

# Removal and/or prevention of limescale in plumbing tubes by a radio-frequency alternating electric field inductance device

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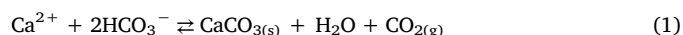
Antifouling technology  
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## ABSTRACT

Fouling problems due to limescale formation are of major concern to many industries. Deterioration of heat transfer equipment performance and substantial increase of pressure drop across piping systems comprise the main problems, resulting in high machinery-maintenance cost and decreased productivity. Limescale removal techniques, like scraping, hydro-blasting, and the use of aggressive chemicals, shorten the life of pipes and machinery. Furthermore, limescale prevention techniques in industrial scale, like ion-exchange or reverse osmosis, require expensive equipment and heavy maintenance. In this paper, an electronic antifouling device is presented which, not only prevents limescale formation, but also removes existing scale in plumbing tubes, at insignificant energy consumption. Induction of a Radio-Frequency Alternating Electric Field (RFAEF) in water at a specific range of frequency and antenna voltage, along with its distinct sinewave waveform, changes the way minerals precipitate, minimizing hard-lime scale by producing instead a non-adherent mineral powder in the bulk water. Moreover, the unsaturated solution that is created, along with enhanced carbon dioxide production, dissolves gradually the existing scale in plumbing tubes. Furthermore, the RFAEF inductance device demonstrates a major improvement over other pulsed-power systems, proving this electronic antifouling technique suitable for both hard and soft waters, as well as for large-scale applications.

## 1. Introduction

Scale is the well-known crusty chalky build up that forms when hard water is being processed in heat transfer equipment, such as, heat exchangers, condensers, evaporators, cooling towers, boilers, pipe walls, as well as, household appliances. Scale composition differs from application to application depending on the mineral content of the utilized water. The most common component of scale though is calcium carbonate ( $\text{CaCO}_3$ ), which occurs naturally as an ingredient of chalk, limestone, and marble. When hard water is pumped into heat transfer equipment, calcium and bicarbonate ions precipitate due to the changes in solubility, forming hard deposits (limescale) on the heat transfer surfaces, clogging pipes and manifolds (Reaction (1)); a phenomenon traditionally called “fouling” [1–3].



Fouling problems are of major concern to many industries using water and heat. Examples include petroleum, food, marine, mining, air compressor, and air separation industries. Once scale forms on a heat transfer surface, at least two major problems associated with the scale

occur. The first problem is the deterioration of the heat transfer equipment performance due to the much lower thermal conductivity of scale compared to that of pipe materials [4–6]. The second major problem is that a small change in tube diameter, substantially increases the pressure drop across the water piping system [7]. Scale creates also secondary problems of a big concern such as, rust accumulation leading to corrosion, increased growth of bacteria in drinking water [8,9], high machinery-maintenance cost, and decreased productivity due to increasing production downtime while equipment is repaired and maintained, equipment failure or even total damage [2,6]. Thus, it is self-evident that if one can reduce or prevent fouling in heat transfer equipment, the savings in energy, maintenance, and replacement of equipment will be truly significant.

Among the current techniques to prevent fouling is the use of scale-inhibiting chemicals, such as dispersing or chelating compounds that chemically grip dissolved cations, thus neutralizing them. Ion exchange and reverse osmosis are also used to reduce water hardness, alkalinity and silica level [2,3]. However, this equipment is expensive in industrial scale and requires heavy maintenance for proper operation. Furthermore, once fouling occurs in the piping system, scales need to be

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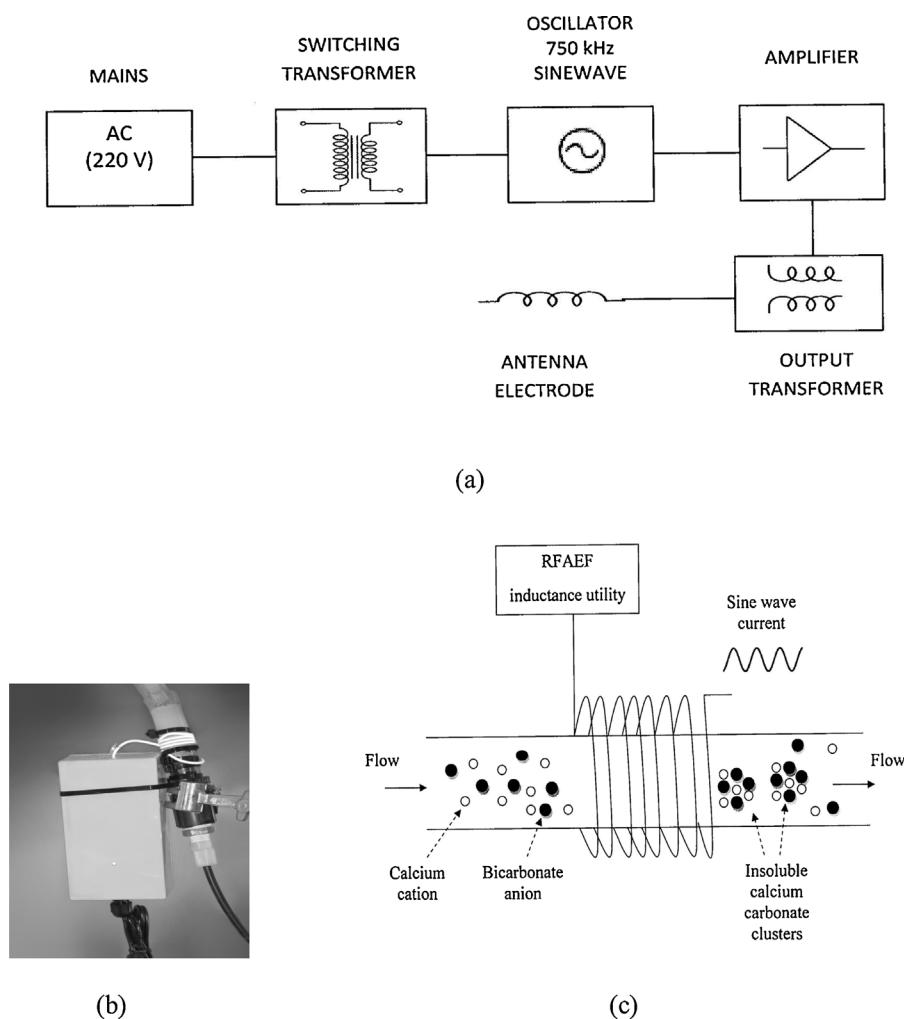


