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MAGNETIC WATER TREATMENT FOR SCALE PREVENTION

C. GABRIELLI*, R. JAOUHARI†, G. MAURIN and M. KEDDAM

UPR 15 CNRS "Physique des Liquides et Électrochimie", Université Pierre et Marie Curie,
Tour 22, 4 Place Jussieu, 75252 Paris, Cedex 05, France

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Abstract—A home-made magnetic device was built with permanent magnets for treating scaling waters. Its efficiency was evaluated by measuring the remaining ionic calcium at the output of the device by means of an ion selective electrode. The scaling power of the treated water was estimated through an electrochemical scaling test. Chronoamperometric curves and chronoelectrogravimetric curves were plotted to obtain the scaling time and the nucleation time of the scale deposition. The variation of the efficiency of the magnetic treatment was studied when the length of treatment, the flow velocity of the scaling water in the device, the material of the pipe where the scaling water flowed were changed. An empirical relationship, which gives the value of the efficiency in function of the length of treatment and the flow velocity, was proposed. Possible mechanisms of action of the magnetic treatment were discussed. © 2001 Elsevier Science Ltd. All rights reserved

Key words—scale, magnets, calcium carbonate, electrochemical scaling

INTRODUCTION

Scale deposits by natural waters often lead to numerous technical and economical problems in industrial plants and domestic equipment by blocking the flow of water in pipes or limiting heat transfer in heat exchangers (Legrand and Leroy, 1990). From the beginning of the century, various chemical or physical treatments have been proposed to decrease scaling. As the use of scaling inhibitors changes the water composition, they have to be avoided for drinking water distribution. Therefore, physical treatments can be used because they do not change the potability of water. In particular, magnetic treatments have attracted much attention for over 100 years. However, their efficiency is still a controversial question as shown by a recent review by Baker and Judd (1996) and the references therein. Recent well-documented laboratory tests have shown that some magnetic devices work well by choosing the good working conditions as shown during the MAG 3 meeting (1999). It has to be noticed that some web sites give plenty of references related to magnetic fluid conditioning (see web site address in the references).

In general, people agree on the fact that magnetic treatments lead to the formation of calcium carbonate particles in the bulk of the scaling water, which cannot precipitate on the walls of distribution pipes and other equipment. These particles are carried away by the water flow and can be eliminated by removing or filtering the resulting calcareous mud. Barrett and Parsons (1998) have ascribed its effect on the formation of CaCO_3 particles by suppressing nucleation and accelerating crystal growth. Other authors have claimed, on the basis on turbidity measurements of the treated water, that homogeneous nucleation was increased giving resultant crystals greater in number with smaller sizes (Wang *et al.*, 1997; Ferreux *et al.*, 1993). Ferreux (1992) has proposed that a magnetic term be involved in the activation energy, which allows the critical radius of nucleation to be lowered. From the microscopic point of view, the magnetic field was shown to influence significantly the zeta potential and size distribution of the particles formed in solution (Parsons *et al.*, 1997).

In this paper, the efficiency of the magnetic treatment of scaling waters was investigated both by following the change of concentration of the ionic calcium at the output of the magnetic device and by evaluating the resulting scaling power of the treated water by an electrochemical test (Gabrielli *et al.*, 1998; Khalil *et al.*, 1999). Various geometry of the magnetic device and various experimental conditions were tested. To have reproducible results,

*Author to whom all correspondence should be addressed.
Tel.: +33-1-4427-4153; fax: +33-1-44-27-40-74; e-mail: cg@ccr.jussieu.fr

†On leave from Laboratoire d'Electrochimie-Corrosion, Université Mohamed V, Faculté des Sciences Département de Chimie, Rabat (Maroc).

Table 1. Composition of the synthetic scaling waters

	CaCO ₃ (g dm ⁻³)	CaCl ₂ , 2H ₂ O (g dm ⁻³)	NaHCO ₃ (g dm ⁻³)	Na ₂ CO ₃ (g dm ⁻³)	NaCl (g dm ⁻³)	pH
200 mg dm ⁻³	0.5					7
Salted water		1.54	0.168	0.021	30	8

carbonically pure water and scaling water made from salts were tested.

EXPERIMENTAL

Carbonically pure water containing 200 mg dm⁻³ Ca²⁺ was prepared by dissolving 500 mg dm⁻³ CaCO₃ in deionized water through bubbling of carbon dioxide. Therefore, the scaling solution contained only Ca²⁺ cations and CO₃²⁻, HCO₃⁻ anions and were used at calcocarbonic equilibrium. The salted water was the same as synthetic seawater following the norm ASTM D1141 modified by adding sulfate ions but without magnesium ions. Its composition is given in Table 1.

These artificial scaling waters were often renewed and their stability was checked by monitoring the pH before and after treatment.

The home-made magnetic device is depicted in Fig. 1. It consisted of a series of pairs of permanent magnets with north and south poles facing each other, which can be associated alternately or not. Figure 1(A) shows the scheme of the device for tests with alternated pairs. Figure 1(B) shows the same without inversion. The water to treat passed through a pipe inserted between the polar pieces in opposition of polarity. In this configuration the magnetic induction was perpendicular to the solution flow. Each polar piece is the assembling of two rectangular permanent magnets (42 × 25 mm² and 6 mm thick). The magnetic circuit of each pair of magnets was partially closed by U-shaped pieces of mild steel, to close the magnetic field in the gap. The various pairs were separated by 12 mm. Figure 1(C) shows the induction of the magnetic field, measured using a Hall probe, when the polarity of the pairs of magnets were alternated the magnetic field was highly discontinuous in the gap. Figure 1(D) shows the induction of the magnetic field when the pairs were all in the same direction, here the magnetic field was almost uniform in the gap (mean value 0.16 T). The small amplitude oscillations were due to the spaces between the various pairs of magnets. The scaling water to be treated was circulated in a pipe through the gap by means of a centrifugal pump (Fig. 2). The pipe, unless specified, was of stainless steel. The water velocity can be changed from a few 0.01 m s⁻¹ to a few m s⁻¹ by changing the diameter of the pipe and the flow rate of the pump.

