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A NEW ELECTRONIC ANTI-FOULING TECHNOLOGY TO CONTROL PRECIPITATION FOULING

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ABSTRACT

An innovative technology to control fouling in heat exchangers was developed. The technology was based on solenoid-induced molecular agitation and will be referred to in the present study as an electronic anti-fouling (EAF) technology. To validate the EAF technology, a recirculating flow loop was built where a main test tube was heated electrically. A series of accelerated fouling tests were conducted, measuring pressure drop across the heating tube and convective heat transfer coefficient as a function of time. For the accelerated fouling test, artificial hard water of 1,000 ppm as $CaCO_3$ was used throughout the tests. The pressure drop obtained with the EAF treatment was approximately 51% less than that without the EAF treatment. Furthermore, the asymptotic heat transfer coefficient when the test fluid was treated by EAF unit was approximately 12% larger than that without the EAF treatment.

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 (Taborek, et al., 1972a; Suitor et al., 1977; Knudsen, 1981). 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. One of the most common forms of scales is calcium carbonate ($CaCO_3$) (Hasson et al., 1968; Watkinson et al., 1974), 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".

Once scales build up in a heat transfer surface, at least two problems associated with scales occur (Branch and Mueller-Steinhagen, 1991). 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 (Metcalf & Eddy, 1991). 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, hydro-blasting, sand blasting, metal or nylon brushes are used - operations which incur downtime and repair costs. If the EAF technology can be used, 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.

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 (Cowan and Weintritt, 1976). Many variables control the scale deposition mechanism, including fluid temperature, surface temperature, flow velocity, pressure, and pH.

The solubility of calcium carbonate decreases with increasing temperature and pH, whereas it decreases with decreasing pressure (Linke, 1958). 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 $CaCO_3$ crystals. This usually happens 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 approximately 10-30 angstrom, a phenomenon known as "the electric double layer" (Atkins, 1986). Subsequently, the electrostatic Coulombic attraction force between the dissolved mineral ions and heat transfer surfaces makes these mineral ions adhere to the surfaces as $CaCO_3$ 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 $CaCO_3$ precipitation occurring inside a heat exchanger, a phenomenon which is called "uncontrolled precipitation" in the present study.

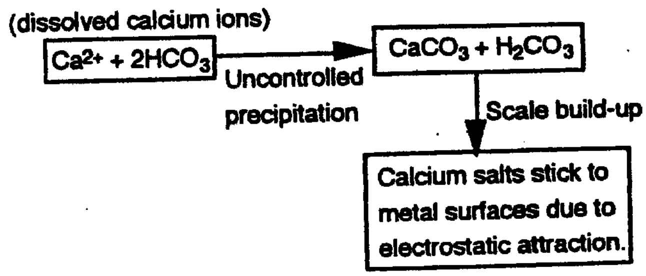


Fig. 1 Block diagram showing uncontrolle precipitation of calcium and bicarbonate ions an subsequent adhesion of $CaCO_3$ crystals to hea transfer surfaces.

OPERATING PRINCIPLE OF THE ELECTRONIC ANTI-FOULING TECHNIQUE

Figure 2 shows a schematic diagram of the operation of an electronic anti-fouling unit. A 16 gauge single stranded wire is wrapped around a feed pipe to a heat exchanger. The two ends of the wire are connected to the electronic anti-fouling 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 (Serway, 1990):

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

where E is an induced electric field vector, s is a line vector along the circumferential direction, B is 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 anti-fouling technology works. The induced electric field which oscillates with time provides the necessary molecular agitation to charged mineral ions such that calcium and bicarbonate ions collide and precipitate. Once dissolved ions are converted into 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.

Because hard water has excess dissolved mineral ions well above the saturation limit of each dissolved ion, the water becomes unstable. 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 (Taborek et al., 1972b). In this case, the fouling problems occur slowly over a period of years. The fouling problems of the present interest occur in a time period of days, weeks or months, which can be attributed to the use of supersaturated water from the beginning.

