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Effects of permanent magnetic field on calcium carbonate scaling of circulating water

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ABSTRACT

In this paper, experimental results on the effect of magnetic field on the precipitation process of calcium carbonate scale from hard water are reported. Permanent magnets with different magnetic flux densities are used for investigating the effect of magnetic field on induction time, electrical conductivity, total alkalinity, and turbidity of water sample. The magnetic flux density range of test equipment is 0.03–3.4 T. The induction time is found to be reduced after magnetic treatment. In other words, the existence of magnetic field increases the nucleation rate of calcium carbonate. The effect of water velocity on induction time is not pronounced. Magnetic field inhibits the reduction of electrical conductivity. The magnetic field inhibits reduction of bicarbonate content and the formation of calcium carbonate precipitation. Turbidity removal efficiency is increased from 60% without magnetic treatment to reach a maximum of 99.48% at magnetic flux density of 0.7 T. In the absence of magnetic field, this ratio was only 18.19% at 1.5 h and its maximum value was 39.14%. There is an optimal water velocity of 1.2 m/s and magnetic flux density of 0.7 T.

Keywords: Permanent magnetic field; Calcium carbonate; Scaling

1. Introduction

A common problem in both industrial and domestic water supplies is the formation of scale deposit, the control of which costs a lot (e.g. around £1 billion per year in china [1]). Traditionally, scale is removed by chemical methods, such as add corrosion inhibitor, scale inhibitor, and fungicide in circulating water. Chemical treatment method is effective, but it is easy to bring secondary pollution. Besides physical method of radiation, microwave treatment cannot be applied due to high energy consumption. Physical method and magnetic treatment are gradually used in industry due to good effect, low cost, and the absence of secondary pollution [2]. The physical treatment method presents a great advantage: we can avoid the use of chemicals, such as strong acids or polyphosphates which are expensive and can be harmful to human life or deleterious for the environment [3]. Calcium carbonate scaling is one of the most common fouling methods found in cooling water applications [4].

Magnetic water treatment is becoming an alternative to the chemical treatment in preventing scale formation in the industrial and some other

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commercial water systems [5]. Different magnetic and electromagnetic devices help to control calcium carbonate scaling formation, which are sold worldwide for domestic and industrial applications [6–9]. However, the mechanism is still not clear. Recent research on this mechanism mainly focused on the following aspects: (1) crystallization processes in solutions nucleation or crystal growth [5,9–11]; (2) crystal structure of precipitated $CaCO_3$ and the main component of precipitation [4,10,12–14]; (3) zeta potential of colloidal particles in electrolyte solutions [6,14–16]; (4) colloidal stability of aqueous dispersions, physicochemical properties of water, and electrolyte solutions such as the surface tension [3,7,8,17–20].

Madsen [21] studied the precipitation of inorganic salts under the influence of magnetic fields, and observed that the mean crystal size of calcium carbonate was reduced, when a static solution of sodium carbonate (Na_2CO_3) and calcium chloride ($CaCl_2$) was placed in a magnetic field of 2,700 Gs. Based on this, Madsen suggested that more nuclei had formed as the result of faster proton transfer from bicarbonate ions to water. The increased proton transfer rate resulted from the influence of magnetic field on proton spin. Wang et al. [22], using turbidity measurements, observed a faster precipitation (i.e. a higher rate of crystallization) and smaller crystals of calcium carbonate in the presence of a magnetic field of up to 8,000 Gs. Jiang et al. [23] pointed out that magnetic treatment can reduce pH value, which will significantly prevent the formation of scale. But, this conclusion is still controversial. Zhou et al. [24] investigated the effect of magnetic effect on the formation of $CaSO_4$−type scale. A simplified model of magnetic interaction was applied to quantitatively calculate the relationship between the magnetic effect and external magnetic field strength. The results showed that additional cohesion was generated by magnetic dipole between water molecules. This would incorporate more water molecules into the second hydration layer and reinforce the bond between ions. As a result, both the number and radius of molecules ion hydration will be increased. The stronger the effect of ion hydration, the more difficult it is to generate $CaCO_3$ spherical molecules. At the same time, the activity of water molecules will be weakened, which will make the dehydration process more difficult. This indicates that the amount of nuclei will be reduced and crystal growth will be promoted. Higashitani et al. [25] also found a reduction of nuclei amount with the influence of magnetic field. They reported that silicon hydration layer became thicker after magnetic treatment.

In the present study, artificial hard water was used to investigate calcium carbonate scaling primarily due to its easier preparation, faster time for scale formation, possibilities of higher calcium carbonate concentration, and more controlled initial water chemistry [3]. The experimental works which are presented in this paper were performed with a magnetic treatment equipment which proved its efficiency, but the scaling potentiality of the treated water was evaluated by inducing the calcium carbonate precipitation. To consider the variations of pH value and calcium concentration, it was possible to evaluate the effect of the magnetic treatment on the nucleation time. Furthermore, the effect of magnetic field on electrical conductivity, and the total alkalinity and turbidity removal efficiency were investigated. The objective of this study was to investigate the effect of permanent magnetic fields on scaling probability and water chemistry during the calcium carbonate scaling process.

