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Enhancing water evaporation by combining dynamic and static treatment of magnetic field

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ABSTRACT

Water evaporation is essential for various applications, including seawater desalination and evaporative cooling system. If the water evaporation rate becomes fast through water treatment technology, satisfactory efficiency can be achieved in these applications. In this study, the potential of enhancing water evaporation by combining dynamic and static treatment of magnetic field was explored. Water was firstly treated by dynamic treatment of the magnetic field. Then the treated water was exposed to the static magnetic field and its evaporation amount was measured. The effect of magnetic field strength on water evaporation was investigated. The surface tension of water was determined to explain the mechanism behind variation of water evaporation. Results show that the single dynamic magnetic treatment can promote the evaporation rate of water. The combination of dynamic and static magnetic treatment generates a synergistic effect and significantly improves the water evaporation, and a maximum enhancement of 14.3% is obtained in this study. The behind mechanism is magnetic field treatments decrease the surface tension of water and induce water molecule to escape from water to air interface easily. This study presents an effective and economical approach to improve water evaporation rate with simple operation and low energy consumption, and contributes to the high efficiency in applications involves water evaporation.

Keywords: Water evaporation; Magnetic field; Dynamic treatment; Static treatment; Surface tension

1. Introduction

Water evaporation is a very important process for bio-transpiration and climate change, as well as many industrial applications [1–4]. In the seawater desalination system, freshwater can be collected when water is evaporated into steam from seawater [5]. Evaporative cooling is the most commonly used technique due to its economic and environmental benefits, only water and air are used as working fluids [6–8]. The water evaporation rate plays a key role in these processes, the high efficiency for the corresponding industrial applications can be obtained if the water evaporation rate increases. It is of great significance to improve the evaporation rate of water. Various strategies have been proposed for enhancing the evaporation rate of water, such as raising liquid temperature, increasing the surface area, and adding hydrophobically modified nanoparticles [9–11]. However, the immense utilization of these strategies in industrial seems to be impractical. For the strategy of raising liquid temperature, a great deal

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of energy is consumed and a large amount of CO_2 is generated in this process. The change of water surface area by spraying water droplets belongs to complex work process, and the addition of hydrophobically modified nanoparticles results in high cost. Therefore, it is quite urgent to seek other effective methods to improve the evaporation rate of water.

Magnetic field (MF) treatment involves altering the properties of materials through MF, which is characterized by simple operation, non-pollution, low energy consumption, and cost [12–14]. In recent years, several studies have focused on the effect of MF on water evaporation [15–18]. Most of these studies investigated the effect of static magnetic treatment on water evaporation rate. Water was exposed to a static magnetic field (SMF) and its evaporation amount was measured. It is well-established that the evaporation rate of water enhances after being subject to static magnetic treatment, and the reason is that the SMF can change the physical properties of water, including pH, conductivity, and viscosity [19–21]. Other studies studied the effect of dynamic magnetic treatment on the water properties. Water first passed through the MF at a certain velocity and then its properties were determined. Results have been demonstrated that the dynamic treatment of water can reduce its scaling potentiality, improve crop growth, and enhance the mechanical properties of concrete [22–24]. Based on the existing research, it seems that the dynamic magnetic treatment can change the water properties of water and produce a positive effect on water evaporation [25,26]. Hence, it can be expected that the evaporation rate of water may remarkably increase if the static and dynamic magnetic treatment combines together. However, to the best of knowledge, the effect of the combination of dynamic and static magnetic treatment on water evaporation rate has not been investigated and still remains unclear.

The objective of this study is to explore an effective way to enhance water evaporation by combining dynamic and static treatment of MF. The magnetic field strength (MFS) for the dynamic treatment was 100, 200, and 300 mT, while the MFS for the static treatment was 45, 150, and 370 mT. The dynamic treatment of water was firstly conducted, and then the treated water was exposed to SMF for the static treatment. The evaporation amount of water in SMF was measured as a function of time. The effect of MFS on the water evaporation was investigated and the possible mechanism behind the variation of evaporation rate was analyzed. The finding of this study is expected to contribute to improving production efficiency and conserving energy in the process which involves water evaporation.

