

USING LOW-VOLTAGE-HIGH-FREQUENCY ELECTRIC FIELD TO MITIGATE MINERAL FOULING IN A HEAT EXCHANGER

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Abstract

This paper presents an investigative study on the efficacy of a new physical water treatment (PWT) technology using an oscillating electric field to mitigate mineral fouling in heat exchangers. Parallel graphite electrode plates immersed in water were used to generate the electric field directly in water. Artificial hard water at 500 ppm hardness was used in all fouling tests. The inlet temperatures were maintained at $23.5\pm 0.5^{\circ}\text{C}$ and $85\pm 0.5^{\circ}\text{C}$ for cold and hot water sides, respectively. The results at a cold water-side velocity of 0.3 m/s showed a 16-60% drop in fouling resistances from the baseline test depending on the frequency of the electric field for the PWT-treated cases.

INTRODUCTION

Mineral fouling is defined as the deposition of inverse solubility salt crystals found in water on heat transfer surfaces as temperature is increased. The formed fouling layer decreases the thermal efficiency of the heat exchanger, and produces a higher pressure drop, which in turn increases the operating cost [1-8]. The use of chemicals is commonly practiced in industries to clean clogged pipes but their high cost and pollution concern necessitates a need to use less costly and environmentally-friendly cleaning means [1, 6, 7]. The use of non-chemical or physical cleaning devices is a good alternative that is safe and effective [7]. Among such is physical water treatment (PWT) which uses electric or magnetic field, catalytic surfaces, ultrasound, or sudden pressure changes. Several studies [1, 3-4, 7-8] showed the efficacy of permanent magnets, solenoid coils and catalytic alloys in mitigating fouling in heat transfer equipment. In the present study, we used two graphite electrode plates oriented in parallel to each other and connected to a controlled voltage power and frequency producing square wave signal. The following were the objectives of the present study: 1) To investigate whether the present PWT using oscillating electric fields could mitigate mineral fouling (i.e. CaCO_3 fouling) in a double-pipe, counter-flow heat exchanger; 2) To determine the

optimum voltage and frequency of the oscillating electric field that produces maximum performance in the fouling mitigation.

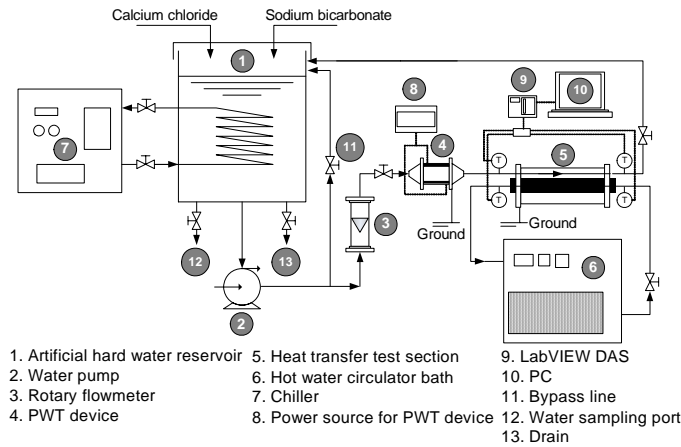


Fig. 1. Schematic diagram of the present experimental set-up.

EXPERIMENTAL FACILITY

The present experimental system (see Fig. 1) was composed of a hard water reservoir (200 L capacity), a pump, two flow meters, two static mixers, a PWT device using two graphite electrodes, a heat transfer test section, a chiller, a hot water bath circulator, four thermocouples, LabView data acquisition system and a personal computer. The heat transfer test section was composed of copper tube, quartz crystal, Teflon heads, and fittings which were arranged in a double-tube, counter-flow configuration. Hot water flowed through the inner copper tube while cold water (i.e. hard water) flowed in opposite direction through the annulus gap between the two tubes. The hot water temperature was maintained constant by a hot water circulator bath. Four copper-constantan type T thermocouples were used to measure the inlet and outlet temperatures of both hot and cold water sides in the heat transfer test section. Styrofoam was covered to the heat transfer test section to reduce any heat transfer losses to the surroundings.