2. Experimental facility and methods

2.1. Test equipment and water analysis

Fig. 1(a) shows the test facility used in the present study. The closed loop was composed of a heating water tank, water pump, water meter, permanent magnetic adjustable equipment, cooling water tank, three-port valve, valve, and filter device. Calcium carbonate scaling was wiped off by the filter device to prevent scaling deposit in the tube. The temperature of circulating water was reduced by passing cooling water in the tank. Water velocity was controlled by adjusting water meter, and its range was 0–2.3 m/s. The water velocity of the test was 0.6, 1.2, and 2.3 m/s, which is based on our own discretion and equipment limitation. Permanent magnetic adjustable equipment consisted of pairs of permanent magnets with north and south poles facing each other. The water passed through a pipe (50 cm long × 5 cm diam) inserted between the polar pieces in opposition of polarity. Each polar piece was the assembling of two rectangular permanent magnets (10×15 cm^2 and 20 mm thick). In this configuration, the magnetic flux density was perpendicular to the water flow. Different magnetic flux densities were gained by changing different magnets. Its range was 0.03–3.4 T. The magnetic flux density of experiment was 0.03, 0.7, 1.7, 2.65, and 3.4 T. The optimum combination of magnetic flux density and water velocity from among the present tested values was chosen and used to determine its effect on $CaCO_3$ scaling at different treatment times.

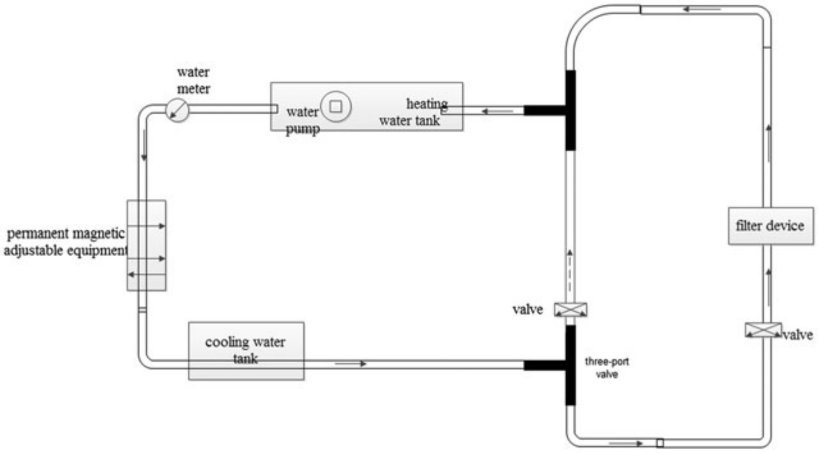

Fig. 1(a). Sketch of the set-up for the magnetic treatment of circulating water.

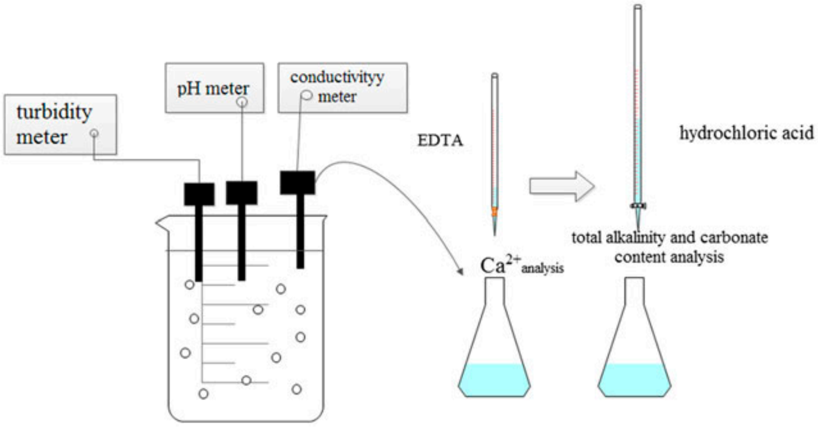

Fig. 1(b). Sketch of the set-up for water analysis.

Fig. 1(b) shows the process of water analysis including pH, electrical conductivity, calcium analysis, total alkalinity, and carbonic acid ion content. Total alkalinity was determined by titration with a standard solution using methyl orange as the indicator. Calcium hardness was determined by titration of EDTA using chrome black T as the indicator. Water analyses method is shown in Table 1.

2.2. Water preparation and experiment method

The artificial hard water in the present study was prepared by mixing appropriate amounts of $CaCl_2$ and Na_2CO_3 powders into $0.03\,m^3$ distilled water. Then, 2.22 g Na_2CO_3 was mixed with 6.24 g of reagent-type $CaCl_2$ in the $0.03\,m^3$ distilled water. It should be noted that in the present study, the initial water chemistry was the same for all tests. Two hundred milliliters of circulating water were taken to measure pH, electrical conductivity, temperature, calcium content, total alkalinity, and carbonate before adjusting for test condition. Then, after adjusting the magnetic flux density and water velocity for every other 1.5 h, 200 ml circulating water was taken to measure the same parameters one more time. All experiments were repeated three times and the average values were calculated. After each experiment, the tubing was thoroughly cleaned; first by circulating a low-concentration acid solution for about 0.5 h and then by deionised water for 10 min. Table 2 shows the value of magnetic flux density, magnetic treatment time, and water velocity in the present study.

