

ANTI-SCALE MAGNETIC METHOD AS A PREVENTION METHOD FOR CALCIUM CARBONATE SCALING

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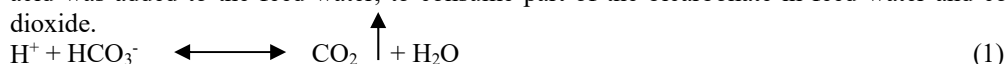
Abstract: The effect of anti-scale magnetic method (AMM) in retarding scaling deposition is confirmed by many researchers, to result in new crystal morphology, crystal which has the tendency to remain suspended more than precipitated. AMM is considered as an economic method when compared to other common methods used for scale prevention in desalination plant as acid treatment and addition of antiscalant. The current project was initiated to evaluate the effectiveness of AMM in preventing calcium carbonate scaling. The AMM was tested at different flow velocities (1.0, 0.5, 0.3, 0.1, and 0.003 m/s), different operating temperatures (50, 70, and 90°C), different feed pH and different magnetic field strength. The results showed that AMM was effective in retarding calcium carbonate scaling deposition, and the performance of AMM depends strongly on the flow velocity. The scaling retention time was found to be affected by the operating temperatures, flow velocity, and magnetic strength (MS), and in general, it was found that as the operating temperatures increased the effectiveness of the AMM in retarding calcium carbonate (CaCO₃) scaling increased.

Key Words: Magnetic field strength, flow velocity, scale retention time.

Introduction

Scaling is considered to be the biggest operating problem in desalination plants. The deposition of scales can lead to a decrease in the operating efficiency, and equipment life, as well as increase in the maintenance cost and energy consumption. Calcium carbonate (CaCO₃) scaling is considered as the most common scale in all desalination plants especially in reverse osmosis plant and in multistage flashing desalination plants. Therefore, it has received since special attention in desalination plant and at different operating temperatures (Segnit et al., 1962; Langmuir, 1968; Brecevic and Nielsen, 1989; Cubillas et al., 2005; Tarek et al., 2012; Chaussemier et al., 2015). CaCO₃ can be precipitated at three different polymorphs such as calcite, vaterite, and aragonite. Aragonite is considered as the easiest form of CaCO₃ and can be removed by flushing with water, because it is a soft scale; while calcite is a hard scale and it could usually be avoided by using antiscant or addition of acid. Aragonite is known with a unique morphology or crystal shape, which makes it be suspended more time than calcite scale. Furthermore, the solubility of aragonite is more than the solubility of calcite at the same temperature and condition (Morse et. al., 1980).

Acid addition is considered as a reliable method to prevent calcite scaling in desalination plants, where acid was added to the feed water, to consume part of the bicarbonate in feed water and convert it to a carbon dioxide.



This type of treatment method will result in shifting reaction 2, which is responsible in the precipitation of CaCO₃ to the left side, and prevents precipitation of CaCO₃.

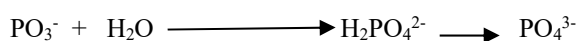


However, acid addition treatment method is always accompanied with corrosion problems and requires special care and precautions. Furthermore, acid cleaning forces the operators to shut down the plant, which could lead to less productivity and low availability. Antiscalant is also considered as a reliable method to prevent calcite precipitation inside desalination plants.

Scale inhibitor can also be considered as a reliable method used for a long time in desalination plant to control CaCO₃ scaling. Antiscalant is a chemical impurity that could modify or change the shape, size, and morphology of crystal formed during crystallization or scale formation processes (Greenlee et. al., 2011).

Polyelectrolytes as polycarboxylate, polyacrylates and polyphosphate have been reported as efficient inhibitors that could control CaCO_3 precipitation, by reacting with mineral nuclei to disrupt the crystallization process and keep the crystal particles dispersed in the scaling solution (Chauhan et. al., 2012). Other types of antiscalant have the ability to retard the crystal growth rate to suppress the scale formation, and then control the scaling processes. The threshold inhibitors are special additives, where threshold inhibitors can retard scale precipitation for a sufficiently long period of time, and the scale will precipitate outside the desalination system. The influence of antiscalant on the precipitation of CaCO_3 was investigated by many authors at different operating pH, and the result confirmed the relation between the functional group in the Antiscalant and increasing the induction time (β), which is the time required for precipitation of CaCO_3 (Amjad et al., 1994; Tarek et al., 2012).

Phosphonate antiscalant additives can be classified to be protonated phosphonate group (PO_3H^-) and fully dissociated group (PO_3^{2-}) that work according to adsorption model, where it can inhibit the growth of crystal by adsorption of the reactive surface site. At present, there are various types of phosphonate antiscalant chemicals, such as condensed polyphosphate, organo phosphate, and polyelectrolyte phosphate; however under neutral pH and low temperatures, linear polyphosphonates undergo relatively slow hydrolysis, and the rate of hydrolysis will increase as the operating temperature increases (Gryta, 2012). Furthermore, it is well-known, that special care must be taken to avoid hydrolysis of sodium hexameta phosphate (SHMP) antiscalant in dosing tank, where the hydrolysis process can be described in the following equation.



the hydrolysis will result to losing the effectiveness of the antiscalant in preventing scaling deposition. Furthermore, hydrolysis process can create a phosphonate scaling risk as illustrated in the following equation



However, high cost is a problem. It has been calculated that the cost of antiscalant chemicals accounts for about 10% in the production of freshwater in Dalian (Li Hai Yan et. al., 2006). In Kuwait, the annual cost for using a low concentration (not exceeding 3 mg/l) of antiscalant chemicals, is about KD0.95 million (MEW, 2010). This annual cost is expected to increase as the production of desalination plant increases.

Even so, Antiscalant chemicals play an important role in preventing CaCO_3 precipitation in reverse osmosis system; they are prone to enhance biofilm growth on reverse osmosis membrane by either altering the membrane surface properties or by serving as nutritional source for microorganisms (Sweity et. al., 2013). In addition, many types of chemical antiscalants on the market are harmful to the environment, and could result to serious environmental influence (Chauhan et. al., 2012). Because of this, researchers have looked for a new promising treatment method referred to as anti-scale magnetic treatment method, which is a nonchemical treatment method, and it is expected to reduce the operating cost of desalination plant. Anti-scale magnetic method (AMM) is a physical pretreatment method, which has been applied as a controlling and/or preventing tool for several decades for the deposition of scale in the domestic and industrial water systems.

Although the operating cost of AMM is very low when compared to that of chemical antiscalant method, the AMM is still not totally accepted by the scientific research community. The main reason for that is the lack of repeatable data, where the AMM was reported to work in some applications and not in the others. Furthermore, until now a few and limited researchers have proposed a scientific theory, explaining the work of AMM. In the last few years, the attention to AMM had increased as an attractive, low cost, treatment method, to prevent scaling deposition in desalination plant. A literature survey has been conducted at KISR on the effectiveness of AMM in preventing CaCO_3 scaling. It was concluded that the AMM can be considered as an effective method in controlling CaCO_3 scaling (Ben Salah, 2015; Cefalas et. al., 2010; Alimi et. al., 2009; Eliassen et al. 1985; Hasson and Bramson, 1985; Baker et. al., 1997; Sohnel and Mullin, 1988; Barrett and Barsons, 1998). Moreover, the result of literature survey confirmed that the AMM cannot totally prevent the formation of CaCO_3 crystals, but it can affect the scale formation process by increasing the retention or conducting time, producing crystals with different morphology (aragonite morphology), higher tendency for suspension and smaller in sizes, which can be carried out away with the brine water flow without Antiscalant treatment. Furthermore, it was found that the effectiveness of the AMM method in preventing precipitation of CaCO_3 was strongly affected by the chemical properties of the scaling solution, magnetic field strength (MFS), water temperature, and flow velocity (Busch et. al., 1986; Biochenko et. al., 1977; Gryta, 2011; Cai et. al., 2009; Gabrielli et al., 2000). Because of the lower operating cost of AMM and the encouraging results obtained from the literature survey, AMM was tested at desalination research plant (DRP), to assess the effectiveness of the AMM in retarding CaCO_3 scaling deposition or increasing the induction time (β) at different operating

temperatures, different feed water pH and different MFS to identify favorable operating conditions for effective CaCO₃ scale prevention. The chemical composition of Kuwait seawater used in the experiments is shown in Table 1, where about 51% of Kuwait seawater showed chloride ions and 29.4% sodium ions. Sulfate ions also compose a high percentage of Kuwait seawater. Scaling of CaCO₃ is the dominated scale expected to precipitate when Kuwait seawater is concentrated to one or more concentration factor, as expected by Staff and Davis saturation index, followed by scaling of calcium sulfate, barium sulfate, and strontium sulfate, but with less amount than CaCO₃ scaling.

Table 1. The Chemical Composition of Seawater at Doha Site

| Parameter | Concentration (mg/l) | % of TDS |
|--------------------------------------|----------------------|----------|
| pH | 8.28 | |
| Temp (°C) | 27.38 | |
| Conductivity (ms/cm) | 61.8 | |
| TDS (mg/l) | 48529 | |
| Turbidity | 0.54 | |
| Na ⁺ (mg/l) | 16353 | 29.408 |
| Ca ²⁺ (mg/l) | 1030 | 1.25 |
| HCO ₃ ⁻ (mg/l) | 130 | 0.327 |
| Cl ⁻ (mg/l) | 25208 | 50.8 |
| Mg ²⁺ (mg/l) | 1536 | 3.53 |
| SO ₄ ²⁻ (mg/l) | 4429 | 9.49 |
| Ba ²⁺ (mg/l) | 0.38 | |
| K ⁺ (mg/l) | 589 | 1.08 |
| Sr ²⁺ (mg/l) | 13 | 0.0308 |
| PO ₄ ³⁻ (mg/l) | 0.23 | 0.0005 |

Experimental Procedures Description

The AMM testing unit was shown in Fig. 1. The test unit primarily consists of two tanks, A and B, fabricated from glass sheets and located inside two water baths to control the temperature of the tested solution. The testing unit also contained a variable speed pump, needle valves to control the flow, thermometers, a pH adjustment section, and a magnetic field section. The magnetic field section contains a permanent antiscalant magnets treatment unit (AMT) as shown in Fig. 1 with north and south facing each other, as a source for the magnetic treatment around the pipe. The magnets were positioned orthogonally to the direction of the flow of fluid inside the pipe. Pairs were changed according to the magnetic field strength required. A Tesla meter was used to measure the strength of the magnetic field in each experiment. An automatic titrator, ion chromatography, spectrophotometer DRL/2000, and other instruments were used for analyzing scaling ions such as Ca²⁺ and HCO₃⁻ ions at the Doha Research Plant (DRP).