Fig. 1. (a) Block diagram, (b) photo, and (c) illustration of the operating principle of the RFAEF inductance utility.

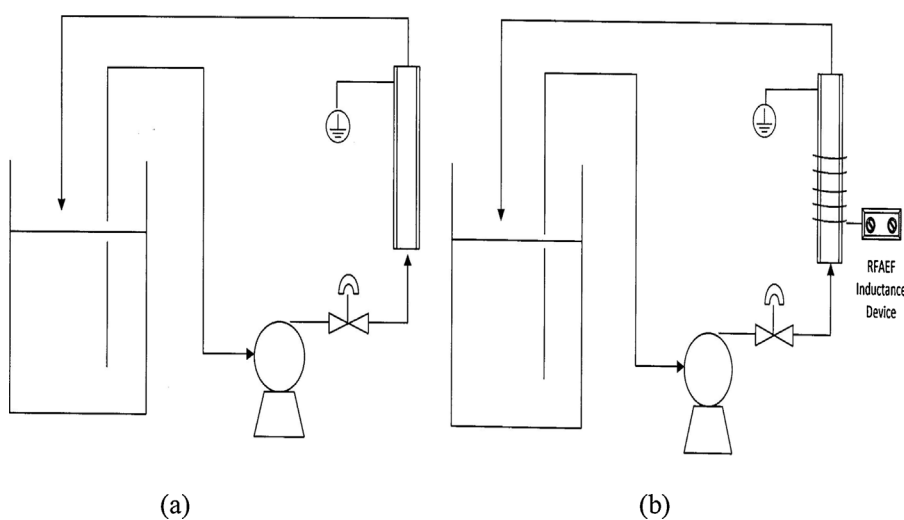


Fig. 2. Flowsheet of the experimental installations; (a) without the RFAEF inductance device, (b) with the RFAEF inductance device fit on the plumbing tube.

**Table 1**  
Scale prevention experiment – water characteristics.

pH	Alkalinity (mg/L $\text{CaCO}_3$ )	Total Hardness (mg/L $\text{CaCO}_3$ )	Conductivity ( $\mu\text{S}/\text{cm}$ )
8.4	600	600	2,030

removed by using several cleaning techniques, like, aggressive acidic chemicals, scraping, hydro-blasting, sand blasting, or the use of metal or nylon brushes. The latter operations incur downtime and repair costs, while they also shorten the life of the pipes and the machinery. Moreover, all the above scale-removing techniques pose danger on both human health and the environment with accidental spills, or accumulated chemical residues over a long period of time [10,11]. Thus, there is an increasing need for a new, environmentally safe and economically

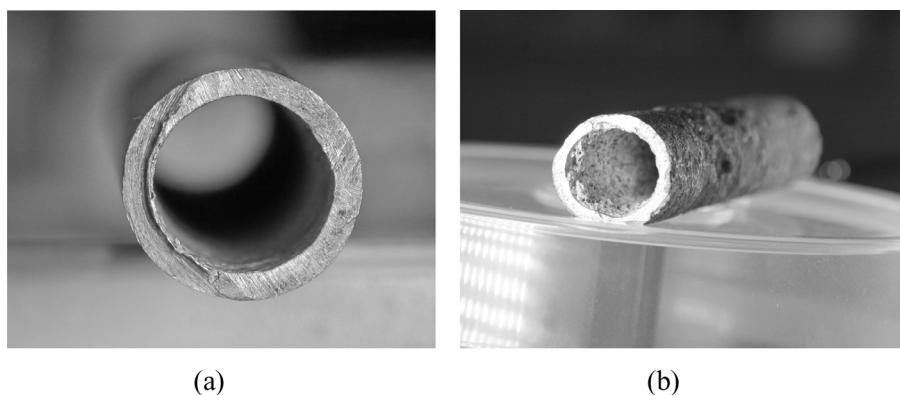


Fig. 3. (a) Photo of an unused brand new plumbing tube, (b) Photo of a plumbing tube rich in scale.