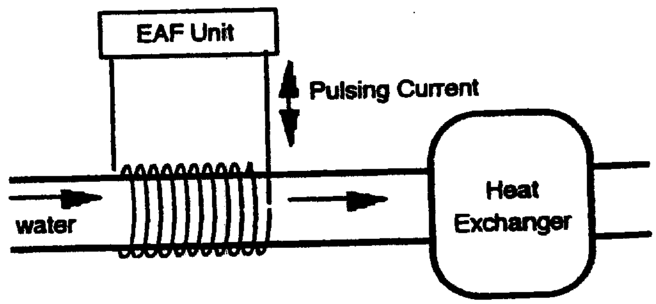


Fig. 2 Schematic diagram of the operation of a electronic anti-fouling (EAF) unit

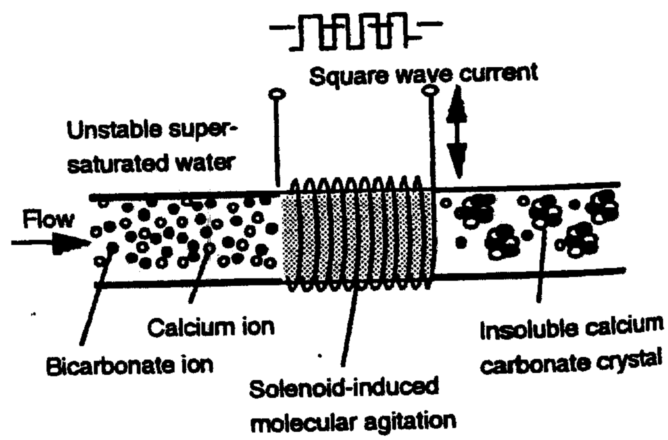


Fig. 3 Schematic diagram of controll precipitation through electronic anti-fouli technology. Solenoid-induced molecular agitati converts dissolved ions to insoluble salt cryst reducing the degree of supersaturation of wa and thereby preventing new scale build-up.

The critical process in the operation of the EAF treatment is the nucleation of dissolved mineral ions by solenoid-induced molecular agitation and subsequent crystallization. The nucleation and crystallization phenomena initiated by the EAF treatment were studied (Fan and Cho, 1997), and theoretical descriptions of the phenomena in relation to the EAF technology were given based on the analysis of Gibbs free energy (Cho et al., 1997). The objective of the present study was to verify whether or not EAF treatment reduces new scale build-up in a simulated heat exchanger experiment.

METHODS

The present study conducted an accelerated fouling experiment, which did not have the typical conditions of industrial heat exchangers. First, we decided to use a relatively small flow rate. Second, we chose a large temperature increase across the heat transfer test section. Third, we had to make artificial hard water. One of the major constraints in conducting a fouling experiment in our laboratory was the lack of an infinite hard water supply. Since the hardness of the city water provided by Philadelphia was only 165 ppm as $CaCO_3$, we could not produce substantial scaling within a couple of weeks even though we used extremely low flow velocity and extremely large temperature changes. Since we wanted to obtain at least one data point every week, we decided to make our own artificial hard water. If we had not chosen these three unusual conditions, the rate of fouling would have been so slow that we could not have obtained fouling test results for various conditions in reasonable time period. Since the purpose of the present study was to verify whether or not the EAF technology significantly reduced new scales, we thought it would not matter under what conditions we did this verification study. In other words, no matter what we do in a university laboratory, we still need to conduct field tests to prove whether or not the EAF technology reduces or prevents new scales in real heat exchangers.

Figure 4 schematically shows a flow loop used in the present study which consists of a reservoir tank, a pump, an electronic anti-fouling unit, the main heat transfer test section, and a heat exchanger. The main test section (4.74 m long) was heated electrically using a 24 kw power supply such that a constant heat flux boundary condition could be maintained at the pipe surface. The main test section was not insulated, resulting in some loss of heat to the surroundings. Hence, 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 0.45 gpm (i.e., average velocity of 0.1 m/s) was used in the recirculating loop, resulting in a Reynolds number of 1,692. This small flow rate was selected to accelerate fouling in a laboratory. Local boiling occurred when we decreased the flow rate below 0.45 gpm. When we increased the flow rate beyond 0.45 gpm, the required time for scale build-up increased substantially due to increased removal rate and decreased bulk temperature change. 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 20°C throughout the experiment. The outlet temperature downstream of the test section was approximately 65°C.