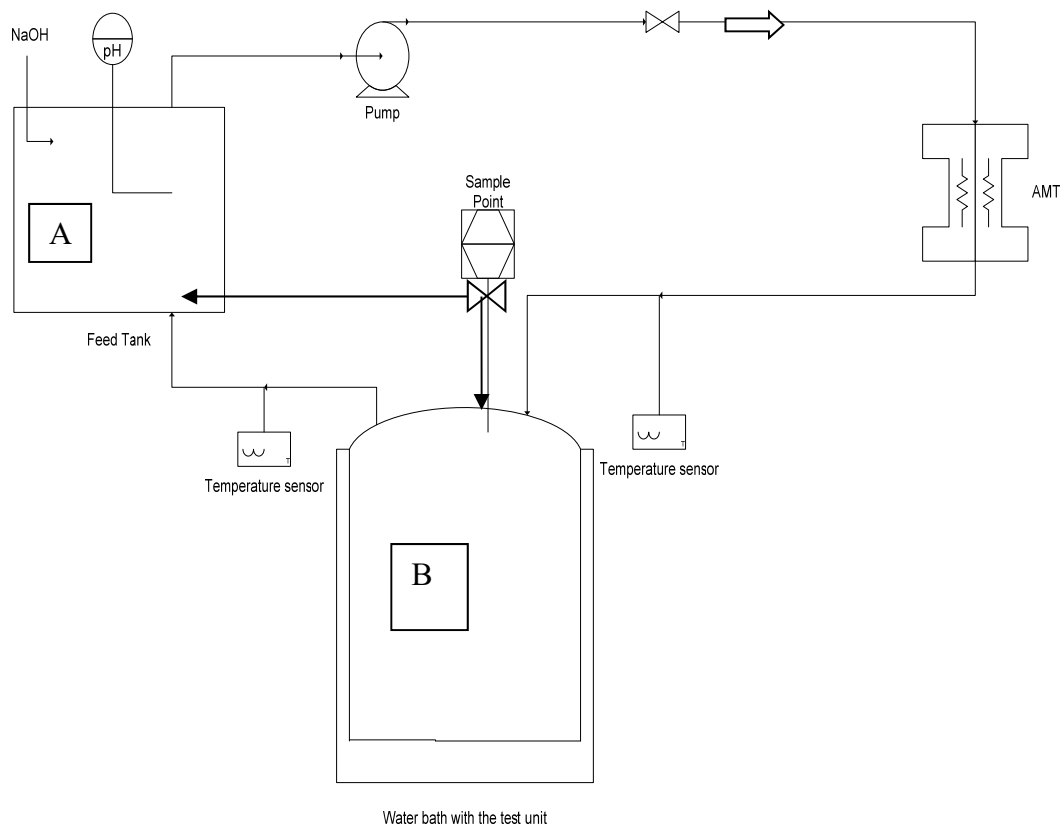


Fig.1. The antiscalant magnetic treatment testing unit.

The two tanks, A and B, are connected to each by a valve and a variable speed pump, which was used to pump the test solution from tank A to tank B, and to circulate the test solution through the magnetic fields at a controlled flow velocity. Both tanks A and B were installed inside a water bath to enable temperature controlling during the tests. Two types of solutions were mixed to prepare the required precipitated salt. Calcium carbonate precipitated scaling (CaCO_3) was prepared by mixing two solutions, which are 0.5 M of CaCl_2 and 0.5 M of Na_2CO_3 . Na_2CO_3 solution was considered as the base solution for preparing CaCO_3 scaling. Hence, the base solution was prepared at tank A; while CaCl_2 was prepared at tank B. First, the pHs of both tested solutions were adjusted to a desirable value using acid. Then, the temperatures were heated to a required testing temperature before mixing the two solutions, using the water baths at both tanks A and B separately. Then, the base solution was circulated through the AMT unit to be magnetically treated without mixing with CaCl_2 solution in Tank B, using a controlled valve and variable speed pump, for almost one hour. Then, the solutions were mixed, and the mixing time was considered as time zero for scale formation, and then, the samples were drawn from tank B every minute for bicarbonate analysis to test the effectiveness of the AMT unit in retarding scale deposition and increasing β . Thus, three MSF were tested (0T, 0.48T and 0.96T), three operating temperature (50, 70 and 90 °C), two PH values (8.3 and 9.5) and different flow velocities (1.0, 0.5, 0.3, 0.1 and 0.03 m/s)

Results and Discussions

Calcium Carbonate Scaling

The performance of AMM in retarding CaCO_3 at a pH of 8.3 and variable magnetic field and operating temperatures, are shown in figs. 2 to 13. Figures 2, 3, and 4 shows the performance of AMM at 0.5 m/s flow velocity, while Figs. 5, 6 and 7 show the performance of AMM at a flow velocity of 0.3 m/s. However, the flow velocity of 0.1 and 0.03 is shown in Figs. 8 to 10 and Figs. 11 to 13 respectively.

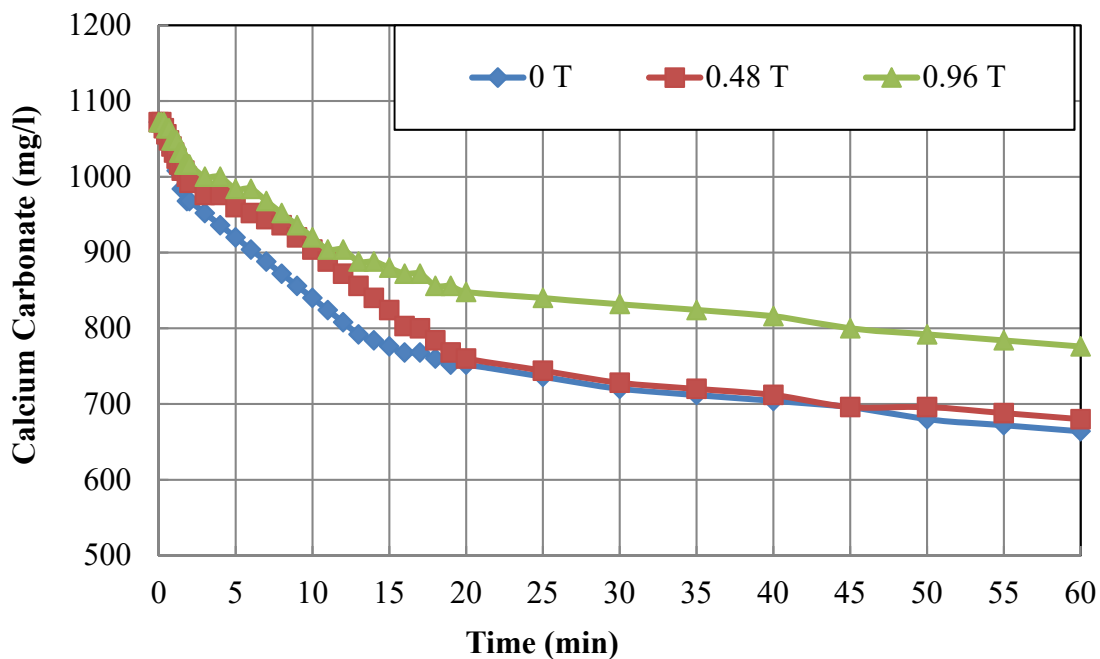


Fig. 2. Calcium carbonate concentration at 0.5 m/s velocity, pH 8.3 and 50°C at different magnetic field.

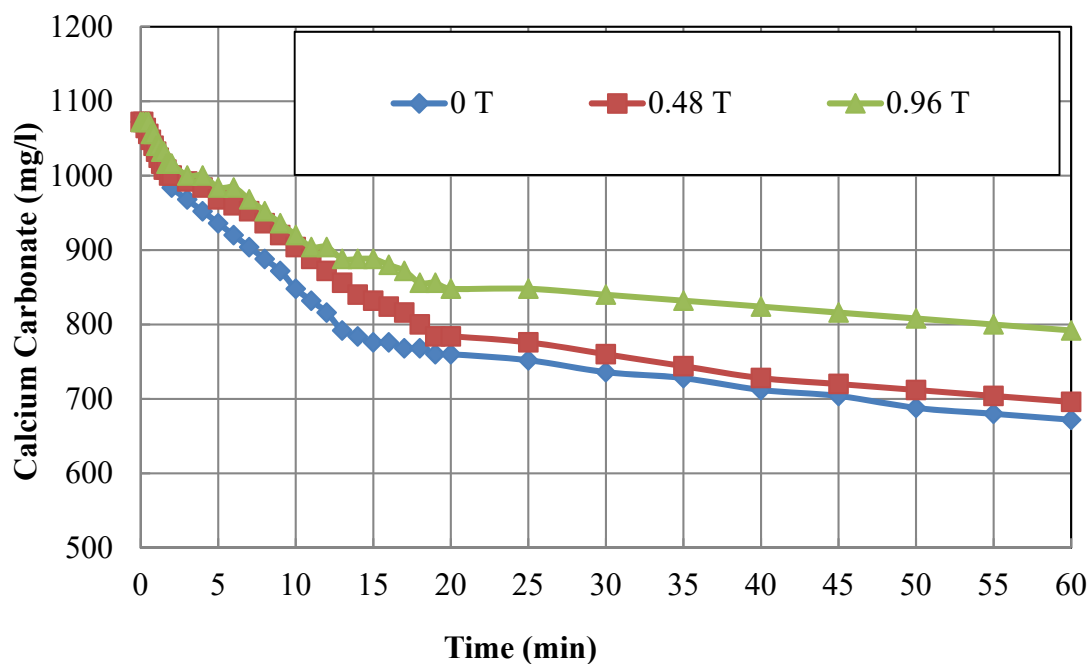


Fig. 3. Calcium carbonate concentration at 0.5 m/s velocity, pH 8.3 and 70°C at different magnetic field.