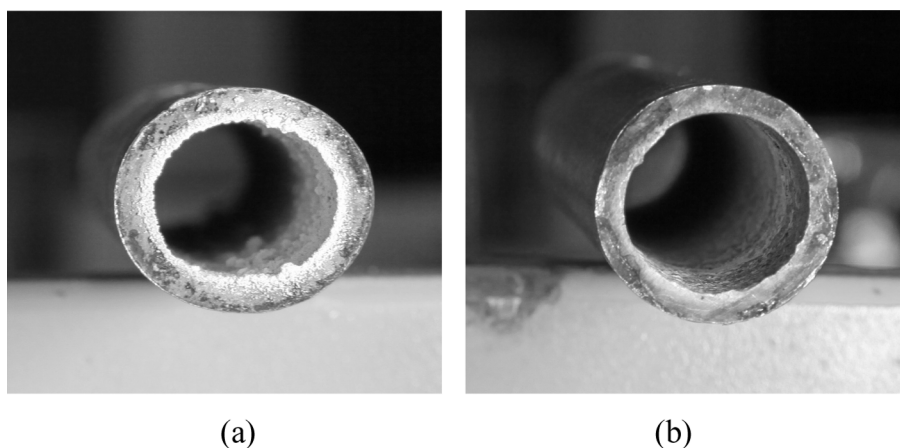


Fig. 4. Photos of plumbing tube cross sections – Scale prevention experiment; (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

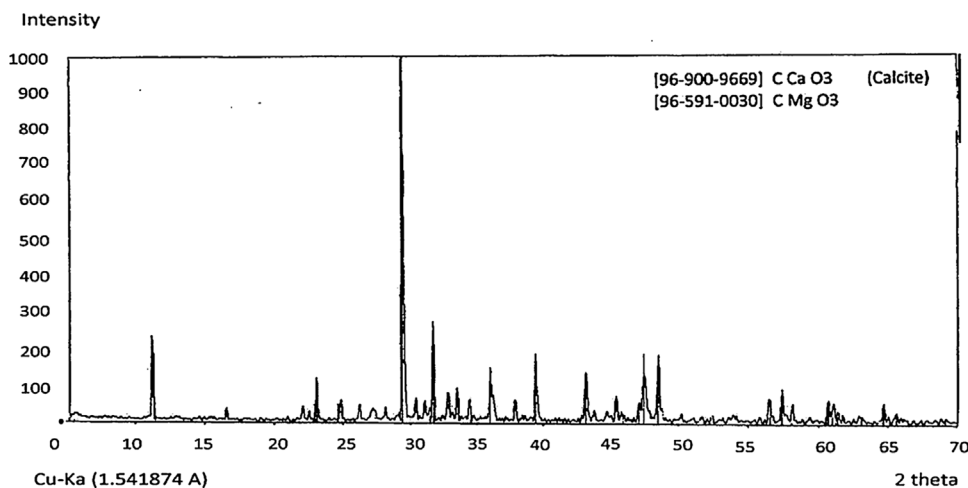


Fig. 5. X-ray diffraction pattern of plumbing tube limescale (Fig. 4(a)).

feasible process, in cleaning and maintenance of heat transfer equipment and piping systems.

In recent years, several physical water treatment methods have been developed in order to mitigate mineral fouling with the use of non-chemical processes, such as, solenoid coils [12,13], magnetic fields [14–16], catalytic material [17,18], electrolysis [19], and ultrasound [20,21]. The use of pulsed-power systems has also been increasingly reported with very promising results [22–26]. Pulsed-power devices impart electro-magnetic fields into the heating or cooling water, having a direct effect in preventing mineral scale formation on equipment surfaces, while also significantly reducing biofilms present in the piping systems [22–26]. The electric signal changes the way minerals in the water precipitate. Thus, the minerals form suspended clusters that turn

into stable crystals when temperature or pressure changes occur; avoiding hard-lime scale by producing instead a non-adherent mineral powder in the bulk water that is readily filterable and easily removed [25,26]. The water chemistry maintained by pulse-powered technology is non-corrosive, operating at the saturation point of calcium carbonate [27–29]. Pulsed-power techniques however, do not work effectively on soft water since the technology is based on changing the way minerals in the water precipitate. Thus, hard water is required in order to dissolve limescale deposits. Moreover, the energy consumption required for large-scale applications may become significant [12,30].

