Proceedings of International Conference on Heat Exchanger Fouling and Cleaning VIII - 2009 (Peer-reviewed) June 14-19, 2009, Schladming, Austria Editors: H. Müller-Steinhagen, M.R. Malayeri and A.P. Watkinson

> Published online www.heatexchanger-fouling.com

MITIGATION OF CALCIUM CARBONATE FOULING USING RF ELECTRIC FIELDS

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ABSTRACT

The present study investigated the efficacy of physical water treatment using radio frequency (RF) electric fields to mitigate calcium carbonate fouling in a double-pipe heat exchanger. Parallel graphite electrode plates were used to generate the electric field directly in water. Artificial hard water at 350 and 550 ppm hardness was used in the fouling tests. The inlet temperatures were maintained at 23.5±0.5°C and 85.5±0.5°C for cold and hot water sides, respectively. The results at a cold water side velocity of 0.3 m/s and at a water hardness of 550 ppm showed a 16-83% drop in fouling resistances from the baseline test depending on the voltage and frequency of the electric field for the PWTtreated cases. At water hardness of 350 ppm, the fouling resistances of the PWT-treated cases decreased by 34-88% from the no-treatment cases depending on the flow velocity. The SEM images revealed agglomerated and hexagonal crystal shapes for PWT-treated cases, which are relatively soft and can easily be removed with enough shear forces from flowing water. The no-treatment cases showed pointed and needle-like crystal structures, which are generally hard and tenacious scales. The best values of voltage and frequency of the electric field to mitigate calcium carbonate fouling in the present study were found to be at 2 V and 13.56 MHz, respectively.

INTRODUCTION

Hard water used for cooling water applications contains mineral ions especially calcium ions which become insoluble when temperature rises. Calcium ions react with carbonate ions present in water to form layers of CaCO₃ deposit on heat transfer surfaces. This decreases the efficiency of heat exchangers to transfer heat because of the insulating effect of the deposits (Bansal et al., 2003; Bott, 1995; Helalizadeh et al., 2000; Somerscales, 1990). Furthermore, the formed deposits reduce the flow area thus needing more pumping power to achieve an equivalent amount of energy at the clean state. A 0.8 mm layer of scale can increase the energy use by about 10% (The US Department of Energy, 1998). Several millions of dollars are budgeted annually for the cleaning and maintenance of heat exchangers especially those utilizing cooling-water (Bansal et al., 2003; Nest and Bennet, 2005; Radler and Ousko-Oberhoffer, 2005; Steinhagen et al., 1993).

Various methods are available to clean clogged pipes and heat exchangers. The use of chemicals are commonly practiced in industries but their high cost and pollution concern require less costly and environmentally-friendly cleaning or mitigating means (Panchal and Knudsen, 1998; Casanueva-Robles and Bott, 2005). The use of nonchemical or physical cleaning devices is a good alternative that is safe and effective (Panchal and Knudsen, 1998; Tijing et al., 2007; Bansal et al., 2003). Among such is physical water treatment (PWT) which uses electric or magnetic field, catalytic surfaces, ultrasound, or sudden pressure changes. Several studies (Fan and Cho, 1997; Cho and Choi, 1999; Cho et al., 2005; Kim et al., 2001; Kronenberg, 1986; Parsons et al., 1997) showed the efficacy of permanent magnets and solenoid coils in mitigating fouling in heat transfer equipment. Catalytic alloys (Lee et al., 2006) and heat-treated titanium balls (Tijing et al., 2007) also decreased the fouling resistances in counter-flow heat exchangers. The PWT-treated cases also produced calcite form of scales which are known to be soft and easily removed through flow shear forces. In the present study, we used two graphite electrode plates oriented in parallel to each other and connected to a power supply where we controlled both the output voltage and frequency over a wide range.

In cooling tower systems, calcium carbonate (CaCO₃) is one of the most common mineral fouling crystals (Cho et al., 2003; Fan and Cho, 1997). Hence, we used hard water of 350 and 550 ppm of CaCO₃ hardness, which was artificially made from the mixture of calcium chloride (CaCL₂) and sodium bicarbonate (NaHCO₃) in right proportions. The following were the objectives of the present study: 1) To investigate whether the present PWT using oscillating electric fields could mitigate CaCO₃ fouling in a doublepipe, counter-flow heat exchanger and; 2) To determine the most effective voltage and frequency of the oscillating electric field that produces maximum performance in mineral fouling mitigation.

