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Reduction in the surface tension of water due to physical water treatment for fouling control in heat exchangers☆

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Abstract

The purpose of the present study was to investigate whether or not a physical water treatment (PWT) reduced the surface tension of hard water. Two different PWT devices were used: a permanent magnet—Drexel University (PMDU) and a solenoid coil electronic device (SCED). The effects of the treatment number of the PWT on the surface tension were studied. Two separate experiments were conducted: one was the measurement of surface tension, and the other was a flow-visualization of dye behavior in water samples. As the number of treatments of the PWT increased, the surface tension of the sample water decreased, a phenomenon that was consistent with the results in the dye flow-visualization experiment.

Keywords: Physical water treatment; Surface tension; Dye-flow visualization

1. Introduction

Fouling is the formation of solid deposits of scale in heat exchangers, and it occurs as hard water is heated and makes contact with pipes and walls of the heat exchanger. Chemical treatment has been the standard method used to prevent and to remove the mineral fouling. However, it requires handling and disposal of hazardous chemicals, raising environmental concerns. Hence, if there can be a physical water treatment method to effectively prevent or mitigate the mineral fouling in the heat exchanger, such a method will be beneficial not only to the industry but also to the environment.

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Among the various physical water treatment (PWT) methods, devices based on permanent magnets and solenoid coils are the two most popular systems. A large number of heat transfer tests were conducted to verify the effect of these PWT devices on the mitigation of mineral fouling [1–7]. The theory of the PWT device can be summarized as follows: when the hard water passes through the PWT device, an induced electric field is created as a result of dynamic and transient magnetic or electric fields. Due to a large local electric field strength due to local roughness in the pipe, a physico-chemical process of calcium carbonate reaction starts, resulting in the bulk precipitation of calcium carbonate particles. These particles act as seeds and grow as the solubility of calcium ions drops inside the heat exchanger. Thus, the PWT of hard water produces soft sludge-type coating, which can be described as a particulate fouling and be removed by shear force created by the flow inside the heat exchanger. On the contrary, in the untreated water, a hard scale deposit takes place on the heat exchanger surface, which is often described as a crystallization fouling and can only be removed by acid cleaning.

The value of the fouling resistance is often used to evaluate the efficiency of the PWT device. However, it takes approximately 2 weeks to obtain a fouling resistance value even in accelerated fouling tests, and fouling tests often require rather sophisticated instrumentation and facility. Some researchers tried to investigate the PWT with several different methods such as crystal morphology, crystal phase, solubility change, and water property change [8–11]. The surface tension of water was mentioned by a former Soviet scientist [12] but there is no specific experimental data reported in the literature.

The purpose of the present study was to investigate whether or not the PWT devices could reduce the surface tension of water. Furthermore, the study conducted a visualization study on the behavior of dye in water and related the dye behavior to the changes in the surface tension of the water.

2. Experimental methods

The present experiment of measuring surface tension is divided into two steps: making a water sample and measuring the surface tension of the water. Fig. 1 shows the schematic diagram of the present test setup for the preparation of water samples, which consists of a reservoir tank, a pump, a flow meter, a control valve, and a PWT device using permanent magnets or a solenoid coil.

Fig. 2 shows the arrangement and dimensions of a PWT device based on permanent magnets fabricated at Drexel University (PMDU). A total of four permanent magnets were used in the present

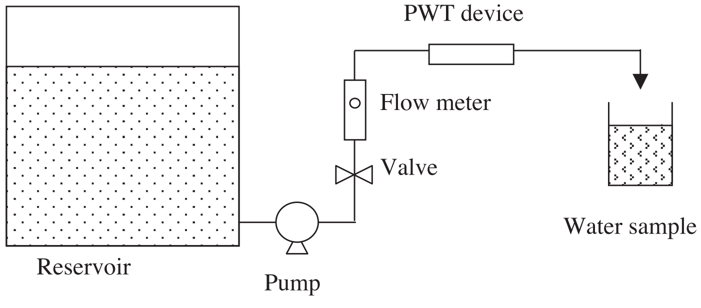

Fig. 1. Schematic diagram of the present test facility for water sampling.