After almost 15 years of continual research and development experimentation, a novel electronic antifouling device has been developed which, not only presents the beneficial advantages of the above-

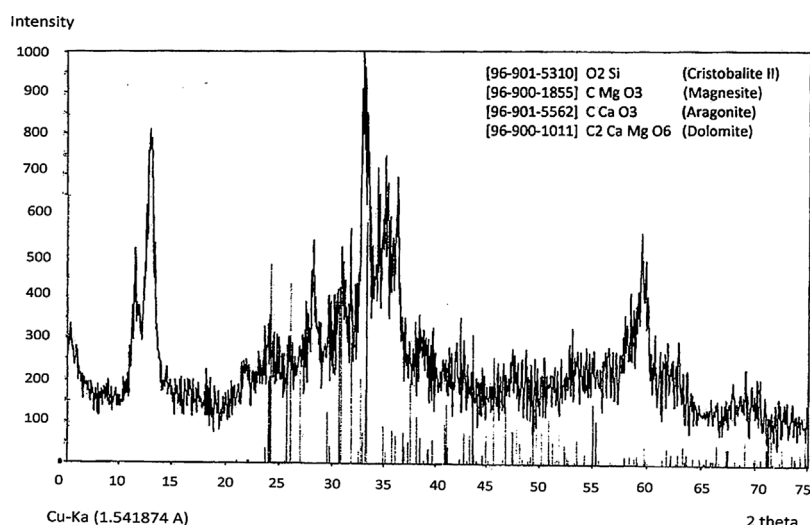


Fig. 6. X-ray diffraction pattern graphics of plumbing tube scale (Fig. 3(b)).

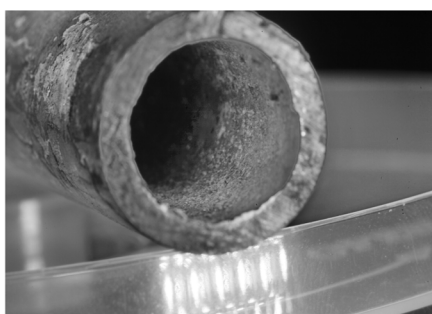
**Table 2**  
Scale removal experiment – hard water characteristics .

	Before experimental run	After experimental run <b>without</b> the RFAEF inductance device	After experimental run <b>with</b> the RFAEF inductance device
pH	8.1	8.5	8.4
Alkalinity (mg/L CaCO <sub>3</sub> )	250	212	188
Total Hardness (mg/L CaCO <sub>3</sub> )	250	192	172
Conductivity (μS/cm)	937	886	847
TSS <sup>a</sup> (mg)	–	161.9	1,826

<sup>a</sup> TSS = Total Settled Solids.



(a)



(b)

Fig. 7. Photos of plumbing tube cross sections – Scale removal experiment (hard water); (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

described similar techniques, but also overcomes the respective disadvantages. In more details, the latter electronic antifouling device works very effectively, not only on hard water, but also on very soft water. Thus, the objective of this paper is, firstly, to demonstrate the capability of the electronic antifouling device to prevent limescale formation in a plumbing tube under conditions of high water hardness concentration. Secondly, to demonstrate the capability of the latter electronic device to remove existing scale in plumbing tubes; utilizing not only hard, but also soft water.

## 2. Materials and methods

### 2.1. The electronic antifouling device

The electronic antifouling device (Fig. 1) is a Radio-Frequency Alternating Electric Field (RFAEF) inductance utility, which operates at 12 V and induces a 300 V pure alternating electric field directly in water; the magnetic induction is practically zero ( $\sim 1 \times 10^{-12}$  Gauss). The device's output produces a frequency of 750 kHz (medium

frequency radio band) with the aid of an advanced oscillator, while there is no need for an earth electrode. Furthermore, the alternating electric field is 100% of the sinewave type, producing a minimum number of harmonic frequencies. The major advantage of this technique is its maximum energy efficiency, since 98% of the electric field strength is induced in the aqueous phase, resulting in truly insignificant energy consumption (4 W).

### 2.2. Experimental installations, materials and procedure

Two identical experimental installations (Fig. 2) were set-up, each of them consisting of a 10 L water vessel, an electric water recirculation pump (flow rate: 9–11 L/min), a 10 cm-long, “½ in.” plumbing tube (inner diameter: 1.27 cm), and all the necessary tubing and connection accessories. The two installations worked simultaneously at each experimental run; the first of them ran without the RFAEF inductance device, while the second one ran with the latter device fit on the plumbing tube (Fig. 2). All the experiments were performed at ambient temperature (18–28 °C). In order to enhance the formation of limescale,

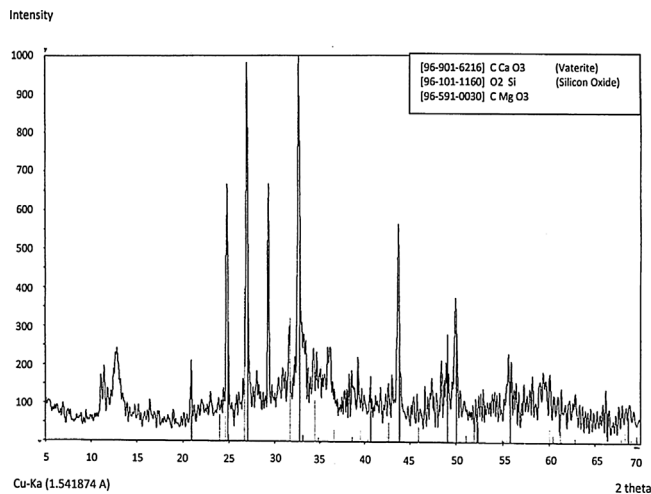


Fig. 8. X-ray diffraction pattern of Settled Solids (Scale removal experiment – hard water).

by assisting attraction of the calcium positive ions ( $\text{Ca}^{2+}$ ) on the inner surface of the plumbing tubes, the latter tubes of both installations were electrically grounded (Fig. 2).