Table 1
Water analyses method

Parameter	Method/device	Details
pH	pH meter	Delta320, Mettler-Toledo instrument
Electrical conductivity	Electrical conductivity meter	Delta326, Mettler-Toledo instrument
Turbidity	Turbidity meter	WGZ-200, Shanghai branch
Calcium analysis	Chemical analysis, EDTA titration	10 mmol/l calcium standard solution
Total alkalinity	pH indicator titration	0.025 mol/l standard solution of hydrochloric acid

Table 2
The selected value of magnetic flux density, time, and water velocity used in the present study

Magnetic flux density (T)	Magnetic treatment time (h)	Water velocity (m/s)
0	0	0.6
0.03	1.5	1.2
0.7	3	2.3
1.7	4.5	
2.65	6.0	
3.4	7.5	

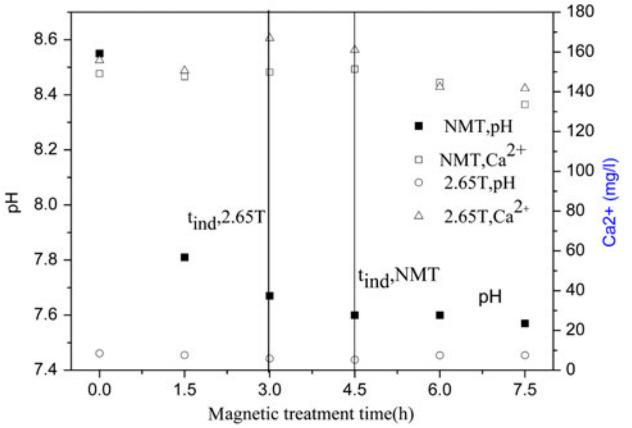

Fig. 2. Variations of pH and calcium ion concentration during precipitation test.

3. Results and discussion

3.1. Effect of magnetic flux density and water velocity on induction time

Fig. 2 shows the typical variations of the pH and the calcium concentration vs. time. The nucleation time (t_{ind}) evaluated from the two curves are in good agreement. The time at which a crystal starts to nucleate is called induction time. Induction time is the moment where calcium concentration begins to decline and pH begins to remain stable. From Fig. 2, it can be observed that the induction time varied from 0 to 7.5 h. The water velocity both are 0.6 m/s and magnetic flux density is 0 T(NMT) and 2.65 T, respectively. This figure demonstrates clearly that these two parameters, treatment time and application of the magnetic field, tend to reduce the induction time. It is equivalent to say that they increase the nucleation rate of calcium carbonate. It can be seen that the induction time of NMT is 4.5 h when the water velocity is 0.6 m/s. The pH value of water sample without magnetic treatment varies from 8.55 to 7.8. It drops steeply and then remains unchanged. The change of pH was easily understandable: calcium carbonate nuclei were formed because of the liberation of H^+ ions, and the pH began to decrease. It can be explained by Eqs. (1–3):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \tag{1}$$

$$H_2CO_3 = H^+ + HCO_3^- \tag{2}$$

$$Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + H^+ \tag{3}$$

The concentration of calcium ion begins to fall after 4.5 h. Induction time decreases to 3 h when the magnetic flux density is 2.65 T. After 3 h, the pH value almost remains constant and the concentration of calcium ion begins to decrease. In the present study, the deposition of $CaCO_3$ on the hot copper tube surface was expected to lower the calcium content of cooling water as the scaling process continues. In other words, when there is high $CaCO_3$ scale deposition, one could also expect a significant drop in calcium content and pH. The process of $CaCO_3$ precipitating is explained by Eqs. (4)–(7).

$$CaCO_3 \text{ saturated solution} \Leftrightarrow CaCO_3 \text{ supersaturated solution} \tag{4}$$

$$CaCO_3 \text{ supersaturated solution} \Leftrightarrow CaCO_3 \text{ molecular cluster} \quad (5)$$

$$CaCO_3 \text{ molecular cluster} \Leftrightarrow CaCO_3 \text{ nuclei of crystallization} \quad (6)$$

$$CaCO_3 \text{ nuclei of crystallization} \rightarrow CaCO_3 \text{ grain growth} \quad (7)$$

The process of $CaCO_3$ precipitation is mainly composed of these steps. Experimental researches focus on (5) and (7), which are calcium carbonate nuclei formation and growth. Induction times were reduced for magnetic treatment, which means the magnetic field promoted nucleation rate. According to Eq. (3) the inhibition of the reduction of pH by the magnetic field inhibited the $CaCO_3$ precipitation. It is reasonable that the magnetic field inhibits crystal particle growth. It is agreement with the results of Georges Maurin [2]. It can be explained by electrical double layer near the charged surface of particles. The aggregation of the $CaCO_3$ colloidal particles under the influence of electrostatic phenomena would contribute to accelerate the formation of crystal nucleus and the precipitation process.

