0.63 to $6.3 \times 10^{-4}\ \text{m}^3/\text{s}$ and compared with the pressure drop data obtained in the initial scale-free state. A Validyne pressure transducer which was calibrated using an U-tube manometer was used. The Reynolds numbers corresponding to 0.63 and $6.3 \times 10^{-4}\ \text{m}^3/\text{s}$ are 200 and 2,000, respectively, based on the inlet flow condition.

Figure 5 shows the test results in the form of pressure drop, ΔP , across the plate-and-frame heat exchanger. When compared with the pressure drop data obtained at the initial clean state, the pressure drop results obtained without the EAFT represents approximately 93% increase from the initial

value, whereas those obtained with the EAF represents approximately 58% increase. The present test results demonstrate that the EAF can significantly reduce new scale deposits even in the accelerated fouling test, which is an extremely harsh fouling environment.

Figure 6 shows field test results obtained from a much large plate-and-frame heat exchanger (Alfa Laval M30). A plate-and-frame heat exchanger having 140 titanium plates with a 35.6cm feed (carbon steel) pipe was used to extract heat from a 7% brine solution whose temperature ranged 90 - 100°C. The brine solution was cooled using fresh river water which was pumped to the other side of the heat exchanger. The hardness of the brine solution was 400 mg/L, whereas the hardness of the river water was approximately 100 mg/L. Scaling occurred in both sides of the heat exchanger, reducing the overall heat transfer coefficient by 10% every week as shown in Fig. 6 (open circles). Scale build-up would force the plant to acid clean the heat exchanger every 5-6 weeks. When an EAF unit was installed, which was about 5 days after acid cleaning, the heat transfer performance (%) was approximately 95%. During the next 16 weeks, the heat exchanger ran without acid clean, while maintaining the initial 95% performance as shown by closed squares in Fig. 6.

CONCLUSIONS

The present paper investigated the validity of electronic anti-fouling (EAF) technology, which was developed as a means to control precipitation fouling in a plate-and-frame heat exchanger. The present test results demonstrated that the EAF technology significantly reduced new scale deposits both in an accelerated fouling test and in a field test.

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

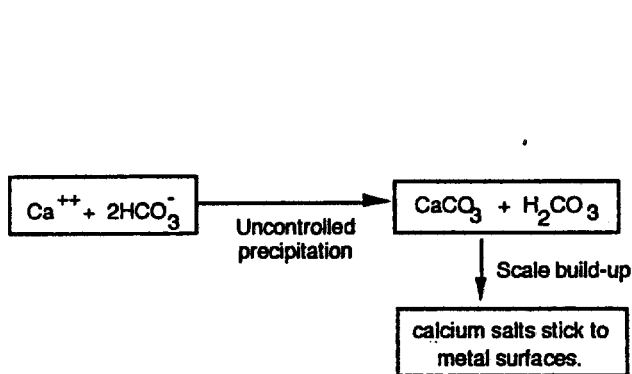


Fig. 1 Block diagram showing uncontrolled precipitation of calcium and bicarbonate ions and subsequent adhesion of $CaCO_3$ crystals to heat transfer surface.