Calcium chloride ( $\text{CaCl}_2$ ) and sodium bicarbonate ( $\text{NaHCO}_3$ ) from Fischer Scientific were utilized in order to prepare aqueous solutions of the desired total hardness concentration. Total alkalinity and total hardness concentrations were determined according to ASTM analysis methods [31], while pH and conductivity were measured by utilizing a Hanna, HI 8424 pH-meter and a Conductivity meter (WTW, LF 191 Conductometer), respectively. A portable oscilloscope (Fluke 123 industrial ScopeMeter) was used in order to measure alternating electric field voltage and waveform. Total Settled Solids (TSS) was collected by filtering with 0.45  $\mu\text{m}$ -pore filter. The solids were then washed with deionized water and left to dry in an oven ( $\sim 60^\circ\text{C}$ ) for 24 h. Scale-solids were collected by scratching with a brush. The latter solids were also collected on a 45  $\mu\text{m}$ -pore filter, washed with deionized water and left to dry in an oven ( $\sim 60^\circ\text{C}$ ) for 24 h. Finally, X-Ray Diffraction (XRD) was utilized in order to analyze the several crystalline phases of the scales and the settled solids. XRD analysis was performed at the Department of Mining and Metallurgical Engineering, at the National Technical University of Athens (NTUA). In more details, Powder XRD analysis was performed on a Bruker D8 Focus X-Ray Diffractometer, operating with  $\text{CuK}\alpha$  radiation. The samples were step-scanned from  $5^\circ$  to  $70^\circ$  ( $2\theta$ ), at a step of  $0.02^\circ$  and step time of 1 s. The major peaks of the XRD pattern were identified based on reference patterns, calculated from crystal structure data (Crystallography Open Database).

### 2.2.1. Scale prevention experimental procedure

The first experiment was conducted with the two installations (Fig. 2) running simultaneously and continually until an adequate scale formation was built-up on the inner surface of the first-installation plumbing tube. Water of a very high hardness concentration (Table 1) and brand new, scale-free, plumbing tubes (Fig. 3(a)) were utilized. The

aim of this experiment was to demonstrate the capability of the RFAEF inductance device to keep the respective plumbing tube clear of lime-scale, at all times. Due to the continual  $\text{CaCO}_3$  precipitation and subsequent drop of total hardness, the water content in both vessels was being replaced with a freshly-prepared one at the end of each week.

### 2.2.2. Scale removal experimental procedure

A series of experiments followed, utilizing this time plumbing tubes rich in scale formation (Fig. 3(b)). All the above tubes originated from a one-meter-long plumbing tube that had been in use for over 20 years in a rural area. Prior to the experimental run, the plumbing tubes were washed inside with tap water in order to remove any non-adherent particles. The experimental installations (Fig. 2) ran once more simultaneously, until a satisfactory removal of scale was observed in the plumbing tube of the second installation (with the RFAEF inductance device on). Hard water was prepared dissolving the proper amounts of  $\text{CaCl}_2$  and  $\text{NaHCO}_3$  in deionized water, while tap water was used in case of soft water experimentation.

## 3. Results and discussion

### 3.1. Scale prevention experiment

The two installations ran simultaneously for 6 months (24 weeks) non-stop under the same water conditions (Table 1). Myriads of tiny bubbles were observed in the water of the second installation (with the RFAEF inductance device on) due to the strong presence of carbon dioxide gas (Reaction (1)); the latter phenomenon was not observed in the first experimental installation. At the end of the 24th week, the experiment was paused and the plumbing tubes were removed. On the inner surface of the first-installation plumbing tube, a scale layer of nearly 1.0 mm was built-up that was very hard to remove by scratching. At the same time, the inner surface of the second-installation plumbing tube was only partially covered (several spots) by a thin layer of limescale that could be very easily removed by washing. Fig. 4 presents photos of the plumbing-tube cross sections revealing the above findings. Before the photos were taken, the plumbing tubes were washed inside with tap water in order to remove the slightly-adherent particles. XRD analysis (Fig. 5) revealed that the limescale of the first installation plumbing tube (Fig. 4(a)), consisted almost entirely of calcite, the most common polymorph of natural calcium carbonate [32]; traces of a magnesium carbonate crystalline formation were also identified.