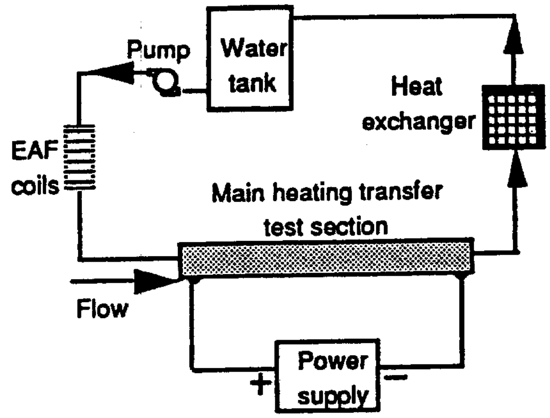


Fig. 4 Schematic diagram of recirculating flow loop where accelerated fouling tests we conducted. Details of EAF coil arrangement a shown in Fig. 5.

The test fluid was prepared by adding 0.01 M calci n chloride $CaCl_2$ and 0.02 M sodium bicarbonate $NaHCO_3$ to tap water available in Philadelphia such that the hardness of the test solution was equivalent to 1,000 ppm as $CaCO_3$. As e recirculated the test fluid, the hardness decreased becai e calcium ions interacted with bicarbonate ions. Solid forms of $CaCO_3$ precipitated out from the test solution and settled at the bottom of the reservoir tank. Therefore, the test fluid had tc e replaced every four hours by draining the water from both e 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 forty hours, we replaced the st solution ten times for each run.

Figure 5 shows a sketch of the application of the EAF unit including the arrangement of EAF coils wrapped around twc different pipe sizes: one was 1.27 cm (OD) and the other is 5.08 cm (OD). As shown in Fig. 5, each electronic anti-fou ig application uses two solenoid coils which are separated by a 10.2 cm gap.

The test results in the present study are presented in the form of pressure drop, ΔP, and the convective heat tran e coefficient, h. The former was measured by a pressure transducer which was calibrated using an U-tube manometer The heat transfer coefficient, h, was calculated from the measured inlet and outlet temperatures of the test solution, the surface temperatures of the main heat transfer test section and flow rate using the following equation:

$$h = \frac{\dot{m}\, C_p}{A} \cdot \frac{T_{m,out} - T_{m,in}}{T_{s,out} - T_{m,out}} \quad (2)$$

where

$\dot{m}$ = mass flow rate, kg/m^3

C_p = heat capacity, J/kg K,

A = interior surface area of heating tube, m^2,

$T_{m,out}$ = mean fluid temperature at the outlet of tube, °C

$T_{m,in}$ = mean fluid temperature at the inlet of tube, °C,

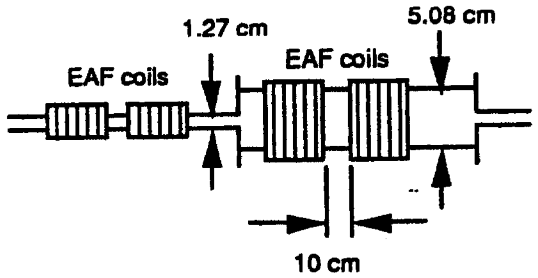


Fig. 5 A detailed view of EAF coil arrangement. EAF coils are used in pairs, each separated by approximately 10 cm. When the EAF coils wrapped in a 1.27 cm pipe were used for testing, the other coils wrapped in a 5.08 cm pipe were electrically disconnected, vice versa. (drawing not scaled)

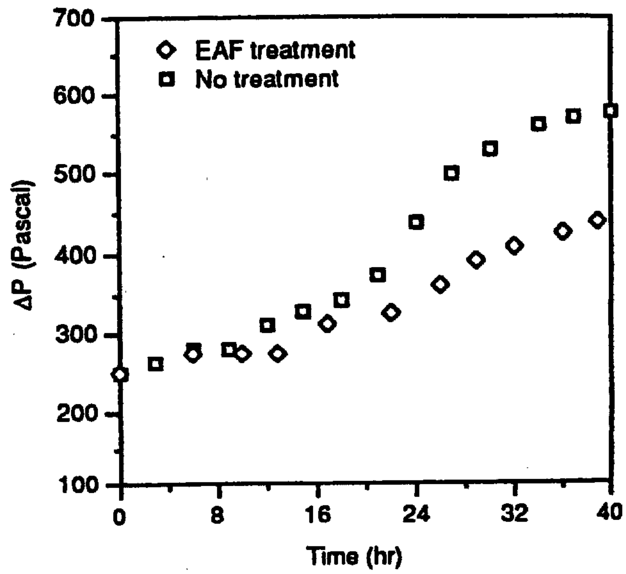
$T_{s,out}$ = (inside) surface temperature of tube near the outlet of tube, °C.