2. Materials and methods

2.1. Materials

Compared with deionized water or pure water, tap water, or treated wastewater is widely used in industrial production. Tap water supplied by the local water supply company was used in this study. The quality of tap water was measured in accordance with Chinese standard GB/T 22235-2008, and the test result is given in Table 1. The cylinder container (Diameter = 100 mm, Height = 60 mm) utilized is made of polypropylene, and the appearance of it is transparent.

Table 1
Test result of tap water quality

Test items	Result	Regulatory standard
Total dissolved solids (mg/L)	423	<1,000
pH	7.36	6.5–8.5
Turbidity	0.6	≤1
Residual chlorine (mg/L)	0.33	≥0.3
Fe (mg/L)	0.019	<0.3
Mn (mg/L)	0.0032	<0.1
Al (mg/L)	0.0025	<0.2

2.2. Dynamic magnetic treatment of tap water

Dynamic treatment of tap water was performed using our developed magnetizing equipment. As shown in Fig. 1, the magnetizing equipment consists of both 2 *U*-shape grooves and PVC pipe. The permanent magnet (40 mm × 25 mm × 10 mm) is sintered NdFeB with the maximum MFS of 280 mT in its surface, and the length of magnetizing equipment is 600 mm. The distance adjustment device could control the distance between 2 *U*-shape grooves, leading to the MFS of the magnetizing equipment ranges from 0 to 600 mT. A PVC pipe (diameter = 8 mm) was inserted between 2 *U*-shape grooves (Fig. 1b). In this configuration, the direction of MF was perpendicular to that of water flow. The total number of permanent magnets used in this study was 26, and the MFS of the dynamic treatment process was determined by measuring the center of PVC with a digital tesla meter (SG-42, Beijing Zhuoshengjia Magnetoelctirc Co., Ltd., China).

There are several parameters in the dynamic treatment process, and the MFS and water velocity are the most two important factors [25]. Based on previously published studies [26,27], three kinds of MFS (100, 200, and 300 mT) were selected for dynamic magnetic treatment. When tap water flows through the PVC pipe, it turns into dynamic treated water (DTW). The velocity of tap water was set as 1 m/s, and the tap water was circulated for 5 min in magnetizing equipment. The tap water without any treatment was taken as the reference group. The tap water after being subject to the dynamic treatment with three types of MFS (100, 200, and 300 mT) was denoted as DTW-100, DTW-200, and DTW-300, respectively.

2.3. Design of SMF

Three types of SMF for the static treatment were designed according to the MFS of a single permanent magnet, that is, weak SMF (45 mT), moderate SMF (150 mT), and strong SMF (370 mT). The MFS (45, 150, and 370 mT) of SMF was determined by measuring the center of the cylinder container bottom with a digital tesla meter. Two permanent magnets were utilized to fabricate the SMF for water evaporation, as shown in Fig. 2. The cylinder container with water was placed on the center of two

