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of Mineral Fouling in Cooling-Tower Water
Applications

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Abstract

The physical water treatment (PWT) device is defined as a non-chemical method of water treatment utilized for the purpose of scale prevention or mitigation. Three different PWT devices, including permanent magnets, solenoid coil device, and high-voltage electrode, were used under various operating conditions. The present study proposed a bulk precipitation as the mechanism of the PWT and conducted a number of experimental tests to evaluate the performance of the PWT. The results of fouling resistances obtained in a heat transfer test section clearly demonstrated the benefit of the PWT when the PWT device was configured at an optimum condition. The results of SEM and X-ray diffraction methods were obtained to further examine the difference in scale crystal structures between the cases of no treatment and PWT. Furthermore, the surface tension of water samples was measured, and it was found that the PWT reduces the surface tension by approximately 8% under repeated treatment as in cooling-tower applications.

PHYSICAL WATER TREATMENT FOR THE MITIGATION OF MINERAL FOULING IN COOLING-TOWER WATER APPLICATIONS

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ABSTRACT

The physical water treatment (PWT) device is defined as a non-chemical method of water treatment utilized for the purpose of scale prevention or mitigation. Three different PWT devices, including permanent magnets, solenoid coil device, and high-voltage electrode, were used under various operating conditions. The present study proposed a bulk precipitation as the mechanism of the PWT and conducted a number of experimental tests to evaluate the performance of the PWT. The results of fouling resistances obtained in a heat transfer test section clearly demonstrated the benefit of the PWT when the PWT device was configured at an optimum condition. The results of SEM and X-ray diffraction methods were obtained to further examine the difference in scale crystal structures between the cases of no treatment and PWT. Furthermore, the surface tension of water samples was measured, and it was found that the PWT reduces the surface tension by approximately 8% under repeated treatment as in cooling-tower applications.

INTRODUCTION

When a heat pump is used, it is used as an air-conditioning system in summer, whereas it is used as a heat pump in winter. When it is used as an air-conditioning system, the outside HX is used as a condenser, where heat has to be rejected to the surroundings. Cooling tower water is used in a water-cooled condenser, and the heat is rejected from the condenser as water evaporates in the cooling tower. Thus, the mineral ions in circulating water are accumulated, and the concentration of the mineral ions increases with time, creating fouling problems in the condenser tubes. Thus, it is essential to prevent the mineral scale build-up inside the condenser while it is used as an air-conditioning device. When the system is switched to a heat pump, this outside HX is used as an evaporator. If the evaporator is fouled from the summer usage, the heat pump will not operate efficiently.

Open cooling water systems such as water-cooled condensing systems are susceptible to scale accumulation on condenser heat transfer surfaces. The precipitated solids form both soft and hard scale deposits on the heat transfer surfaces, increasing the resistance to heat transfer and subsequently decreasing the thermal efficiency of the equipment.

Physical water treatment (PWT) methods include the use of magnetic fields, electric fields, alteration of surface charges of water, and mechanical disturbance such as a vortex flow device, ultrasound, and sudden pressure changes. The apparent PWT effect is to prevent the formation of scale on surfaces, allowing the dissolved solids to be carried along with the process water or removed in concentrating conditions, such as blowdown in cooling towers.

Numerous researchers investigated the feasibility of using permanent magnets in reducing mineral fouling. Kronenberg (1985) and Parsons (1997) reported that magnetically treated water produced different types of scale formation due to the modification of solution properties. Kronenberg (1985) reported that the calcium carbonate from magnetically treated water formed a soft sludge instead of hard lime scale clinging to surface. Donaldson and Grimes (1990) speculated that magnetic fields acted at the surface of crystallites, modifying the nature of the charges at the surface. Parsons (1999) reported at the symposium Cranfield University (U.K.) observed that the most successful reports of magnetic water treatment applications occurred in continuous recirculating flow systems. They concluded that the magnetic treatment produced softer, less tenacious scale, and the anti-scale effect resulted from changes in crystallization behavior promoting bulk solution precipitation rather than the formation of adherent scale. Also, they pointed out that successes occurred only under dynamic magnetic treatment, i.e., when the solution moved sufficiently rapidly through the predominantly orthogonal magnetic field.

The effectiveness of the permanent magnet appears to be strongly related to a flow velocity passing through magnetic fields (Baker 1996; Sandulyak and Krivstov 1982; Grutch and McClintock 1984; Szostak 1985; Parker 1985; Kronenberg 1985; Busch and Busch, 1997; Baker et al. 1997; Busch et al. 1985; Parsons et al. 1997). Accordingly, one may ask whether there is an optimum flow velocity, which makes the PWT device very effective. Grutsch and McClintock (1984) reported through a full-scale field test that scaling was completely prevented at a flow velocity of 6 m/s using a magnetic device (1,700 gauss).

Szostak (1985) reported that he could operate a cooling tower at 3,000-ppm hardness without scale buildup by using a magnetic fluid conditioning system. Busch et al. (1997,

1985) reported that a certain minimum flow rate might be necessary to produce an anti-scaling effect.

A solenoid-coil induction device is another PWT method, which has been reported to mitigate scale deposits on heat transfer equipment. Cho et al (1997, 1998, 1999a, 1999b) and Kim et al. (2001) conducted various heat transfer experiments and reported that fouling resistances could be significantly reduced in cases with the PWT compared with the cases without it.

The objective of this study was to investigate the efficiency of physical water treatment (PWT) technologies in preventing and controlling calcium scale accumulation on heat transfer surfaces in re-circulating open cooling-tower water systems. The physical water treatment technologies studied in the present study include permanent magnets, a solenoid-coil induction device, and a high-voltage electrode device. The scope of the research entails the experimental investigation of physical water treatments currently being used for preventing scale accumulation, encompassing experiments to determine scale accumulation quantities and scale characteristics, blowdown characteristics, and thermal resistance of accumulated scale in a laboratory scale cooling-tower water system. All tests were conducted with a biocide, glutaraldehyde (Union Carbide) in the present mineral fouling study. Accordingly, biological fouling was controlled so that it did not influence the fouling test results.