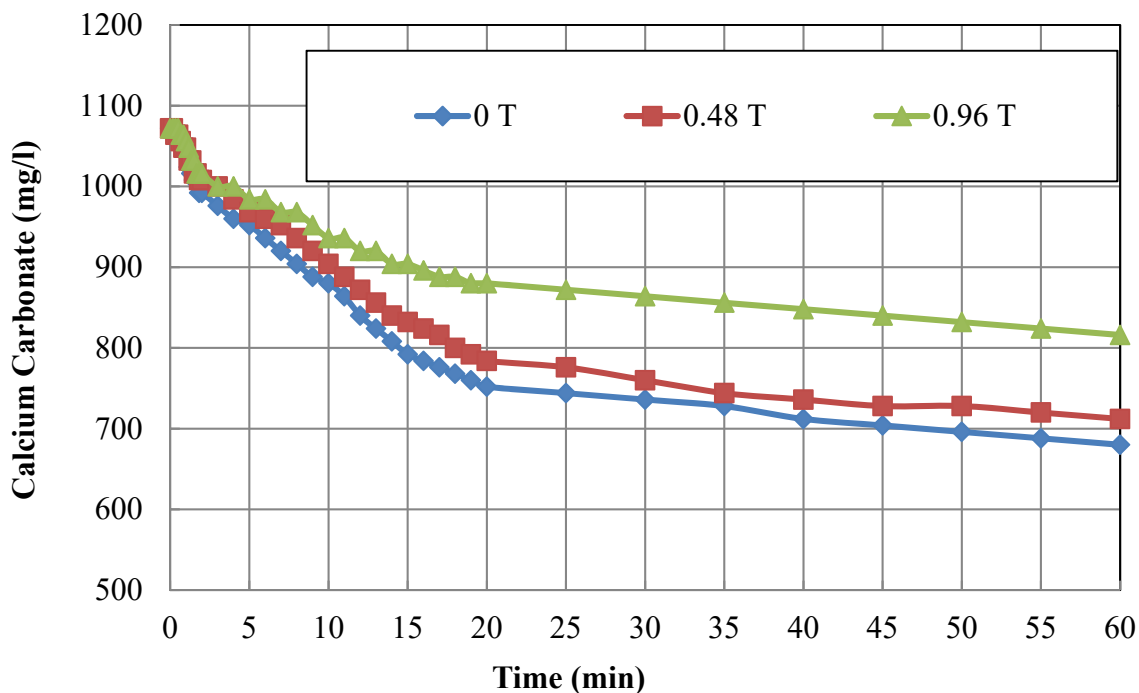


Fig. 4. Calcium carbonate concentration at 0.5 m/s velocity, pH 8.3 and 90°C at different magnetic field.

Performance of Magnetic Treatment Method in Retarding Calcium Carbonate at a Flow Velocity of 0.5 m/s. The AMM was tested at three magnetic field strength which are 0 Tesla, (without magnetic treatment method), 0.48 Tesla and 0.96 Tesla. Although the differences between the three magnetic field is not too much clear in Figures 2 to 4. However, it is clear that the ATM decreased the potential for calcium carbonate scaling, and the power for retarding calcium carbonate by AMM can be increased when the applied magnetic field strength (MFS) is increased.

The AMM increased β for calcium carbonate scaling at a concentration of 1000 mg/l of HCO_3^- from less than 3 min to 5 min at 0.96 T magnetic fields. Moreover, it can retard the carbonate scaling at a concentration of 800 mg/l of HCO_3^- for about 45 min as shown in Fig. 2, when compared to 12 min without applying AMM with increment equal to 2.75 times. The increment in β is calculated as follows:

$$\text{Increment in } \beta = \frac{\text{The retention time } \beta \text{ under AMM} - \text{retention time } \beta \text{ without AMM}}{\text{Retention time } \beta \text{ without AMM}}$$

Thus, it is clear that AMM is a selective treatment. However, knowing that the bicarbonate concentration in Kuwait seawater does not exceed 200 mg/l (Salman et. al., 2013), this implies that the AMM could be effective in retarding calcium carbonate scaling. Figs. 3 and 4 show the performance of AMM in retarding calcium carbonate concentration under pH 8.3 and flow velocity of 0.5 m/s and a temperature of 70°C and 90°C. Both figures show that the AMM could increase β for about 50 min instead of 12 min without AMM at a concentration of 800 mg/l of calcium carbonate scaling, which represent an increment of 3.16 fold as shown in Figs 3 and 4 under 0.96 T. β was increased to 60 min when the operating temperature was increased from 70°C to 90°C as shown in Fig. 4.

Performance of Magnetic Treatment Method in Retarding Calcium Carbonate at a Flow Velocity of 0.3 m/s. Figs. 5, 6, and 7 show the performance of AMM at different operating temperatures and different magnetic fields under 0.3 m/s of flow velocity.

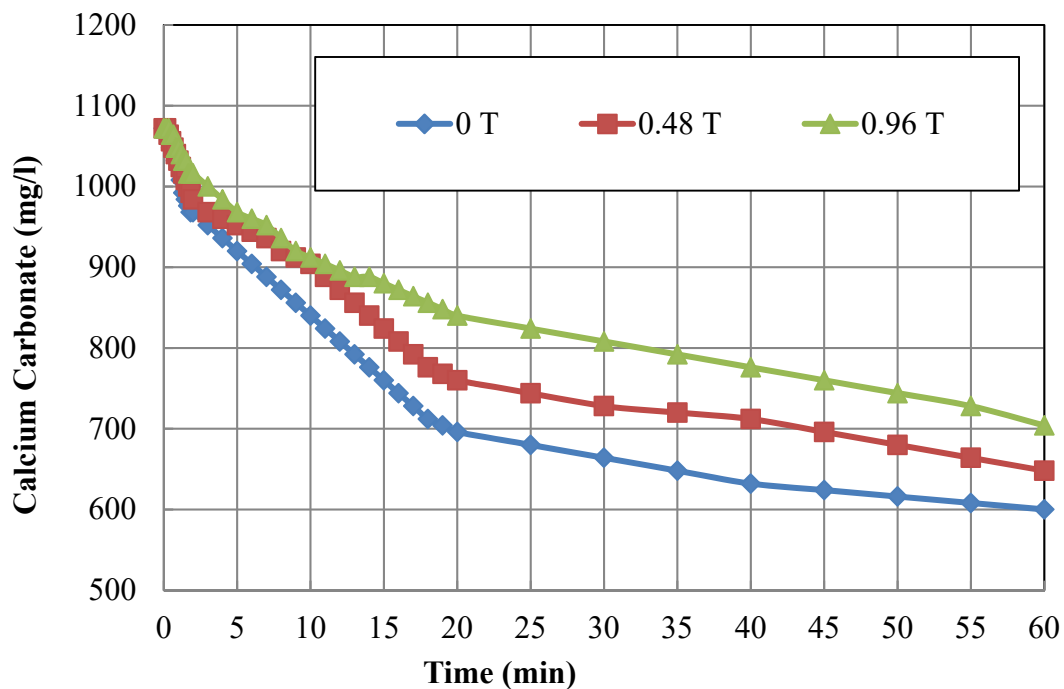


Fig. 5. Calcium carbonate concentration at 0.3 m/s velocity, pH 8.3, and 50°C at different magnetic field.

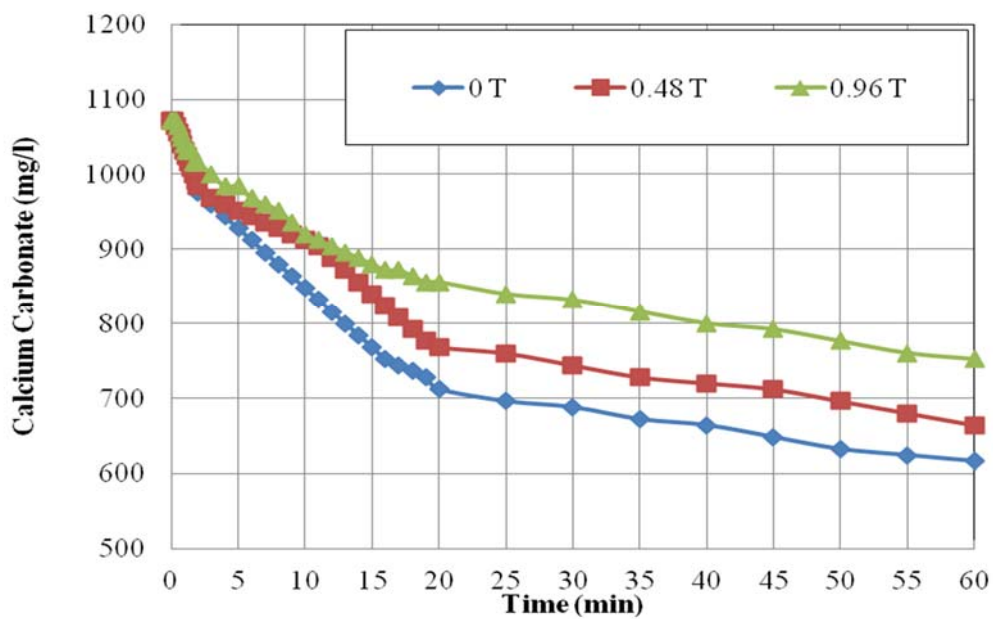


Fig.6. Calcium carbonate concentration at 0.3 m/s velocity, pH 8.3 and 70°C at different magnetic field.

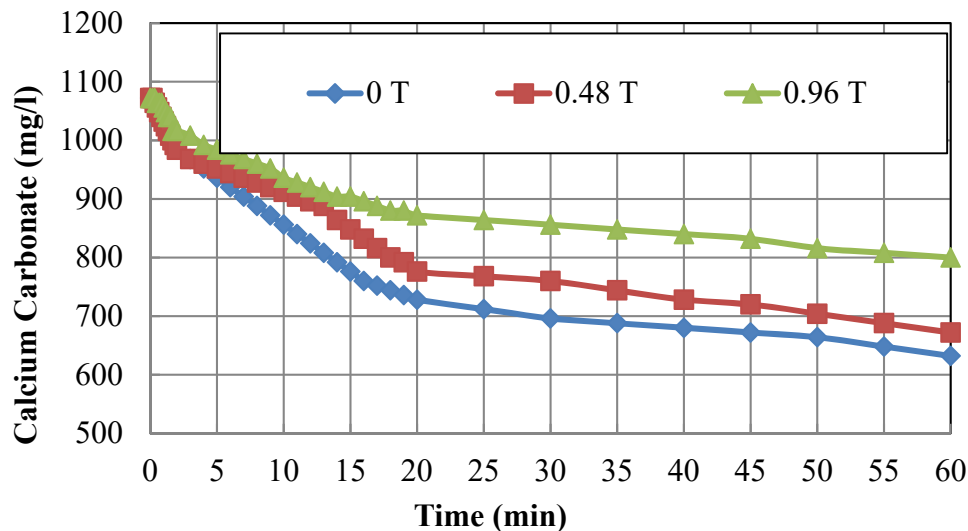


Fig.7. Calcium carbonate concentration at 0.3 m/s velocity, pH 8.3 and 90°C at different magnetic field.

From Figs 5, 6, and 7, it is clear that the AMM succeeded in increasing the retention time from 11 min at 800 mg/l of calcium carbonate concentration to about 35 min at 0.96 T and an operating temperature of 50° C as shown in Fig. 5. Moreover, β was increased from 12 min without AMM to about 40 min at an operating temperature of 70°C and 0.96 T as shown in Fig. 6. The β at 800 mg/l of calcium carbonate concentration was increased from 14 min to 55 min as shown in Fig. 7.