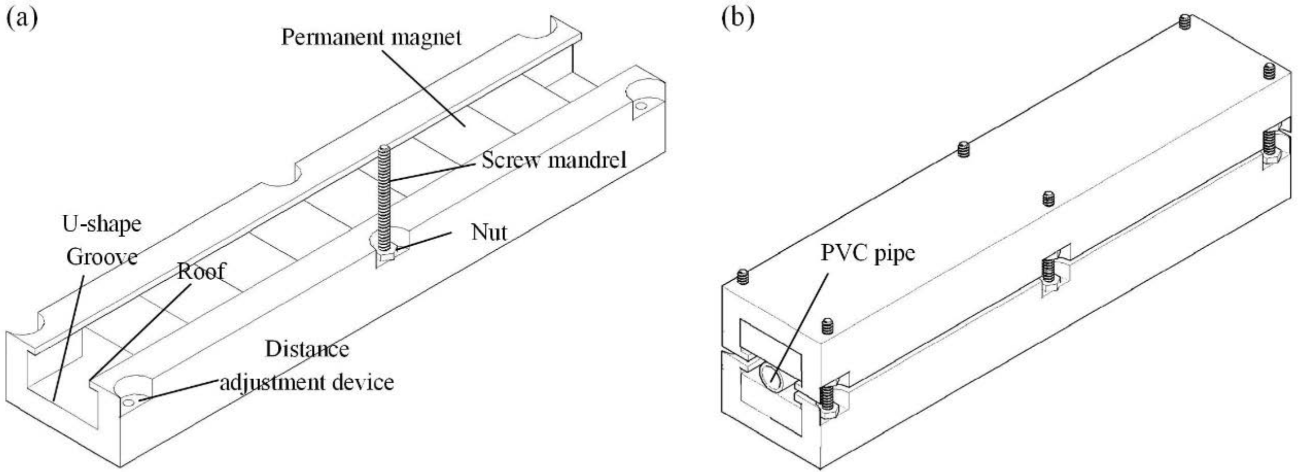


Fig. 1. Structure diagram of the magnetizing equipment: (a) *U*-shape grooves and the position of permanent magnets and (b) half side view of the magnetizing equipment.

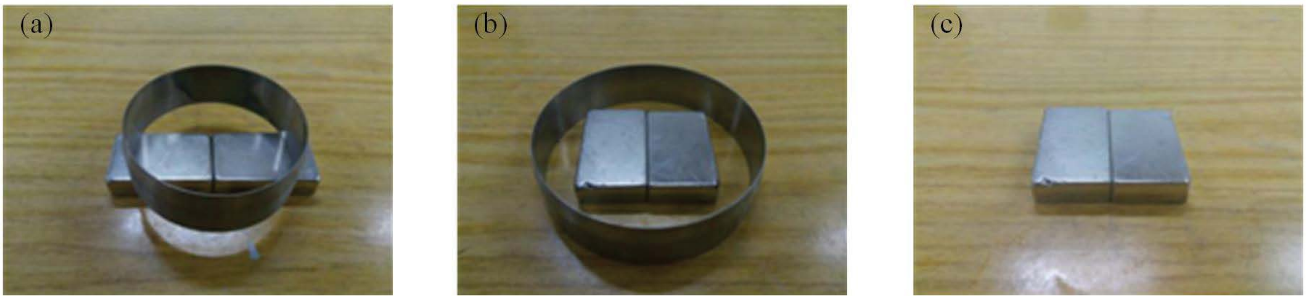


Fig. 2. Experimental setup of SMFs for the static treatment: (a) weak SMF (45 mT), (b) moderate SMF (150 mT), and (c) strong SMF (370 mT).

permanent magnets. The weak and moderate SMFs consists of permanent magnets and non-magnetic steel ring, as shown in Figs. 2a and b, and the cylinder container with water was placed on the ring. The diameter of the rings in Figs. 2a and b is 61.8 and 79.8 mm, respectively. There was no ring for the strong SMF and the cylinder container was in direct contact with two magnets.

2.4. Measurement of water evaporation

In order to prevent accidental error, parallel tests were performed during the experiment in this study. Three samples were taken from one group and the water evaporation measurement was performed through an electronic balance (Shanghai Guangzheng Medical Equipment Co., Ltd., China). The measuring precision of the electronic balance was 0.01 g. The same weight of tap water and DTW samples (80 g) was poured into the cylinder containers. In the open literatures, the measurement time of water evaporation in the MF was several minutes to hours [15,16,28]. In order to acquire the long-term effect of dynamic and static magnetic treatments on water evaporation, the whole evaporation time was 78 h in our research.

All the samples were weighed at the specified times after the measurement, that is, 6, 18, 30, 42, 54, 66, and 78 h. The evaporation of tap water and DTW were calculated as the differences between the sample weights. Measurements were carried out at a hermetic laboratory, and the humidity and temperature were 65% ± 5% and (20°C ± 1°C), respectively, and the fluorescent lamp turned on during the whole measurement process. The reported results were averaged from three samples. The evaporation rate of water was calculated as follows:

$$E_r = \frac{m_w}{t} \tag{1}$$

where E_r (g/h) is the evaporation rate of water, m_w (g) is the evaporation amount of water, and t (h) is the time of the evaporation experiment.