Types of Mineral Fouling

Fouling in Untreated Water: Crystallization Fouling

Circulating cooling tower water typically contains excess amount of mineral ions such as calcium and magnesium due to the evaporation of water, thus making the water hard. When the hard water is heated inside heat transfer equipment, the calcium and bicarbonate ions precipitate due to a sudden drop in solubility, see Bott (1995), Cowan and Weintritt (1976), Hasson et al. (1968), forming hard scale on heat-transfer surfaces and manifolds. Such a hardened scale is common in heat transfer equipment using untreated water as a cooling medium. It is well known that such a hardened scale cannot be removed by brush punching, Cho et al. (1999a). An acid cleaning is often required to remove the hardened scale, which may eventually lead to premature equipment failure and producing chemical wastes for disposal.

When any undesirable material deposits on a heat exchanger surface, it is called fouling, Taborek et al. (1972); Watkinson and Martinez, (1975); Morse and Knudsen (1997); Somerscales (1990); Muller-Steinhagen (1999); Snoeyink and Jenkins (1982). Factors affecting nucleation and subsequent crystal formation are the concentration of fouling materials (foulants), temperature, pH, pressure, time,

flow velocity, mechanical motions, radiation, and impurities).

Particulate Fouling

Since the physical water treatment (PWT) is closely related to particulate fouling, the definition and characteristics of the particulate fouling are briefly described. Particulate fouling is a deposition process of particles carried by a flowing fluid as well as by matters generated in a solution. When compared with the scales produced in crystallization fouling, the scales produced in particulate fouling are much softer. The term "particle" is general and may refer to particulate matter, bacteria, corrosion products and so on, see Bott (1995).

Beal (1970) categorized the particulate fouling into three major processes: transport of the particles from the bulk fluid to the surface, the attachment of the particles to the surface, and re-entrainment of previously deposited particles from the surface back into the bulk fluid. Bott (1995) divided particle deposition into transport mechanism and agglomeration. First the particle has to be transported to the surface by one or a combination of mechanisms including Brownian motion, turbulent diffusion, or by virtue of the momentum possessed by the particle. The particulate fouling differs from the crystallization fouling: the former generally produces soft sludge scale coating while the latter often produces tenacious hardened scale on heat transfer equipment. Note that the soft scale coating from the particulate fouling can become hardened scale if left on the heat transfer surface for extended periods.

Calcite and Aragonite

Calcium carbonate is one of the most common scale types. The two structures of calcium carbonate crystal commonly found in nature are calcite and aragonite in morphology. They have the same chemical component, CaCO_3 , but differ in many aspects. Calcite is formed at room temperature (i.e., below 30°C), easily removable with weak hydrochloric acid, less adherent than aragonite, and has a hexagonal crystal shape, with a specific gravity of 2.71, see Cowan and Weintritt (1976). Aragonite 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. Aragonite is a more troublesome form of calcium carbonate than calcite because it forms a harder and denser deposit than calcite in heat transfer equipment, Cowan and Weintritt (1976).

It has been of interest to see whether calcium carbonate scales produced in water treated by a PWT device is calcite or aragonite. The present study investigates this issue by analyzing scale samples using an X-ray diffraction method.

BODY

Mechanism of PWT for the Mitigation of Mineral Fouling

It is known that the magnetic and electric fields affect the characteristics for the nucleation of mineral ions and other electrically charged submicron particles, Kashchiev (2000). One of the most reasonable mechanisms in fouling mitigation by externally applied electro-magnetic fields is a generation of nucleation in a bulk solution. For example, Al-Qahtani (1996) reported that the magnetic treatment processes accelerated the coagulation-flocculation of solid particles suspended in water and increased the crystal formation on the bulk solution instead of deposition on heat-transfer surfaces.

It is hypothesized that the water treated by a PWT device produces particles of CaCO_3 and other mineral salts in bulk water, resulting in particulate fouling. Accordingly, the PWT produces soft sludge coatings on the heat transfer surface. If the shear force generated by the flow velocity in heat transfer equipment is sufficiently large to remove the soft sludge coating, then the PWT can prevent new scale deposit or significantly mitigate the scale. Hence, the magnitude of the flow velocity inside heat transfer equipment plays a critical role in the success of the PWT.

Physical Laws behind PWT Devices

Next, we briefly introduce the basic operating principle and general specification of three PWT devices tested in the present study. When charged molecules or ions pass through a region under magnetic fields, electric fields are induced, which can be described as (Serway 1990):

$$E = V \times B \quad (1)$$

where E [V] is an induced electric field in a permanent magnet, V [m/s] is a flow velocity vector, and B [Wb/m^2] is a magnetic field strength vector created by the permanent magnet. When a charge of water molecule is multiplied to both sides of the above equation, we get Lorentz force. According to the above-mentioned hypothesis, the objective of a magnetic treatment is to produce the bulk precipitation of mineral ions. As shown in the above equation, the flow velocity is directly involved in the bulk precipitation process. Hence, in the present study, we investigated the effects of flow velocity through permanent magnets on the efficiency of the permanent magnets for scale mitigation.

Furthermore, one can predict from the above equation that the bulk precipitation using permanent magnets should be more efficient when the directions of the induced electric fields E or magnetic fields B change along the flow direction.

Thus, the present study investigated the effect of geometric arrangements of permanent magnets on the efficiency of the permanent magnets.