To better compare, the induction times of different magnetic flux density is determined. In all cases, the water velocity was kept constant, 0.6 m/s. The measured induction times are listed in Table 3. In Table 3, the influence of the magnetic flux density on the induction time in the presence or the absence of magnetic field is illustrated. One can observe that in all cases, there was an optimum induction time of about 1.5 h and a magnetic flux density is 0.7 T, which respectively correspond to the smaller induction time and the higher nucleation rate. For a higher magnetic flux density, paradoxically the effect of magnetic field was less pronounced.

Table 3
Variations of induction time during various magnetic field intensity and a flow velocity of 0.6 m/s

Water velocity	Magnetic flux density (T)	Induction time (h)
0.6 m/s	0	4.5
	0.03	3
	0.7	1.5
	1.7	4.5
	2.65	3
	3.4	3

Table 4
Variations of induction time for different magnetic flux density and water velocity

Water velocity (m/s)	Magnetic flux density (T)	Induction time (h)
1.2	0	6
	0.03	4.5
	0.7	1.5
	1.7	3
	2.65	3
	3.4	3
2.3 m/s	0	6
	0.03	4.5
	0.7	3
	1.7	4.5
	2.65	3
	3.4	4.5

The influence of water velocity on the induction time was also investigated. Table 4 shows that the induction time is different for the same magnetic flux density. But, the induction time of both water velocities of 4.5 h when the magnetic flux density is 0.03 T. and the shortest induction time is 1.5 h when the magnetic flux density is 0.7 T; regardless of water velocity. It shows that nucleation rate is fastest for the magnetic flux density of 0.7 T. The effect is not pronounced with the increase of magnetic flux density. In the presence or not of magnetic field, induction times do not depend significantly on the water velocity.

3.2. Effect of magnetic flux density on electrical conductivity

Fig. 3(a) shows the change in electrical conductivity for different magnetic flux densities at a water velocity of 1.2 m/s. Electrical conductivity, without magnetic treatment drops from 1,100 at 0 h to 1,022 at 1.5 h, continues to decrease with the increasing time. It means that a lot of calcium carbonate precipitation is formed. In the presence of magnetic field, the reduction of electrical conductivity is inhibited. For example, only electrical conductivity at 1.5 h is lower than 0 h for a magnetic flux density of 0.7 T. This indicated that the electrical conductivity is related to the magnetic flux density. The effect is better with increasing magnetic flux density.

Fig. 3(b) shows the change in electrical conductivity in the presence of magnetic field (B = 0.7 and 1.7 T) or not for 1.5, 3, 4.5, 6, and 7.5 h at the water velocity of

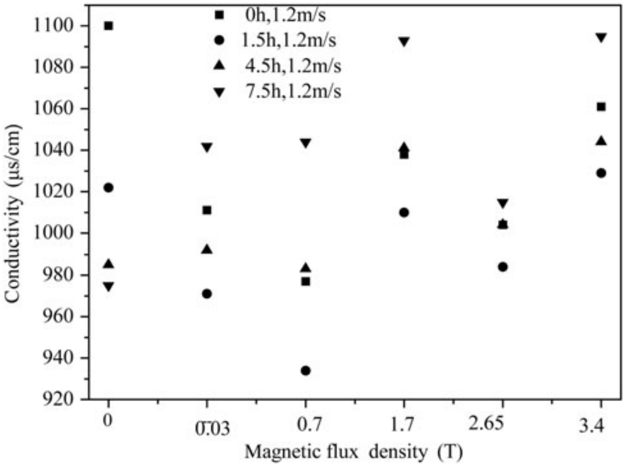

Fig. 3(a). Electrical conductivity for different magnetic flux density at water velocity of 1.2 m/s.

1.2 and 2.3 m/s. When calcium carbonate separates out from solution, the total ion content can reduce and the electrical conductivity value will change. According to the change trend of electrical conductivity, we used water sample's electrical conductivity after magnetic treatment to subtract electrical conductivity before treatment as y-coordinate, which depicts Δk. It is $\Delta k = k_1 - k_2$, where k_1 means electrical conductivity after magnetic treatment, and k_2 means electrical conductivity before treatment.

Fig. 3(b) shows that electrical conductivity sharp reduces without magnetic treatment at a water velocity of 1.2 m/s. It reduces from −80 at 1.5 h to −120 at 3 h, by 50%. k increases from −120 to −55 at 7.5 h. It can be explained that solution forms a lot of calcium carbonate precipitation, ion content is reduced, and electrical conductivity drops. Δk also reduces to the minimum value of −40 at 6 h and increases to 5 at 7.5 h. It can be seen that electrical conductivity obviously increases for magnetization and water relative to no magnetized sample appears. The difference in electrical conductivity attains its maximum value after 3 h for B = 0.7 T at the water velocity of 2.3 m/s. Δk changes from 50 at 1.5 h to 100 at 3 h. It slightly reduces after 4.5 h. It is worth noticing that k increases from −45 at 1.5 h to 60 at 7.5 h for magnetic intensity of 0.7 T, water velocity of 1.2 m/s, and by 105.