Up to 10 pairs of magnets can be used to vary the treatment length with a quasi-uniform field or an inhomogeneous field by inverting the polarity of the pairs of magnets. Usually, unless specified, only five pairs of magnets were used in this study. The influence of the flow velocity at constant flow, the material of the pipe and the composition of the treated water was investigated.

The efficiency of the magnetic treatment was tested in two ways. First, the ionic calcium content, [Ca²⁺]_i, was measured at the output of the device by using an ionic selective electrode to calcium. In fact, it was calcium activity but it will be called simply as concentration in the following. The efficiency, E_m , of the magnetic treatment, can be defined by

$$E_m = \frac{[Ca^{2+}]_i - [Ca^{2+}]_f}{[Ca^{2+}]_i} \text{ in \%} \quad (1)$$

where [Ca²⁺]_i and [Ca²⁺]_f are the calcium concentration at the input of the magnetic device and the calcium concentration after magnetic treatment, respectively.

Once magnetically treated by means of one or several passes, the water was put in a reservoir and the scaling power of the treated water was evaluated by using an electrochemical test. The gold electrode of a quartz crystal microbalance immersed in the scaling water was polarized at a potential where dissolved oxygen reduction occurred. The reduction of oxygen induced a pH increase at the electrode, which made the calcium carbonate to precipitate on it. The oxygen reduction current and the deposited mass were recorded against time (chronoamperometric and chrono-electrogravimetric curves). The comparison of these two quantities allows the scaling power of the water to be assessed by evaluating the scaling time and the nucleation time.

For the electrochemical tests, a potentiostat (SOTELEM-VINCI) was used in connection with an ammeter to plot the chronoamperometric curves. A home-made quartz crystal microbalance (6 MHz) was used. All the experimental set-up was computer-controlled. The current passing through the electrode and the frequency of the microbalance were simultaneously measured with respect to time, during calcareous deposition while the electrode was polarized at the diffusion limiting current of the oxygen reduction (c.a. -1 V vs. SSE for carbonically pure water and -0.95 V for salted water). Mass transport was controlled by using an impinging jet cell, where a 360 ml min⁻¹ flow was imposed.

RESULTS

As a preliminary assay, the carbonically pure water containing 200 mg dm⁻³ Ca²⁺ was treated by the magnetic device by cycling the water for a time sufficient to decrease the ionic calcium content down to 120 mg dm⁻³ Ca²⁺. Then, the scaling power of the treated water was compared with the scaling power of a directly prepared 120 mg dm⁻³ Ca²⁺ carbonically pure water obtained by dissolving 300 mg dm⁻³ CaCO₃. Figure 3 shows the results of the electrochemical test. The decrease of the current flowing through the electrode (chronoamperometric curve) shows the increase of the coverage of the electrode by the scale, which is an insulating material (Fig. 3(A)). A scaling time was defined when the current reached a very low value close to the residual current observed when the electrode was totally scaled. Simultaneously, the mass change directly indicated the mass of scale deposited on the electrode surface (Fig. 3(B)). Here, a nucleation time was defined when the mass neatly increased after some delay. These two characteristic times were very close for the two types of water. This showed that the scaling power of the two waters were similar,