EXPERIMENTAL FACILITY

The present experimental system (see Fig. 1) was composed of a hard water tank (200 L capacity), a pump (Daesung, Korea), flow meters (KOTECO, Korea), static mixers, a PWT device using two graphite electrode plates, a



Fig. 1. The schematic drawing of the present experimental set-up.

heat transfer test section, a chiller (Hyundai Auto Chiller HD-05A, Korea), a hot water bath circulator (MCB-600DS, Monotech Eng. Co. Ltd., Korea), temperature sensors (Sentech, Korea), LabView data acquisition system (NI SCXI-1000 block, modules SCXI-1300 and SCXI-1303, National Instruments, USA) and a personal computer. The main fouling system loop connections were made up of both copper tubes and expandable hoses with metal clips. A bypass flow was maintained throughout the tests to help keep the water temperature at the reservoir constant. Copper tube coils inside the hard water reservoir were connected to the chiller serving as the cooling heat exchange system. Two drain valves were positioned at the bottom of the reservoir tank for the purpose of both draining and sampling the hard water.

Heat transfer test section

Fig. 2 shows the heat transfer test section which was composed of copper tube, quartz crystal, Teflon heads, and fittings which were arranged in a double-tube, counter-flow configuration. The inner copper tube had dimensions of 1.386 cm x 1.6 cm x 49.9 cm ($d_i x d_o x L_c$) and the quartz crystal had dimensions of 2.48 cm x 2.81 cm x 49.9 cm ($D_i x D_o x L_q$). The cross-sectional areas for the copper tube and the annulus formed were 1.51 x 10⁻⁴ m² and 2.82 x 10⁻⁴ m², respectively. Both tubes were fitted in Teflon heads with connection fittings. The Teflon heads minimized the axial heat transfer losses in the test section. O-rings were provided inside the Teflon heads to prevent leakages. 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. Static mixers were set in place at the outlet points of the hot and cold water sides. Thermocouples and RTDs (Sentech, Korea) were used to measure the inlet and outlet temperatures of both hot and cold water sides in the heat transfer test section. These temperature sensors were calibrated using a thermocouple bath calibration unit (Isothermal Technology Ltd), a precision thermometer (Model F250, Automatic Systems Laboratories), and the Measurement and Automation Explorer (MAX Version 4.0, National Instruments). The precision thermometer served as the reference temperature with a precision of $\pm 0.01^{\circ}$ C. Styrofoam was covered to the heat transfer test section to reduce any heat transfer losses to the surroundings.

PWT device

As shown in Fig. 3, two rectangular graphite plate electrodes were placed in parallel to each other inside a stainless steel casing. The graphite plate electrodes had identical dimensions of 7.65 mm x 35 mm x 155 mm (t x h x L). The distance between the two plate electrodes was fixed at 20 mm. In order to ensure that the plate electrodes did not touch any metal parts in the case, a cylindrical Teflon block with square cross-section which was tightly fit between the casing and the electrodes was used. The present device was also specially designed so that the plate







Fig. 3. Schematic of the present PWT graphite plate electrode device.

electrodes could be screwed at opposite sides from the outside of the device through screw ports, which served as the connections for the power supply, thus eliminating any direct contact of water to the electric wire for power supply.

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. For a volume flow rate of $8.33 \times 10^{-5} \text{ m}^3/\text{s}$ (300 L/h), the equivalent water velocity in the graphite electrode device was 0.12 m/s. The power supply was composed of a programmable function generator and a voltage source (100 mA, ±15 V). The function generator could generate square wave signals in a frequency range of 1 to 50 MHz. The power supply was connected to the graphite electrode through alligator clips attached on the screws. The present study used voltages of 2 V, 10 V, and 13 V and at varying frequency levels.