Performance of Magnetic Treatment Method in Retarding Calcium Carbonate At a Flow Velocity of 0.1 m/s. Figs. 8, 9, and 10 show the performance of AMM at different operating temperatures and different magnetic fields under 0.1 m/s flow velocity.

From Figs. 8, 9, and 10, it is clear that the effective concentration level was decreased from 800 mg/l to about 700 mg/l, where noticeable rise in retention time can be found. The increment in β at 800 mg/l was almost small and did not exceed 7 min at 0.96 T and an operating temperature of 90° C. However, at a concentration of 700 mg/l, marked rise in retention time β was noticed. This implies that the performance of AMM decreased strongly, with a decrease in flow velocity, than that of a reduction in operating temperatures.

The AMM succeeded in increasing the β from 17 min at 700 mg/l of calcium carbonate concentration to about 35 min at 0.96 T and an operating temperature of 50° C as shown in Fig. 8. Moreover, the retention time β increased from 19 min. without AMM to about 35 min. at an operating temperature of 70°C and 0.96 T as shown in Fig. 9 at the same level of calcium carbonate concentration. However, at 90°C as shown in Fig. 10, the retention time β at 700 mg/l of calcium carbonate concentration increased from 19 min to 40 min, which is an increase of 110.5 %.

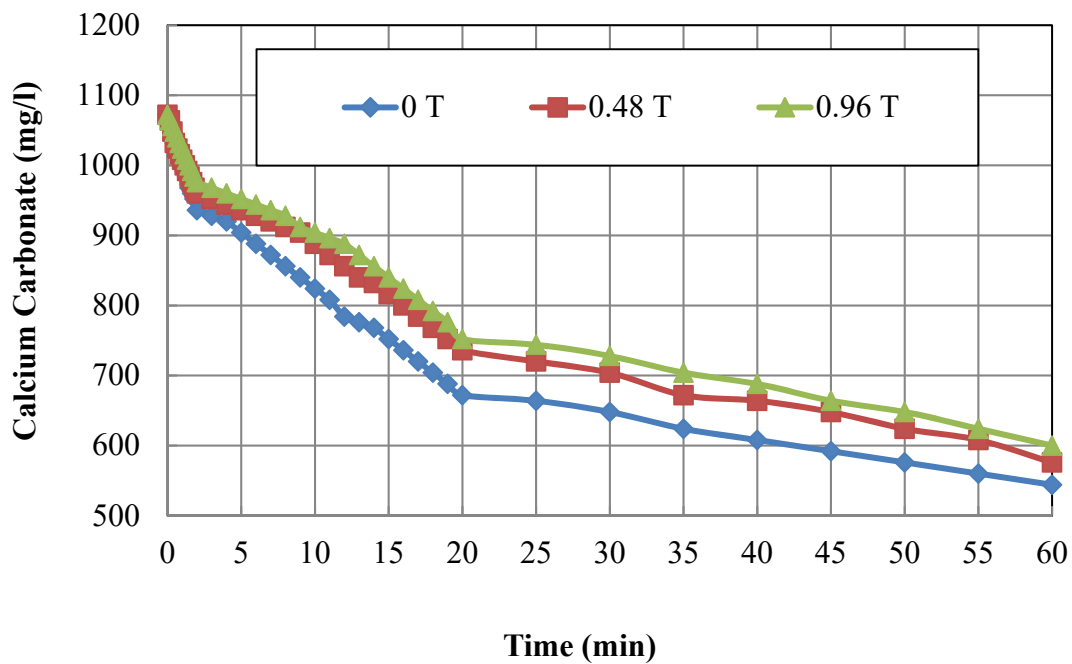


Fig.8 . Calcium carbonate concentration at 0.1 m/s velocity, pH 8.3 and 50°C at different magnetic field.

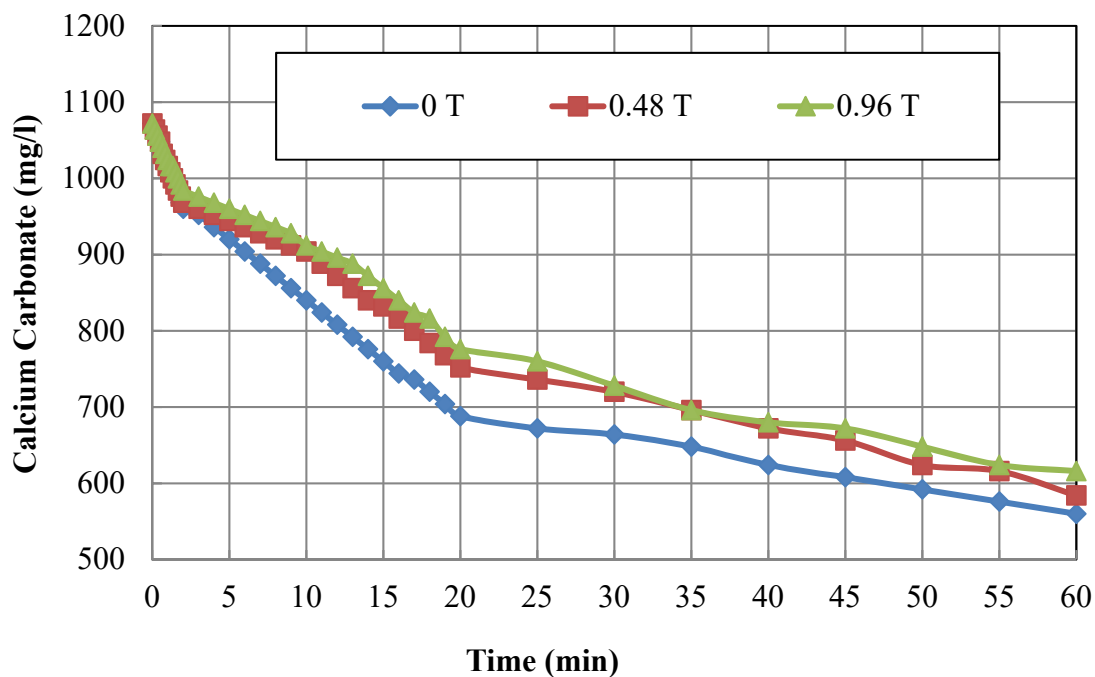


Fig.9. Calcium carbonate concentration at 0.1 m/s velocity, pH 8.3 and 70°C at different magnetic field.

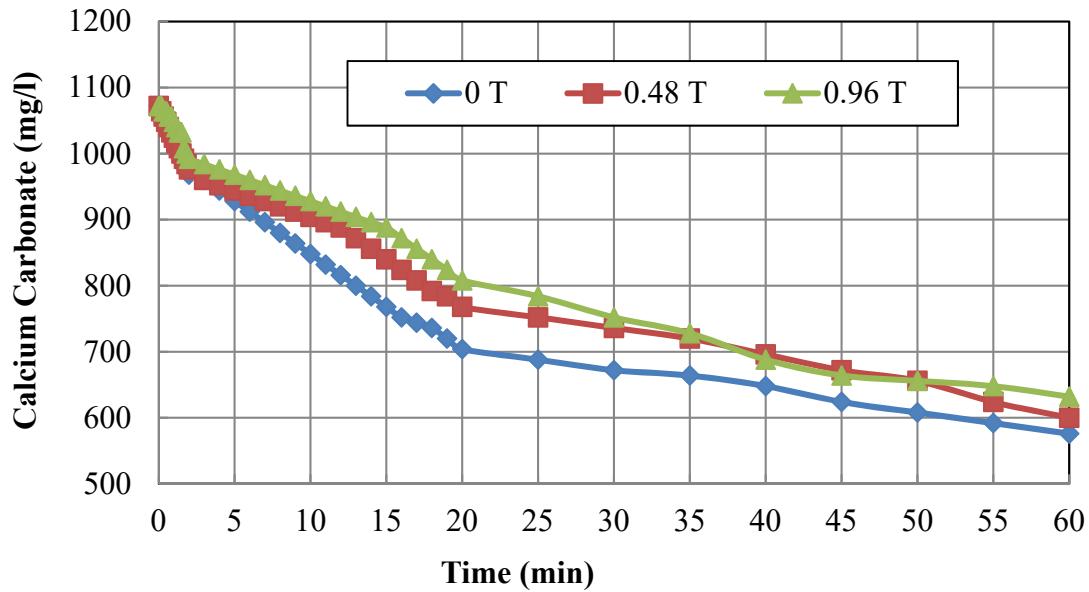


Fig.10 . Calcium carbonate concentration at 0.1 m/s velocity, pH 8.3, and 90°C at different magnetic field.

Performance of Anti-Scale Magnetic Treatment Method in Retarding Calcium Carbonate at a Flow Velocity of 0.03 m/s. Figs. 11, 12 and 13 show the performance of AMM at different operating temperatures and at different magnetic fields under 0.03 m/s flow velocity.

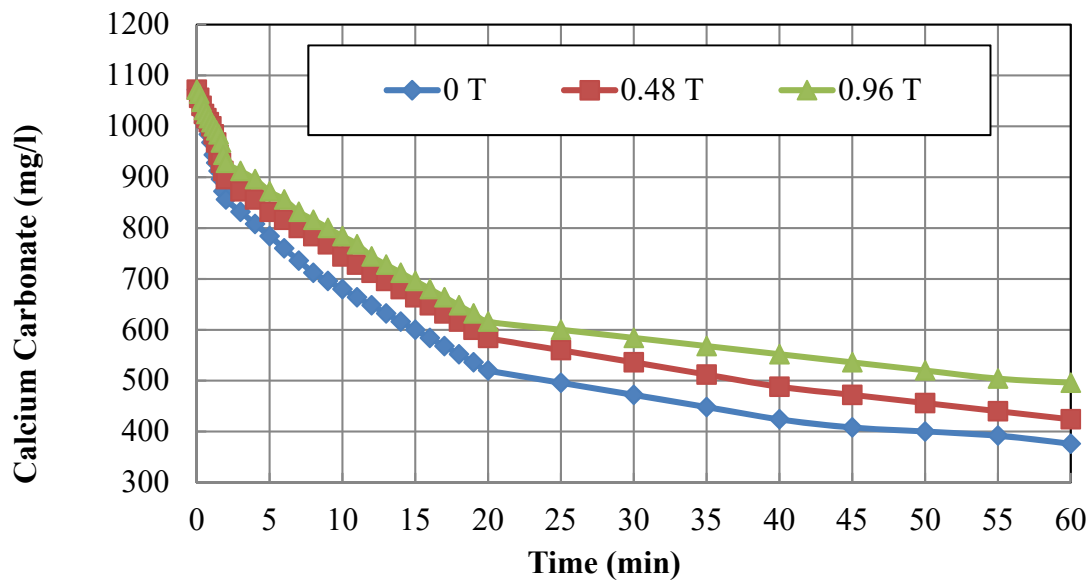


Fig.11. Calcium carbonate concentration at 0.03 m/s velocity, pH 8.3 and 50° C at different magnetic field.