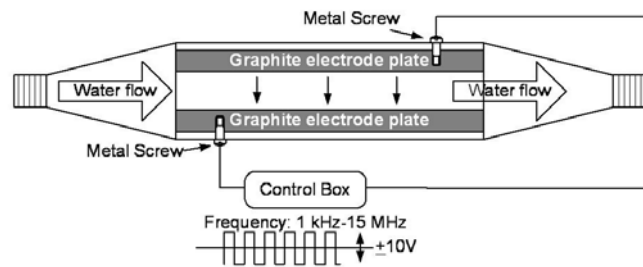


Fig. 2. Schematic of the present PWT graphite electrode plate device.

As shown in Fig. 2, two rectangular graphite electrode plates were placed in parallel to each other inside a stainless steel casing. The graphite electrode plates had identical dimensions. The distance “D” between the two electrode plates was fixed at 20 mm. The present PWT device used a stainless steel cylinder casing where diverging and converging sections were used at the inlet and outlet of the casing for smooth transitions of flow, respectively. The detachable heads were used in the main cylinder casing with

screw type locks with rubber seals for service. The power supply which was composed of a programmable function generator and a voltage source (100 mA, ± 15 V) was connected to the graphite electrode plates to provide a controlled voltage and frequency level for the PWT device. The present PWT device utilized oscillating electric fields that were produced directly in water using two graphite electrode plates submerged in water.

EXPERIMENTAL PROCEDURE

Preparation of Artificial Hard Water

To get 500 ppm of CaCO_3 water hardness, the following chemical reagents were added to a tank reservoir with 0.175 m^3 of distilled water: CaCl_2 : Mw = 110.98 g/mol ~ 97.02 g; NaHCO_3 : Mw = 84.01 g/mol ~ 146.89g. Water analyses were conducted on the hard water within an hour of water sampling.

Fouling tests

The inlet temperatures of the hot and cold water sides of the heat transfer test section were maintained throughout the tests at $85 \pm 0.5^\circ\text{C}$ and $23.5 \pm 0.5^\circ\text{C}$, respectively. The temperature difference at the hot water side was maintained at $2\text{-}4^\circ\text{C}$ to provide uniform fouling conditions along the test section. The hot and cold water sides were maintained at flow velocities of 1.1 m/s and 0.3 m/s, respectively. Both the heat transfer test section and the PWT device were electrically grounded. The duration for each fouling test was about 30-36 hrs. The heat transfer rate from the hot and cold water sides were estimated using the following equation [1-4, 7-8]:

$$Q = \dot{m}c_p \Delta T \quad (1)$$

The discrepancy in heat transfer rates between the hot and cold-water sides was found to be $\pm 8\%$. The heat transfer rate in the cold-water side Q_c was used to calculate the overall heat transfer coefficient considering heat losses in the hot-water side might have incurred to the surroundings although the hot-water side was insulated [1-4, 7-8].

The fouling resistance was calculated using the following equation [1-4, 7-8]:

$$R_f = \frac{1}{U_{\text{fouled}}} - \frac{1}{U_{\text{initial}}} \quad (2)$$

where U_{fouled} is the overall heat transfer coefficient for the fouled case, while U_{initial} is the overall heat transfer coefficient for the initial clean condition. This overall heat transfer coefficient was calculated using the following equation [1-4, 7-8]:

$$Q = UA_o \Delta T_{LMTD} \quad (3)$$

where T_{LMTD} is the log-mean-temperature difference which was determined from measured temperatures at the inlet and outlet of hot and cold water which is given as [1-4, 7-8]:

$$\Delta T_{LMTD} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln \left[\frac{(T_{h,o} - T_{c,i})}{(T_{h,i} - T_{c,o})} \right]} \quad (4)$$

EXPERIMENTAL RESULTS AND DISCUSSION

The fouling tests were done in two cases: a) baseline (no-treatment) case, and b) PWT-treated cases. The baseline test served as the reference test where the PWT-treated cases were compared to view any effects of PWT in the fouling resistances and water chemistry through time. A fixed voltage of ± 10 V was used at four different frequency levels for the PWT-treated cases: 13.56 MHz, 1 MHz, 100 KHz, and 1 kHz.