By comparing the two photos (Fig. 4), it can be safely concluded that the induced RFAEF, changed indeed the way calcium carbonate precipitates in water. Moreover, it is evident that the above alternating electric field generated an increased number of inter-ionic-species collisions among calcium cations and bicarbonate anions (Fig. 1(c)), which resulted in the formation of stable clusters (nuclei) of calcium carbonate in bulk water. Thus, the formation of hard-lime scale on the metal surface was minimized; instead, a non-adherent powder was created. The latter results come in accordance with a phenomenon that has already been described and theoretically-approached by other researchers working on pulsed-power systems [7,24]. However, the RFAEF inductance device (Fig. 1) demonstrates a major improvement

Table 3  
Scale removal experiment – soft (tap) water characteristics.

	Before experimental run	After experimental run without the RFAEF inductance device	After experimental run with the RFAEF inductance device
pH	8.4	8.35	8.55
Alkalinity (mg/L $\text{CaCO}_3$ )	120	118	114.5
Total Hardness (mg/L $\text{CaCO}_3$ )	140.6	139.5	121.3
Conductivity ( $\mu\text{S}/\text{cm}$ )	285	282	278
TSS <sup>a</sup> (mg)	–	121	1,983.3

<sup>a</sup> TSS = Total Settled Solids.



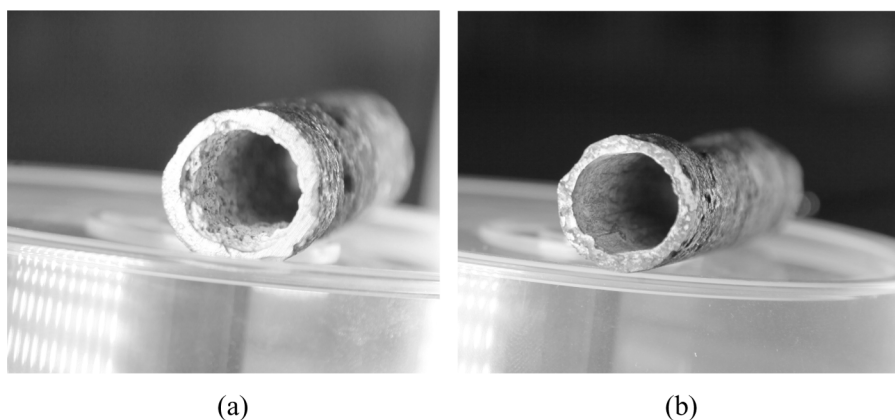


Fig. 9. Photos of plumbing tube cross sections – Scale removal experiment (soft water); (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

over the above mentioned pulsed-power systems [22–26]; as it imparts a considerable higher energy level into the water due to the specific combination of high frequency (0.65–1.1 MHz) and high antenna voltage (290–312 V), along with its distinct alternating electric field waveform (sinewave). Thus, as indeed verified by experiments and field measurements, 98% of the electric field strength is induced in the aqueous phase, contrarily to only around 20% of the above mentioned pulsed-power systems [22–26]. Furthermore, the created electric field can be measurable in a one (1) meter distance away from the antenna (left and right), as opposed to only a few millimeters in the previous pulsed-power systems. As a consequence, the RFAEF inductance device proves to be much more efficient compared to other pulsed-power systems [22–26], making this electronic antifouling technique suitable not only for hard but also for soft waters, as well as, suitable for large-scale applications.

### 3.2. Scale removal experiments

#### 3.2.1. Hard water experiment

Scale-rich plumbing tubes (Fig. 3(b)) were employed this time. XRD analysis of the scale (Fig. 6) identified four (4) main crystalline structures; namely, aragonite ( $\text{CaCO}_3$ ), magnesite ( $\text{MgCO}_3$ ), dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), and cristobalite II ( $\text{SiO}_2$ ). Hard water was prepared and utilized for the first experimental run (Table 2).

The experimental installations ran for a period of 48 days, until a satisfactory removal of scale was observed in the plumbing tube of the second installation (with the RFAEF inductance device on). At the same time, the scale in the first installation plumbing tube remained essentially unchanged (Fig. 7). From the beginning of the experiment, it was evident (by the myriads of existing bubbles) that the RFAEF inductance device enhanced Reaction (1) in the bulk solution; causing the immediate release of carbon dioxide. Thus, unsaturated solution was created by the process of homogeneous crystallization which, along with carbon dioxide, dissolved/removed gradually the existing surface scale that precipitated then in bulk solution; ending up on the bottom of the water vessel (the settled solids were obvious to the naked eye). Table 2 shows that the drop of alkalinity, total hardness, and conductivity was slightly higher in the second experimental installation. However, the mass of Total Settled Solids (TSS) was more than tenfold higher compared to the first installation, revealing the transfer of scale from the surface of the plumbing tube to the bottom of the water vessel.