Another PWT device, a solenoid coil device (SCED), uses a solenoid coil wrapped over a pipe, where cooling water passes. Two ends of the solenoid coil are connected to an electronic control unit. The SCED control unit uses a pulsing current at a range of 500-3,000 Hz. Subsequently, an induced pulsating electric field is generated inside the pipe according to Faraday's law (Serway 1990):

$$\int E \cdot ds = -\frac{\partial}{\partial t} \int B \cdot dA \quad (2)$$

where E [V] is an induced electric field vector, s is a line vector along the circumferential direction, B [Wb/m^2] is a magnetic field strength vector, and A is the cross sectional area of the solenoid coil.

Another PWT device studied can be described as a high-voltage electrode device, where the electrode is positioned at the center of a pipe filled with water. The voltage varies with time, producing time-varying electric field in the water medium between the electrode and pipe wall.

Although the above three PWT devices use three different hardware, what they produce is "induced electric fields" in a pipe, where water is flowing. The induced electric fields, generated by a PWT device, vary directions with time or along the flow direction, causing the bulk precipitation of calcium carbonate crystals in solution. As described in the above hypothesis, this results in particulate fouling of soft sludge coating, which must be removed by the shear force produced by flow velocity.

Experimental Facility and Procedure

This section describes the experimental facility and test procedure used in the study to validate the above hypothesis for the PWT. The tests were limited to cooling-tower water applications, where water is repeatedly treated by a PWT device.

Figure 1 shows a schematic diagram of the test facility, which consists of a water-circulating loop, a cooling tower, a side-stream flow loop, a PWT device, a pump, a heat transfer test section, a conductivity meter, a floating-ball valve for automatic feeding of make-up water, and an automatic blowdown system controlled by a solenoid valve. The heat transfer test section consisted of a copper plate as a heat-transfer surface, an observation window, a cooling-water channel, and a hot-water channel.

References	Heat flux (kW/m ²)	Flow velocity (m/s)	Concentration (ppm)
Hasson et al. (1968)	1.6	0.25 - 0.82	110 - 575
Kim and Webb (1991)	13	0.8 - 1.82	1500
Somerscales et al. (1991)	28 - 52	0.9 - 1.0 1.4 - 1.5	2500
Nasrazadani & Chao (1994)	137	1 - 1.98	300 - 450
Sheikholeslami and Watkinson (1986)	120 - 220	0.3 - 0.8	603 - 700
Morse and Knudsen (1997)	276	1.0	490 - 650
Helalizadeh & Muller-Steinhagen (2000)	100 - 400	0.5 - 2.0	1.0 - 2.5 / 0.25 - 1.0
Present study	380-485	1.2-1.5	600-1500

Table 1. Test conditions used by previous researchers who conducted fouling experiments

The cooling water and hot water flowed in opposite directions, thus forming a counter-flow heat exchanger. The dimension of a rectangular cooling-water channel was 1.6 mm x 6.4 mm x 254 mm (height x width x length), whereas the dimension of the hot-water channel was 13.7 mm x 6.4 mm x 254 mm (height x width x length). Flow rates of both the cooling water and hot water were measured by rotameters (Omega Engineering), which were calibrated using a precision weighing balance. The flow velocity of circulating-cooling water in the cooling-water channel was varied in a range of 1.2 - 1.5 m/s in the study, and the corresponding Reynolds number was 3,350 - 4200, based on the hydraulic diameter of the rectangular cooling-water channel.

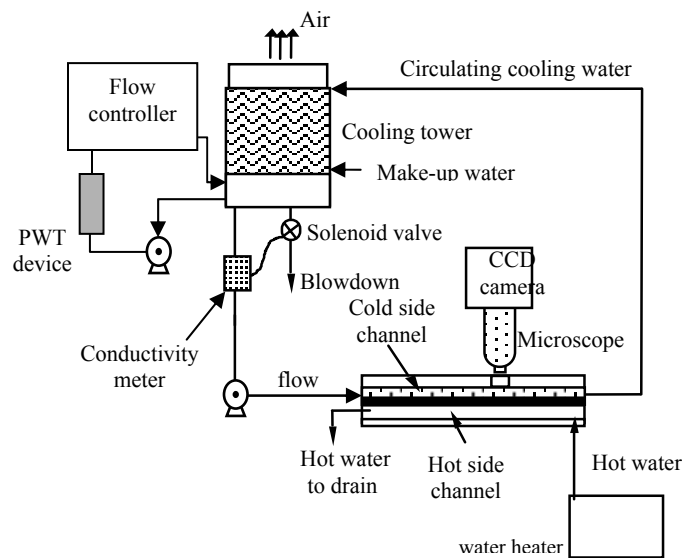


Fig. 1 Schematic diagram of fouling test facility. The application of PWT (physical water treatment) device is done at a side-stream flow loop.

T-type thermocouples were used to measure the inlet and outlet temperatures of both the cooling water and hot water. The inlet temperature of the circulating water prior to the heat-transfer test section was maintained at $20 \pm 1^\circ\text{C}$ by means of the evaporative cooling tower, whereas the inlet temperature of the hot water was maintained at 89 to 92°C throughout the entire experiments. Table 1 shows the test conditions used by the previous researchers who conducted fouling experiments in laboratories, which include heat flux, flow velocity, water concentration and types of foulant. In the present study, a heat flux between heating and cooling sides of the copper plate was in a range of $380 - 485 \text{ kW/m}^2$. The high heat flux was utilized in the study in order to accelerate fouling process.

Fouling resistance was estimated by the following equation [20]:

$$R_f = \frac{1}{U_{fouled}} - \frac{1}{U_{initial}} \quad (3)$$

where $U_{initial}$ and U_{fouled} are the overall heat transfer coefficients at the initial time and at $t \geq 0$, respectively. In order to calculate a surface temperature, Chiranjivi and Rao's convective heat-transfer correlation in a bottom-wall-heated rectangular duct case (see Ebdadian and Dong 1998) was used as follows:

$$h = 0.79Re^{0.4}Pr^{0.52} \frac{k_w}{D} \tag{4}$$

where h is the convective heat-transfer coefficient, k_w is the thermal conductivity of water, and D is the equivalent diameter for the cross-sectional area in the cooling flow channel. To calculate the average surface temperature, Newton’s law of cooling (Serway 1990) was introduced as following:

$$Q = hA_s(T_s - T_m) \tag{5}$$

where h is the convective heat-transfer coefficient, A_s is the heat-transfer surface area, T_s is the surface temperature, and T_m is the mean temperature of the fluid. The average surface temperature of the copper plate, T_s , was estimated using Eqs. (2) and (3). In the calculation of Langelier saturation index (LSI), the heat-transfer-surface temperature was applied.