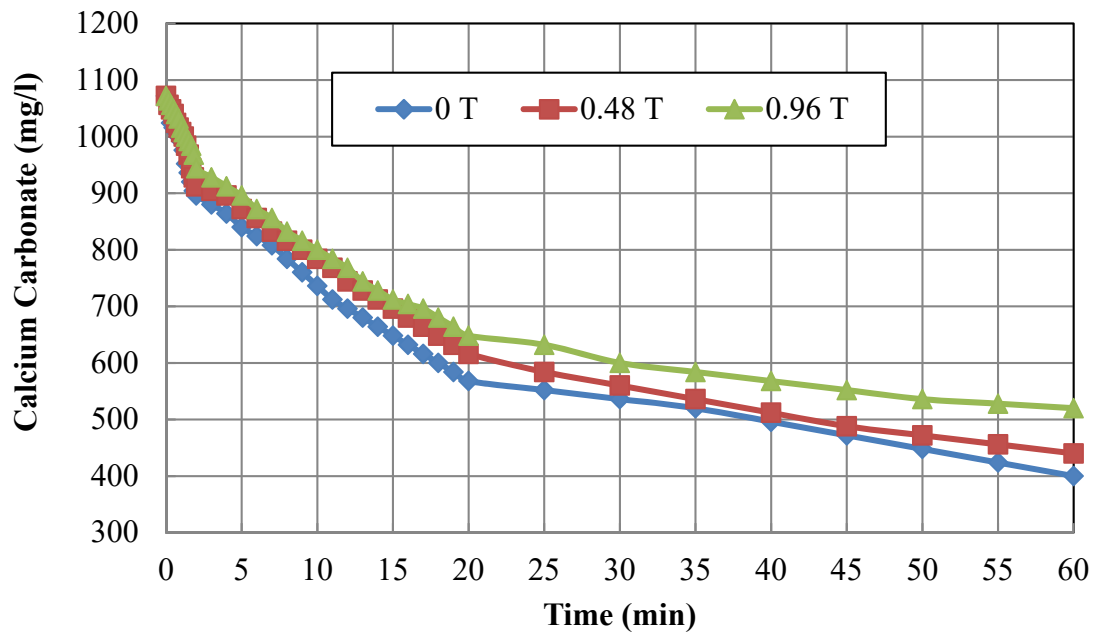


Fig. 12. Calcium carbonate concentration at 0.03 m/s velocity, pH 8.3 and 70° C at different magnetic field.

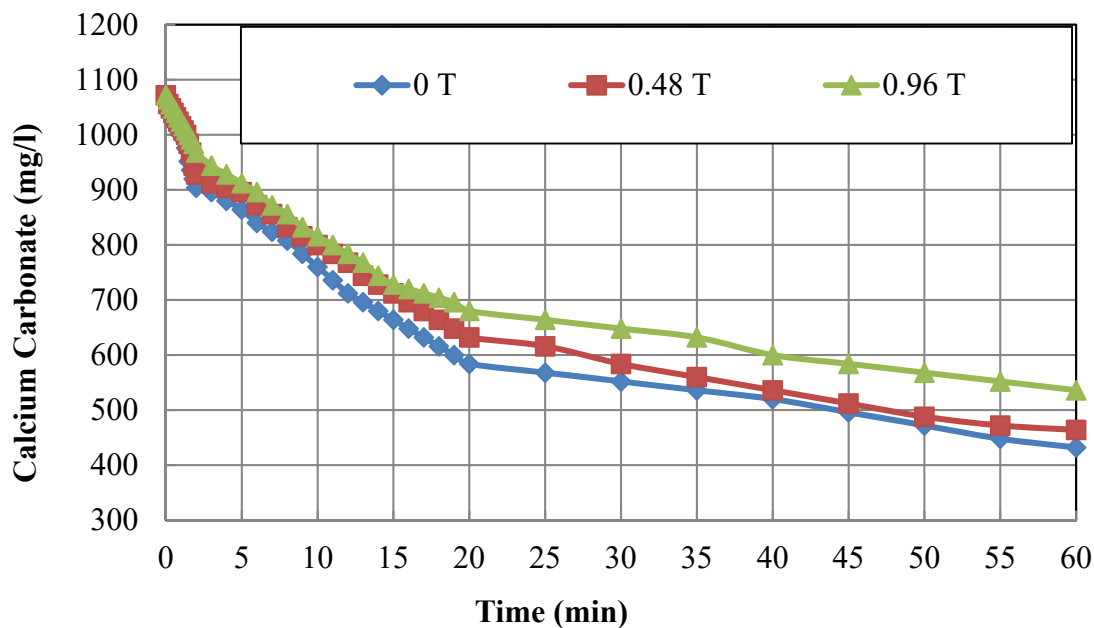


Fig.13 . Calcium carbonate concentration at 0.03 m/s velocity, pH 8.3 and 90° C at different magnetic field.

From Figs. 11, 12, and 13 it is clear that the effective concentration level reduced from 700 mg/l at flow velocity of 0.1 m/s to about 500 mg/l at a flow velocity of 0.03 m/s, where a noticeable increment in the retention time can be found. Thus, the increment in β at 700 mg/l was almost small and did not exceed 7 min at 0.96 T and operating temperature of 90°C. However, at a concentration of 500 mg/l, a big increment in retention time can be noticed. This confirms the fact concluded before, where the performance of AMM decreased more strongly with a decrease in flow velocity, than that of the decrease in operating temperatures or a decrease in magnetic field strength.

The AMM succeeded in increasing the retention time from 20 min at 500 mg/l of bicarbonate concentration to about 55 min at 0.96 T and an operating temperature of 50°C as shown in Fig. 11. Moreover, the retention time increased from 20 min without AMM to about 55 min. at an operating temperature of 70°C

and 0.96 T as shown in Fig. 12 at a concentration level of 550 mg/l of bicarbonate. However, at 90°C as shown in Fig. 13, the retention time at 700 mg/l of bicarbonate concentration increased from 19 min to 40 min, which represents an increment of 110.5 %.

Performance of Magnetic Treatment Method in Retarding Calcium Carbonate at pH of 9.5. Figures 14 to 16 show the performance of the AMM at a flow velocity of 0.5 m/s at different operating temperatures at different magnetic field strengths and a higher pH of 9.5.

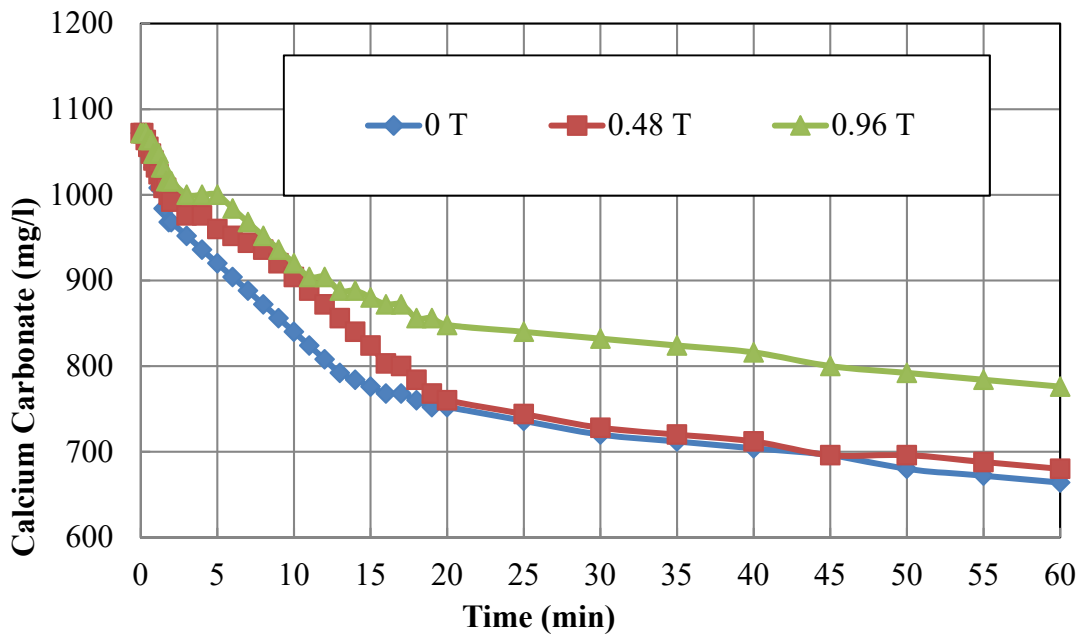


Fig.14. Calcium carbonate concentration at 0.5 m/s velocity, pH 9.5, and 50°C at different magnetic fields.

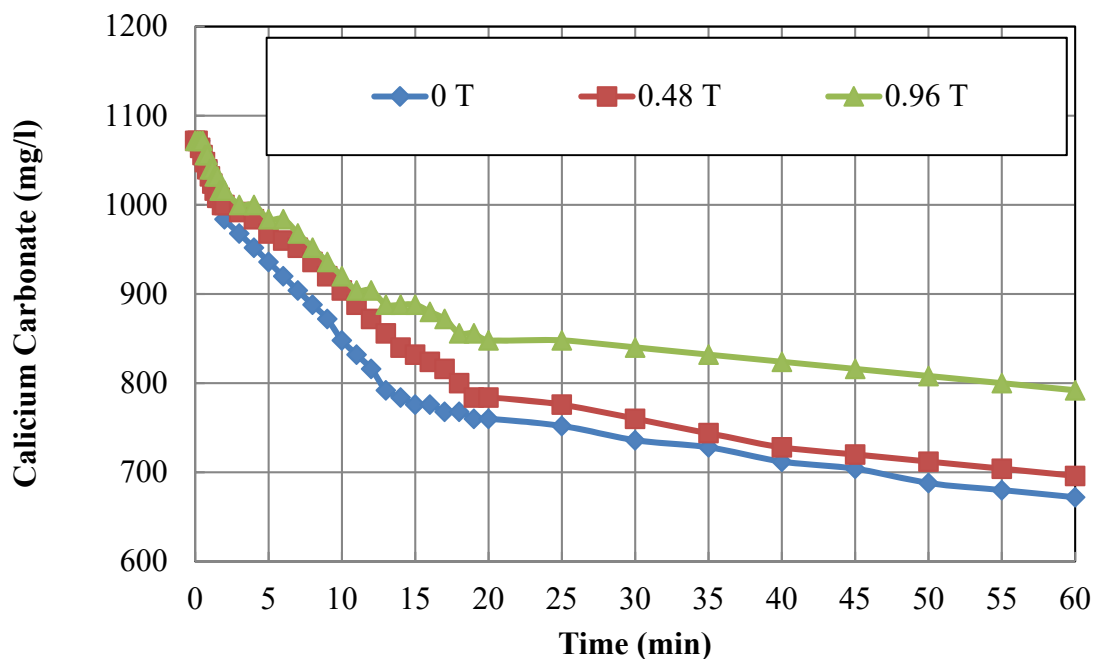


Fig.15. Calcium carbonate concentration at 0.5 m/s velocity, pH 9.5, and 70°C at different magnetic fields.