The changes in electrical conductivity following the application of magnetic field increase with the time. Water velocity does not have a significant effect on Δk. It is verified that Δk is not directly proportional to magnetic flux density and water velocity. The optimum value of density and velocity is existed. This phenomenon is hard to explain based on the available theories concerning magnetic field acting on water and aqueous solution. Indeed, more experiments should be conducted to better recognize this unusual behavior.

Because of the changes in electrical conductivity following the application of magnetic field, it seemed interesting to learn the influencing extent that how the stronger magnetic flux density influences electrical conductivity of magnetized water. Table 5 shows the

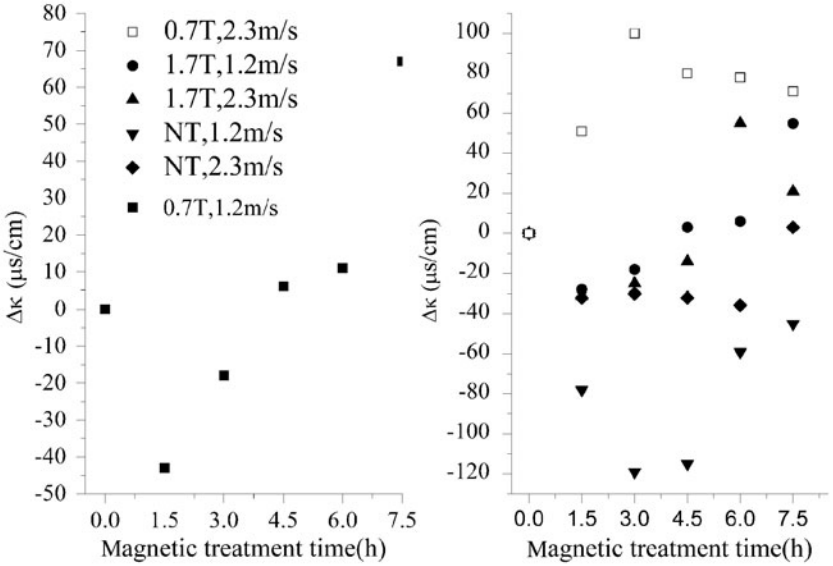

Fig. 3(b). Differences in electrical conductivity for magnetized and no-magnetized treatment at different flow rates.

Table 5
Variations of maximum difference value for different magnetic field intensity and water velocity

Magnetic flux density (T)	Water velocity (m/s)	Corresponding time (h)	Maximum difference value (μs/cm)
0	1.2	3	−120
0.7	1.2	1.5	−43
1.7	1.2	1.5	−31
0	2.3	6	−36
0.7	2.3	3	100
1.7	2.3	6	55

maximum difference that electrical conductivity after magnetic treatment to subtract electrical conductivity before treatment is shown at different magnetic fields and water velocity.

Table 5 shows maximum difference is shorter with increasing magnetic flux density for water velocity of 1.2 m/s. In other words, solution has not formed more calcium carbonate precipitation. It is proved again that magnetic field inhibits $CaCO_3$ crystal particle to grow up. The corresponding time means the time at which maximum difference value appears. Maximum difference changes a lot when the water velocity is 2.3 m/s. Maximum difference value are positive, which means that it improves the increase of the ion content of the solution. Magnetic field promotes nucleation rate due to the reduction of induction time after magnetic treatment**.** Due to magnetic field inhibits grain growth, the maximum difference reduces. In this paper, it was proved that magnetic treatment affects calcium carbonate crystallization by increasing the total precipitating amount. For the same magnetic flux density, maximum difference increases with water velocity. The reason may be that when the velocity is faster, retention time is shorter. Magnetization time is shorter because the corresponding time of maximum difference value is longer. Taking electrical conductivity and induction time into consideration, it is concluded that magnetic flux density of 0.7 T is the optimum value.

3.3. *Effect of magnetic flux density and magnetic treatment time on total alkalinity and carbonate*

For most water sample, alkalinity producing in water has five situations. To be explained distinctly, *P* indicates the consumed amount of standard solution of hydrochloric acid for phenolphthalein as indicator, *M* stands for the consumed amount of the standard solution of hydrochloric acid for methyl orange as indicator, and *T* is equal to *M* and *P*, which means the total consumption of standard solution of hydrochloric acid. When *P* is less than 1/2 T, it means $M > P$. Therefore, carbonate is equal to 2*P*, and bicarbonate is equal to T-2*P*. The Eqs. (8)–(10) can calculate total alkalinity, carbonate alkalinity, and bicarbonate alkalinity.

$$\text{total alkalinity (expressed as } CaCO_3, \text{mg/l)} = c(P+M) \times 50.05 \times 1{,}000/V \tag{8}$$

$$\text{carbonate alkalinity (expressed as } CaCO_3, \text{mg/l)} = c \times P \times 50.05 \times 1{,}000/V \tag{9}$$

$$\text{bicarbonate alkalinity (expressed as } CaCO_3, \text{mg/l)} = c(T-2P) \times 50.05 \times 1{,}000/V \tag{10}$$

where *c* is the solution concentration of hydrochloric acid (mol/l) and *V* is the volume of water sample (ml).