The cooling-tower system had a sump tank, where fresh make-up water entered through a floating-ball valve, thereby maintaining a constant water volume in the cooling tower. Tap water provided by the City of Philadelphia was used as the make-up water. The amount and frequency of blowdown of the circulating cooling water was automatically controlled with a solenoid valve (see Fig. 2). Water samples were collected for water analysis and an example of water analysis is shown in Table 2, which show the water properties of makeup and circulating water with the PWT. Detail water analysis data for each test is available in ASHRAE report, see Cho (2002).

RESULTS AND DISCUSSION

Figure 3 represents fouling resistance values vs. time for five different cases obtained with a permanent magnet device. The characteristics of fouling resistance for the no treatment case was that the increasing rate of scale deposition was not steep in the first 200 hours and then suddenly increased very rapidly and reached the asymptotic value. This phenomenon represents that a relatively long induction period existed due to the low water concentration (i.e., 2,000 μ S/cm). When the flow velocity through the PWT was 2.3 m/s, the asymptotic value of the fouling resistance for the PWT case decreased by 80% from the value of the no-treatment case. Note that the flow velocity at the heat transfer test section was maintained constant at 1.2 m/s in all cases. For the cases of the flow velocity of 1.1 and 1.7 m/s, the fouling resistance decreased by 25 and 42%, respectively. The asymptotic final fouling resistance

Measured properties	Make up	PMSM V=2.3m/s
pH	7.7	8.3
Sp Cond @ 25C, μ mhos	525	2030
Alk, “P” as CaCO3, ppm	0	8.3
Alk, “M” as CaCO3, ppm	70	229
Sulfur, as SO4, ppm	54	184
Chloride, as Cl, ppm	81	410
Hardness, Total, as CaCO3, ppm	185	853
Calcium, Total, as CaCO3, ppm	126	581
Magnesium, Total, as CaCO3, ppm	58	271
Copper, Total, as Cu, ppm	<0.05	0.26
Iron, Total, as Fe, ppm	<0.05	<0.05
Sodium, as Na, ppm	39	134
PO4, Ortho, as PO4	1.2	0.9
Silica, Total, as SiO2, ppm	5.7	13.9

Table 2. Water quality data measured for make-up and circulating water which was treated by PMSM (a PWT device) with four different flow velocities through magnetic device.

for the flow velocity 3.0 m/s was only reduced 32% comparing to the no treatment case.

Figure 4 show the percentage reduction of the fouling resistance vs. flow velocity for the PMSM-1 case. As can be seen in Fig.4, the permanent magnet device has its own optimum flow velocity range. Figure 5 shows photographs of fouled surfaces taken after the fouled heat-transfer surfaces were completely dried. No-treatment cases resulted in much more severe fouling than PWT case using PMSM-1 with a flow velocity of 2.3 m/s. However, in the PWT cases, the amount of fouling deposit decreased with increasing flow velocity until $V = 2.3$ m/s. When the flow velocity was greater than 2.3 m/s such as 3.0 m/s, the amount of scale deposition was significantly increased again, see Cho (2002).

It is not clear why the performance of the magnetic treatment using PMSM-1 shows the optimum behavior at a specific velocity of 2.3 m/s. One may speculate as follows: For the no treatment case, the scale deposition is mainly

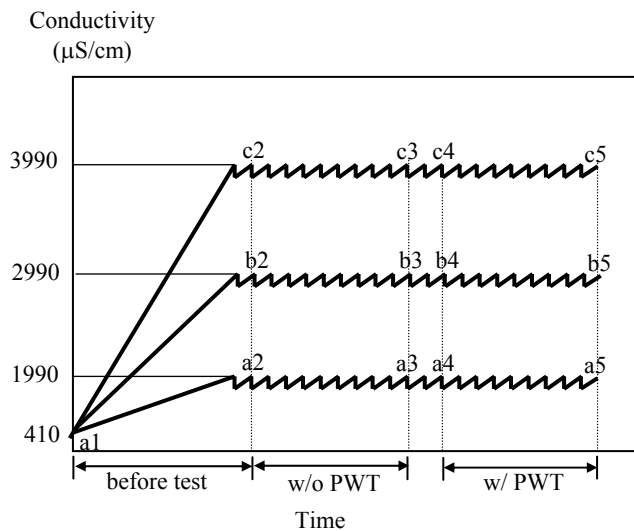


Fig. 2 Variations of electric conductivity of circulating water in a cooling tower. Blowdown was maintained using a solenoid valve, which was controlled by an electric conductivity meter with preset upper and lower limits.