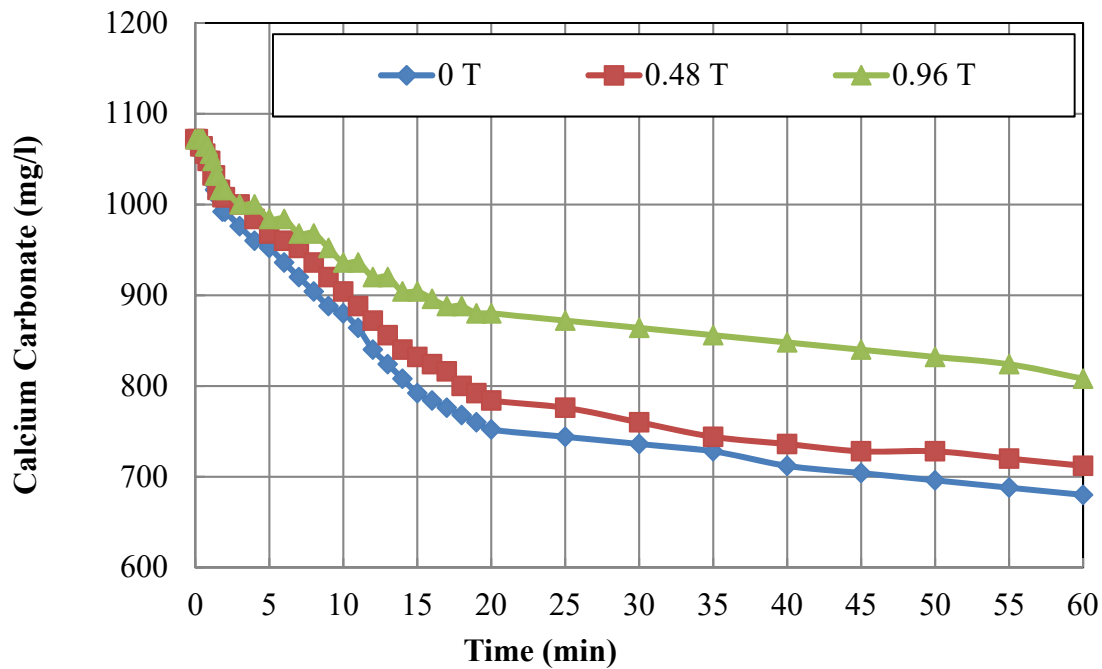


Fig.16. Calcium carbonate concentration at 0.5 m/s velocity, pH 9.5, and 90°C at different magnetic field.

The result showed a similar performance of AMM at 9.5 to that at pH 8.3. At pH of 9.5, the AMM effectiveness was found to be increasing with increasing magnetic field from 0.48 T to 0.96 T as shown in Fig. 14. This trend was observed also at 70 and 90°C (Figs. 15 and 16).

It is clear from Fig. 14 that the AMM at a pH of 9.5 and flow velocity of 0.5 m/s increased the retention time at 800 mg/l from 12 min to about 45 min using 0.96 T magnetic fields with an increment of 2.75 equal to exactly the increment at a pH 8.3. On the other hand, the retention time increased from 12 to about 55 min at 800 mg/l concentration as shown in Fig. 15. However, the AMM could increase the retention time at 800 mg/l from 14 min to about more than 60 min, as shown in Fig 16. Hence, we can conclude that the AMM shows the same performance at a pH of 8.3 and 9.5.

Critical Flow Velocity Using Magnetic Treatment Method for Retarding Calcium Carbonate. Table 2 summarizes the performance of AMM at different flow velocities where it is clear that the critical velocity was 0.5 m/s for calcium carbonate scaling, and when the flow velocity exceeded this value, the AMM was not a more effective method in retarding carbonate scale as shown in Table 2.

Table 2. The Effect of Different Flow Velocity on the Performance of Magnetic Treatment Method for Retarding Calcium Carbonate Scaling Solution

| Flow Velocity (m/s) | Effectiveness |
|---------------------|---------------|
| 1.0 | No effect |
| 0.5 | Effective |
| 0.3 | Effective |
| 0.1 | Effective |
| 0.03 | Effective |

The performance of AMM in retarding calcium carbonate at different flow velocities is presented in Figs. 17, 18, and 19 for four flow velocities (0.5, 0.3, 0.1, and 0.03) and the three operating temperatures as 50, 70, and 90°C.

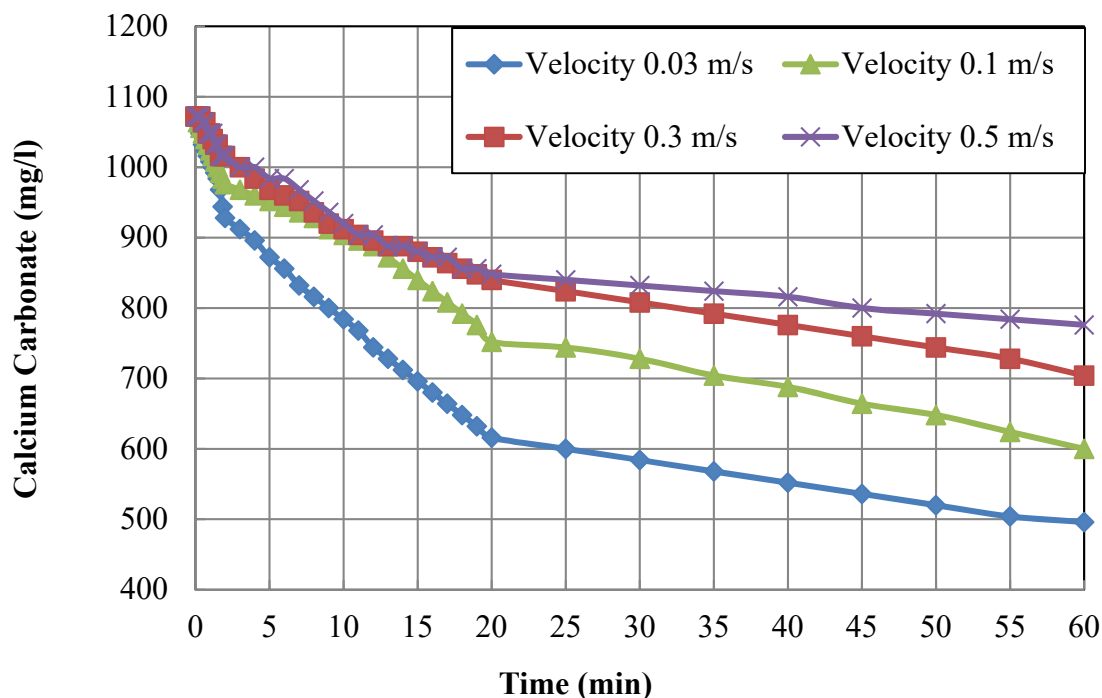


Fig. 17. Calcium carbonate concentration at pH 8.3, 50°C, and 0.96 T magnetic fields at different velocities.

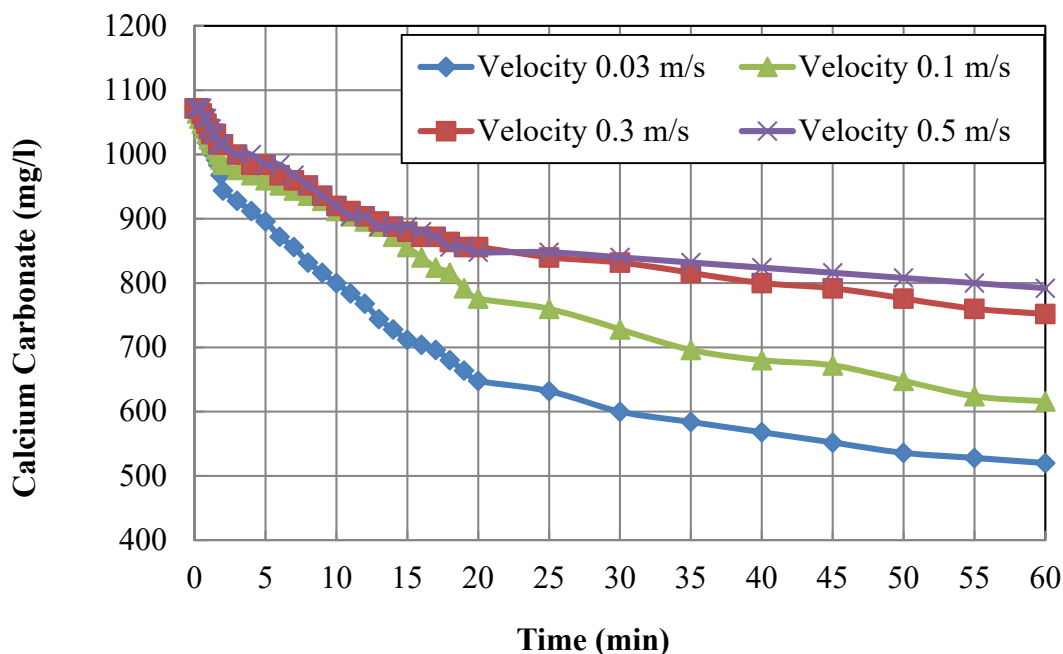


Fig. 18. Calcium carbonate concentration at pH 8.3, 70°C, and 0.96 T magnetic field at different velocities.