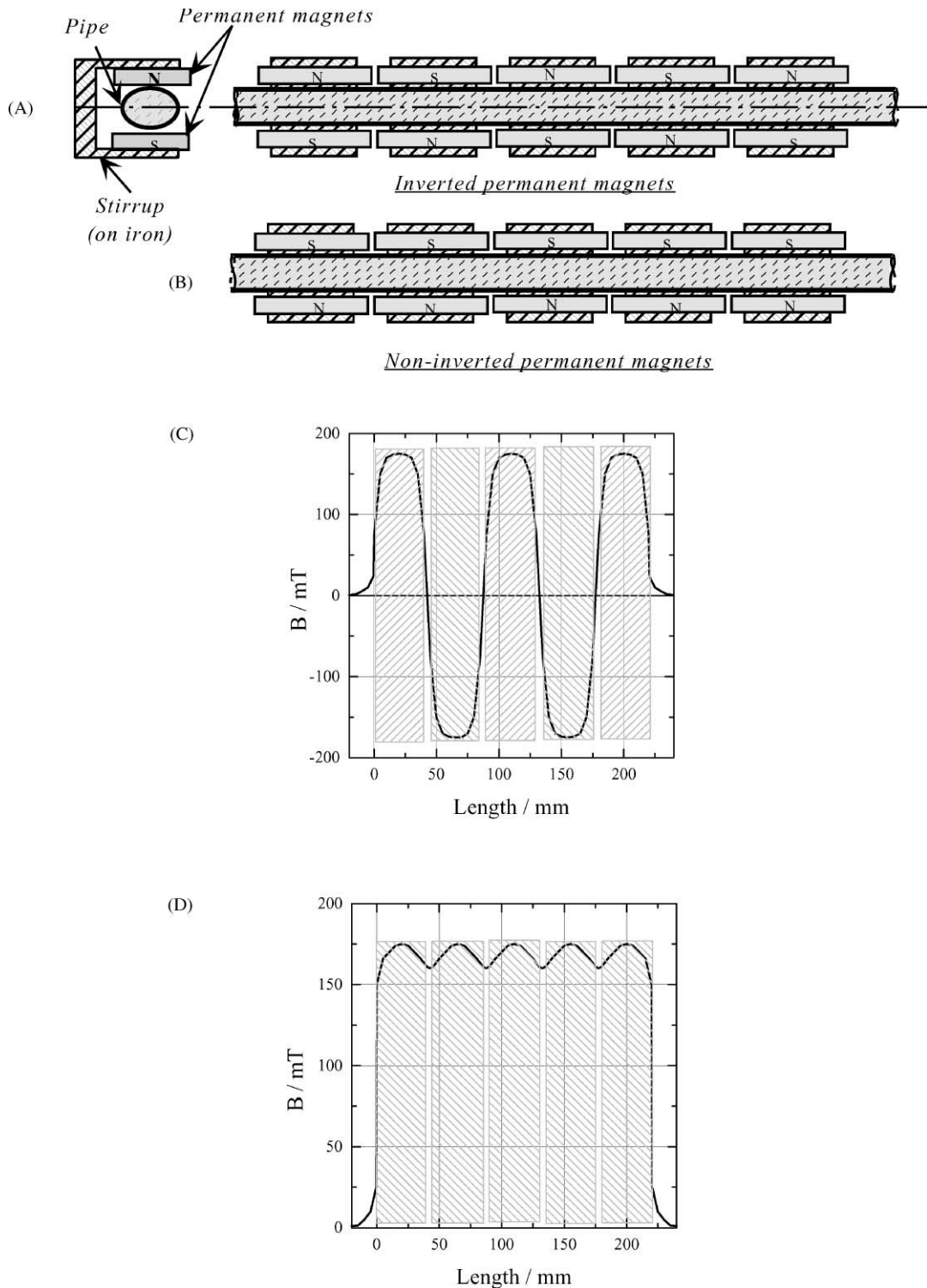


Fig. 1. Description of the home-made magnetic device. (A) Scheme of the device with alternated polar pieces, (B) scheme of the device without inversion of the polar pieces, (C) variation of the magnetic induction in the gap for inverted pairs of permanent magnets, (D) variation of the magnetic induction in the gap for non-inverted pairs of permanent magnets.

although the slight deviation from one to another should indicate a difference in morphology of the deposited scales. This demonstrated the efficiency of the magnetic treatment used here because

after treatment the scaling power of the water has actually decreased as only 120 mg dm^{-3} of active calcium remained over the 200 mg dm^{-3} initially prepared.

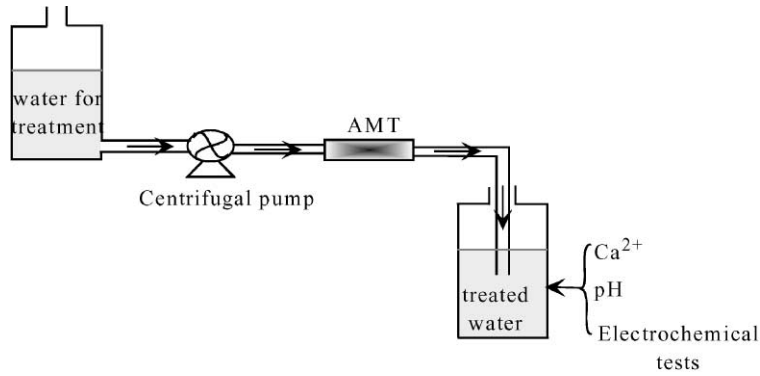


Fig. 2. Experimental arrangement for the magnetic treatment and the analytical and electrochemical tests of the scaling water.

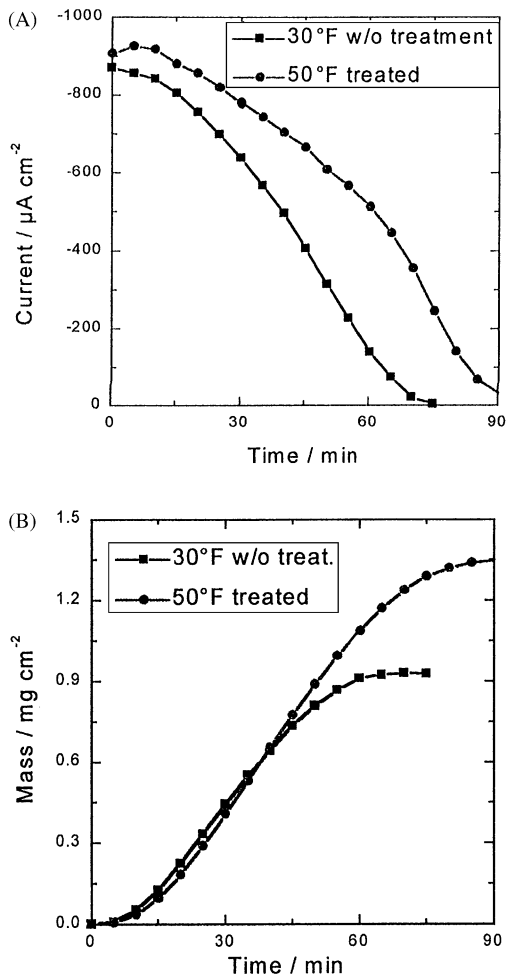


Fig. 3. Comparison of the scaling power of magnetically treated carbonically pure water containing $200 \text{ mg dm}^{-3} \text{ Ca}^{2+}$ down to 120 mg dm^{-3} and directly prepared carbonically pure water containing $200 \text{ mg dm}^{-3} \text{ Ca}^{2+}$ (A) Chronoamperometric curves and (B) chronoelectrogravimetric curves.

Composition of the scaling water

The influence of the composition of the scaling water was tested to see whether adding foreign

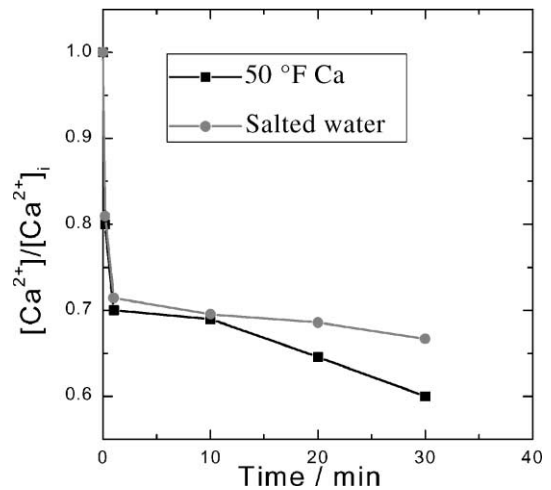


Fig. 4. Variation of the concentration of the ionic calcium against cumulated treatment time by recycling for carbonically pure water and salted water (see composition in the text).