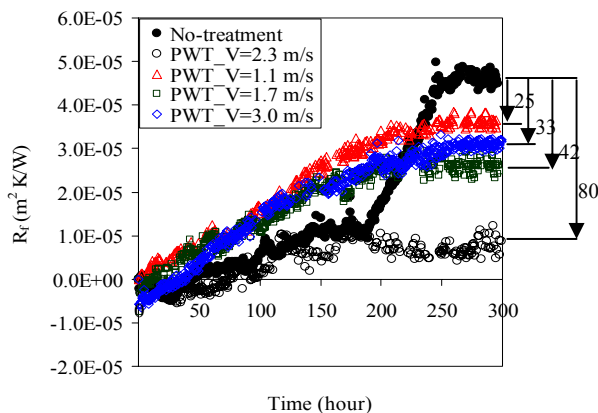


Fig. 3 Variations of fouling resistance vs. time for four different flow velocity cases through PMSM-1

due to the diffusion of dissolved mineral ions, which results in crystallization fouling and tenacious hardened scale. When the cooling water was treated by the PWT at the optimum velocity through the magnet (i.e., 2.3 m/s for this case), the mineral ions that dissolved in the cooling water precipitated in the bulk water, and therefore, these precipitated particles grew in size and eventually were deposited on the heat exchanger surface in the form of a particulate fouling. Particles deposited on the heat transfer surface as a soft sludge coating, which are easily removed by shear force unlike the hardened scale deposit produced by the diffusion of ions. However, this significant reduction of fouling resistance could only be obtained when flow velocity

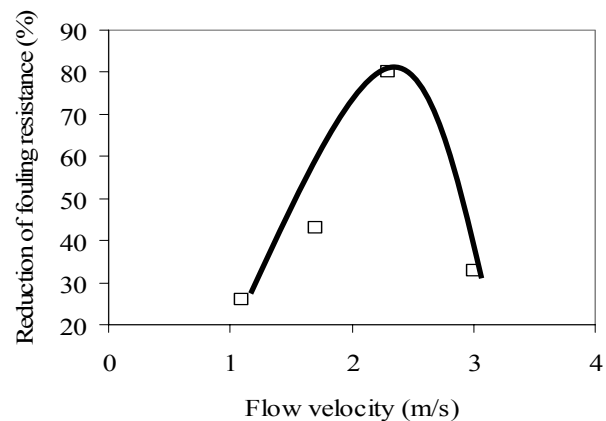


Fig. 4 Percentage variations of fouling resistance vs. time for four different flow velocity cases through PMSM-1

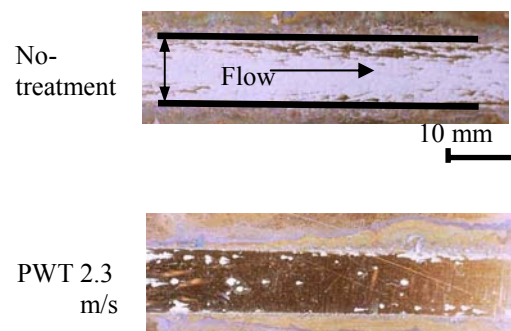


Fig. 5 Photographs of scaled heat transfer surfaces for No-treatment and PWT cases. Both 2,000 $\mu\text{S}/\text{cm}$

was reached at a certain optimized point such as 2.3 m/s.

When the flow velocity through the magnets was different from this optimum velocity, it is not clear why the performance of the magnetic treatment significantly decreased. When the flow velocity was greater than the optimum value, one can consider that the contact residence time was too short to be affected by the magnetic field. When the flow velocity was much smaller than the optimum value, the agitating force via Lorentz force (see Serway 1990) may not be sufficient to cause effective bulk precipitation. The exact mechanism of the existence of the optimum condition in the magnetic treatment needs to be further investigated in the future.

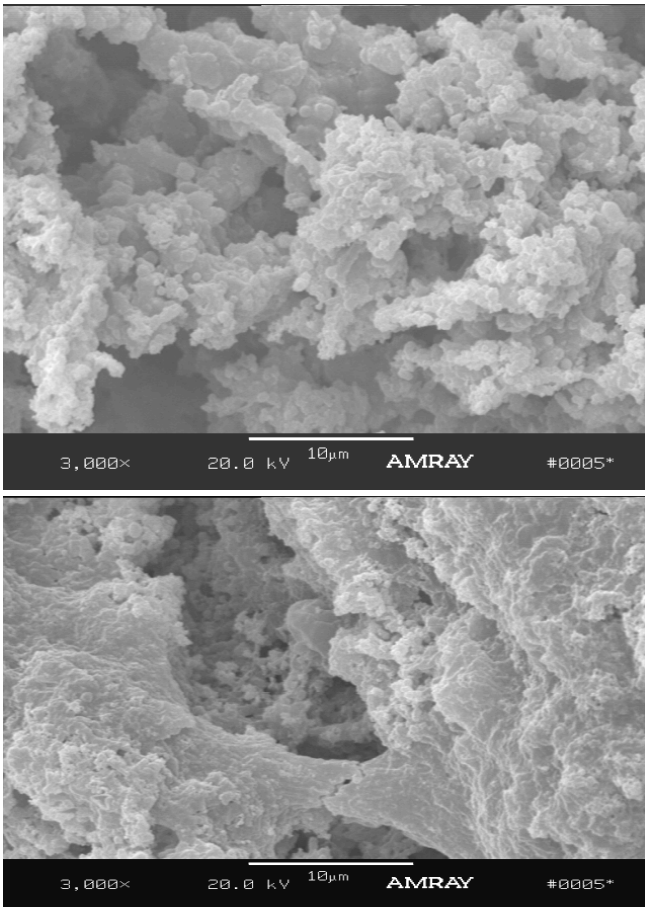


Fig. 6 SEM (scanning electron microscopy) photographs: top = no treatment case, bottom = PWT-2.3 m/s case, both 2,000 μ S/cm

Figure 6 shows SEM photographs of scale layer for the above two cases (no treatment and PWT with a velocity of 2.3 m/s) to investigate the effect of flow velocity through the PWT device. The two cases have very different morphology. For the no-treatment case, numerous tiny crystals were agglomerated. Plenty of rhombic shape tiny crystals could be found in scale samples obtained in the no treatment case. The average size of each crystal was estimated as 0.5 μ m. On the contrary, in the case of PWT-2.3 m/s, it looked like one huge particle composed of multi-layers of scale. SEM photographs for other cases are available in Cho (2002).