EXPERIMENTAL PROCEDURE

Pre-fouling tests

Hot water was first passed through the inner tube of the test section for about 10-20 minutes to see any leakage in the inner tube. No water was flowing at the annulus at this stage. After making sure that there's no leakage in the inner tube, the cold water was then passed through the annulus of the test section, and likewise was checked for any leakages. When no leakage was found, both hot and cold water sides were kept flowing in opposite directions in the heat transfer test section for at least one hour to stabilize them at the desired temperatures and flow rates. Distilled water was used. The stabilized system at the desired parameters was continuously run to test for heat exchanger efficiency. The heat transfer test section was found to have an error of $\pm 8\%$, which was good enough to carry on fouling tests.

Preparation of artificial hard water

One of the most common forms of scale is calcium carbonate, which possesses inverse solubility characteristics (i.e., its solubility decreases when temperature increases) (Bott, 1997). In the present study, we wanted to have calcium carbonate fouling so that we prepared hard water artificially for more controlled water chemistry by mixing chemical reagents of calcium chloride (CaCl₂) and sodium bicarbonate (NaHCO₃) in distilled water. The mixture of both chemicals resulted in the following chemical reaction:

 $CaCl_2 + 2NaHCO_3 \rightarrow CaCO_3 + 2NaCl + H_2O + CO_2$ (1)

To get 350 ppm of CaCO₃ water hardness, the following chemical reagents were added to a tank reservoir with 0.150 m^3 of distilled water:

Calcium chloride (Mw = 110.98 g/mol) \sim 58 g Sodium bicarbonate (Mw = 84.01 g/mol) \sim 88 g

The CaCl₂ was first added to the distilled water and was mixed through stirring with a stick and recirculating in the reservoir for around 20-30 minutes using a by-pass line of the system loop. Then, NaHCO3 was added and was also stirred and recirculated making sure that almost all chemical powders were dissolved in water. During this process, we observed that there was particle formation in the solution as the test water solution became cloudy. All test water preparations had the same process and observation. After 30 min of recirculating the mixture water solution, the test was started. It is noted that there were no additional chemicals (CaCl₂ or NaHCO₃) added in the system during the whole duration of the fouling tests. In other words, we allowed that the hardness level gradually decreases with time due to fouling deposit in the present study. There was no filter used in the system. Since all test liquid preparations were the same, we wanted to test the bulk precipitation capability of our present PWT device that could help in lessening fouling at the heat transfer surface.

Fouling tests

The inlet temperatures of the hot and cold water sides of the heat transfer test section were maintained throughout the tests at $85.5\pm0.5^{\circ}$ C and $23.5\pm0.5^{\circ}$ C, respectively. The inlet-outlet temperature difference in the hot water side was maintained at 2-4°C to provide uniform fouling conditions along the test section. The cold water mass flow rate was maintained at 0.084 – 0.281 kg/s which was equivalent to a flow velocity of 0.3 – 1.0 m/s at the heat transfer test section (cold water side). The hot water side had flow

velocity of 1.1-1.3 m/s (0.162 - 0.194 kg/s). The mean temperatures for both hot and cold water sides served as the reference temperatures for specific heat and density values. The temperature readings were measured every five minutes with a real-time DAS using LabView program (National Instruments). Both the heat transfer test section and the PWT device were electrically grounded. The duration for each fouling test was about 36-40 hours. Table 1 presents the parameters used in the present study.

The fouling tests were conducted 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. Voltages at 2 V, 10 V and 13 V were used at five different frequencies based on FCC allowable radio frequencies for the PWT-treated cases: 1 kHz, 100 KHz, 1 MHz, 13.56 MHz, and 27.12 MHz (FCC, CFR, 2007).

Table 1. Experimental details

	HOT WATER	COLD WATER
Inlet Temp. (°C)	85.5 ± 0.5	23.5 ± 0.5
LMTD (°C)	53 - 56	
Flow velocity (m/s)	1.1 - 1.3	0.3 - 1.0
Mass flowrate (kg/s)	0.162 - 0.194	0.084 - 0.281
Heat transfer rate (W)	2,900 - 5,800	
Reynolds number	43,000 - 53,000	1,100 - 3,900
Water hardness (ppm)	10-50	350 - 550
Water alkalinity (ppm)	12	420 - 630
pH of water	6.2	7.6 - 8.0
Electrical conductivity of water (umhos/cm)	50-100	3,500 - 5,400