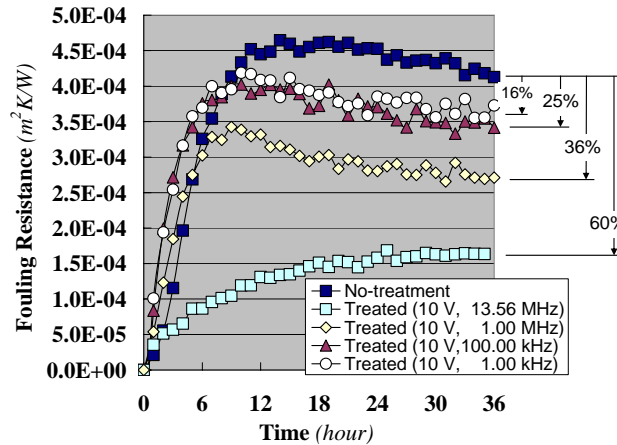


Fig. 3. Fouling resistance versus time for both no-treatment and PWT-treated cases (10 V) at 0.3 m/s cold-water side velocity.

Fouling Resistance

Figure 3 shows the fouling resistances versus time for both no-treatment and PWT-treated cases. All fouling resistances for both cases did not show any induction period [5]. The high water hardness, high heat transfer surface temperature, and low flow velocity must have affected the negligible induction periods [5, 7]. The presence of vast number of calcium ions in bulk water at a low flow velocity (i.e., low flow shear rate) should have been the primary factor in the rapid scale deposition on the first few hours of the test as indicated in the drastic increase of fouling resistance. The fouling resistance for the no-treatment case increased exponentially to its maximum value of $4.7 \times 10^{-4} \text{ m}^2\text{K/W}$ after $t = 12$ hrs of test and then gradually decreased and reached $4.2 \times 10^{-4} \text{ m}^2\text{K/W}$ at the end of $t = 36$ hrs. The whole copper tube surface was already fully covered with white scale deposits after $t = 6$ hrs when checked visually. At the end of the test, the dried scale deposits on the copper tube showed rough deposit surfaces.

The PWT-treated cases showed lower fouling resistances as compared to the no-treatment case. In the case of PWT-treatment at $f = 13.56$ MHz, the fouling resistance decreased by 60% from the no-treatment case at the end of the test. It reached its asymptotic value of $1.65 \times 10^{-4} \text{ m}^2\text{K/W}$ at $t = 34$ hrs. The fouling deposit layer on the copper showed a smoother surface as compared to the no-treatment case. It was obviously thinner when checked with visual inspection though no thickness measurement was done. The scale deposits had a bluish-green color as opposed to the white-colored scales at the no-treatment case. For the case of PWT-treatment at $f = 1$ MHz, the fouling resistance had an asymptotic value of $2.7 \times 10^{-4} \text{ m}^2\text{K/W}$ after $t = 36$ hrs, which was a 36% decrease from the no-treatment case. The fouling deposits were white in color and with rough surface though lesser in the degree of roughness than that

of the no-treatment case. At a much lower frequencies of 100 kHz and 1 kHz, the fouling resistances decreased by about 25% and 16%, respectively from the no-treatment case after $t = 36$ hrs. Both fouling deposits had white-colored scales. As one can notice in the fouling resistances, the first 10-12 hrs of test is crucial in the crystal growth and adhesion for crystallization fouling using artificial hard water. The effect of frequency on the mitigation of fouling in the present study had better performance as frequency was increased. After each test, the surfaces of the graphite electrode plates did not show any scaling.

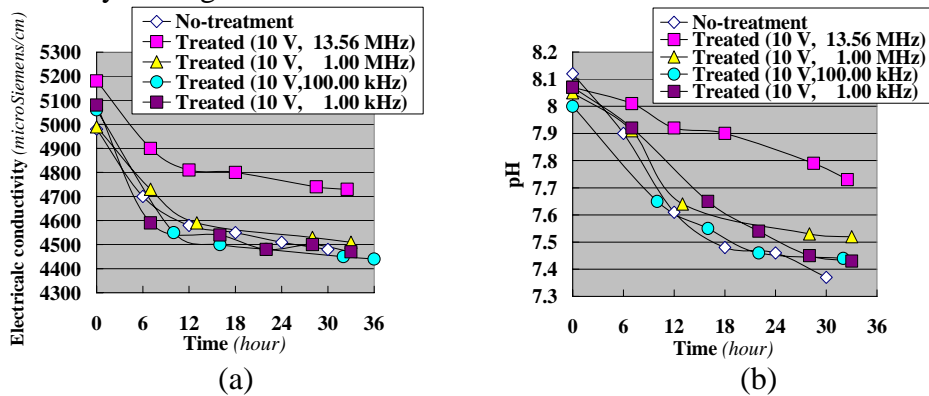


Fig. 4. (a) Electrical conductivity; and (b) pH versus time for no-treatment and treated cases.