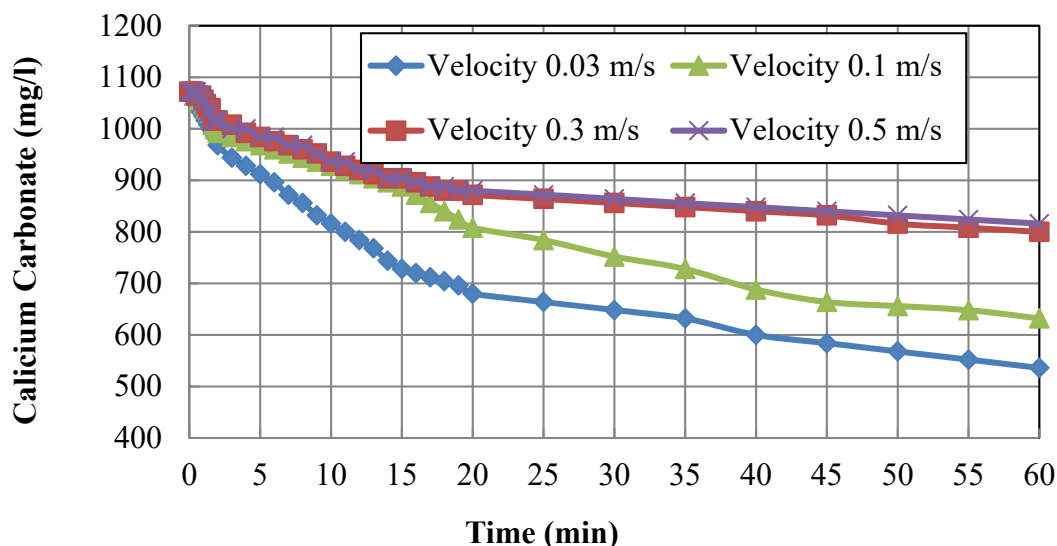


Fig. 19. Calcium carbonate concentration at pH 8.3, 90°C, and 0.96 T magnetic field at different velocities.

Fig. 17 shows the performance of AMM at 50°C; while Figs. 18 and 19 show the performance of AMM in retarding calcium carbonate at 70 and 90°C, respectively.

It is clear from Fig. 17 that the effective concentration decreased as the flow velocity decreased, where at 0.5 m/s, the effective concentration was 800 mg/l which decreased to 500 mg/l at a flow velocity of 0.03 m/s.

It can be concluded from Fig. 17 that the performance of AMM improved when the flow velocity increased from 0.03 m/s to 0.1, then to 0.3, until a critical flow velocity, equal to 0.5 m/s was reached. After the critical flow velocity, the effect of AMM would be demolished.

Figures. 18 and 19 confirm the fact that as the flow velocity increased, the effectiveness of AMM in retarding calcium carbonate increased. Furthermore, Figs. 18 and 19 confirm the effect of temperatures, where, as the operating temperature increases, the performance of AMM improved.

Performance of Magnetic Treatment Method in Retarding Calcium Carbonate at Different Operating Temperatures. Figures. 20, 21, 22, and 23 show the effect of different operating temperatures on the performance of AMM under the highest magnetic field strength at 0.96 T and a pH of 8.3, and different operating temperature.

It can be concluded from Fig. 20 that when the flow velocity was low at 0.03 m/s, the calcium carbonate scaling can be retarded for about 20 min at 50°C and a concentration of 600 mg/l, the retention time increased to 30 min when the operating temperature increased to 70°C. However, the retention time increased to 40 min when the temperature increased to 90°C.

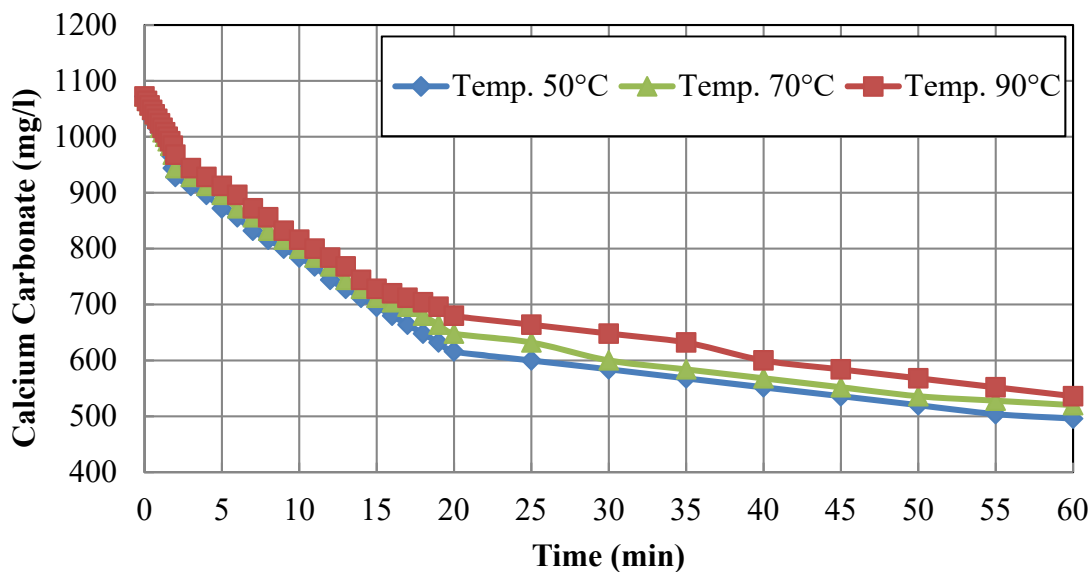


Fig. 20. Calcium carbonate concentration at 0.03 m/s velocity, pH 8.3, and 0.96 T magnetic field at different temperatures.

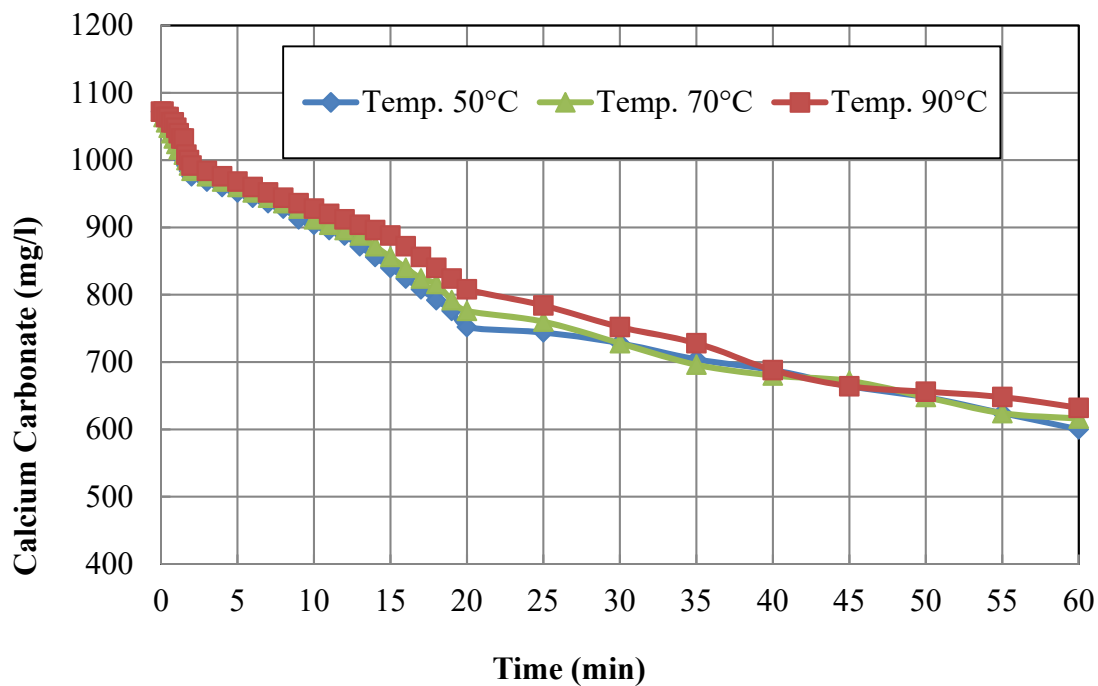


Fig. 21. Calcium carbonate concentration at 0.1 m/s velocity, pH 8.3, and 0.96 T magnetic field at different temperatures.

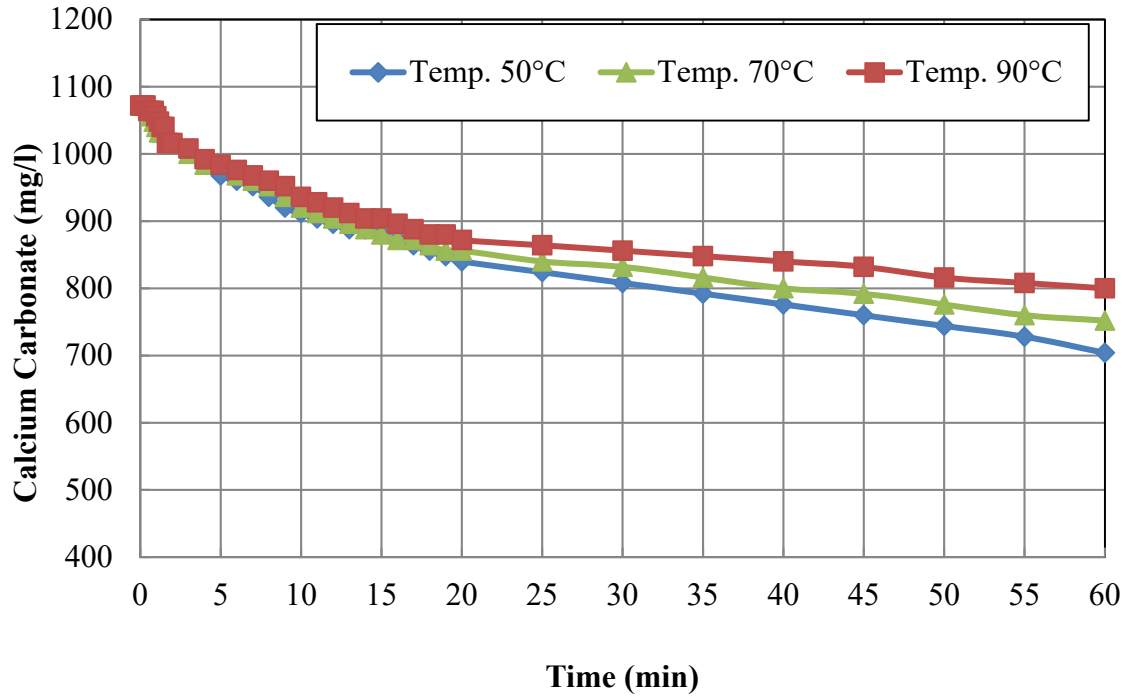


Fig. 22. Calcium carbonate concentration at 0.3 m/s velocity, pH 8.3, and 0.96 T magnetic field at different temperatures.