REFERENCES

- Atkins, P.W., 1986, *Physical Chemistry*, 3rd ed., pp. 791-792, W.H. Freeman and Company.
- Cho, Y.I. et al., 1997, Theory of Electronic Anti-fouling Technology of Control Precipitation Fouling in Heat Exchangers, *Int. Comm. Heat Mass Transfer*, vol. 24, pp. 757-770.
- Cowan, J.C. & Weintritt, D.J., 1976, *Water-Formed Scale Deposit*, Gulf Publishing Company.
- Fan, C. & Cho, Y.I., 1997, Microscopic Observation of Calcium Carbonate Crystallization Induced by an Electronic Anti-fouling Technology, *Int. Comm. Heat Mass Transfer*, vol. 24, pp. 747-756.
- Incropera, F.P. & DeWitt, D.P., 1996, *Fundamentals of Heat and Mass Transfer*, Fourth Edition, John Wiley & Sons.
- Knudsen, J.G., 1981, Cooling Water Fouling - A Brief Review, *Fouling in Heat Exchanger Equipment*, 20th ASME/AIChE Heat transfer Conference, vol. 17-HTD, pp. 29-38, Milwaukee, WI, Aug. 2-5, *Considerations*, pp. 999-1011.
- Linke, W.F., 1958, *Solubilities - Inorganic and Metal-organic Compounds*, Vol. 1, 4th ed., D. Van Nostrand Company, Inc.
- Mullin, J.W., 1993, *Crystallization*, 3rd Ed., Butterworth-Heinemann Ltd.
- Munson, B.R. et al., 1994, *Fundamentals of Fluid Mechanics*, Third Edition, Wiley.
- Serway, R.A., 1990, *Physics for Scientists and Engineers*, third Ed., pp. 874-891, Saunders College Publishing.
- Snoeyink, V.I., & Jenkins, D., 1982, *Water Chemistry*, Wiley.
- Suitor, J.W. et al., 1977, The History and Status of Research in Fouling of Heat Exchangers in Cooling Water Service, *The Canadian J. of Chem. Eng.*, vol. 55, pp. 374-380.
- Taborek, J. et al., 1972, Fouling: The Major Unresolved Problem in Heat Transfer, *Chemical Engineering Progress*, vol. 68, No. 2, pp. 59-67.

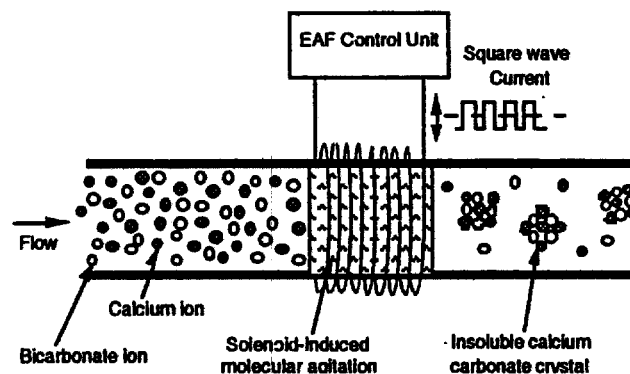


Fig. 2 Schematic diagram of controlled precipitation through electronic anti-fouling technology.

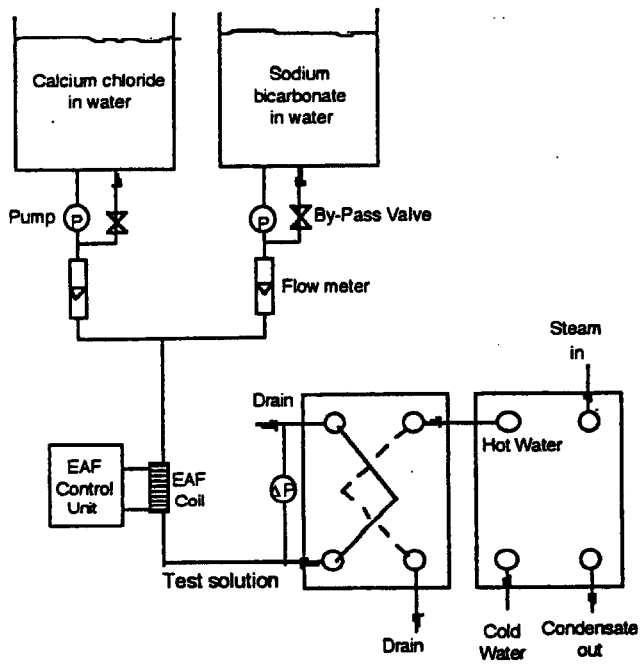


Fig. 3 Schematic diagram of once-through flow system for accelerated fouling tests.