3. Results

3.1. Effect of dynamic magnetic treatment

The evaporation rate of tap water after the single dynamic magnetic treatment is illustrated in Fig. 3. It was observed that the evaporation rate of water gradually increased with the time. The constant temperature means that the heat for water evaporation was same during the measurement. However, the residual amount of water reduced with the time due to the evaporation. At the same

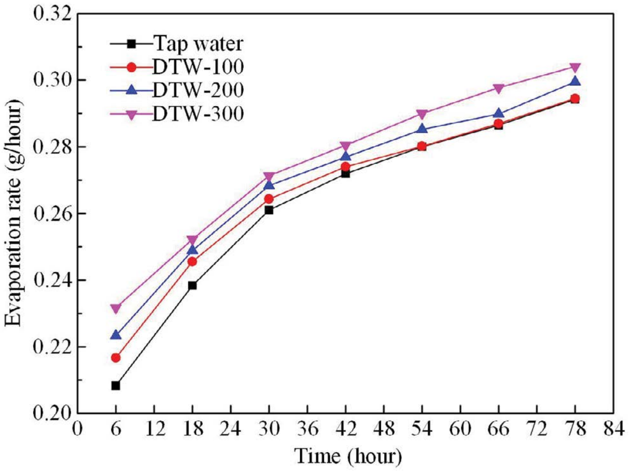


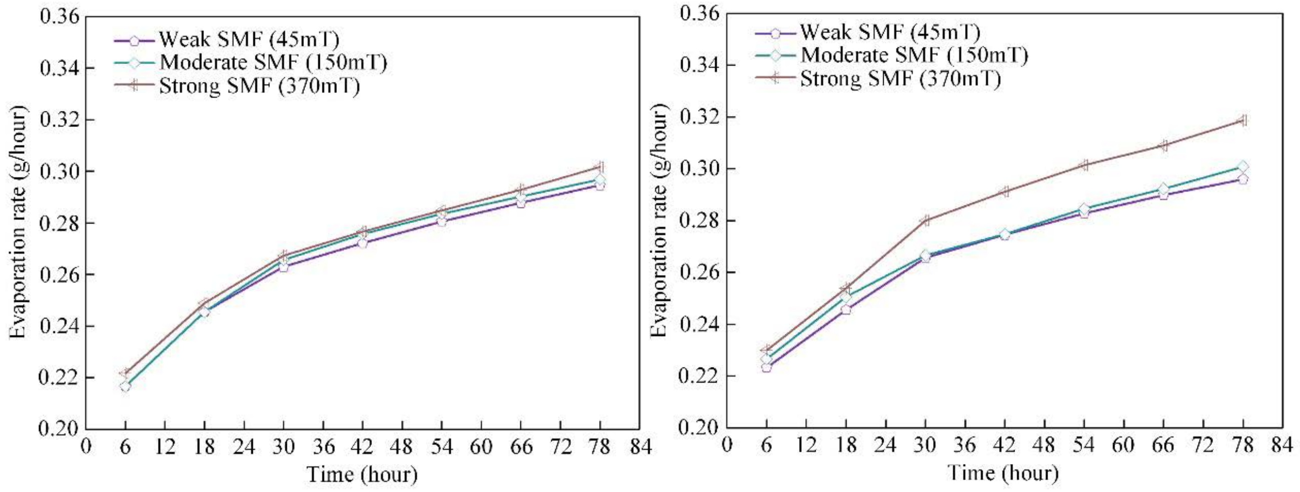
Fig. 3. Comparison of the evaporation rate between tap water and DTW.

heat, the reduced amount of water results in higher evaporation rate. Thus, the increase in evaporation rate was observed in all groups with the time. As shown in Fig. 3, the evaporation rates of DTW-100, DTW-200, and DTW-300 at 6 h were improved by 4.0%, 7.2%, and 11.2%, respectively, compared to that of tap water. It should be noted that the improvement ratio decreased over time, and the corresponding values of DTW-100, DTW-200, and DTW-300 at 42 h were 0.7%, 1.0%, and 1.3%, respectively. In particular, the evaporation rate of DTW-100 was 0.304 g/h at 78 h, which was almost the same as that of tap water (0.294 g/h). Such phenomena is caused by the "memory effect", it has been well-established that the MF treated water has a memory time [17,18]. After removing the MF, the impact on water-induced by MF would not disappear immediately, and it can last from several hours to a few days. The lasted time is related to the parameters during the magnetization process. In general, the single dynamic magnetic treatment can improve the evaporation rate of tap water, and the evaporation rate increased with the rise of MFS in the dynamic magnetic process.

