

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

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Abstract

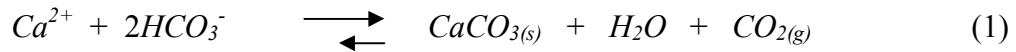
Fouling problems due to limescale formation are of major concern to many industries. Degradation in the performance of heat transfer equipment and substantial increase of pressure drop across piping systems comprise the main problems, resulting in high machinery-maintenance cost, decreased productivity and equipment failure. Limescale removal techniques, such as, scraping, hydro-blasting, sand blasting, and the use of aggressive chemicals, shorten the life of the pipes and the 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 truly insignificant energy consumption. Induction of a radio-frequency alternating electric field in water changes the way minerals precipitate; totally avoiding hard-lime scale by producing instead a non-adherent mineral powder in the bulk water. Moreover, the unsaturated solution that is created by the process of homogeneous crystallization, along with enhanced carbon dioxide production, dissolves the existing scale in plumbing tubes. Finally, unlike other similar physical water treatment methods (pulsed-power techniques), the above electronic antifouling technique proved very effective, not only on hard water, but also on very soft water.

Keywords

Antifouling technology; electronic descaling device; limescale prevention; plumbing tube; radio-frequency alternating electric field

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 ($CaCO_3$), 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 degradation in the performance of the heat transfer equipment 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 heat transfer equipment [7]. Scale creates also secondary problems of a big concern such as, rust accumulation leading to corrosion, increased growth of bacteria in drinking water, high machinery-maintenance cost, and decreased productivity due to increasing production downtime while equipment is repaired and maintained, equipment failure or even total damage. 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 [2, 6].

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 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 [8, 9]. Thus, there is an increasing need for a new, environmentally safe and economically 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 [10, 11], magnetic fields [12-14], catalytic material [15, 16], electrolysis [17], and ultrasound [18, 19]. The use of pulsed-power systems has also been increasingly reported with very promising results [20-24]. 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. 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; totally avoiding hard-lime scale by producing instead a non-adherent mineral powder in the bulk water that is readily filterable and easily removed [23, 24]. Bacteria are encapsulated into this mineral powder and cannot reproduce, thereby resulting in low bacteria populations. The water chemistry maintained by pulse-powered technology is non-corrosive, operating at the saturation point of calcium carbonate [25-27]. 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 [10, 28].

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-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. Experimental

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 Watt).

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, a 10 cm-long, "½ inch" 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, by assisting attraction of the calcium positive ions (Ca^{2+}) on the inner surface of the plumbing tubes, the latter tubes of both installations were electrically grounded (Fig. 2).