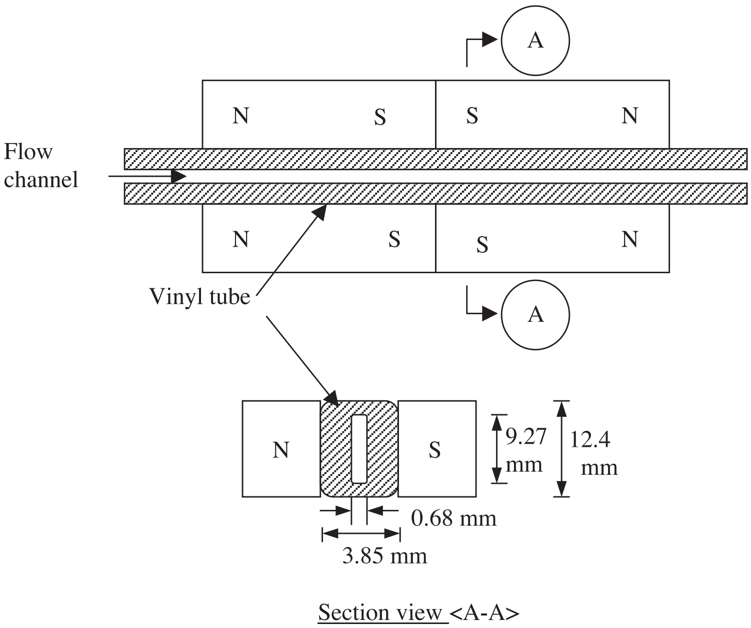

Fig. 2. Arrangement of permanent magnets and cross-sectional dimension.

experiment, an arrangement that should maximize the magnetic treatment on water. The maximum strength of the magnetic field was measured to be 0.16 T (or 1600 G) by using an Alphalab DC Magnetometer. The cross-sectional dimension of the flow channel in the PMDU was 0.68 mm×9.27 mm×100 mm ($H \times W \times L$). This arrangement of the PMDU was fixed through the entire experiment with the PMDU.

Fig. 3 shows a sketch of a PWT device using a solenoid coil (SCED). The solenoid coil was wrapped over a plastic tube with an outside diameter (OD) of 50.8 mm. A 14-gage wire was wound with 80 turns. Two ends of the solenoid coil were connected to a SCED-control unit. The SCED-control unit produced

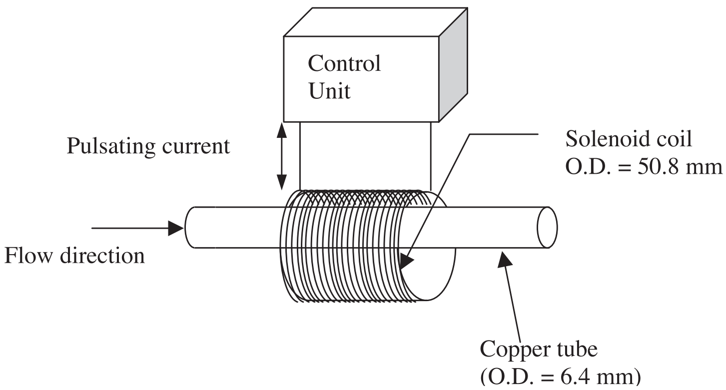

Fig. 3. Sketch of a SCED unit and a solenoid coil.

a pulsing current at a frequency of 600 Hz. Subsequently, an induced pulsating electric field was generated inside the pipe by Faraday's law [13]:

$$\int E\mathrm{d}s = -\frac{\partial}{\partial t}\int B\mathrm{d}A$$

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. Details of the operating principle of the SCED treatment including the precipitation mechanism by the induced pulsating electric field can be found elsewhere [5,7]. Copper tube carrying test water was located at an off-centered position relative to the solenoid coil since the strength of the induced electric field had a maximum value at the surface of the coil and a minimum value at the center of the coil.