XRD analysis of the settled solids (Fig. 8) identified vaterite ( $\mu\text{-CaCO}_3$ ), silicon oxide ( $\text{SiO}_2$ ), and magnesium carbonate ( $\text{MgCO}_3$ ), as the main crystalline phases. Vaterite, a metastable phase of calcium carbonate, is less stable than either calcite or aragonite and can easily convert to calcite after exposure to water at ambient conditions [30]. From the above analysis it can be concluded that aragonite ( $\text{CaCO}_3$ ), magnesite ( $\text{MgCO}_3$ ), and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), found initially in the scale (Figs. Figure 3(b), Figure 6), were gradually dissolved during the

course of the experiment, while the liberated calcium and magnesium ions precipitated then as vaterite (or even possibly as calcite) and magnesium carbonate, respectively. Meanwhile, large pieces of the scale (silica particles) were detached from the wall of the plumbing tube and settled down on the bottom of the vessel. The existence of a high proportion of impurities in scale, such as silica particles (Fig. 6), may have attributed to the relatively long time for scale removal. Furthermore, it is well known that aragonite, the second most common polymorph of natural calcium carbonate after calcite, forms hard and dense deposits leading to difficult scale removal [7,32].

#### 3.2.2. Soft water experiment

Soft water was utilized for the second experiment. Moreover, tap water from the city's water supply network (Athens, Greece) was tested. Table 3 presents the main physico-chemical characteristics of this water before and after the experimental runs. In this experiment, it took longer time for the RFAEF inductance device to satisfactorily dissolve/remove the scale from the plumbing tube (second installation). Meanwhile, and as actually expected, no essential change was observed in the scale of the first experimental installation plumbing tube. Fig. 9 presents photos of the plumbing tubes, 72 days after continual experimentation.

The latter finding comes in accordance with the above-described scale dissolving mechanism. Softer water is characterized by a lower calcium-ion ( $\text{Ca}^{2+}$ ) concentration; thus, the production rate of carbon dioxide (Reaction (1)) is lower compared to hard water. Being unsaturated, water dissolves the existing scale on the metal surface, however at a lower rate; leading thus to a prolonged time for full scale removal. As also in the previous experiment, the drop of alkalinity, total hardness and conductivity, was slightly higher in the second experimental installation (Table 3). However, the mass of Total Settled Solids (TSS) in the second experimental installation, was once more a lot higher (~16 times) compared to the first installation (Table 3); revealing again the transfer of scale-solids from the surface of the plumbing tube to the bottom of the water vessel.

Future work will focus on large-scale applications (industry, municipal drinking water distribution systems) and the research and development of advanced electronic antifouling devices.

### 4. Conclusions

An electronic antifouling device, which induced a radio-frequency alternating electric field in water, at a specific range of frequency and antenna voltage, along with its distinct waveform (sinewave), proved very efficient in preventing limescale formation in a plumbing tube while utilizing highly hard water. Furthermore, the same electronic antifouling device proved also very efficient in removing existing scale from plumbing tubes, using not only hard but also soft water. By utilizing the above electronic antifouling technique, removal and/or

prevention of limescale in plumbing tubes can be achieved at almost negligible energy consumption.