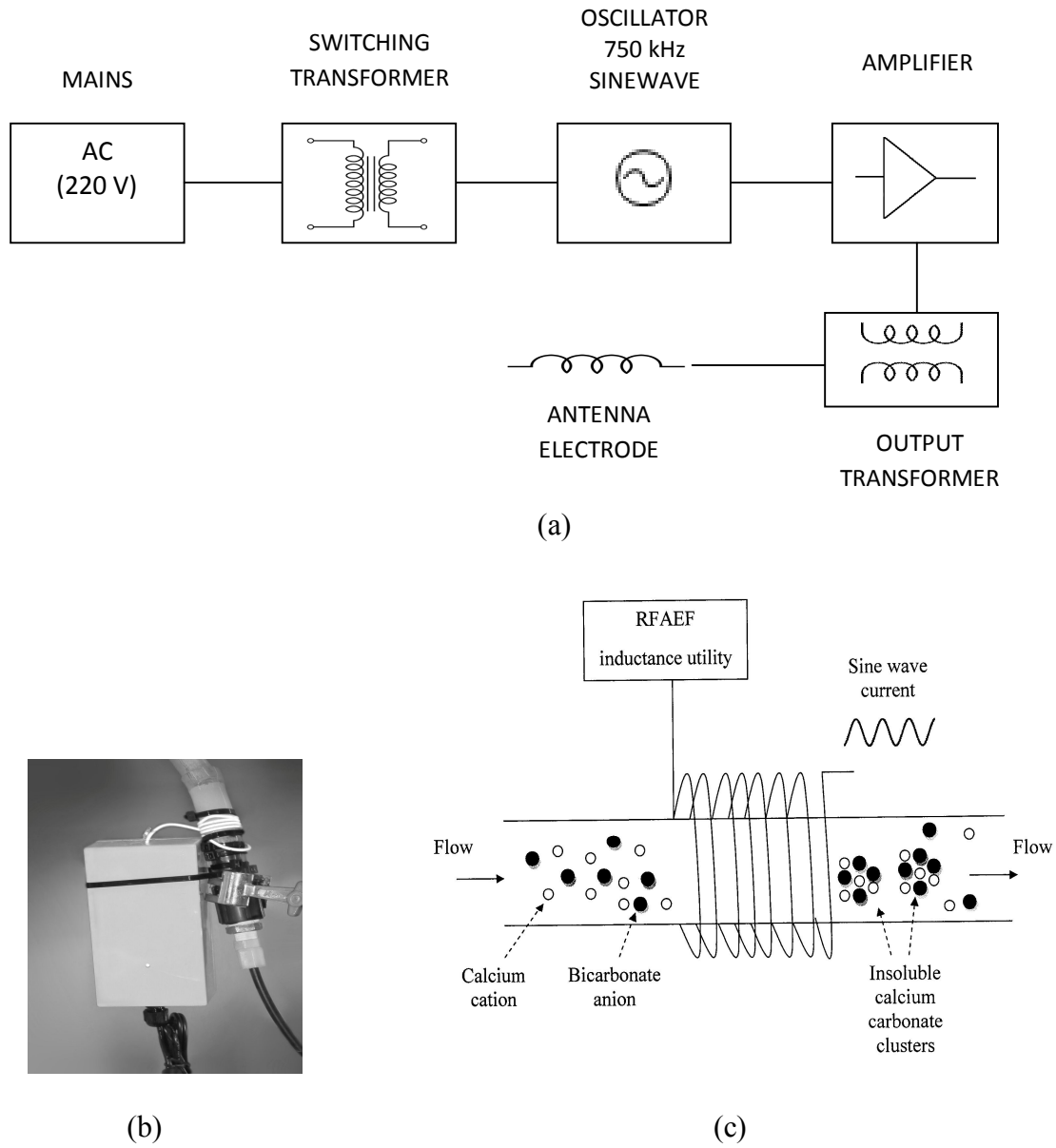


Fig. 1. (a) Block diagram, (b) photo, and (c) illustration of the operating principle of the RFAEF inductance utility.

Calcium chloride (CaCl_2) and sodium bicarbonate (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 [29], while pH and conductivity were measured by utilizing a Hanna, HI 8424 pH-meter and a Conductivity meter (WTW, LF 191 Conductometer), respectively. Total Settled Solids (TSS) were collected by filtering with 0.45 μm -pore filter. The solids were then washed with deionized water and left to dry in an oven ($\sim 60^\circ\text{C}$) for 24 hours. Scale-solids were collected by scratching with a brush. The latter solids were also collected on a 45 μm -

pore filter, washed with deionized water and left to dry in an oven ($\sim 60^{\circ}\text{C}$) for 24 hours. 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° to 70° (2θ), at a step of 0.02° 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).