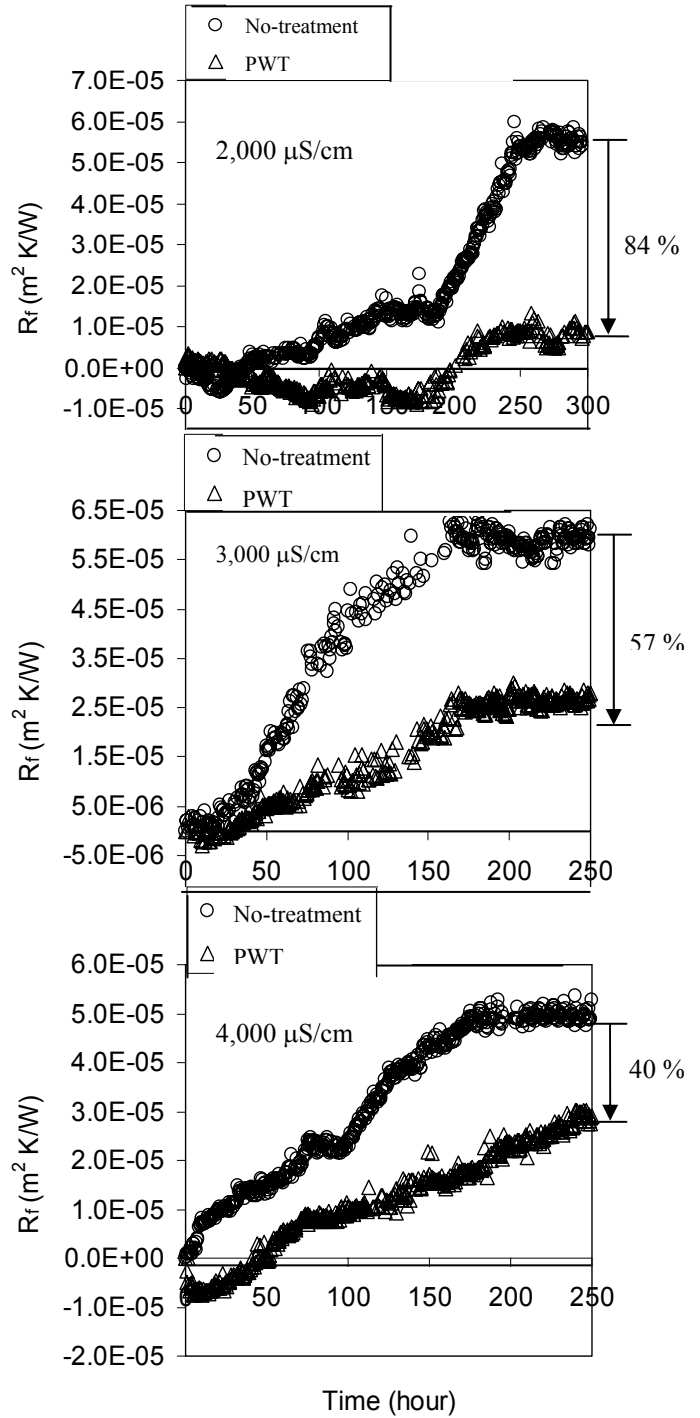


Fig. 8 Concentration effect on the performance of permanent magnets (PMDU)