ions, in addition to the fundamental constituents, change the effect of the magnetic treatment. $200 \text{ mg dm}^{-3} \text{ Ca}^{2+}$ (50°F) carbonically pure water was compared with salted water. Figure 4 shows the change of the calcium concentration with the number of passes in the magnetic device. As, for the flow velocity used in this experiment, a single pass corresponded to a 12 s residence time in the magnetic field the output calcium concentration was plotted against the cumulated treatment time. A single passage reduced the initial concentration of calcium by 20% for both types of water. One minute of circulation (five passages) reduced the concentration of free calcium by 30% for the two waters. The increase of the number of passages up to 150 did not decrease very much more the ionic calcium concentration especially for the salted water. For the carbonically pure water the slight decrease observed should be due to the carbon dioxide degassing, which increased the pH and then could lead to the precipitation of calcium carbonate in the bulk solution which, consequently, decreased the ionic

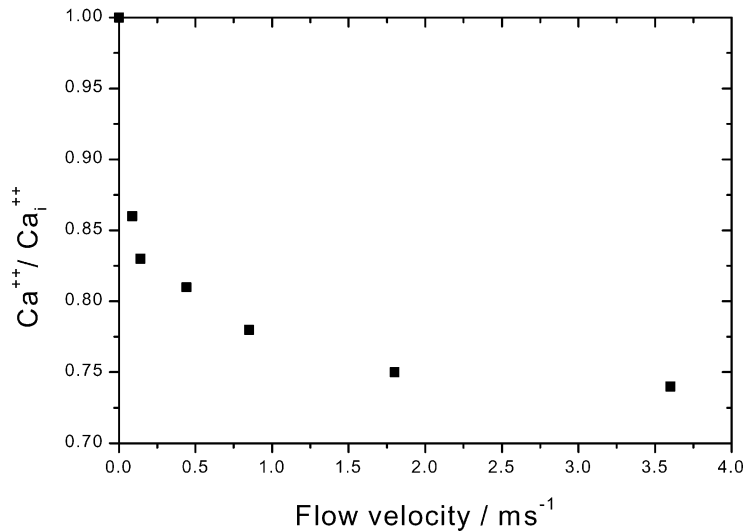


Fig. 5. Variation of the concentration of the ionic calcium against the flow velocity.

calcium concentration. The magnetic treatment gave similar results for the two types of water although the salted water was equivalent to a $420 \text{ mg dm}^{-3} \text{ Ca}^{2+}$ content. Therefore, the efficiency of the magnetic treatment seemed to be independent of the water hardness. As, the pH was more stable with the salted water, this water composition was used in the following.

Influence of the flow velocity

The salted water was passed 5 times in the magnetic device at various flow velocities (Fig. 5). When the treatment was achieved, the concentration of the ionic calcium and the pH were measured. Whatever be the flow velocity the pH at the output did not change. Figure 5 shows that even a low velocity was sufficient to observe an appreciable effect of the magnetic treatment. A 0.074 m s^{-1} velocity induced a 15% decrease of the ionic calcium concentration and reached 25% at a 1.8 m s^{-1} . The efficiency did not practically increase for a twice-faster velocity.

Then, the scaling power of the treated solution was tested by using an electrochemical scaling test. Chronoamperometric curves and chronoelectrogravimetric curves were plotted at two flow velocities in Fig. 6. A 0.074 m s^{-1} velocity increased twice the scaling time compared to a quiescent solution (Fig. 6(A)). The residual current remained practically the same. The increase of the velocity from 0.074 to 0.885 m s^{-1} increased the scaling time from 180 to 225 min.

The increase of the circulation velocity of the treated solution in the magnetic device had practically no influence on the initial value of the current nor on the residual current.

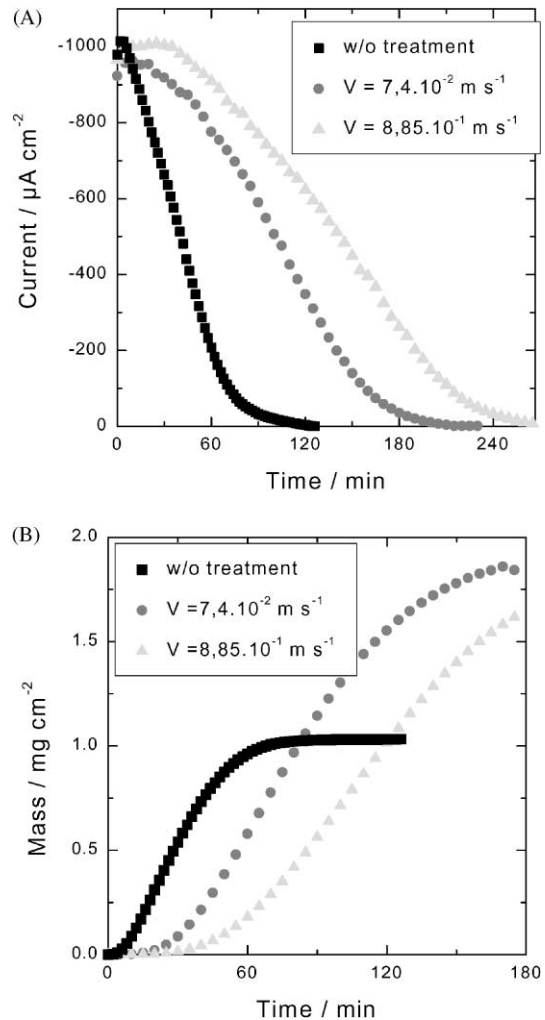


Fig. 6. Comparison of the scaling power of salted water magnetically treated at two flow velocities. (A) Chronoamperometric curves and (B) chronoelectrogravimetric curves.