It is of note that $T_{s,out}$ was the inside surface temperature which was calculated from the actual measurement of outside surface temperature. Also note that when one has a constant heat flux boundary condition the difference between tube wall temperature and bulk temperature remains constant in a relatively long insulated tube. Therefore, one can use $T_{s,out}$ - $T_{m,out}$ for the calculation of the convective heat transfer coefficient. In our experiment, we decided not to insulate the heat transfer test section because we believed that the heat loss to the surroundings might be related to the rate of fouling.

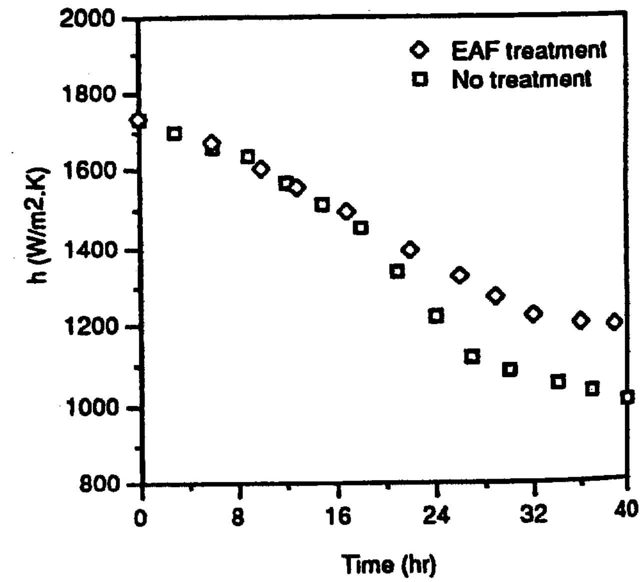
RESULTS AND DISCUSSION

Figure 6 shows pressure drop, ΔP, and the convective heat transfer coefficient, h, as a function of time. The top figure, Fig. 6(a), shows that for the case without the EAF treatment, ΔP changed relatively little during the first 10 hours, after which it increased gradually from its initial value of 249 Pa and eventually reached a plateau value of 580 Pa at the end of the test (i.e., t = 40 hours). For the case with the EAF treatment, there was almost no change in ΔP during the first 14 hours, after which ΔP gradually increased from the initial value of 249 Pa to a plateau value of 435 Pa. When one compares these two plateau values of ΔP, the case with the EAF treatment shows approximately 51% less ΔP than that without the EAF treatment.

Figure 6(b) shows the corresponding heat transfer coefficient, h, as a function of time. The initial value of h before the fouling test was 1732 $W/m^2 \cdot K$, which decreased to 990 $W/m^2 \cdot K$ for the case without the EAF treatment. For the case with the EAF treatment, the heat transfer coefficient decreased to 1191 $W/m^2 \cdot K$ by the end of the test. The heat transfer coefficient at the end of the test with the EAF treatment was approximately 12% greater than the case without the EAF treatment.



(a)



(b)

Fig. 6 The effect of electronic anti-fouling (EA treatment on (a) pressure drop, ΔP, and (b) h transfer coefficient, h. The results with the E treatment were obtained with EAF coils wrapped a 5.08 cm tube.

Figure 7 presents similar results obtained from two different pipe diameters, from which one can examine the effect of the solenoid coil size on the performance of the EAF unit. The circles in Fig. 7(a) represent ΔP changes obtained from a pipe of 5.08 cm diameter, whereas the triangles show those from a pipe of 1.27 cm diameter. The results obtained without the EAF treatment are also shown as square symbols for comparison.