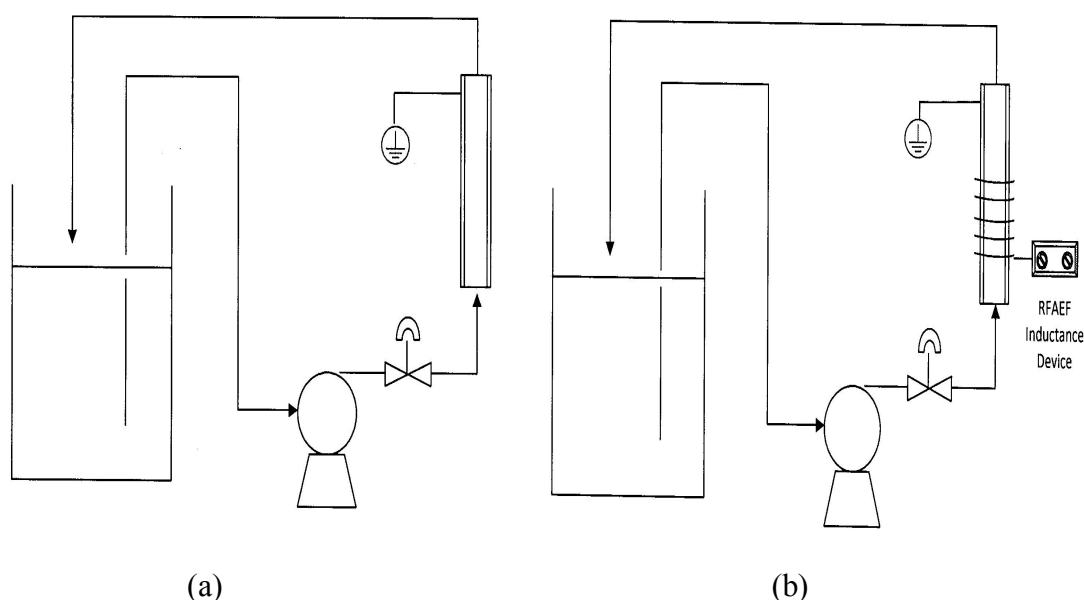


Fig. 2. Flowsheet of the experimental installations; (a) without the RFAEF inductance device, (b) with the RFAEF inductance device fit on the plumbing tube.

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) 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 limescale, at all

times. Due to the continual 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.

Table 1

Scale prevention experiment - water characteristics

pH	Alkalinity (mg/L CaCO_3)	Total Hardness (mg/L CaCO_3)	Conductivity ($\mu\text{S}/\text{cm}$)
8.4	600	600	2,030

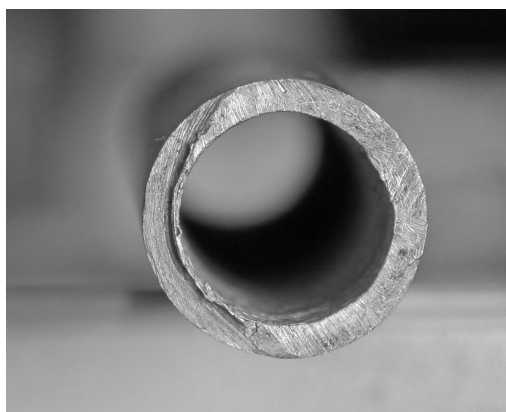


Fig. 3. Photo of an unused brand new plumbing tube.

2.2.2 Scale removal experimental procedure

A series of experiments followed, utilizing this time plumbing tubes rich in scale formation (Fig. 4). 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, around 80 Km north of Athens, Greece. 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 CaCl_2 and NaHCO_3 in deionized water, while tap water was used in case of soft water experimentation.



Fig. 4. Photo of a plumbing tube rich in scale

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. 5 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.

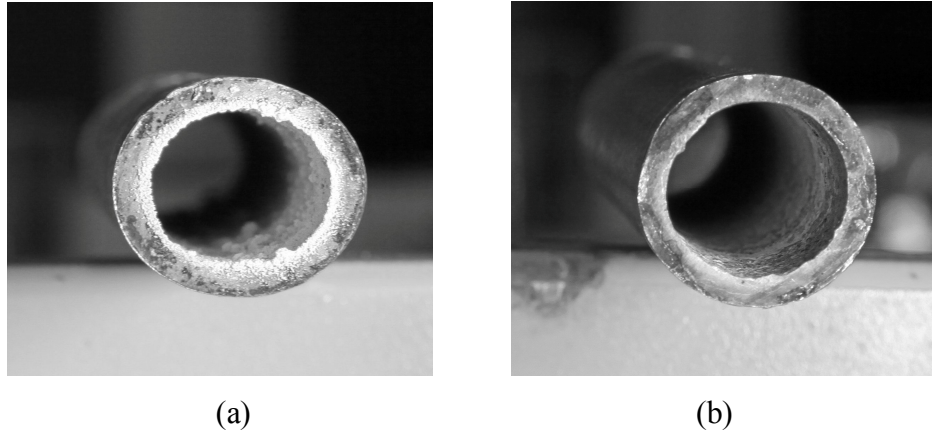


Fig. 5. Photos of plumbing tube cross sections - Scale prevention experiment; (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