3.2. *Effect of the combination of dynamic and static magnetic treatment*

The data in Figs. 4 and 5 represent the evaporation rate tap water, DTW-100, DTW-200, and DTW-300 in SMF, respectively. The evaporation rate of all samples increased after the static magnetic treatment. Take the weak SMF (45 mT) for example, the evaporation rate of tap water, DTW-100, DTW-200, and DTW-300 at 6 h were 0.216, 0.223, 0.235, and 0.237 g/h, respectively. While the corresponding values of tap water, DTW-100, DTW-200, and DTW-300 without SMF at 6 h were 0.208, 0.217, 0.223, and 0.232 g/h (Fig. 3), respectively. The results reveal that static magnetic treatment can improve the evaporation rate of tap water and DTW. The increased evaporation of untreated distilled or deionized water in SMF was also reported in other studies [15,17,28]. Holysz et al. [15] found the evaporated amount of distilled water improved when the distilled water was exposed to a SMF (15 mT). Szcześ et al. [28] concluded the SMF enhanced the amount of evaporated distilled water. Seyfi et al. [17] investigated the effect of SMF on the evaporation rate of deionized water, and an 18.3% increase in water evaporation rate was observed in the presence of SMF. When the DTW was exposed to SMF, the evaporation rate of DTW increased with the rise of MFS in dynamic magnetic treatment, and the evaporation rate of DTW-300 was the highest in all samples. In addition, the evaporation rate of tap water was lower than that of DTW in three types of SMFs, and the evaporation rate of tap water was also the smallest without SMF (Fig. 3). These phenomena imply that the evaporation rate of DTW is bigger than that of tap water whether the static magnetic treatment is applied or not.

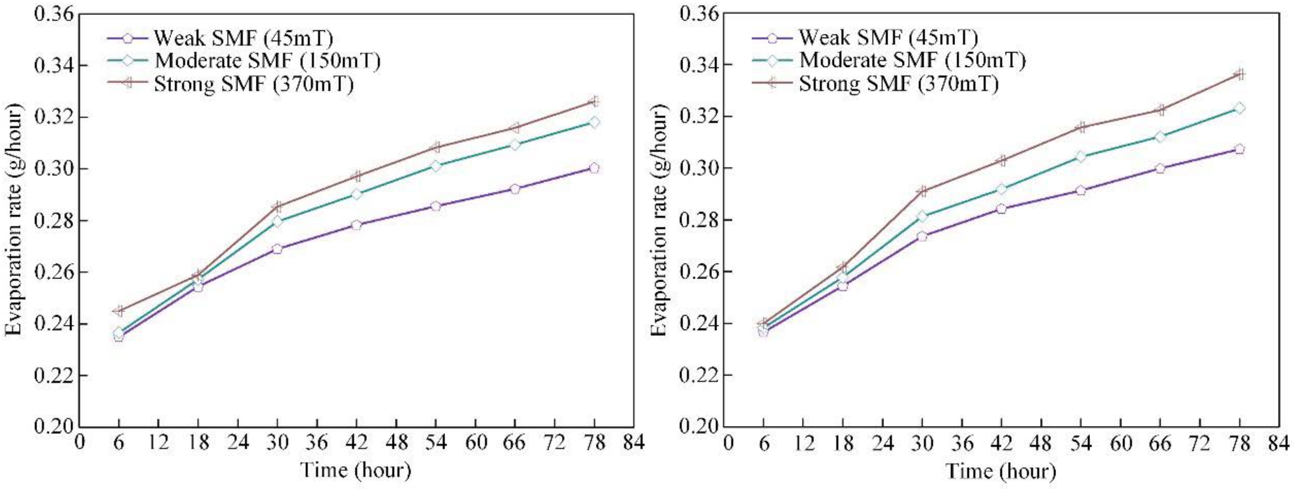
For the tap water, the highest evaporation rate was obtained in strong SMF (370 mT) and the least evaporation rate was obtained in weak SMF (45 mT). Similar trends



(a) Tap water

(b) DTW-100

Fig. 4. Evaporation rate of tap water and DTW-100 after the static treatment.