Fig. 4 shows that ▲ means the total alkalinity without magnetic treatment. It gradually declined with an increase of magnetic treatment time, and the concentration of carbonated root ion slightly reduced. Total alkalinity declines from 228 mg/l at 1.5 h to 205 mg/l at 7.5 h. It was reduced by 10.09%. Because the total alkalinity is the sum of the carbonated root and the bicarbonate, bicarbonate reduces. The solution mainly includes $CaCl_2$ and Na_2CO_3. Eqs. (11)–(12) may be the reason for the decrease of bicarbonate.

$$HCO_3^- + OH^- = CO_3^{2-} + H_2O \tag{11}$$

$$CO_3^- + Ca^{2+} = CaCO_3 \tag{12}$$

Water sample without magnetization form more carbonate, and it thus speeds up the formation of calcium carbonate precipitation. Concentration of total alkalinity slightly declines for $B = 0.7\,T$ and $v = 1.2$ m/s, and the concentration of carbonate increases. Total alkalinity declines from 238 mg/l at 1.5 h to 234 mg/l at 7.5 h. It shows magnetic field inhibits decrease of bicarbonate, and then inhibits formation of calcium carbonate precipitation. This gave the optimum values of magnetic flux density and water velocity with the optimum results in the

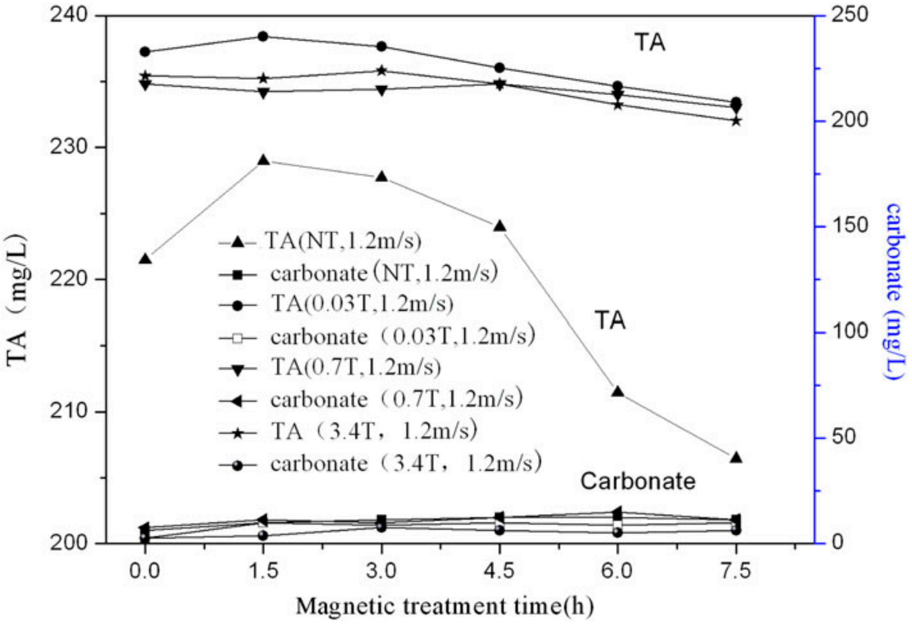

Fig. 4. Total alkalinity and carbonate content in the presence of magnetic treatment or not for water velocity of 1.2 m/s.

decreasing total alkalinity and carbonate. This phenomenon is still obvious at 3.4 T. Nevertheless, since 1941, it is known that hard waters contain various ionic associations such as $CaCO_3$ ion pair. Therefore, magnetic field can intervene on these ionic pairs, ionic complexes ($CaHCO_3^+$), and hydrated ions Ca^{2+}, HCO_3^- and CO_3^{2-}. Magnetic field induces faster proton transfer from hydrogen carbonate to water, due to proton spin inversion in the field of diamagnetic salts. The increased formation of CO_3^{2-} ions would explain the beneficial effect of magnetic filed on the amount of precipitate [2].

To compare the effectiveness of magnetization time, the experiments were conducted at $B = 0.7$ T, i.e. magnetized by permanent magnets for 3, 6 h. Total alkalinity and carbonate content at various levels of water velocity are plotted in Fig. 5. This figure demonstrated clearly that the application of the magnetic field significantly increased the concentration of total alkalinity, and had no effect on carbonate. For the three cases, the total alkalinity increased with an increase in velocity. It is also shown in Fig. 5 that the total alkalinity has no change for v = 2.3 m/s. For instance, the total alkalinity increased from 223 mg/l at 0 h to 226 mg/l at 3 h for v = 0.6 m/s, and almost had no change at 6 h. To compare with NMT, total alkalinity not only did not decline, but also increased. Carbonate content increased. Total alkalinity increased by 8 mg/l at 6 h for v = 1.2 m/s. It was also shown in Fig. 5 that the magnetization time effect on total alkalinity was less significant after 3 h. Total alkalinity kept constant for v = 2.3 m/s, no matter whether magnetization time was 3 or 6 h. This demonstrated clearly that magnetic field had no significant for total alkalinity at the highest flow rate. The actual mechanism of magnetic effect is not clear at the present time. We believe that the different total alkalinity was due to the difference in magnetic flux density and operation mode. This magnetic field effect on carbonate is less important for 3 and 6 h.