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## References

- [1] J. MacAdam, P. Jarvis, Zahid Amjad, Kostas Demadis (Eds.), *Water-Formed Scales and Deposits: Types, Characteristics, and Relevant Industries, Mineral Scales and Deposits, Scientific and Technological Approaches*, 2015, pp. 3–23 Chapter 1.
- [2] P.G. Koutsoukos, Zahid Amjad, Kostas Demadis (Eds.), *Water Chemistry and Its Role in Industrial Water Systems, Mineral Scales and Deposits, Scientific and Technological Approaches*, 2015, pp. 25–45 Chapter 2.
- [3] T.A. Hoang, Zahid Amjad, Kostas Demadis (Eds.), *Mechanisms of Scale Formation and Inhibition, Mineral Scales and Deposits, Scientific and Technological Approaches*, 2015, pp. 47–83 Chapter 3.
- [4] J.G. Knudsen, Cooling water fouling-a brief review, fouling in heat Exchanger Equipment, 20th ASME/AICHE Heat Transfer Conference, Milwaukee, HTD – 17, 1981, pp. 29–38.
- [5] C.F. Fan, A Study of Electronic Descaling Technology, Ph.D Thesis, Drexel University, Philadelphia, PA, 1997.
- [6] Y.I. Cho, B.G. Choi, Electronic anti-fouling technology to mitigate precipitation fouling in plate-and-frame heat exchangers, *Int. J. Heat Mass Transfer* 41 (17) (1998) 2565–2571.
- [7] Y.I. Cho, C.F. Fan, B.G. Choi, Theory of electronic anti-fouling technology to control precipitation fouling in heat exchangers, *Int. Commun. Heat Mass Transfer* 24 (1997) 757–770.
- [8] K.C. Makris, S.S. Andra, G. Botsaris, Pipe scales and biofilms in drinking-water distribution systems: undermining finished water quality, *Crit. Rev. Environ. Sci. Technol.* 44 (13) (2014) 1477–1523.
- [9] A. Mahapatra, N. Padhi, D. Mahapatra, M.B.D. Sahoo, S. Jena, D. Dash, N. Chayani, Study of biofilm in bacteria from water pipelines, *J. Clin. Diagn. Res.* 9 (3) (2015) DC09–DC11.
- [10] C.B. Panchal, J.G. Knudsen, Mitigation of water fouling: technology status and challenges, *Adv. Heat Transfer* 31 (1998) 431–474.
- [11] H. Muller-Steinhagen (Ed.), *Handbook of Heat Exchanger Fouling-Mitigation and Cleaning Technologies*, Publico Publications, Germany, 2000.
- [12] C.H. Sohna, C.S. Kim, S.Y. Moona, Y.I. Cho, Effect of a longitudinally positioned solenoid coil on electronic descaling, *Int. Commun. Heat Mass Transfer* 32 (2005) 240–247.
- [13] Y.I. Cho, H.S. Kim, Zahid Amjad, Kostas Demadis (Eds.), *Nonchemical Methods to Control Scale and Deposit Formation, Mineral Scales and Deposits, Scientific and Technological Approaches*, 2015, pp. 193–221 Chapter 9.
- [14] J.S. Baker, S.J. Judd, Magnetic amelioration of scale formation, *Water Res.* 30 (2) (1996) 247–260.
- [15] S.A. Parsons, B.L. Wang, S.J. Judd, T. Stephenson, Magnetic treatment of calcium carbonate scale – effect of pH control, *Water Res.* 31 (2) (1997) 339–342.
- [16] R.D. Ambashtaa, M. Sillanpaa, Water purification using magnetic assistance: a review, *J. Hazard. Mater.* 180 (2010) 38–49.
- [17] P.P. Coetzee, M. Yacoby, S. Howell, S. Mubenga, Scale reduction and scale modification effects induced by Zn and other metal species in physical water treatment, *Water SA* 24 (1) (1998) 77–84.
- [18] G.J. Lee, L.D. Tijting, B.C. Pak, B.J. Baek, Y.I. Cho, Use of catalytic materials for the mitigation of mineral fouling, *Int. Commun. Heat Mass Transfer* 33 (1) (2006) 14–23.
- [19] C. Gabrielli, G. Maurin, H.F. Chausson, P. Thery, T.T.M. Tran, M. Tlili, Electrochemical water softening: principle and application, *Desalination* 206 (2006) 150–163.
- [20] S. Min, H. Jian, L. Yinhui, C. Jianxin, Z. Yingying, K. Chadwick, Ultrasonic crystallization of calcium carbonate in presence of seawater ions, *Desalination* 369 (2015) 85–90.
- [21] B. Pecnik, M. Hocevar, B. Sirok, B. Bizjan, Scale deposit removal by means of ultrasonic cavitation, *Wear* 356–357 (2016) 45–52.
- [22] Y.I. Cho, J. Laneb, W. Kim, Pulsed-power treatment for physical water treatment, *Int. Commun. Heat Mass Transfer* 32 (2005) 861–871.
- [23] X. Xiaokai, Research on the electromagnetic anti-fouling technology for heat transfer enhancement, *Appl. Therm. Eng.* 28 (2008) 889–894.
- [24] Y. Yang, H. Kim, A. Starikovskiy, A. Fridman, Y.I. Cho, Application of pulsed spark discharge for calcium carbonate precipitation in hard water, *Water Res.* 44 (2010) 3659–3668.
- [25] L.D. Tijting, H.Y. Kim, D.H. Lee, C.S. Kim, Y.I. Cho, Physical water treatment using RF electric fields for the mitigation of CaCO<sub>3</sub> fouling in cooling water, *Int. J. Heat Mass Transfer* 53 (2010) 1426–1437.
- [26] L.D. Tijting, D.H. Lee, D.W. Kim, Y.I. Cho, C.S. Kim, Effect of high-frequency electric fields on calcium carbonate scaling, *Desalination* 279 (2011) 47–53.
- [27] U. Zimmermann, The effect of high intensity electric field pulses on eukaryotic cell membranes: fundamentals and applications, in: U. Zimmermann, G.A. Neil (Eds.), *Electromanipulation of Cells*, CRC Press, Boca Raton, 1996, pp. 1–106.
- [28] S.Y. Ho, G.S. Mittal, J.D. Cross, Effects of high field electric pulses on the activity of selected enzymes, *J. Food Eng.* 31 (1997) 69–85.
- [29] R. Shafiu, Pulsed electric fields in food Preservation, *Handbook of Food Preservation Technology & Engineering*, (1999).
- [30] Y.I. Cho, W. Kim, S. Lee, ASHRAE Paper CH-03-3-3 (RP-1155). Physical water treatment for the mitigation of mineral fouling in cooling-tower water applications, *ASHRAE Trans.* 109 (1) (2003) 346–357.
- [31] APHA, AWWA, WEF, E.W. Rice, R.B. Baird, A.D. Eaton, L.S. Clesceri (Eds.), *Standard Methods for the Examination of Water and Wastewater*, 22nd Edition, 2016.
- [32] F.W. Tegethoff, A.G. Springer-Basel (Ed.), *Calcium Carbonate: From the Cretaceous Period into the 21st Century*, Birkhäuser, 2001.