By comparing the two photos (Fig. 5), it can be safely concluded that the induced radio-frequency alternating electric field, changed indeed the way calcium carbonate precipitates in water. Thus, under the influence of the above alternating electric field, stable crystals of calcium carbonate were formed in bulk water (by homogeneous crystallization), avoiding hard-lime scale on the metal surface; producing instead a non-adherent powder. The latter results come in accordance with a phenomenon that has already been described and theoretically-approached by other researchers [7, 24]. Moreover, XRD analysis (Fig. 6) revealed that the limescale of the first installation plumbing tube (Fig. 5 (a)), consisted almost entirely of calcite, the most common polymorph of natural calcium carbonate [30]; some traces of a magnesium carbonate crystalline formation were also identified.

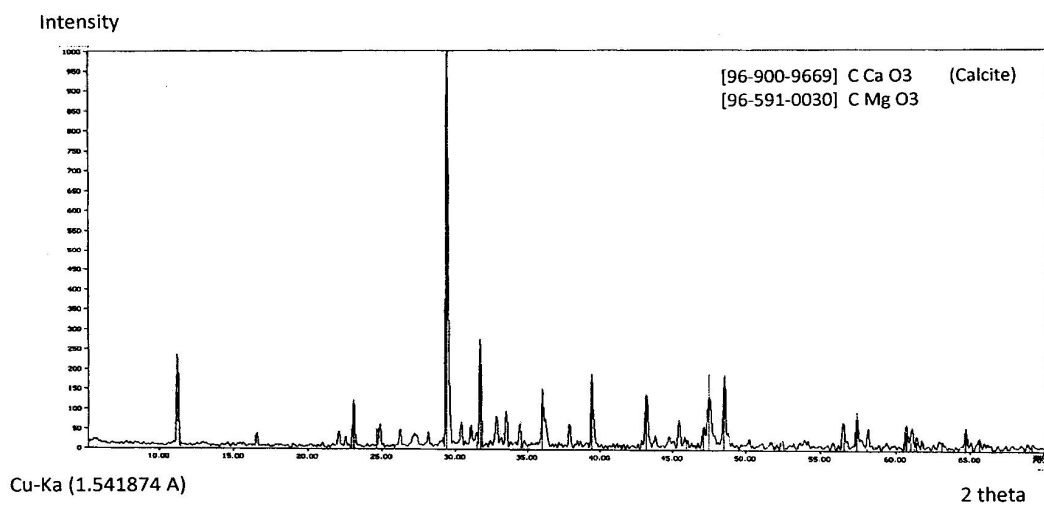


Fig. 6. X-ray diffraction pattern of plumbing tube limescale (Fig. 5 (a)).

3.2 Scale removal experiments

3.2.1 Hard water experiment

Scale-rich plumbing tubes (Fig. 4) were employed this time. XRD analysis of the scale (Fig. 7) identified four (4) main crystalline structures; namely, aragonite (CaCO_3), magnesite (MgCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), and cristobalite II (SiO_2). Hard water was prepared and utilized for the first experimental run (Table 2).

Table 2

Scale removal experiment - hard water characteristics

	Before experimental run	After experimental run without the RFAEF inductance device	After experimental run with the RFAEF inductance device
pH	8.1	8.5	8.4
Alkalinity (mg/L CaCO_3)	250	212	188
Total Hardness (mg/L CaCO_3)	250	192	172
Conductivity ($\mu\text{S}/\text{cm}$)	937	886	847
TSS* (mg)	-	161.9	1,826