After each fouling test, the artificial hard water was drained out of the system loop. Since the hard water was drained right away after the test, the remaining scales in the hard water reservoir as well as in the system loop could be relatively easily removed. We cleaned the reservoir tank with a brush and flushed it with high pressure water jet. Then, tap water was recirculated through the loop continuously for 2-5 hours. At this point, the system was considered to be ready for the next test and new distilled water of 0.150-0.175 m³ was poured into the reservoir. A new, smooth and clean copper tube was installed in the heat transfer test section for each fouling test. Prior to this cleaning process, the heat transfer test section was removed from the system loop and the scaled pipe was dried off for inspection and SEM photography.

The heat transfer rate from the hot-water side was estimated using the following equation (Cho et al., 2003; Cho and Choi, 1998; Kim et al., 2001; Tijing et al., 2007):

$$Q_h = \dot{m}_h c_{p_h} \Delta T_h \tag{2}$$

The heat transfer rate at the cold-water side can be described in a similar manner:

$$Q_c = \dot{m}_c c_{p_c} \Delta T_c \tag{3}$$

The discrepancy in heat transfer rates between the hot and cold-water sides was found to be $\pm 8\%$ using the following equation:

Heat exchanger efficiency =
$$\left[\frac{(Q_h - Q_c)}{Q_c}\right] \times 100\%$$
 (4)

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 (Cho et al., 2003; Cho and Choi, 1998; Kim et al., 2001; Tijing et al., 2007).

The overall heat transfer coefficient U was calculated using the following equation:

$$U = \frac{Q_c}{A_o \Delta T_{LMTD}}$$
(5)

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. The heat transfer surface area A_o was calculated using the outer diameter of the copper tube ($d_o =$ 16 mm) with an effective heat transfer length of L = 600 mm (i.e., $A_o = \pi d_o L$). The ΔT_{LMTD} is the log-meantemperature-difference which is described as follows:

$$\Delta T_{LMTD} = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln \left[\frac{(T_{h,o} - T_{c,i})}{(T_{h,i} - T_{c,o})} \right]}$$
(6)

The fouling resistance, R_f was calculated using the following equation:

$$R_f = \frac{1}{U_f} - \frac{1}{U_i} \tag{7}$$

where U_f is the overall heat transfer coefficient for the fouled case, while U_i is the overall heat transfer coefficient for the initial clean condition. The latter (U_i) was determined using distilled water only (without chemicals) and without the use of PWT-device during the initial run prior to the artificial hard water fouling tests but the same experimental conditions. The former (U_f) was obtained from each fouling test using artificial hard water.

EXPERIMENTAL RESULTS AND DISCUSSION

Fouling resistance

Figure 4 shows the fouling resistances versus time for both no-treatment and PWT-treated cases at a water hardness of 550 ppm and a velocity of 0.3 m/s. All fouling resistances for both cases did not show any induction



Fig. 4. Fouling resistance curves for the no-treatment and PWT-treated cases (550 ppm water hardness, 0.3 m/s flow velocity).

period. An induction period is the time wherein a stable crystal nucleation takes place and slowly spreading out laterally until completely covering the heat transfer surface with scale deposits (Fan and Cho, 1997; Yang et al., 2002). It is indicated by a straight line in the beginning of the fouling test. The high water hardness, high heat transfer surface temperature, and low flow velocity must have affected the negligible induction periods (Yang et al., 2002). 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 x 10^{-4} m²K/W after t = 12 hrs of test and then gradually decreased and reached 4.2×10^{-4} $m^{2}K/W$ 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 (see Fig. 5b) as compared to the clean tube (Fig. 5a).

The PWT-treated cases showed lower fouling resistances as compared to the no-treatment case. The fouling resistance dropped by 76% from the no-treatment when treated at 2 V, 13.56 MHz. At 13 V, 27.12 MHz, the fouling resistance also dropped by 83% from the notreatment case. The photographic images for the fouled tubes are shown in Figs. 5g and 5h, respectively. In the case of PWT-treatment at V = 10 V and 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 (Fig. 5f) 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 bluishgreen 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 x 10^{-4} m²K/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 (see Fig. 5e). 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 (Figs. 5d and 5c). 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.