As shown in Figs. 7(a) and 7(b), the larger pipe diameter shows a better performance of the EAF unit both in the pressure drop and heat transfer coefficient. There are two basic reasons for the improvement observed with a bigger pipe. One is that the test fluid experienced more treatment in the larger diameter pipe. Since the flow rate was fixed, the EAF treatment time in the 5.08 cm diameter pipe was 16 times longer than in the 1.27 cm diameter pipe. Another reason is that the actual induction is greater in the larger diameter pipe than that in the smaller pipe. According to Faraday's law, the electrical induction is proportional to a solenoid diameter:

$$\text{Induction} \sim \int E \cdot ds = -\frac{\partial}{\partial t}\int B \cdot dA \sim \frac{R}{2}\frac{\partial B}{\partial t} \qquad (3)$$

where R is the radius of pipe. Therefore, one can anticipate the improvement of the EAF performance in a large diameter pipe.

Figure 8 shows the results obtained with two different sizes of signal cables. The circles were obtained with a gauge 14 lead wire whose diameter was 2.5 mm OD. The triangles were obtained with a gauge 18 magnet wire whose diameter was 1.0 mm OD. For both cases, the total length of the solenoid (i.e., along the pipe) was equal to 30.2 cm. In other words, 120 turns were used for the gauge 14 lead wire, and 290 turns were used for the gauge 18 magnet wire. Figures 8(a) and 8(b) show that there was no significant difference between the two cases, indicating that there was no particular advantage to using a large gauge wire or a small one. It should be cautioned that when the pipe diameter increases, the impedance due to 'self induction' also increases greatly, thereby prohibiting the use of the magnet wire for the EAF application. The effect of the self induction on the performance of the EAF unit is reported elsewhere (Fan, 1997).

CONCLUSIONS

The present study demonstrated that the electronic anti-fouling (EAF) technology could significantly reduce the fouling in a heat exchanger, even in conditions of extremely harsh fouling (i.e., 1,000 ppm $CaCO_3$ and a small flow rate of 0.1 m/s). Based on a number of preliminary field test results the EAF technique alone is found to prevent fouling deposits when the flow rate increases beyond 1 m/s, which is often the case in most industrial applications using heat exchangers. The results from the field tests will be reported in the future.