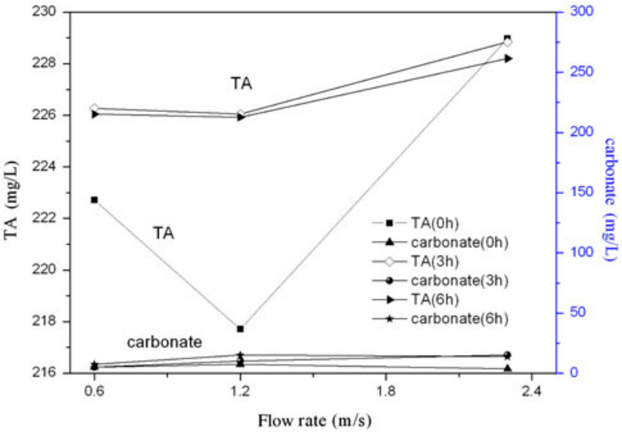

Fig. 5. Total alkalinity and carbonate between magnetized and no-magnetized at water velocity of 0.6, 1.2, and 2.3 m/s for $B = 0.7$ T.

3.4. Effect of magnetic flux density, time on turbidity removal efficiency

In this experiment, the effect of different magnetic flux density on the turbidity removal efficiency was investigated at water velocity of 1.2 m/s. Fig. 6 shows the change of turbidity removal efficiencies as a function of magnetic flux density. To better compare, DIFF indicate turbidity removal efficiencies using the following equation:

$$\mathrm{DIFF}\% = \frac{B_{7.5} - B_0}{B_0} \times 100\% \tag{13}$$

where B_0 means turbidity without magnetic treatment, and B_0 is turbidity magnetization after 7.5 h, respectively.

Fig. 6 is clear that turbidity removal efficiency is increased from 60% without magnetic field to reach a maximum of 99.48% for 0.7 T. There is no advantage of increasing magnetic flux density after 0.7 T. The magnetic field significantly decreased turbidity. The magnetic force increased turbidity removal efficiency, but it was not true the higher of magnetic flux density was always better. Magnetic field application has a magneto-hydrodynamic (MHD) effect. Lorenz forces exerted on charged species induce local convection movements in the liquid which could contribute to accelerate associations between ions or colloidal particles. Moreover, MHD phenomena induce eddy currents which flattened the fluid velocity profile in the tube. These can result in turbidity removal.

To investigate the effect of magnetic treatment time on the turbidity, a number of experiments were performed at different magnetic flux density for water velocity of 1.2 m/s. Fig. 7 shows that the turbidity decline, which was observed between the beginning and the end of without magnetic treatment, did not exceed two units. It means the process does not induce turbidity decline, and no $CaCO_3$ precipitation can be removed. It was clear that turbidity at magnetic flux density of 0.03 T reduced from 13 for 0 h to reach a minimum of 0.5 at 4.5 h, by 96.15%. There is no advantage of reduction after 4.5 h. The same is true for the effect of increasing magnetic flux density on the turbidity removal. The turbidity of 0.7 T reduced from 17.5 at 0 h to a minimum value of 0.2 at 4.5 h, by 98.85%. It decreased from 1.5 to 0.2 when magnetic treatment time varied from 1.5 to 7.5 h. As the magnetic flux density increased, the extent of turbidity decline did not increase. The value reduced by 94.44 and 96.4% for B = 1.7 and 3.4 T, respectively. The phenomenon was agreed with the result of DIFF. It may have the optimum magnetic flux density for the equipment. The effect is the greatest for certain magnetic flux density, magnetic treatment time, and water velocity. Considering its higher turbidity removal efficiency, less reducing of total alkalinity, and the shortest induction time, the optimum magnetic flux density and water velocity was 0.7 T and 1.2 m/s, respectively.

Besides magnetic flux density and magnetic treatment time, the influence of water velocity on turbidity was also investigated. Fig. 8 shows turbidity obtained for the systems in the absence and the presence of a magnetic field is compared at different levels of water

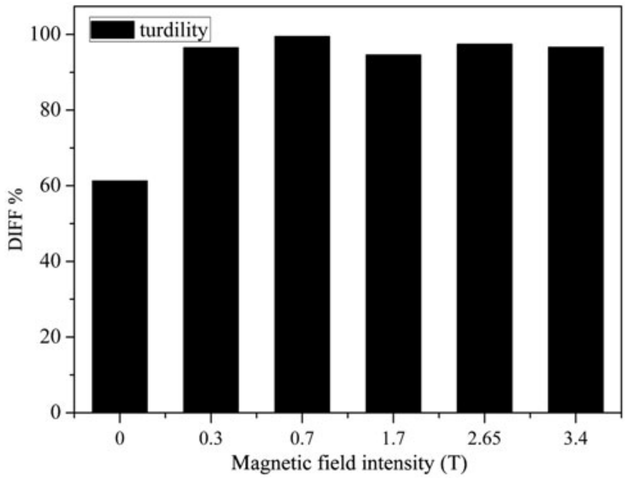

Fig. 6. DIFF during different magnetic flux density for v = 1.2 m/s.