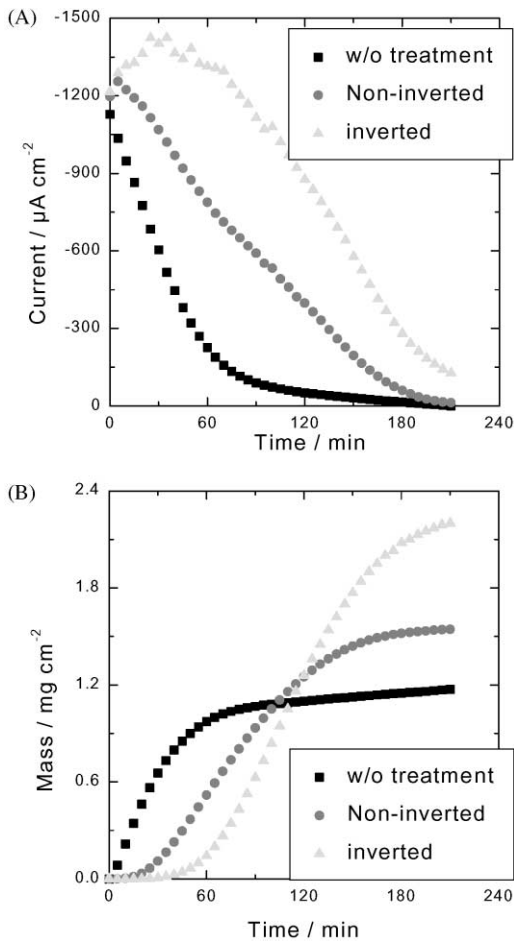


Fig. 7. Comparison of the scaling power of magnetically treated salted water with inverted and non-inverted pairs of permanent magnets. (A) Chronoamperometric curves and (B) chronoelectrogravimetric curves.

Table 2. Scaling times, t_s , and nucleation times, t_n , observed for various flow velocities

	Without treatment	$V = 0.074 \text{ m s}^{-1}$	$V = 0.885 \text{ m s}^{-1}$
t_s (min)	75	180	225
t_n (min)	5	30	50

The time evolution of the deposited mass followed the changes of the current. The nucleation time was multiplied by a factor of 6 by treating the solution at a 0.074 m s^{-1} (Fig. 6(B)) and still more for a 0.885 m s^{-1} velocity. The height of the mass plateau was changed by the magnetic treatment according to the change of the nucleation time observed. Values of the scaling times and nucleation times are gathered in Table 2.

Influence of the periodical inversion of the magnetic field

To examine the influence of the non-uniformity of the magnetic field, the device was modified in order

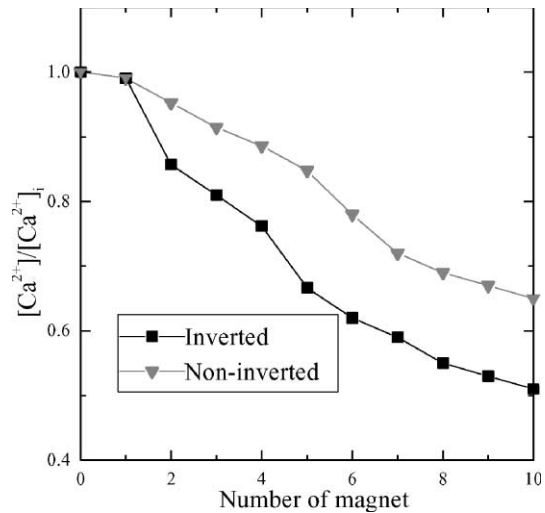


Fig. 8. Variation of the concentration of the ionic calcium against the length of the magnetic device obtained by varying the number of inverted or non-inverted pairs of permanent magnets.

Table 3. Scaling times, t_s , and nucleation times, t_n , observed for various geometry of the device (salted water, 0.6 m s^{-1} flow velocity)

	Without treatment	Without inversion	With inversion
t_s (min)	75	180	215
t_n (min)	5	25	60

to have a magnetic induction like the ones represented in Fig. 1(C) and (D). Figure 7 shows the chronoamperometric curves (Fig. 7(A)) and the chronoelectrogravimetric curves (Fig. 7(B)) for a 0.6 m s^{-1} flow velocity. The inversion of polarity improved the efficiency of the magnetic device. If the scaling time was the double of the scaling time observed without treatment, it was the triple when the pairs of magnets were alternated. On the chronoelectrogravimetric curves an increase of the multiplying factor of the nucleation delay from 5 to 12 times, compared with the delay without treatment, was clearly observed when inversion was applied. Concomitantly the mass plateau increased when inversion was applied. Table 3 gathers the experimental values obtained in these conditions.

Influence of the increase of the number of polar pieces

To examine the influence of the number of polar pieces of the magnetic device, i.e. to change its length, the output concentration of the ionic calcium was plotted against the number of polar pieces (Fig. 8). A neat improvement of the efficiency of the magnetic device was observed when its length was increased. The improvement was even better, as shown previously, when the polar pieces were inverted. If for one pair of magnets the result was the same, as soon as the number was increased the effect was amplified

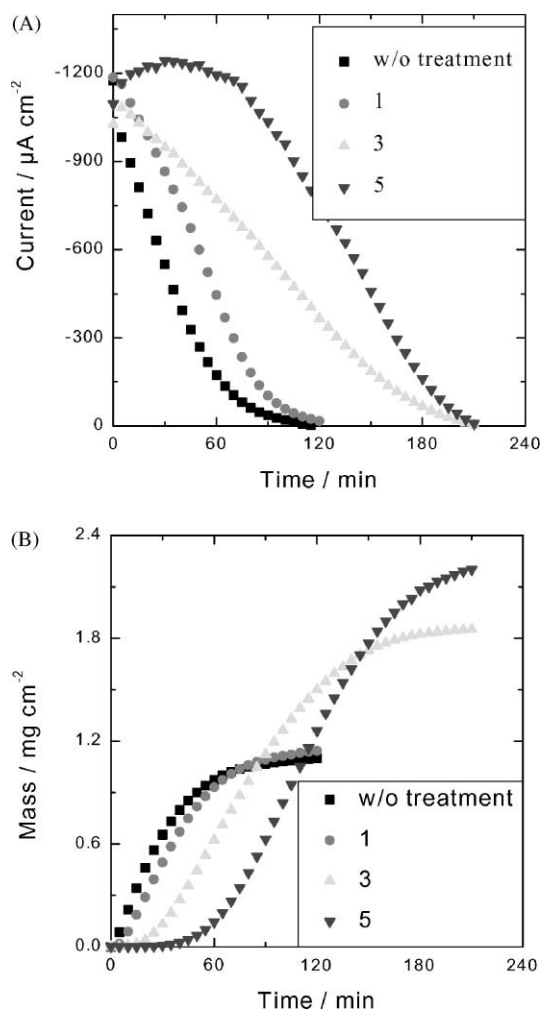


Fig. 9. Comparison of the scaling power of magnetically treated salted water with various number of inverted pairs of permanent magnets. (A) Chronoamperometric curves and (B) chronoelectrogravimetric curves.