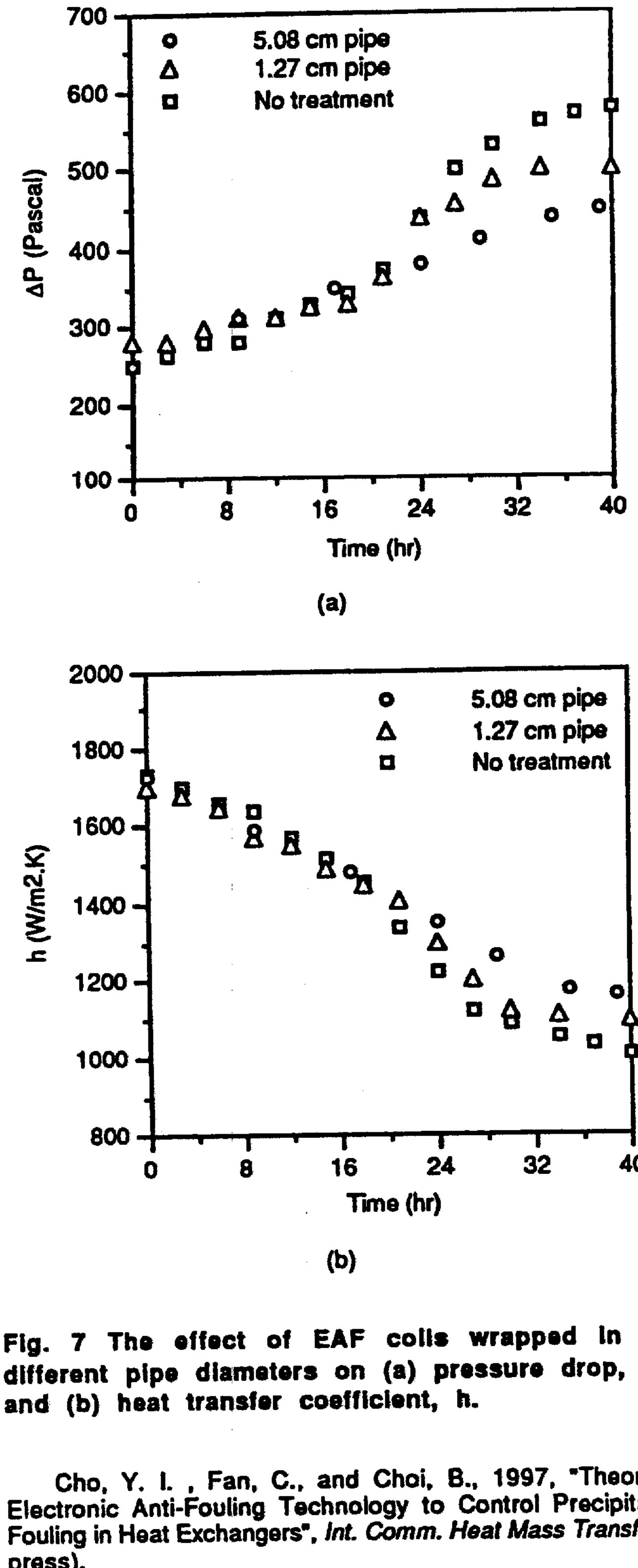


Fig. 7 The effect of EAF coils wrapped in t[illegible] different pipe diameters on (a) pressure drop, ΔP, and (b) heat transfer coefficient, h.

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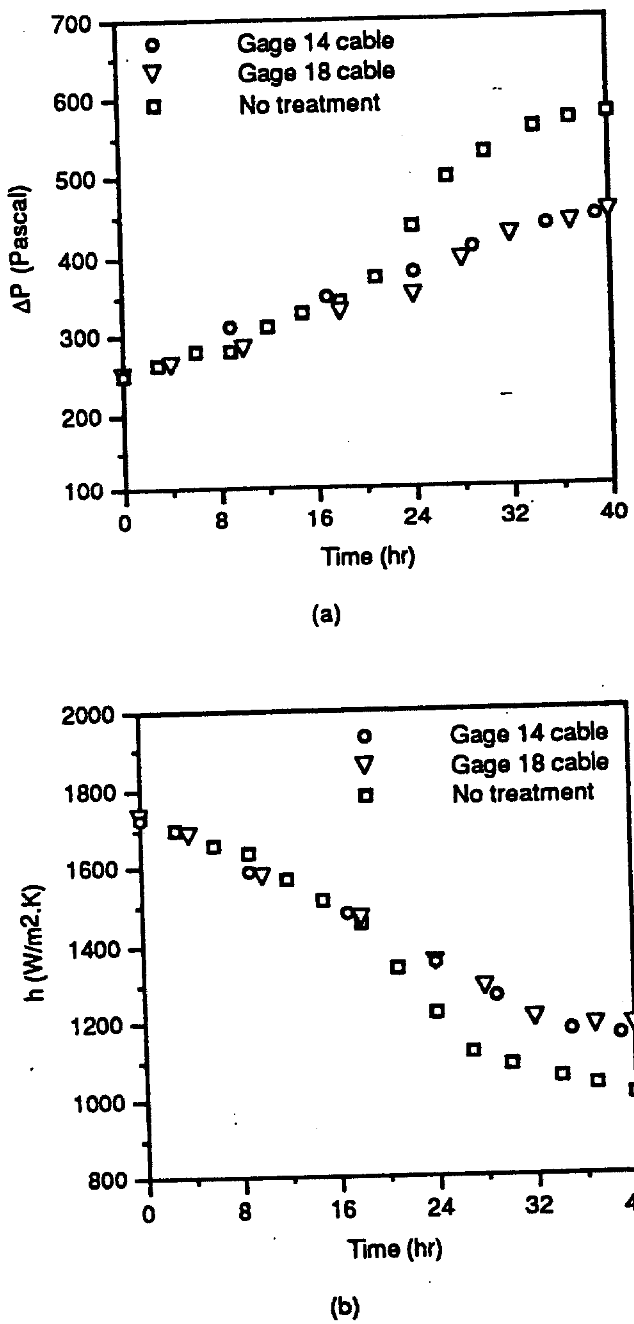

Fig. 8 The effect of the size of signal cables on (a) pressure drop, ΔP, and (b) heat transfer coefficient, h.

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