(c) DTW-200 (b) DTW-300

Fig. 5. Evaporation rate of DTW-200 and DTW-300 after the static treatment.

were also observed in the groups of DTW-100, DTW-200, and DTW-300. It can be concluded that the evaporation rate of both tap water and DTW improved with the rise of SMF intensity (from weak SMF to strong SME). The strong SMF (370 mT) was more effective in improving the evaporation rate of tap water and DTW. The evaporation rate of tap water, DTW-100, DTW-200, and DTW-300 in strong SMF (370 mT) at 78 h were 0.302, 0.319, 0.326, and 0.336 g/h, respectively. It increased by 2.7%, 8.5%, 9.0%, and 10.5%, respectively, compared to those of samples without SMF. In the presence of SMF, the increment in evaporation rate of DTW was significantly higher than that of tap water. For the evaporation rate of tap water, when the tap water was firstly subjected to dynamic treatment (300 mT), and then exposed to a strong SMF (370 mT), a maximum enhancement of 14.3% was obtained. The combination of dynamic and static magnetic treatment generates a synergistic effect on water evaporation. Based on the above results, the evaporation rate of tap water can be enhanced dramatically by combining the dynamic and static treatment of MF together.

3.3. *Effect of parameters in dynamic magnetic treatment*

To evaluate the effect of MFS in the dynamic treatment process on the water evaporation rate, the water evaporation amount of all groups is displayed and compared in Fig. 6. When the MFS of dynamic treatment was 100 mT, the evaporation amount of water gradually increased from weak SMF (45 mT) to strong SMF (370 mT). Similar trends were also observed when the MFS of dynamic treatment were 200 and 300 mT. However, compared to the dynamic treatment with 100 mT, the increment in evaporation amount was more obvious when the MFS of dynamic treatment was 200 and 300 mT. Such results indicate the MFS in dynamic treatment process is closely related to the water evaporation rate. This is probably because the dynamic treatment of MF changed the properties of tap water. The variation in water properties was dominated by the MFS in dynamic treatment process. Sohaili et al. [29] described that the low concentrations of calcium in samples were observed with the MFS increased from 100 to 400 mT in the dynamic treatment process. Liu et al. [25] reported the chemical and physical properties of wastewater changed greatly when the MFS of dynamic magnetic treatment was 750 mT. In this study, the optimal MFS is 300 mT during the dynamic treatment process.

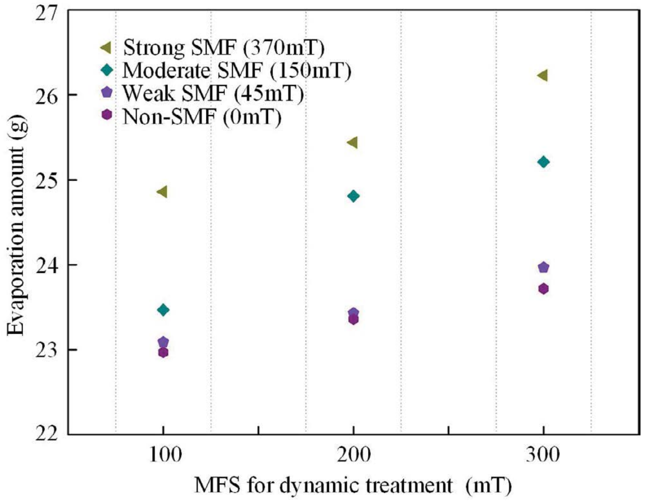


Fig. 6. Effect of MFS in dynamic magnetic treatment process on the water evaporation.

4. Discussion

The experimental results demonstrate that the evaporation rate of tap water improves significantly when the static and dynamic treatments combine together. Currently, the underlying mechanism of magnetic field treatment is still a controversial topic. Cai et al. [30] stated the average size of water clusters became large after magnetic field treatment, and the activation energy of increased over the treatment time. Seyfi et al. [17] analyzed the enhancement mechanism in water evaporation from the perspectives of kinetic energy and the Lorentz force among water molecules. Otero et al. [31] pointed out that deep insight into the mechanism of magnetic field treatment could be obtained by quantum electrodynamics rather than classical physics. Although many hypotheses regarding the mechanisms of magnetic field treatment have been proposed, there is no agreement on the precise mechanism about it from micro-scale [12,31,32]. The opinion that magnetic field treatment can alter the physical properties of water is less in conflict. Therefore, the mechanism of magnetic field treatment is analyzed from macro-scale in this study.