when inversions were applied. However, the improvement seemed to be of the same amount whatever be the number of pairs, i.e. the curve obtained with inversion is shifted by the same amount from the curve without inversion. By using 10 pairs of magnets the efficiency decreased from 50% when the pairs were inverted to 35% without inversion.

To test the scaling power of the treated waters an electrochemical test was achieved. Figure 9 shows the results of this test for inversion of polarity. The scaling power decreased when the number of pairs of magnets was increased. Concerning the chronoamperometric curves (Fig. 9(A)), a pair alone lead to a 33% increase of the scaling time compared to untreated water, but three pairs gave a scaling time twice larger and five pairs gave a scaling time thrice larger. The chronoelectrogravimetric curves lead to similar results (Fig. 9(B)). Tables 4 and 5 give the results about the scaling time and the nucleation time

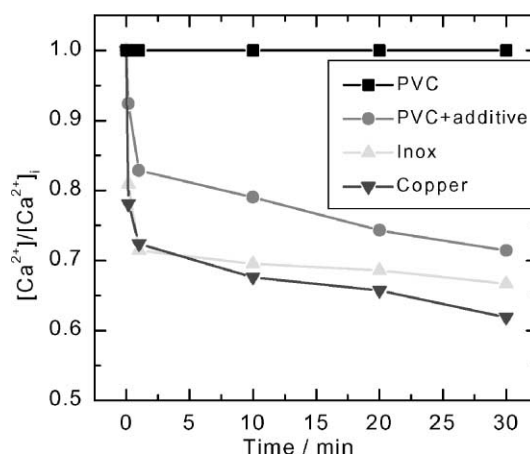


Fig. 10. Variation of the concentration of the ionic calcium against the cumulated treatment time for various materials of the pipe used to flow the water through the gap of the magnetic device.

Table 4. Scaling times, t_s , and nucleation times, t_n , observed for various number of inverted pairs of magnets (salted water, 0.6 m s^{-1} flow velocity)

With inversion	0	1	3	5
t_s (min)	75	100	170	215
t_n (min)	5	7	25	60

Table 5. Scaling times, t_s , and nucleation times, t_n , observed for various number of non-inverted pairs of magnets (salted water, 0.6 m s^{-1} flow velocity)

Without inversion	0	1	3	5
t_s (min)	75	80	140	180
t_n (min)	5	8	12	25

obtained with and without inversion of the pair of magnets.

Influence of the material of the pipe

So far, only a pipe made of stainless steel, which conducted the scaling water to treat across the gap, was used to test the efficiency of the magnetic device. The influence of the nature of the material, which constituted the pipe was investigated. Various conducting and insulating materials were tested in addition to stainless steel. Copper and two types of polyvinyl chloride (PVC) called PVC I and PVC II were used. PVC I was pure PVC, the tubing made of PVC I was transparent and flexible. PVC II was loaded with calcium carbonate and alumina, the tubing made with PVC II was grey and rigid, it is the usual tubing used in plumbing. Figure 10 shows the change of the concentration of ionic calcium when the scaling water was recycled in the magnetic device (i.e. plot vs. the cumulated treatment time).

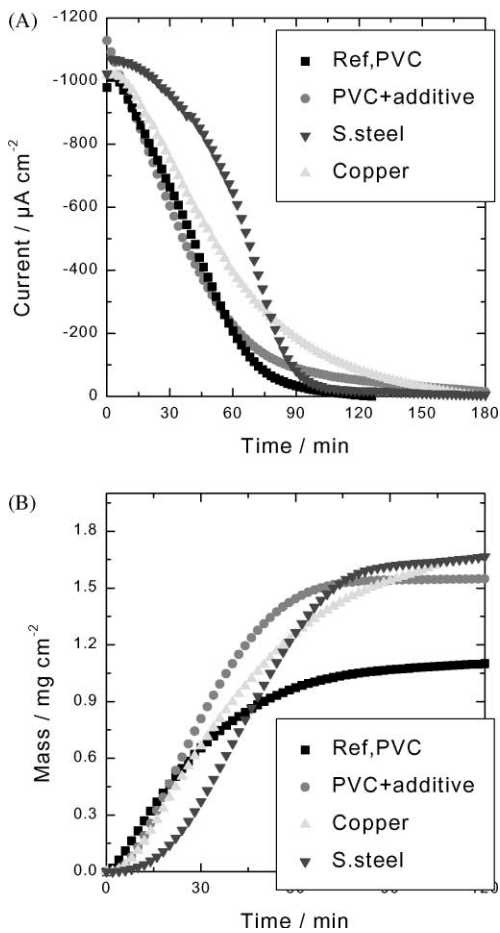


Fig. 11. Comparison of the scaling power of magnetically treated salted water for various materials of the pipe used to flow the water through the gap of the magnetic device. (A) Chronoamperometric curves and (B) chronoelectrogravimetric curves.

After five passages in the gap (i.e. 1 min treatment) the concentration of the ionic calcium was reduced by 18% for a pipe made of PVC II, whereas it was reduced by 28% for stainless steel and copper. The increase of the treatment time did not increase very much the effect of the device. So, an increase from 5 to 150 passages improved the efficiency by 5% only. When the pipe was made from PVC I the magnetic treatment was inefficient whatever be the number of passages.