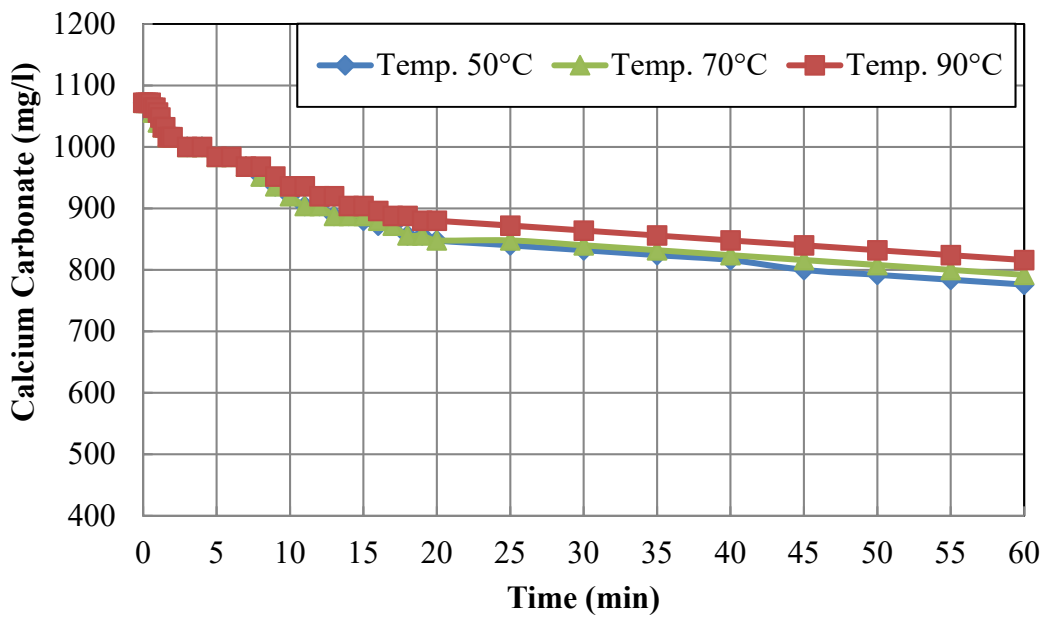


Fig. 23. Calcium carbonate concentration at 0.5 m/s velocity, pH 8.3, and 0.96 T magnetic field at different temperatures.

The same trend in Fig. 20 was observed within Figs. 21, 22, and 23 as the temperature increased and the retention time increased, which implies that as the operating temperature increased, the performance of AMM in retarding the calcium carbonate scale improved.

Effect of pH on the Performance of Magnetic Treatment Method in Retarding Calcium Carbonate.

Figures 24 to 26 show the effect of different pH on the performance of AMM under 0.5 m/s flow velocity and a variable operating temperature and magnetic field.

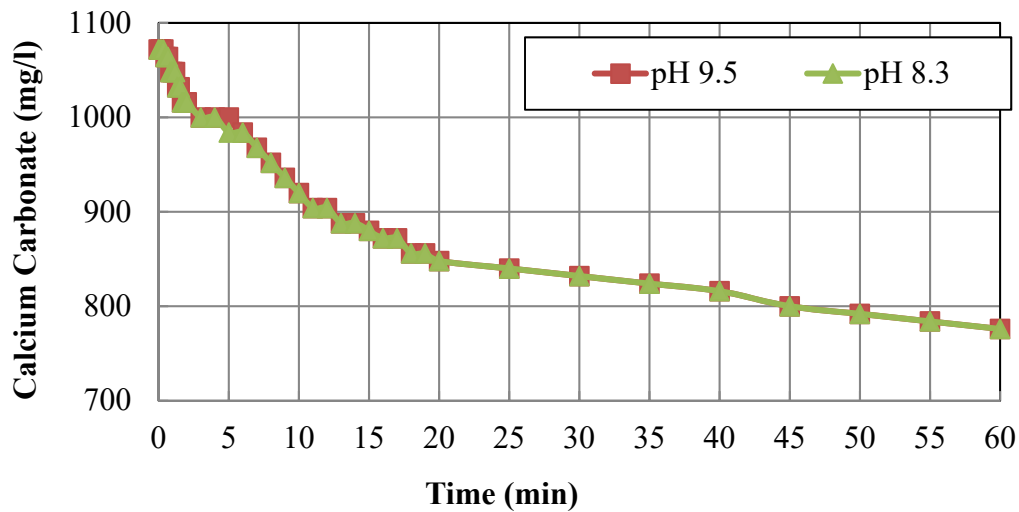


Fig. 24. Calcium carbonate concentration at 0.5 m/s velocity, 50°C, and 0.96 T magnetic field at different pH.

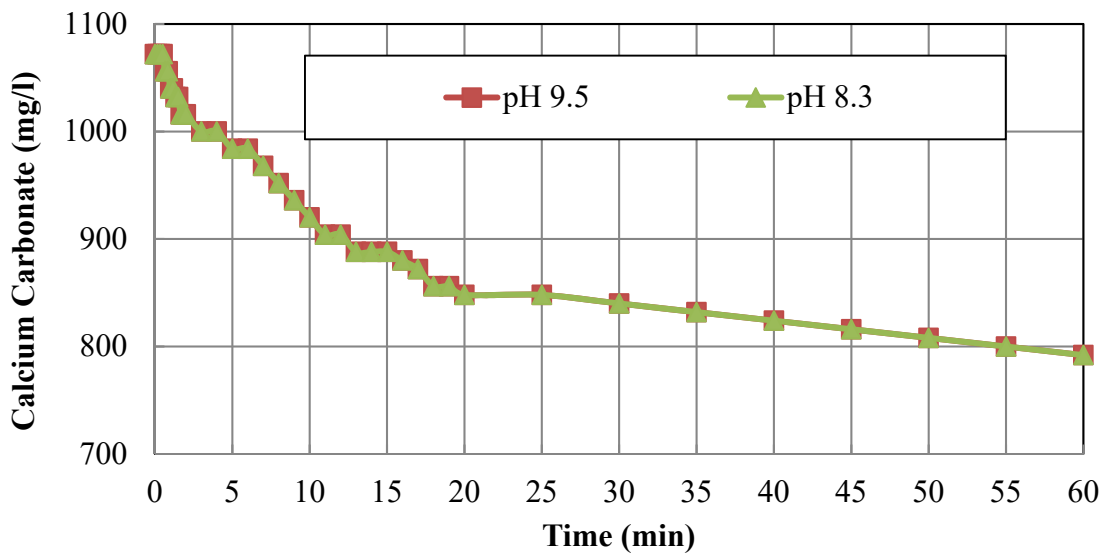


Fig. 25. Calcium carbonate concentration at 0.5 m/s velocity, 70°C, and 0.96 T MFS and different pHs.

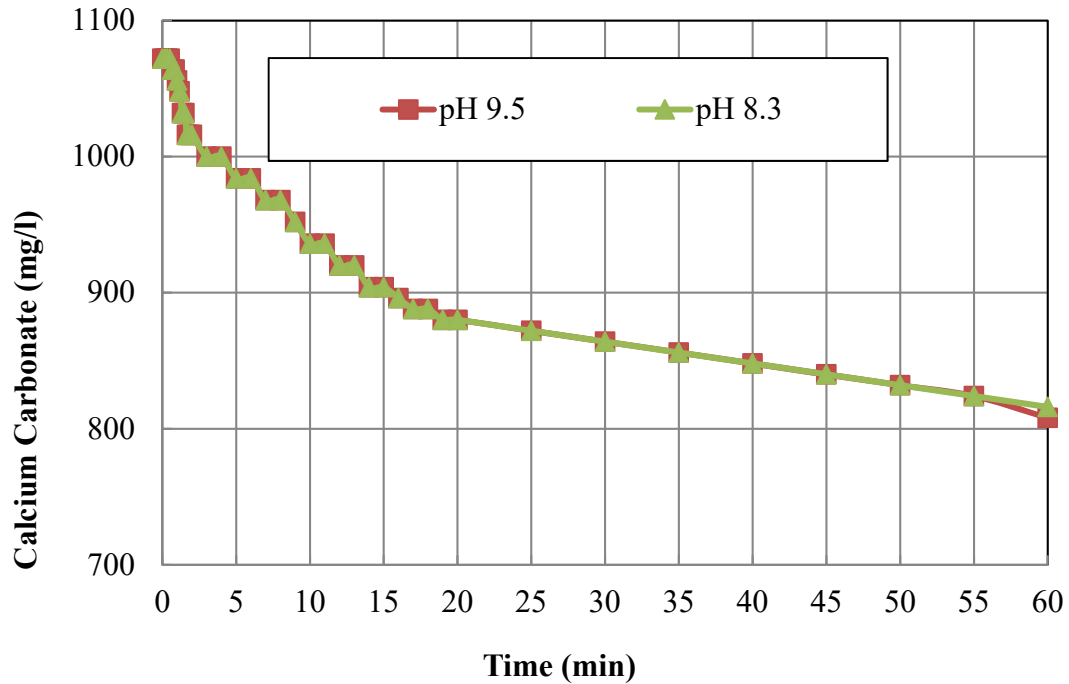


Fig. 26. Calcium carbonate concentration at 0.5 m/s velocity, 90°C, and 0.96 T MFS at different pHs.

It was found that from previous Figs. 23, 24, 25, and 26, the effect of pH on the performance of AMM in retarding calcium carbonate at high flow velocity (0.5 m/s) was negligible, where a similar effect was found in Figs. 24, 25, and 26. Hence, pH cannot be considered an effective parameter on the performance of AMM in retarding calcium carbonate scaling.

Conclusions

Based on the test results and data analysis, the following conclusions have been derived.

- It was confirmed that the effectiveness of AMM increased as the magnetic field strength increased.
- The performance of AMM in retarding calcium carbonate could depend on different parameters as flow velocity, operating temperatures, and magnetic strength.
- AMM decreased the potential of calcium carbonate scaling, at a concentration of 800 mg/s of calcium carbonate and at a flow velocity of 0.5 m/s by a three-fold increase.
- The power to retard calcium carbonate using AMM increased when the applied magnetic field was increased.
- The power to retard calcium carbonate using AMM increased when the operating temperatures were increased.
- AMM was effective in retarding calcium carbonate at a concentration level of 700 mg/l when the flow velocity was 0.1. However, the effective concentration level decreased to 500 mg/l as the flow velocity decreased to 0.03 m/s.
- The flow velocity is the key parameter of the performance of AMM in retarding calcium carbonate, while other effecting parameters had lower effect on the performance of AMM in retarding calcium carbonate.
- The performance of AMM in retarding calcium carbonate scaling at pH 8.3 and 9.5 was found to be similar, and the pH cannot be considered an effective parameter on the performance of AMM in retarding calcium carbonate scaling.

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