* TSS = Total Settled Solids

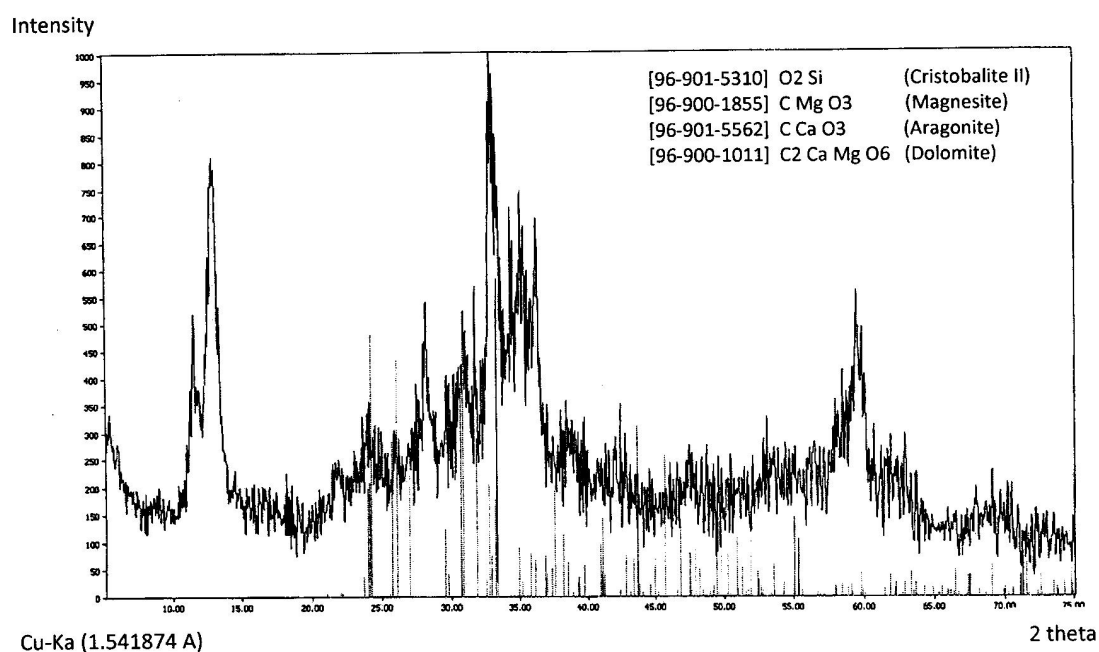


Fig. 7. X-ray diffraction pattern graphics of plumbing tube scale (Fig. 4).

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. 8). 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.

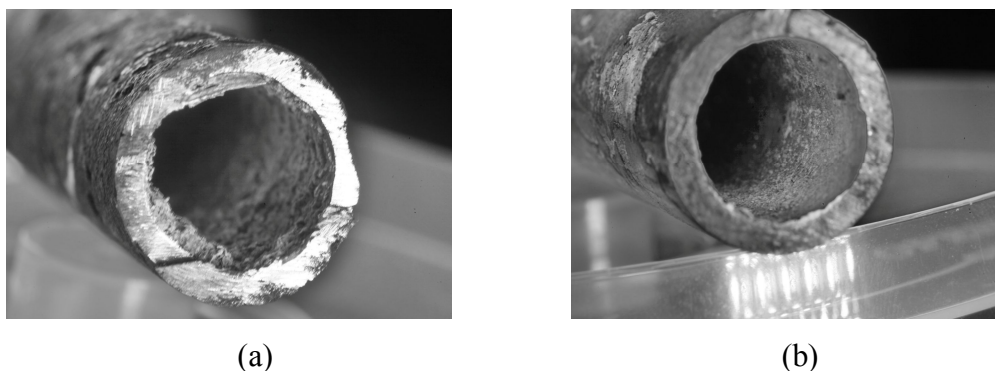


Fig. 8. Photos of plumbing tube cross sections - Scale removal experiment (hard water); (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

XRD analysis of the settled solids (Fig. 9) identified vaterite ($\mu\text{-CaCO}_3$), silicon oxide (SiO_2), and magnesium carbonate (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 (CaCO_3), magnesite (MgCO_3), and dolomite ($\text{CaMg}(\text{CO}_3)_2$), found initially in the scale (Figs 4,

7), 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. 7), 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, 30].