The scaling power of the water treated through the various materials was examined. Figure 11 shows the chronoamperometric curves (Fig. 11(A)) and the chronoelectrogravimetric curves (Fig. 11(B)) recorded after that the scaling water had pass once in the magnetic device for each of the various tubing materials employed. It demonstrates that the effect is more pronounced for conducting materials than for insulators although the effect was still easily visible for PVC II. Table 6 gives the experimental parameters obtained through this experiment.

DISCUSSION

In this paper, it has been proved that the magnetic treatment of scaling waters is efficient by decreasing the ionic calcium content of the solution, even for a

Table 6. Scaling times, t_s , and nucleation times, t_n , observed for various materials of the pipe

	Without treatment	PVC I	PVC II	Copper	Stainless steel
t_s (min)	70	80	90	90	90
t_n (min)	2	5	10	18	18

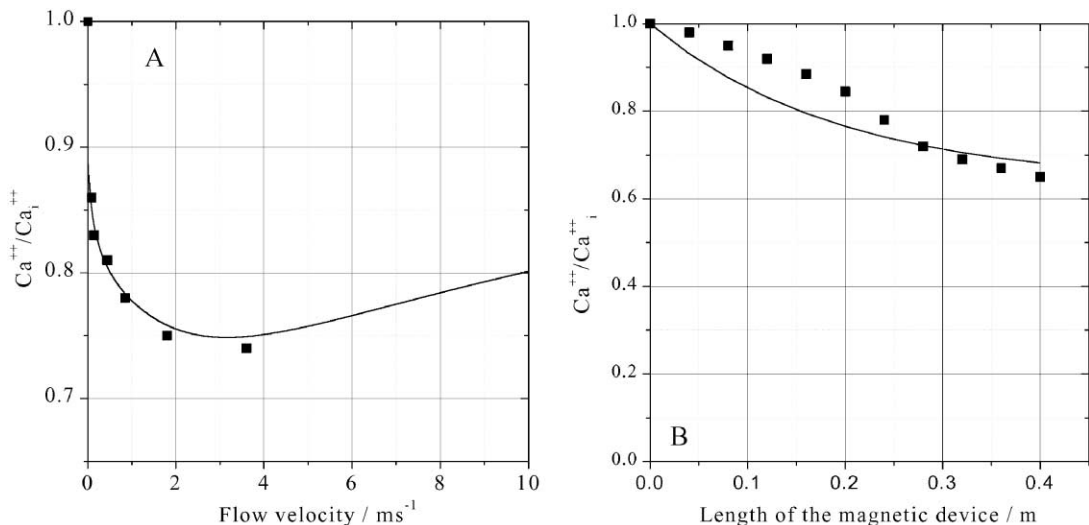


Fig. 12. Ionic calcium concentration at the output of the magnetic device against (A) the flow velocity and (B) the length of the device, calculated from equation (10) (parameters are given in the text).

single-pass. This was shown by measuring the calcium concentration just after the magnetic treatment. It was also proved, thanks to an electrochemical test, that this decrease in ionic calcium content lead to a decrease of the scaling power of the treated water. Therefore, the magnetic treatment trapped a part of the ionic calcium, which is then inactive for scaling.

Concerning possible mechanisms, Busch *et al.* (1986) and Maydatchevsky (1998) have invoked magnetohydrodynamic (MHD) processes to explain the action of the magnetic field on scaling, i.e. some processes based on the product $\mathbf{B} \times \mathbf{v}$ where \mathbf{B} and \mathbf{v} are the magnetic induction and the flow velocity, respectively. This would explain why the effect increase with \mathbf{B} and \mathbf{v} , at least to some extent, and that the effect is maximum when \mathbf{B} and \mathbf{v} are perpendicular. In particular, Busch *et al.* (1986) demonstrated that voltages are produced across the device and localized pH shifts occur inside the pipe, which contains the solution, when a conducting solution is made to flow through a magnetic device. They concluded that currents are generated within the solution and return through the body of the device. This feature supposes that the body is conducting. However, our results, and common practice, demonstrate that magnetic devices work also with non-conducting pipes or bodies. They found cathodic regions of high alkalinity on the walls of the device. They suggested that dissolved oxygen reduction was responsible for OH^- release, which could force calcium carbonate to precipitate and build seeds, which continue to grow in the bulk. This mechanism supposes conducting walls and above all corrosion of the iron of the wall of the pipe. The present experiments showed that conducting walls are not necessary, so Busch's results have to be revisited.

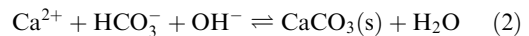
It is known that an ionic solution passing through a pipe gives rise to a streaming potential related to the velocity especially for dielectrics (Newman, 1973), this was observed for conducting materials too (Hurd and Hackerman, 1955, 1956). Recently, Martemyanov and Sviridov (1999) have shown that the profile of the flow of a conducting solution in a pipe is perturbed when a magnetic field is applied. At constant flow, the flow rate is accelerated along the walls and therefore is reduced along the central axis. Then, as the streaming potential is velocity dependent, it should increase with the magnetic field. In addition, streaming potentials depend on the nature of the surface and exist whether or not the material is conducting. Usually, this phenomenon changes the charge of the surface, which could throw out of balance the calco-carbonic equilibrium. In the vicinity of a surface positively charged (respectively, negative), negative ions and namely CO_3^{2-} , HCO_3^- , OH^- are attracted (respectively, repelled) whereas positive ions, namely H^+ , Ca^{2+} are repelled (respectively, attracted). This local modification of the

concentrations of the ions would shift the chemical equilibria and lead to a local increase of the saturation rate of calcium carbonate so that precipitation nuclei might be generated (Crolet and Ledion, 1988). Then, nuclei of calcium carbonate could appear close to the walls and departing in the bulk could give rise to seeds for growing calcium carbonate particles. It has to be noted that electrokinetic processes have also been invoked to explain the efficiency of the electrostatic treatment of scaling waters (Taillet, 1997). One of the referee suggested that van der Waals forces can also be involved as well, because they can be directly changed by a magnetic field.