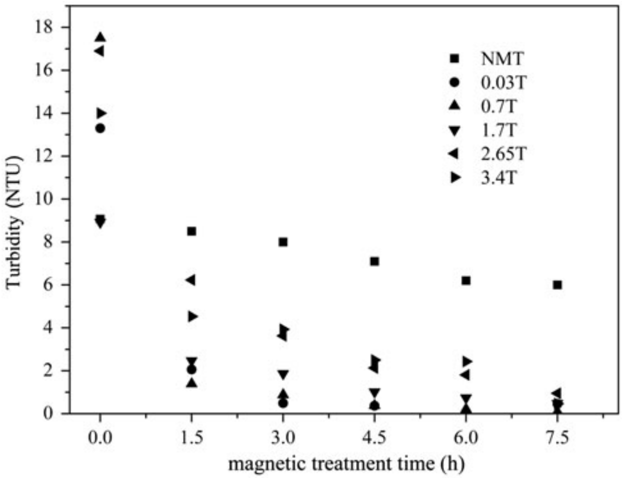

Fig. 7. Turbidity for different magnetic flux density for v = 1.2 m/s.

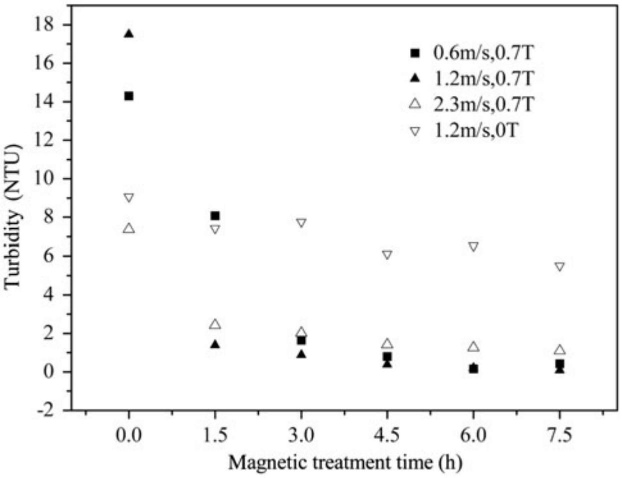

Fig. 8. Variations of turbidity for different water velocity for $B = 0.7\,\text{T}$.

velocity and magnetic treatment time, varying from 0.6 to 2.3 m/s and from 0 to 7.5 h, respectively. The turbidity reduced with increasing time and tended to remain constant at longer time for both cases. In the absence of magnetic field, turbidity slightly reduced with time. It was clear turbidity reduced from 9.07 at 0 h to reach a minimum of 5.52 at 7.5 h, by 39.14%. Turbidity did not reduce much after 1.5 h. The application of magnetic field encouraged decline of turbidity. Turbidity reduced from 14.4 at 0 h to 8.08 at 1.5 h for water velocity of 0.6 m/s, by 43.89%. It reached the minimum value of 0.15 at 6 h, and remained constant at longer time. To compare with water velocity of 0.6 m/s, turbidity declined from 17.5 at 0 h to 1.39 at 1.5 h, was about 92.06%. This ratio was only 43.89% for water velocity of 0.6 m/s, almost was double. It reached the minimum value of 0.09 at 7.5 h, about was 99.48%. In the absence of magnetic field, this ratio was only 18.19% at 1.5 h and 39.14% for the maximum value. A slight difference for 2.3 m/s was that the extent of decline was not bigger than water velocity of 1.2 m/s. They give evidence that there is an optimal water velocity (about 1.2 m/s), which corresponds to larger turbidity removal efficiency, less decrease of bicarbonate, and shorter induction time.

4. Conclusions

The present results show that the circulation of water in a permanent magnetic field reduces the nucleation induction time and extent of decline of total alkalinity, inhibits reducing of electrical conductivity, and has larger turbidity removal efficiency. Magnetic treatment increases the nucleation rate of calcium carbonate, and inhibits crystal particle growth. The existence of magnetic field increases the nucleation rate of calcium carbonate. The effect of water velocity on induction time is not pronounced. The magnetic field inhibits bicarbonate content to decrease, and thus inhibits formation of calcium carbonate. Magnetic field significantly reduces turbidity. Turbidity removal efficiency is increased from 60% without magnetic treatment to reach a maximum of 99.48% at magnetic intensity of 0.7 T. There is an optimal water velocity of 1.2 m/s and magnetic flux density of 0.7 T.

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Nomenclature

t_{ind}	induction time (h)
Δk	difference value of electrical conductivity (μs/cm)
P	consumed amount of standard solution of hydrochloric acid for phenolphthalein as indicator (ml)
M	consumed amount of standard solution of hydrochloric acid for methyl orange as indicator (ml)
T	total consumption of standard solution of hydrochloric acid (ml)
DIFF	turbidity removal efficiencies (dimensionless)
B	magnetic flux density (T)
v	water velocity (m/s)
TA	total alkalinity (mg/l)

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