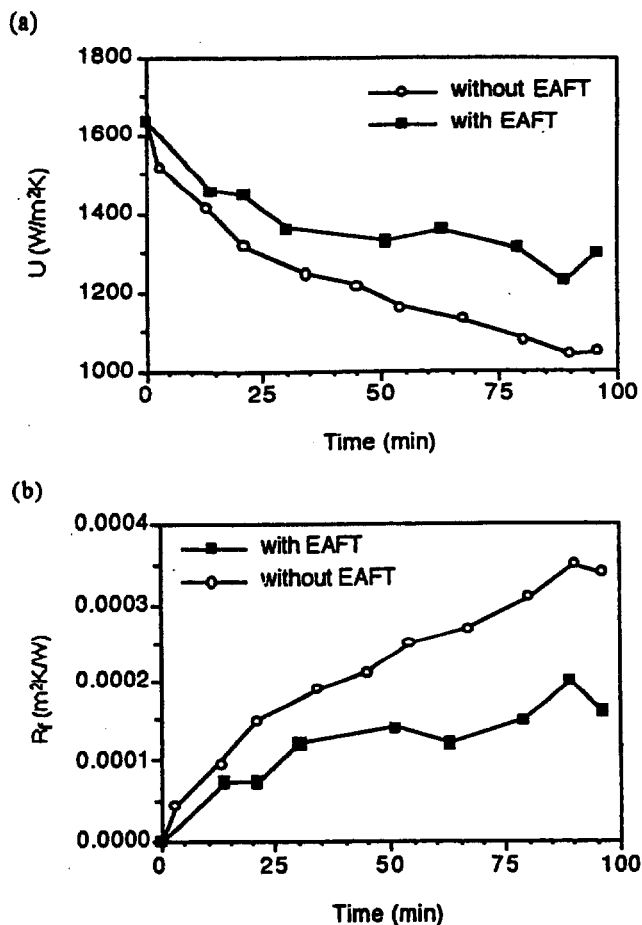


Fig. 4 (a) Overall heat transfer coefficient vs. time during once-through accelerated fouling test with 1,000 mg/L hard water at $6.3 \times 10^{-3} \text{ m}^3/\text{s}$. (b) Fouling factor vs. time

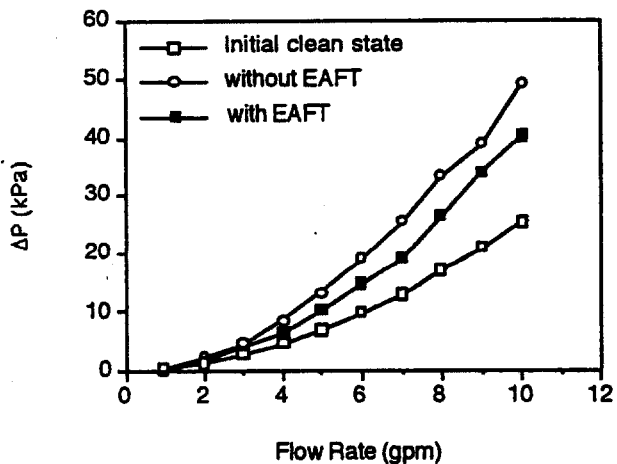


Fig. 5 Pressure drop across plate-and-frame heat exchanger over a range of flow rate for initial scale-free state and after accelerated fouling run, with and without electronic anti-fouling treatment.

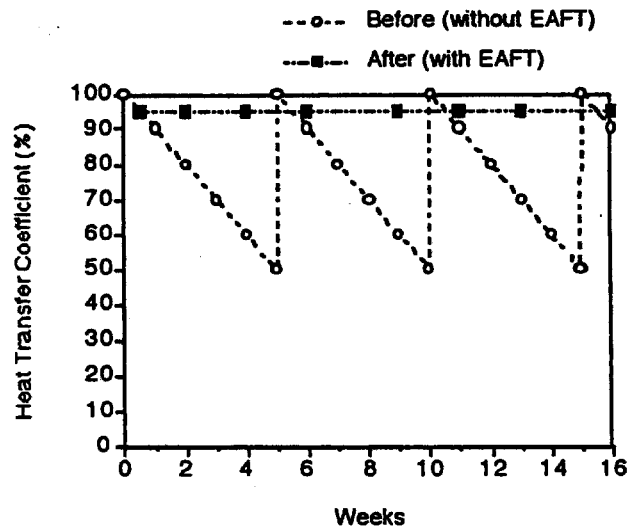


Fig. 6 Results from a field study with a large plate-and-frame heat exchanger.