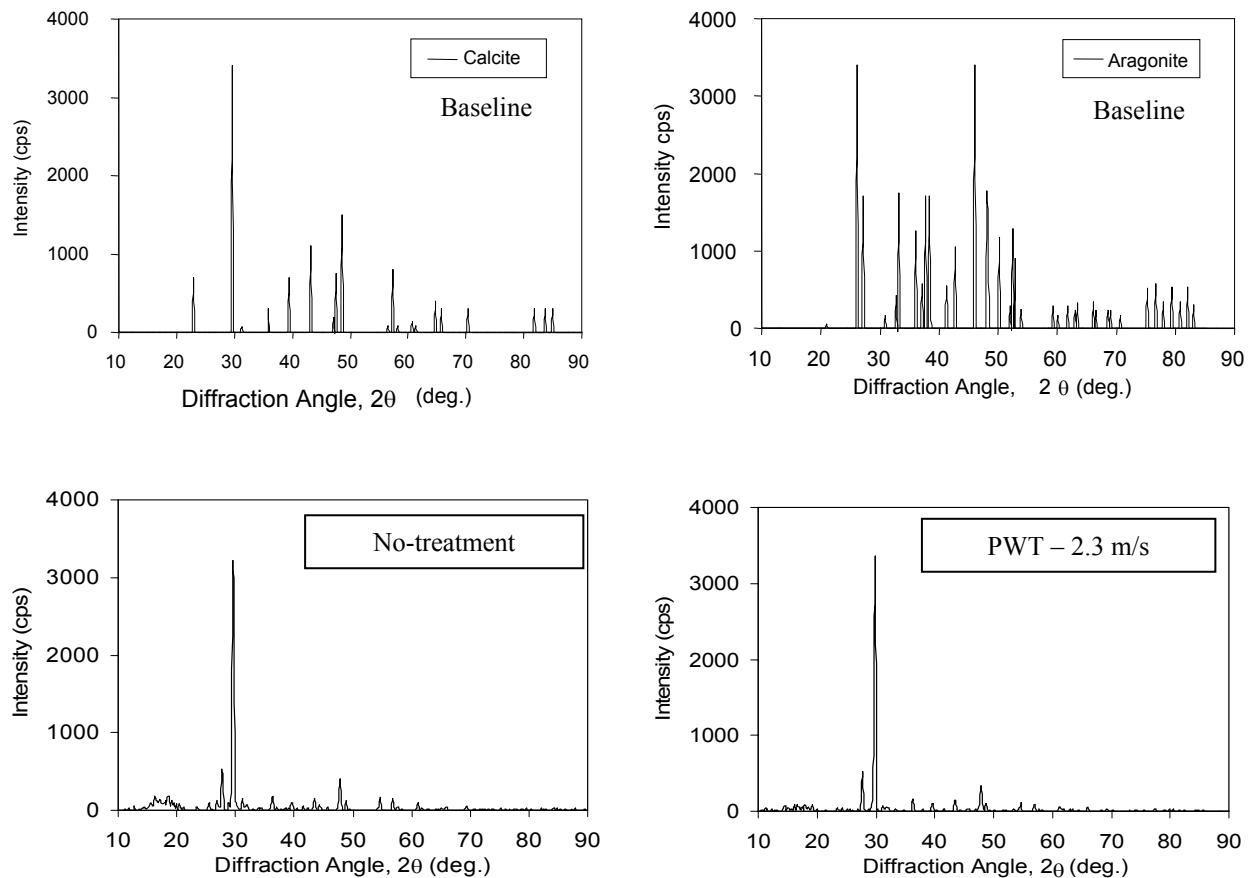


Fig. 7 Results of X-ray diffraction measurements of scale

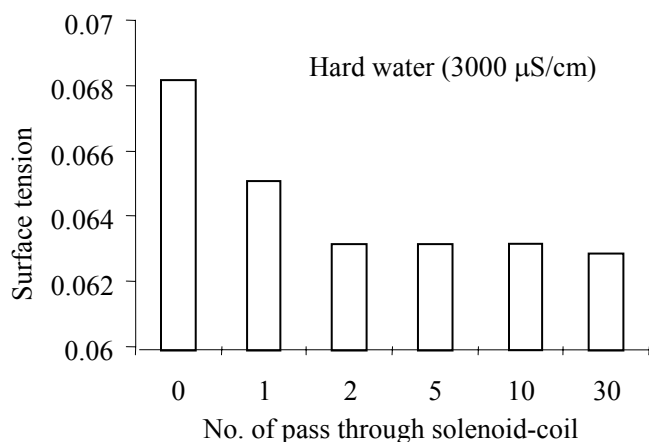


Fig. 9 The results of the surface tension of the sample water treated by a PWT (using a solenoid coil). Water conductivity = 3,000 $\mu\text{S}/\text{cm}$

Figure 7 presents the results of a scale characterization study using an X-ray diffraction method. The first two figures at the top show the baseline data for calcite and aragonite, whereas the bottom two figures show the present measurements for the cases of no-treatment and the PWT (using PMSM-1). As one can see in Figure 7, both scale crystals had the same structure of calcium carbonate scale, which was calcite. Hence, it can be concluded that the PWT produced a calcite form of calcium carbonate, and there is no difference in the structure of the scale crystals removed from the heat transfer test section between the untreated and PWT cases.