The presence of calcium carbonate in the material constituting the tubing may also influence the nucleation rate of the seeds. These seeds seem to be necessary to initiate the magnetic treatment. Their growth can, eventually, also be related to electrokinetic phenomena as Higashitani *et al.* (1995) and Higashitani and Oshitani (1998) have shown that a magnetic field affects both the thickness of the adsorbed layer, the zeta potential and the diffusivity of colloidal particles even for quiescent solutions.

It was shown that high gradients of the magnetic induction improve the efficiency of the magnetic treatment. It has to be noticed that even for a quasi-uniform induction in the gap, the flowing water was submitted to a positive and a negative gradient of magnetic induction at the input and at the output of the magnetic device. Oshitani *et al.* (1999) have discussed this point: as water molecules are diamagnetic, a high gradient of magnetic field generates a strong attractive force between ions and water molecules, improving the efficiency of the magnetic treatment.

On a more macroscopic point of view, the global mechanism of precipitation of calcium carbonate is



Therefore, the precipitation rate is equal to

$$\frac{d[\text{CaCO}_3]}{dt} = k(B, v)[\text{Ca}^{2+}][\text{HCO}_3^-][\text{OH}^-] - k'[\text{CaCO}_3] \quad (3)$$

where $k(B, v)$ is the precipitation (forward) rate constant and k' is the dissolution (backward) rate constant of reaction (2).

As ionic calcium is supposed to be trapped in the form of CaCO_3

$$[\text{Ca}^{2+}] + [\text{CaCO}_3] = [\text{Ca}^{2+}]_i \quad (4)$$

where $[\text{Ca}^{2+}]_i$ is the ionic calcium concentration at the input of the magnetic device,

$$\frac{d[\text{CaCO}_3]}{dt} = -\frac{d[\text{Ca}^{2+}]}{dt} \quad (5)$$

Therefore,

$$\frac{d[\text{Ca}^{2+}]}{dt} = -k_1 \times \{B, v, [\text{HCO}_3^-], [\text{OH}^-]\} [\text{Ca}^{2+}] + k'([\text{Ca}^{2+}] - [\text{Ca}^{2+}]) \quad (6)$$

where $k_1 = k(B, v)[\text{HCO}_3^-][\text{OH}^-]$,
i.e.,

$$\frac{d[\text{Ca}^{2+}]}{dt} = -(k_1 + k')[\text{Ca}^{2+}] + k'[\text{Ca}^{2+}]_i \quad (7)$$

If the scaling water remains during a time T (residence time) in the magnetic device, the concentration of the ionic calcium at the output is equal to

$$[\text{Ca}^{2+}] = \frac{k'}{k_1 + k'}[\text{Ca}^{2+}]_i + \frac{k_1}{k_1 + k'}[\text{Ca}^{2+}]_i \exp[-(k_1 + k')T] \quad (8)$$

with $T = L/v$, where L is the length of the device and v the flow velocity. If k_1 is supposed of the form

$$k_1 = k_0 B^m v^n \quad (9)$$

so that

$$\frac{[\text{Ca}^{2+}]}{[\text{Ca}^{2+}]_i} = \frac{k'}{k_0 B^m v^n + k'} + \frac{k_0 B^m v^n}{k_0 B^m v^n + k'} \exp\left[-(k_0 B^m v^n + k')\frac{L}{v}\right] \quad (10)$$

The curves of Figs 5 and 8 can be fitted with equation (10) as in Fig. 12. Notice that $[\text{Ca}^{2+}]$ tends towards $[\text{Ca}^{2+}]_i$ when the flow velocity tends to infinity in agreement with Kronenberg (1985), which has showed that there is an optimum velocity where the magnetic effect is maximum. Therefore, when the flow velocity increases too much, the residence time is too short and the magnetic treatment becomes inefficient. At a constant flow velocity, if the residence time increases too much the ionic calcium concentration decreases up to the point where the backward reaction of reaction (2) dissolves the formed particles of calcium carbonate to reach an equilibrium. Therefore, when the length of the device increases, the ionic calcium concentration tends to a limiting value.

By plotting $\log\{-\log[\text{Ca}^{2+}]/[\text{Ca}^{2+}]_i\}$ against $\log v$, a value close to $n = \frac{1}{3}$ (0.178) can be found. Such fractional coefficients are common in some magnetic-assisted processes, as in magnetic effect on mass transport in electrochemistry (Aaboubi *et al.*, 1990). To find the value of the exponent m of the induction of the magnetic field would necessitate a thorough investigation of the influence of the magnitude of the magnetic field on the efficiency of the magnetic device. Curves of Fig. 12 were plotted from equation

(10) by taking $k' = 0.28$, $k_0 B^m = 0.08$, $n = 0.2$ and L in meters (0.04 m per magnet). It shows an optimum flow velocity, around 3.5 m s^{-1} , where the magnetic treatment efficiency is maximum. Concerning the length of the magnetic device (or the duration of the treatment) influence, the model is globally in agreement with experiments, but it seems that a second process is involved, which is not taken into account here.

CONCLUSION

The magnetic treatment of scaling waters was proved to be efficient. The efficiency obtained with this very simple magnetic device can be very much improved if the geometry is better devised. An empirical relationship which gives the change of the ionic calcium concentration in function of the length of the device and of the flow velocity of the scaling water was established. There is a maximum efficiency at an optimal flow of the water to treat.

Commonly, authors have ascribed the magnetic treatment effect to MHD processes. However, the efficiency of the magnetic treatment depends on the material used to build the pipe where the water flows through the gap of the device. This may indicate that electrokinetic phenomena could be involved, alone or in conjunction with MHD processes, at the level of the walls of the pipe to generate calcium carbonate nuclei and even at the level of the growth of the calcium carbonate particles in the water bulk.

Thorough experiments have to be conducted to check these hypothesis and to assess the possible mechanisms of antiscaling action of the magnetic field.

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