Tests for Water Chemistry

Figure 4a shows the electrical conductivity through time of both no-treatment and PWT-treated cases. The initial conditions were kept similar at 5,000-5,200 microSiemens/cm. The results showed a similar decreasing trend for all tests. The no-treatment case dropped by 10% after $t = 30$ hrs from its initial value. The electrical conductivities for the PWT-treated cases also similarly dropped from 8.6%-12.3% depending on the frequency applied. The electrical conductivity is directly related to the number of conductive ions in the solution, thus with the continuous deposition of CaCO_3 scales, electrical conductivity decreased through time.

The acidity or alkalinity of a solution says a lot in its precipitating capability. In the present study, the pH of the hard water was measured from the similar initial value for all cases, until $t = 36$ hrs. The results shown in Fig. 4b signifies that as mineral crystals are depositing on heat transfer surfaces, the alkalinity of the solution decreases. For the case of the PWT-treated case at $f = 13.56$ MHz, there was 4% decrease in pH after 32 hrs as compared with 9% decrease for the no-treatment case. The results for the other PWT-treated cases varied from 6-8% drop in pH from their initial values.

Figure 5a shows the water hardness versus time for the present study. The no-treatment case decreased by 22% after the fouling test. The PWT-treated case at $f = 13.56$ MHz showed the lowest percentage decrease at 9.6%, and as the frequency was lowered, the percentage decrease also increased to 18.6%, 21% and 26% for $f = 1$ MHz, $f = 100$ kHz and $f = 1$ kHz, respectively. It is of note that the hardness component of the present artificial hard water was due to calcium ions. Calcium ions combine with carbonate ions found in water to form the scales so that the more deposition that takes place, the lesser will be the water hardness through time. Alkalinity is the measure of the carbonate and bicarbonate concentrations in water. The alkalinity results in Fig. 5b show a decrease in the range of 12-25% from their initial values for the no-treatment

and PWT-treated cases.

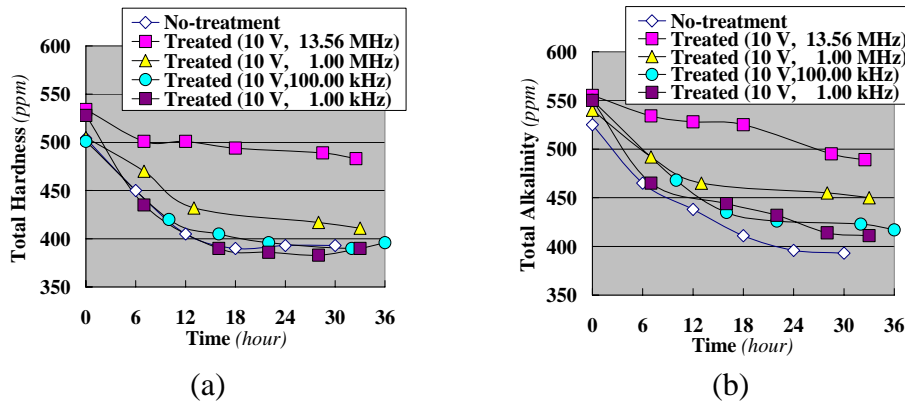


Fig. 5. (a) Total hardness; and (b) Total alkalinity versus time for no-treatment and treated cases.

CONCLUSION

The present results showed that the PWT device performed better with increasing frequency. In the present study the maximum frequency tested was 13.56 MHz, where the best performance was obtained for the mitigation of mineral fouling. At this frequency, the fouling resistance decreased by 60% from the no-treatment case. One may obtain a better performance at a frequency greater than 13.56 MHz. However, since 13.56 MHz is the frequency allowed for industrial applications by FCC, it may be concluded that the present test showed the maximum performance of the present PWT operation.

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