The repeated treatment effect of the PWT on the surface tension of water was studied with the Philadelphia City tap water and natural hard water that was made through evaporation in a cooling-tower system. Tap water in the reservoir tank was pumped up and passed through a flow meter and a PMDU or SCED system and finally collected in another tank at the ground level (see Fig. 1). The treatment number of the PWT was changed from 0 to 30, i.e., 0 means no treatment, and 30 means the water sample passed

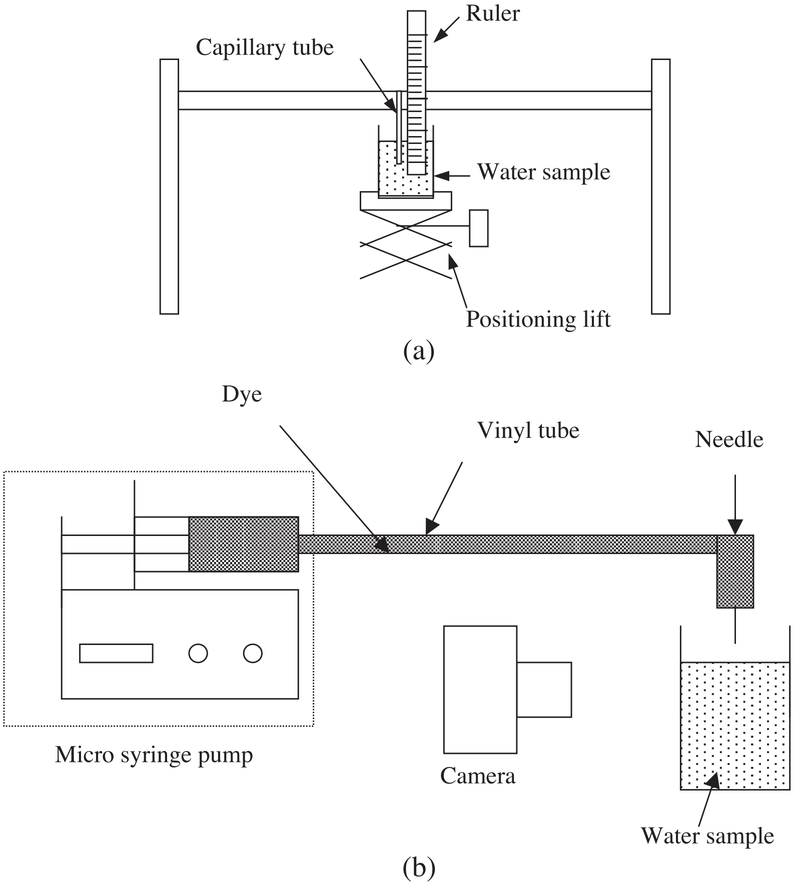

Fig. 4. (a) Schematic diagram of capillary tube system. (b) Schematic diagram of dye injection experiment system.

the PWT device 30 times. The flow velocities through the PMDU and SCED devices were 6.3 and 1.0 m/s, respectively. Note that the flow velocity of 6.3 m/s was the optimum treatment velocity for the PMDU [14].

After finishing each test run, the surface tension of the sample water was measured with precision glass capillary tubes, Corning Pyrex. Fig. 4a shows a schematic diagram of the capillary-tube system used for surface tension measurements. A glass capillary tube was attached beside a ruler, and then a 100-ml beaker was placed on an adjustable jack so that the capillary tube was positioned at the center of the sample water in the beaker. The capillary tube was first wetted with the sample water by raising the beaker, and then the beaker was lowered slowly. When the water level reached near the bottom of the capillary tube, a point exactly 5 mm from the bottom, the height of the water level inside the capillary tube was read. This step was repeated 10 times for each water sample and the average of the 10 measurements was used. The maximum reading error on the height of the water was estimated to be $\pm 1\%$. The dimension of the tube was 1.15 mm$\times$100 mm (I.D.$\times$Length). Through the whole experiment, the temperature of the sample water was controlled at 25 °C.