Figure 6 presents the effect of velocity on the fouling formation using artificial hard water with hardness of 350 ppm with (treated) and without the use of PWT (notreatment). Comparing the no-treatment results, they show that as velocity increases, the fouling resistance decreases. There was no induction period for all cases. This was because the chemicals used reacted instantly at the hot copper tube outside surface when hard water touched it. At the lowest test velocity of 0.3 m/s, the fouling resistance was at its highest as expected (4.5 x 10^{-4} m²K/W). The reason behind this would be that the flow shear forces at 0.3 m/s are not high enough to continuously remove the scales depositing directly at the heat transfer surface. As velocity was increased to 0.8 m/s and 1.0 m/s, the fouling resistances decreased to 2.5 x 10^{-4} m²K/W (39% reduction) and 1.0 x 10^{-4} m²K/W (77% reduction), respectively from the fouling resistance at 0.3 m/s. This supports the results of previous studies (Yang et al., 2002; Panchal and Knudsen, 1998) that at higher velocities, even if there is higher mass deposition rate, the high flow shear forces are enough to continuously remove the scales.



Fig. 5. Photographic images of clean and fouled tubes.

From the test for optimum voltage and frequency of the graphite electrode device, we utilized 2 V, 13.56 MHz as the best configuration for the device based from Figure 4. The fouling resistances dropped in the range of 30-88% using the present PWT device (graphite electrode plates). The fouling resistance at the PWT-treated case (0.3 m/s) decreased by about 88% from the no-treatment case. The

high-frequency oscillating electric field, which gives higher tendency for ions to collide with each other, should have precipitated the particles in bulk water at a longer duration inside the PWT device and they attached on the heat transfer surface in the form of particulate fouling. The particulate fouling deposits were not so adherent to the pipe surface and with each other (scale-to-scale adherence), thus even at low flow velocities, the scales were continuously detached by the low flow shear forces. The fouling resistances at V = 0.8 m/s and V = 1.0 m/s decreased by 65% and 34% from the no-treatment cases, respectively. As the velocity was increased, the "treatment" time of the hard water inside the device was lessened, which could have produced fewer precipitated particles in bulk water. The precipitated particles in bulk water compete with ions directly precipitating on heat transfer surfaces and with the higher flow shear forces, there was constant deposition and detachment of deposits until reaching an optimum height for the deposit to hold on to (plateau condition) where additional deposition and removal rates are similar. The recirculating set-up (closed flow system) also allowed the hard water to be continuously "treated" with higher "treatment" frequency as the velocity was increased.

Scanning electron microscopy (SEM) photographs

The SEM photographs for both no-treatment and treated cases at 550 ppm and 0.3 m/s are shown in Fig. 7. The specimens with fouling deposit for SEM photography were prepared by drying the fouled tubes thoroughly after each test at room temperature. An approximately 5 mm by 5 mm specimen (i.e. copper tube with scale on surface) was manually cut from the fouled tube using a cutting saw (Magic saw, Han-A Tools Co., Ltd., Korea). The SEM results in Fig. 7 show different crystal structures between the no-treatment and the treated cases. The no-treatment case (Fig. 7a) showed sharp and needle-like crystals depicting an aragonite form of scale (less than 1 μ m in



Fig. 6. Fouling resistance curves for the no-treatment and PWT-treated cases (350 ppm water hardness, 0.3-1.0 m/s flow velocity).

thickness). The treated case at V = 10 V and at f = 1 kHz, at f = 100 kHz, and at f = 1 MHz (Figs. 7b, 7c, and 7d, respectively) showed flower-like crystal structures and agglomerated scales. At 10 V, f = 13.56 MHz (Fig. 7e), it showed blunt crystal tip and edges and were a bit thicker in width than those in no-treatment. The SEM images at higher 2V, 13.56 MHz (Fig. 7f) and at 13 V, 27.12 MHz (Fig. 7g) showed hexagonal crystal structures and were thicker in size (>3 μ m). These depict calcite form of scale. Aragonite crystal structures are known to be harder to remove as compared to the calcite crystal structures. Thus, the PWT-treated results suggest an easier to remove scales.