The evaporation rate of water is affected by many factors, including temperature, humidity, air flow velocity, and the area of water–air interface. When these conditions are same, the evaporation rate of water is dominated by surface tension. The essence of water evaporation is the process of water molecules escape from liquid water, this phenomenon occurs only when the energy of water molecule is enough to get away from the control of water surface tension. At the same temperature, the energy of water molecule remains constant. In this situation, if the water surface tension becomes small, the energy threshold for water evaporation would reduce. As a result, more water molecules can get into the air and a larger evaporation rate can be obtained. It has been reported that a decrease in surface tension was observed after the static magnetic treatment [12,19]. In order to investigate the effect of dynamic magnetic treatment on the water surface tension, the surface tension of water after the dynamic treatment process was determined by Du Nouy ring method (BZY-B Automatic Surface Tensiometer, Shanghai China, sensitivity 0.01 mN/m). Each sample was measured three times at a temperature of 20°C ± 1°C.

Fig. 7 displays the results of the surface tension of tap water and DTW. The results clearly show that the dynamic magnetic treatment reduced the surface tension of tap water. Compared to the tap water, the surface tension of DTW decreased sharply when the MFS increased from 100 to 300 mT. For example, the surface tension of tap water, DTW-100, DTW-200, and DTW-300 were 72.28, 71.15, 70.28, and 68.17 mN/m, respectively. For the DTW-300, the energy threshold for water evaporation was the smallest among groups, thus leading to the most water molecules escapes from the liquid water. Such variation in surface tension results in the evaporation rate of water improved greatly after the dynamic magnetic treatment, especially in DTW-300. As mentioned above, the decreased surface tension of water after static magnetic treatment was also observed by some researchers. It can be concluded that the combination of dynamic and static magnetic treatment brings a "synergistic effect" on reduction in the surface tension of water. As a result, the proposed method in this study can enhance water evaporation rate effectively.

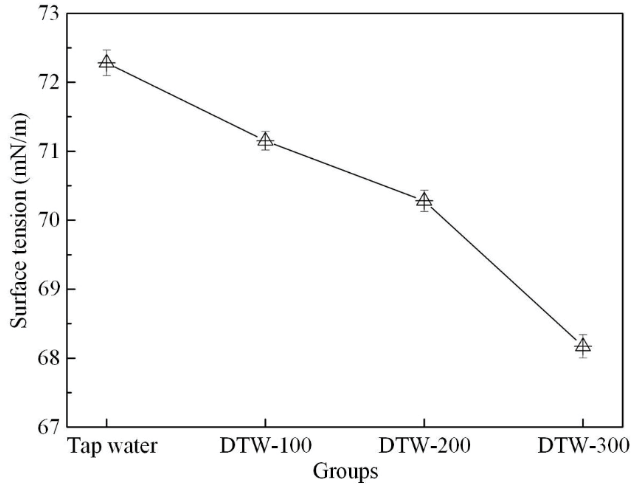


Fig. 7. Results of the surface tension of tap water and DTW.

5. Conclusions

In this study, the dynamic and static treatment of MF was combined together for enhancing the evaporation rate of water. The evaporation amount of water in SMF before and after the dynamic treatment was measured. The effect of MFS in the dynamic treatment on the evaporation rate of water was evaluated. The surface tension of water was determined to reveal the mechanism behind the variation in evaporation rate of water. The experimental results show that the single dynamic magnetic treatment increases the evaporation rate of water. The combination of dynamic and static magnetic treatment significantly improves the water evaporation rate, a maximum enhancement of 14.3% is obtained in this study. For the combination of dynamic and static magnetic treatment, the MFS of the dynamic treatment is an essential factor for evaporation rate, and the desirable evaporation rate of water is reached when the MFS of dynamic treatment is 300 mT. The mechanism for the enhancement of water evaporation is the dynamic and static treatment of MF generates a synergistic effect, which substantially decreases the surface tension of water, resulting in more water molecules escape from the liquid water. The proposed method is characterized as simple operation, low cost, and environmental friendliness, and further improves the production efficiency involving water evaporation. This method can be easily implemented in practical engineering. The findings in this study can provide a new and effective pretreatment approach for improving water evaporation rate.

Acknowledgments

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