Fig. 4b shows a schematic diagram of the system used for the present dye flow-visualization experiment that consists of a micro-syringe pump, a needle with a vinyl tube, and a camera system. The dye flow-visualization test was performed to investigate the surface tension effect on the motion of dye. Eriochrome Black T (SG=1.109, Aldrich Inc.) was used for the test. A micro-syringe pump (kd Scientific Co.) was used to deliver an exact amount of dye, 0.005 ± 0.0003 g, without manual interventions. The tip of the needle (21G1.5, Precision Glide) used for dye injection was always positioned at 3 mm above the surface of the sample water.

3. Results and discussion

Table 1 gives the result of water analysis that was performed with standard titration methods for both tap water and natural hard water that were made from a cooling-tower system. The natural hard water had five to eight times higher total hardness than that of the tap water. Before starting with a PWT device, the relationship between the effect of the surface tension and the experimental system itself was established as the baseline data. After 30 passes, the surface tension dropped by 2% maximum comparing to that of the initial state. This result may be attributed to the fact that pump agitation itself might have reduced the surface tension through bulk precipitation although the amount was small.

Fig. 5 shows the results of the surface tension of the sample water treated by the PMDU. In the case of the tap water (see Fig. 5a), the maximum reduction of the surface tension was 7.7%, and for the natural

Table 1
Water quality data of tap water and natural hard water

	Tap water	Hard water
Conductivity (μmhos/cm)	450–570	2990
pH	7.1–7.4	8.3
Total hardness (mg/l)	140–204	1190
Ca^{++} hardness (mg/l)	120–142	780
Total alkalinity (mg/l)	65–75	320
Chloride (mg/l)	75–95	640

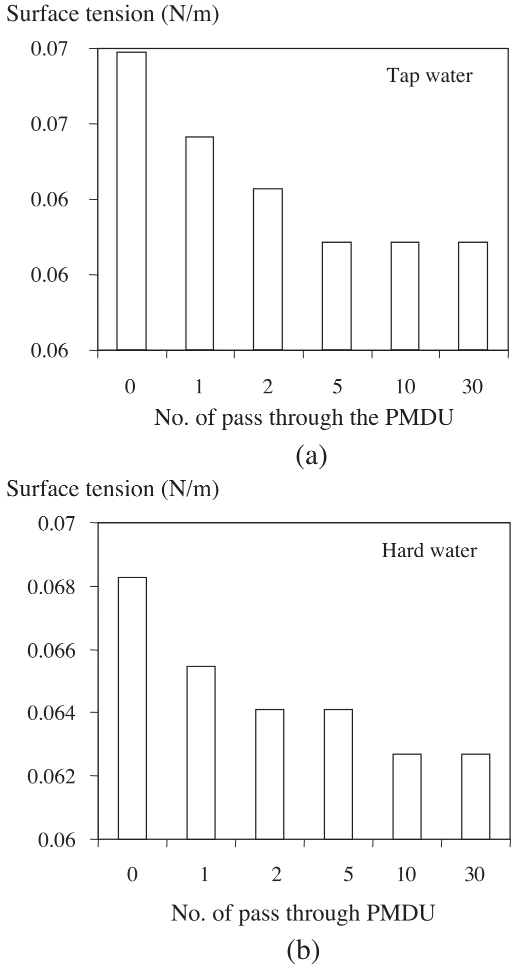

Fig. 5. (a) Results of the surface tension of tap water (570 μmhos/cm) with changing of the number of PMDU treatment (b) for natural hard water (2990 μmhos/cm).

hard water case it was 8.2% (see Fig. 5b). This suggests that water hardness does not affect the reduction of the surface tension much. A possible explanation could be as follows: when the hard water passes through the PMDU, the mineral ions dissolved in the cooling-tower water collide with anionic ions such as bicarbonate and make colloidal particles in the bulk water. Therefore, 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.