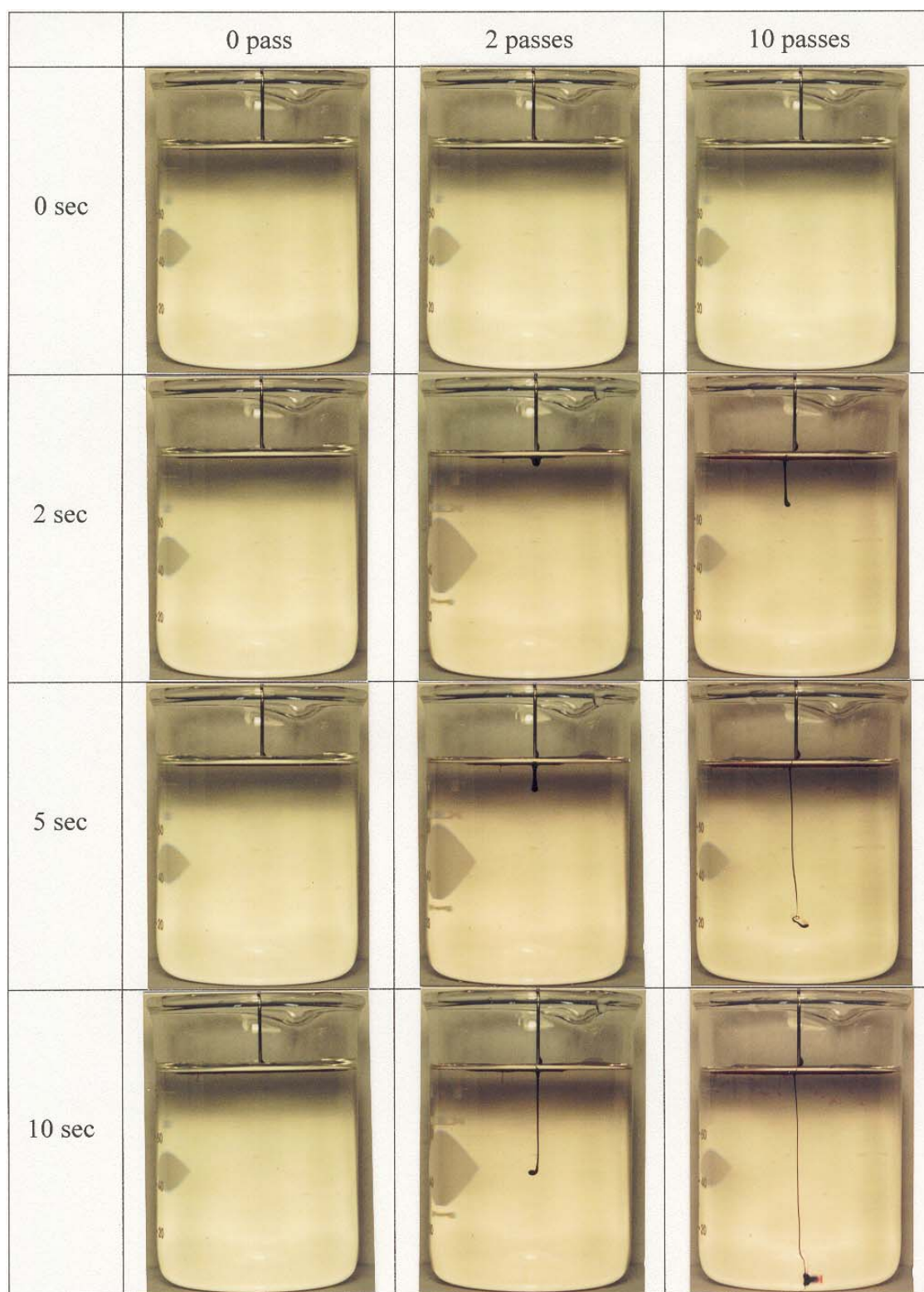


Fig. 10 photographs of the dye-injection experiment with three water samples (i.e., no-treatment, 2 passes, and 10 passes through the solenoid coil). Water conductivity = 3,000 $\mu\text{S}/\text{cm}$

Donaldson and Grimes (1988); Higashitani K., et al, (1993); Kobe et al. (2001) reported that the crystal phase of scale deposits was aragonite when they applied physical water treatment (PWT) in a beaker at a laboratory without a heat source. The present study found that the crystal phase of the scale sample changed with time. When we measured a scale sample within the first two hours of scale formation in a beaker following the same procedure as the previous researchers, we also observed mostly aragonite. When the same scale sample was analyzed again three days later, the scale sample was changed to calcite (see details in Cho 2002). This explains why the X-ray diffraction results from the scale samples collected from the heat transfer test section were the calcite form of CaCO_3 . Note that each heat transfer test in the present study took more than two weeks.

Figure 8 represents fouling resistance values vs. time for three different conductivity cases obtained with another type of a permanent magnet device (identified as PMDU in ASHRAE Report, Cho 2002). The objective of the test was to examine the effect of water concentration on the performance of the PWT. When the electric conductivity of the cooling-tower water was $2,000 \mu\text{S}/\text{cm}$, the fouling resistance for the PWT case decreased by 84% from the value of the no-treatment case. For the case of the conductivity of $4,000 \mu\text{S}/\text{cm}$, the fouling resistance decreased by 40%. This result could be explained as follows: For the untreated $2,000 \mu\text{S}/\text{cm}$ case, the scale deposition is mainly due to the diffusion of dissolved mineral ions, i.e., crystallization fouling. Since the PWT can reduce the dissolved ions in water, the reduction in the fouling resistance was great, i.e., 84%. However, for the untreated $4,000 \mu\text{S}/\text{cm}$ case, the scale deposition is due to both the diffusion of the dissolved ions (i.e., crystallization fouling) and the deposition of large precipitated particles (i.e., particulate fouling). Since the PWT only affects the crystallization fouling by reducing the number of dissolved ions in water, the reduction in the fouling resistance (i.e., 40%) was much smaller than that in the $2,000 \mu\text{S}/\text{cm}$ case.

Figure 9 shows the results of the surface tension of the water treated by a PWT (using a solenoid coil). In the case of hard water of $3,000 \mu\text{S}/\text{cm}$, the maximum reduction of the surface tension was 8.2%. This reduction in the surface tension can be explained as follows: when the hard water passes through the PWT device, the mineral ions dissolved in the cooling-tower water collide with anionic ions such as bicarbonate and make large colloidal particles in the bulk water. As the number of passes through the PWT device increases, the number and/or the size of the colloidal particles increase, thus reducing the surface tension of the water. Refer Cho (2002) for the other surface tension data obtained with permanent magnets.

Figure 10 shows photographs of the dye-injection experiment with three water samples (i.e., no-treatment, 2 passes, and 10 passes through the solenoid coil). The conductivity of the water was $3,000 \mu\text{S}/\text{cm}$. As can be seen, the dye drop in the no-treatment case rapidly spread out radial direction: in other words, dye did not fall through the water but stayed on the top surface of the water indefinitely. But when the dye was introduced to the water sample that passed 10 times through the PWT device, the dye quickly fell through the water as it was released from the needle and reached the bottom of the beaker in approximately ten seconds. This result can be attributed to the reduction of surface tension caused by the PWT. Similar dye-drop photographs obtained using permanent magnets are available in Cho (2002).

Due to limited space, many interesting test results including those with a solenoid coil device and a high-voltage electrode could not be presented in the present paper, and more complete information is also available in Cho (2002).

CONCLUSIONS

1. The present study proposed the mechanism of a physical water treatment (PWT). The PWT produces a bulk precipitation in water. As the solubility of treated water decreases inside heat transfer equipment, the tiny particulates produced by the PWT grow in size, thus preventing crystallization fouling. Since the particulates tend to deposit on the heat transfer surface, it is essential for flow to be able to remove the soft sludge coating from the heat transfer surface.

2. The present study conducted a number of experimental tests to validate the above hypothesis. The results of fouling resistances obtained in a heat transfer test section clearly demonstrated the benefit of the PWT when the PWT device is configured at an optimum condition.

3. The results of scanning electron microscopy (SEM) and X-ray diffraction methods were obtained to further examine the difference in scale crystal structures between the cases of no treatment and PWT.

4. The surface tension of water samples was measured, and it was found that the PWT reduced the surface tension by approximately 8% under repeated treatment as in cooling-tower applications.

5. The dye-drop experiment suggests that fewer reactions occurred between the dye and mineral ions in water in the treated water, supporting the bulk precipitation hypothesis.

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NOMENCLATURE

A	cross-sectional area, m ²
A _s	total heat transfer surface area, m ²
B	magnetic field strength, Wb/m ²
D	equivalent hydraulic diameter, m
E	induced electric field vector, V
Pr	Prandtl number
Q	heat transfer rate, W
Re	Reynolds number
R _f	fouling resistance, m ² K/W
T	temperature, °C
U	overall heat transfer coefficient, W/m ² K

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