Figure 8 shows the SEM images at 350 ppm and at 3 varying velocities. The SEM images at the no-treatment cases for V = 0.3 m/s and V = 0.8 m/s had less than 1 μ m in crystal thickness and at V = 1.0 m/s had less than 3 μ m in thickness. All of the three no-treatment cases show sharp and pointed crystal structures which depict aragonite crystal forms. The sharp and pointed crystal tips could have increased the attachment capability of the deposit to adhere on the heat transfer surface more strongly. On the other hand, the PWT-treated cases (2 V, 13.56 MHz treatment) show larger crystal structures with blunt and dull crystal surfaces. At 0.3 m/s, the crystal is like a bigger version of the crystals at the no-treatment condition but with dull surface and thickness of more than 4 μ m. The crystal

structure at 8 m/s (PWT-treated) was hexagonal in shape with thickness of over 4 μ m. The PWT-treated crystal structures at 1.0 m/s show flat and flaky-type agglomerated scales. One can see the lesser steepness in structure of the images of those in PWT-treated cases as compared with those in no-treatment cases especially when velocity was increased (i.e., larger flow shear forces acting on the deposit). The PWT-treated cases resemble those of calcite crystal structures which are softer in nature and are easily detached if there is enough flow shear force.



Fig. 8. SEM images (5,000x) for the no-treatment and PWT-treated cases at 350 ppm water hardness.

CONCLUSION

The objectives of the present study were to investigate the efficacy of the new PWT device for the mitigation of mineral fouling in heat exchangers and to determine the optimum voltage and frequency for the electric field. The PWT device used RF electric fields which were generated using two graphite plate electrodes submerged in water. The PWT device was operated at different voltages and in a frequency range of 1 kHz – 27.12 MHz . Artificial hard water at 350 and 550 ppm of calcium carbonate hardness was utilized in all fouling tests, with cold water flow velocities of 0.3, 0.8 and 1.0 m/s.

The present results showed that the PWT device performed better with increasing frequency. At different combinations of voltages and frequencies (V = 2, 10, 13 V; f = 1 kHz, 100 kHz, 1 MHz, 13.56 MHz, 27.12 MHz), the fouling resistance decreased by 16-83% from the notreatment case. In the present study, from among the tested voltages and frequencies, the best result (optimum) was obtained at 2 V, 13.56 MHz for the mitigation of calcium carbonate fouling. At these values, the fouling resistance decreased by 34-88% depending on the artificial water hardness and flow velocities. The SEM images in the PWT- treated cases showed agglomerated and hexagonal crystal structures. These are believed to be less adherent to the heat transfer surface and can easily be removed with enough flow shear forces. On the other hand, the no-treatment cases revealed pointed and needle-like crystal structures, that seemed to be more tenacious and troublesome kind of crystal phase.

NOMENCLATURE

- Outside surface area of the copper tube (m^2) A_o
- Specific heat of water (J/kg K) c_p f
- Frequency (Hz)
- 'n Mass flow rate of water (kg/s)
- Q Heat transfer rate (W)
- \tilde{R}_{f} Fouling resistance (m²K/W)
- T_i Inlet temperature of water (°C)
- T_o Outlet temperature of water (°C)
- Log-mean-temperature difference (°C) ΔT_{LMTD}
- Overall heat transfer coefficient $(W/m^2 K)$ U

Subscripts

- Cold side с
- f Fouled state using hard water
- h Hot side
- Initial clean state using distilled water i
- 0 Outlet

ACKNOWLEDGMENT

This work was supported by a grant of Post-Doctoral Research Program at Chonbuk National University, South Korea.

REFERENCES

Bansal, B., Chen, X.D., and Muller-Steinhagen, H., 2003, Use of non-crystallising particles to mitigate crystallization fouling, International Communications in Heat and Mass Transfer, Vol. 30, Issue 5, pp. 695-706.

Bott, T.R., 1995, Fouling of Heat Exchangers, Elsevier Science B.V., Netherlands, pp. 55-133.