Surface tension can be described as the surface energy per unit area. The surface energy of a liquid–liquid state is less than that of a solid–liquid state in water [15–17]. Hence, the surface energy at the interface of water molecule and glass tube is much bigger than that between two water molecules. But as the number of the colloidal particles increases in the water, the surface energy at the interface of water molecule and colloidal particle increases. In other words, the surface energy at the interface between water molecule and glass tube decreases relatively. Therefore, the surface tension of the water will decrease as the number of colloidal particles increases in the water.

Fig. 6 shows the results of the surface tension of the sample water as the water was repeatedly treated by the SCED. As the number of passes through the SCED was increased, the surface tension of the treated water sample decreased by 5.9% and 7.8% from those of the untreated tap water and natural hard water, respectively. The reduction amount of the surface tension in the natural hard water was slightly larger than that in the tap water, suggesting that the efficiency of SCED might be somehow proportional to the water hardness; in other words, the fraction of the collisions of ions that led to bulk precipitation might have increased in the hard water. Generally, the surface tension results gave positive correlations with the results of the fouling-resistance experiment [14].

Fig. 7 shows photographs of the dye-injection experiment with three water samples (i.e., no treatment, 2 passes, and 10 passes through the SCED). The dye drop in the no-treatment case rapidly spread out along the 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 SCED, the dye drop quickly fell through the water as it was released from the needle and reached the bottom of the

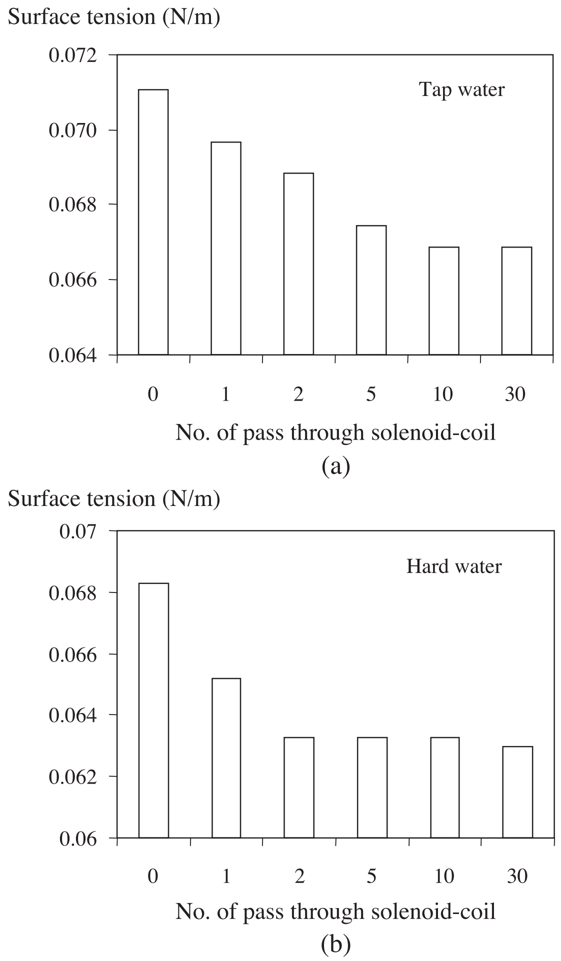

Fig. 6. (a) Results of the surface tension of tap water (450 μmhos/cm) with changing of the number of SCED treatment (b) for natural hard water (3000 μmhos/cm).