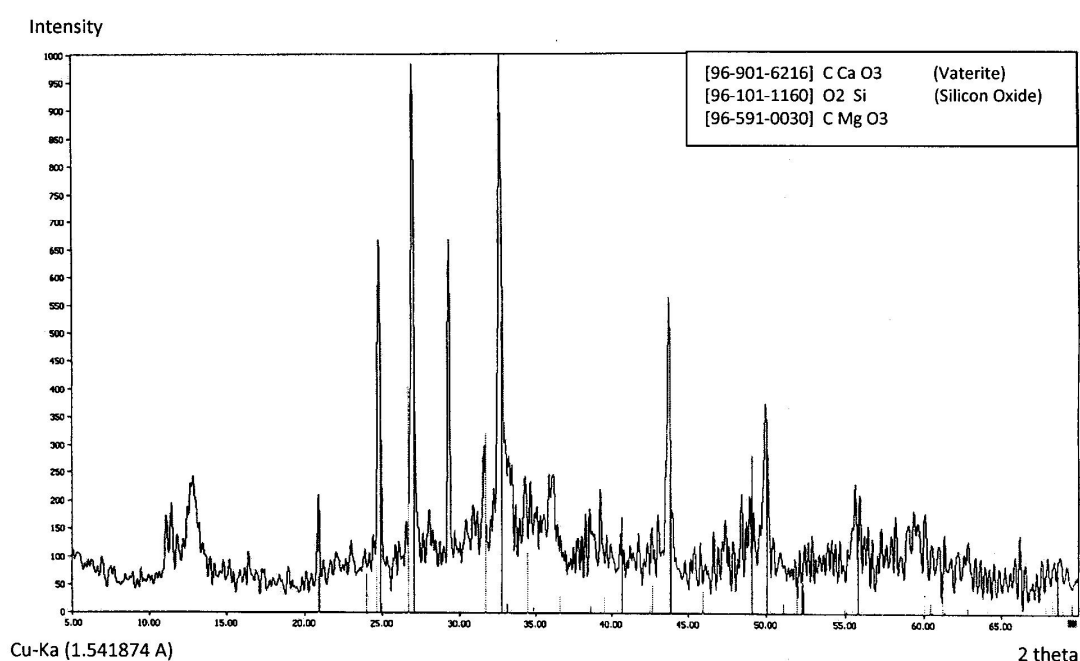


Fig. 9. X-ray diffraction pattern of Settled Solids (Scale removal experiment – hard water).

3.2.2 Soft water experiment

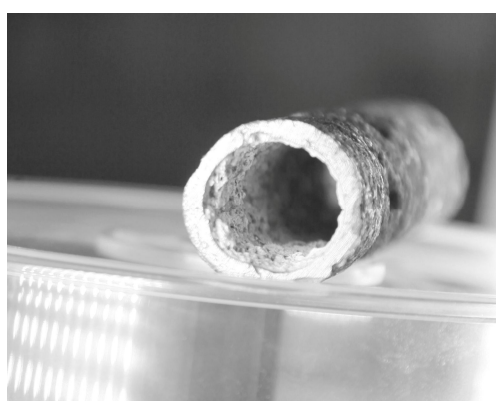
Soft water was utilized for the second experiment. Moreover, tap water from the city's water supply network (Athens, Greece) was tested. Table 3 presents the main physico-chemical characteristics of this water before and after the experimental runs. In this experiment, it took longer time for the RFAEF 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. 10 presents photos of the plumbing tubes, 72 days after continual experimentation.

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 CaCO ₃)	120	118	114.5
Total Hardness (mg/L CaCO ₃)	140.6	139.5	121.3
Conductivity (μS/cm)	285	282	278
TSS* (mg)	-	121	1,983.3

* TSS = Total Settled Solids



(a)



(b)

Fig. 10. Photos of plumbing tube cross sections - Scale removal experiment (soft water); (a) Without the RFAEF inductance device; (b) With the RFAEF inductance device.

The latter finding comes in accordance with the above-described scale dissolving mechanism. Softer water is characterized by a lower calcium-ion (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.

4. Conclusions

An electronic antifouling device, which induced a radio-frequency alternating electric field in water, 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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Footnotes

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