Bott, T.R., 1997, Aspects of crystallization fouling, Experimental Thermal and Fluid Science, Vol. 14, pp. 356-360

Casanueva-Robles, T., and Bott, T.R., 2005, The environmental effect of heat exchanger fouling: A case study, Proc. Of the 6th International Conference on Heat Exchanger Fouling and Cleaning - Challenges and **Opportunities** RP2.

Cho, Y.I., and Choi, B-G., 1999, Validation of an electronic anti-fouling technology in a single-tube heat exchanger, Int. J. Heat Mass Transfer, Vol. 42, pp. 1491-1499.

Cho, Y.I., Lane, J., and Kim, W., 2005, Pulsed-power treatment for physical water treatment, International Communications in Heat and Mass Transfer Vol. 32 pp. 861-871.

Cho, Y.I., Lee S.H., and Kim, W., 2003, Physical water treatment for the mitigation of mineral fouling in coolingwater applications, ASHRAE, pp. 346-357.

Fan, C. and Cho, Y.I., 1997, Microscopic observation of calcium carbonate particles: Validation of an electronic anti-fouling technology, International Communications in Heat and Mass Transfer, Vol. 24, Issue 6, pp. 747-756.

Helalizadeh, A., Muller-Steinhagen, Н., and Jamialahmadi, M., 2000, Mixed salt crystallization fouling, Chemical Engineering and Processing, Vol 39, pp. 29-43.

Kim, W.T., Cho, Y.I., and Bai, C., 2001, Effect of electronic anti-fouling treatment on fouling mitigation with circulating cooling-tower water, International Communications in Heat and Mass Transfer, Vol. 28, Issue 5, pp. 671-680.

Kronenberg, K.J., 1986, Physical Water Treatment Demystified, Magnets, pp. 6-15.

Lee, G.J., Tijing, L.D., Pak, B.C., Baek, B.J., and Cho, Y.I., 2006, Use of catalytic materials for the mitigation of mineral fouling, International Communications in Heat and Mass Transfer, Vol. 33, pp. 14-23.

Nesta J. and Bennet C.A., 2005, Fouling mitigation by design, Proc. of the 6th International Conference on Heat Exchanger Fouling and Cleaning - Challenges and **Opportunities** RP2.

Panchal, C.B. and Knudsen, J.G., 1998, Mitigation of water fouling: Technology status and challenges, Advances in Heat Transfer, Vol. 31, pp. 431-474.

Operating frequencies, 2007, Federal Communications Commission, Code of Federal Regulations, USA, Title 47 Vol. 1, Part 18, 18.301

Parsons, S.A., Judd, S.J., Stephenson, T., Udol, S., and Wang, B.L., 1997, Magnetically augmented water treatment, Vol. 75, Issue B2, pp. 98-104.

Radler, S. and Ousko-Oberhoffer, U., 2005, Optimised heat exchanger management- Achieving financial and environmental targets, Proc. of the 6th International Conference on Heat Exchanger Fouling and Cleaning -Challenges and Opportunities RP2.

Somerscales, E.F.C., 1990, Fouling of heat exchangers: An historical review, Heat Transfer Engineering, vol. 11, issue 1, pp. 19-36..

Steinhagen, R., Muller-Steinhagen, H.M., and Maani, K., 1993, Fouling problems and fouling costs in New Zealand industries, Heat Transfer Engineering.

The U.S. Department of Energy, 1998, Non-chemical technologies for scale and hardness control, DOE/EE-0162.

Tijing, L.D., Pak, B.C., Lee, D.H., and Cho, Y.I., 2007, Heat-treated titanium balls for the mitigation of mineral fouling, Experimental Heat Transfer, Vol. 21, Issue 2, pp. 115-132.

Tijing, L.D., Pak, B.C., Lee, D.H., Baek, B.J., and Cho, Y.I., 2007, An experimental study on the bulk precipitation mechanism of physical water treatment for the mitigation of mineral fouling, International Communications in Heat and Mass Transfer, Vol. 34, Issue 6, pp. 673-681.

Yang, Q., Liu, Y., Gu, A., Ding, J., and Shen, Z., 2002, Investigation of the induction period and morphology of CaCO₃ fouling on heated surface, Chemical Engineering Science, Vol. 57, pp. 921-931.