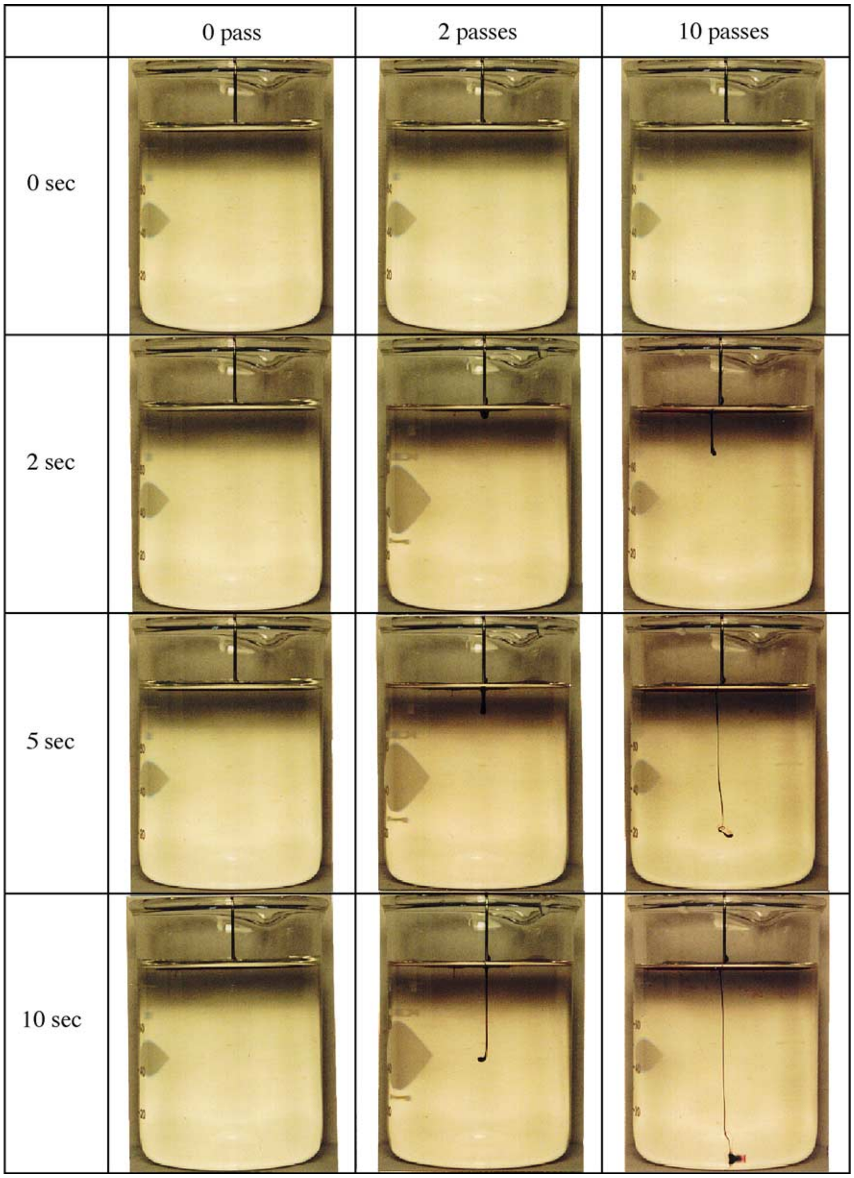

Fig. 7. Photographs of dye injection experiment with water samples treated by SCED (3000 μmhos/cm).

beaker in approximately 10 s. This result can be attributed to the reduction of the surface tension caused by the PWT. Similar results were observed for cases with the PMDU and are available elsewhere [18].

4. Conclusions

In the present study, the surface tension was measured with precision glass capillary tubes. A dye-injection experiment was performed to examine whether or not the changes in the surface tension can be manifested qualitatively in the diffusion characteristics of the dye in water. As the PWT was repeated, the surface tension of the treated water reduced by approximately 8% compared to that of the no-treatment case. The study suggests that the simple measurement of the surface tension and dye flow visualization can be used to qualitatively evaluate the efficiency of a physical water treatment method for the prevention of mineral fouling in heat exchangers.

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