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Calcium and silica removal from water in evaporative cooling systems, using precipitation and electrocoagulation

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ABSTRACT

One of the main problems of evaporative cooling systems is incrustation, mainly caused by calcium (Ca) and silica (SiO_2), present in raw water or make up water. Its elimination might be complicated and expensive due to the use of specialized personnel and equipment. In this paper, removal of both Ca and SiO_2 using precipitation and electrocoagulation (EC) is evaluated. First, individual tests for precipitation and EC were made, followed by batch combined precipitation and EC tests. Last, a 2^3 experimental design was used to evaluate the effect of three factors; the direct current voltage applied (DCV), flow, and reactor configuration. The obtained results are encouraging, with just 5 min of residence time for precipitation and 2 min for EC, the achieved removal efficiency for both Ca and SiO_2 were higher than 91%.

Keywords: Electrocoagulation; Scaling; Evaporative cooling systems

1. Introduction

Water is considered as a quasi-universal solvent, in it practically all substances are soluble in different degrees. Raw water carries different quantities of dissolved salts and minerals depending on the source. These salts and minerals affect its electrical conductivity, so it is possible to indirectly measure the approximate content of dissolved solids in water.

Extraction of water for industrial use, regarding its relative low volume compared to agriculture and cattle rising, has become an important factor, due to the competence with other users for supplying, as well as for the quantity and diversity of contaminants discharged. Industrial cooling systems are required to keep the temperature specified for the process. Water is the most used refrigerant for its high calorific capacity, its availability and easy management. Water used for cooling towers in thermoelectric plants reaches an annual volume of 200 million m^3. However, this sector is now competing with other users, especially in places where overexploitation of the resource is an important factor, as it happens in La Comarca Lagunera in Mexico [1]. Social pressure, shortage and an increasing astringent legislation and over all, the high price of potable water, obligate companies to look for solutions in order to reduce consumption and to reuse process water.

Evaporative cooling systems, evaporate a portion of the water in the system, and consequently reduce the temperature of the remaining water. However, the evaporated water does not take with it the dissolved salts and minerals, even worse they are left as a heritage, increasing its concentration in cooling water. Some of those salts and

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minerals increase their solubility with temperature, but not all of them. Those that decrease their solubility tend to form deposits that favor incrustation and/or corrosion in piping and equipment. To overcome these effects it is necessary: to purge a portion of the water with high concentration of dissolved solids and feed make up water to compensate both, the purged and the evaporated water in order to keep in the acceptable specified limits substances that favor incrustation/corrosion, and the addition of different chemicals such as sulfuric acid to increase solubility of Ca, incrustation and corrosion inhibitors. Additionally, evaporative cooling systems are open processes that allow dirty and biological contamination, which implies that a periodic cleaning of the system has to be carried out, and the use of microbicides.

Corrosion and incrustation affect the cost of operation of cooling systems due to: the deficiency on heat transfer, and dead time of operation for the activities of maintenance and reparations. These control and maintenance costs are millions of dollars a year.

Concentration cycles (CC) in cooling systems point out how many times raw water is used before it is eliminated via the purge. CC give an idea of the reusing of water in cooling systems. The number shows the relationship of minerals in cooling water to minerals in raw water, usually Ca and/or SiO_2 are used for determination of the CC. Of course, the higher the CC with no incrustation or corrosion problems, the better the efficiency and the lower the costs for water and treatment. In fact if CC are raised, in the same proportion costs for water and treatment are reduced. Main limitations to increase the recycle of cooling water are associated with water quality problems, being the most commune the formation of inorganic compounds that form deposits on the surface of heat exchangers, causing efficiency loss. A great variety of chemical deposits have been found, however, those that include Ca and/or SiO_2 are of particular interest. Removal of calcium and silica is an attractive way of controlling those deposits.

Cooling systems are affected for the quality of the make-up water, usually raw water (RW). Quality of RW is variable, depending on its source, superficial, groundwater, or the actual tendency of focusing in the use of treated municipal wastewater. Cooling systems are also affected by the environment where the system is installed, and of course for the operating conditions. So, it not easy to propose definitive solutions for any system. Nonetheless, the more common causes of incrustation and corrosion problems are water hardness and silica, beside of microbiological problems. Usually, these problems are faced in an individual way or with expensive solutions. Some of the proposed and conventional water treatments for control of scaling and corrosion in cooling systems are: lime – soda ash softening, zeolite softening, demineralization, reverse osmosis (RO), electrodialysis, coagulation, and the use of corrosion and incrustation inhibitors, and biocides. And some non-conventional water treatments such as electrocoagulation, and the use of magnets. They have been used alone or combined with different degrees of success. Of course all of them have advantages and disadvantages. Among the disadvantages are: expensive equipment, the cost for the use of chemicals and the associated generation and management of wastes, the required area, the high pressure requirements for operation, energy consumption, and the need of specialized personnel to operate the treatment system. On the other hand, removal of silica from water cooling systems using electrocoagulation (EC), with Fe or Al electrodes have proved to be effective, and it has also been combined with RO with good results but high cost [2].

Electrocoagulation (EC) is an electrochemical technology for the treatment of water and wastewater. In its simplest form, EC uses an electrochemical cell with a DC voltage applied to usually iron or aluminum electrodes, with water or wastewater as the electrolyte. EC involves the generation of coagulant in situ by dissolution of metal from the anode with simultaneous formation of hydroxyl ions and hydrogen gas at the cathode. This process produces the corresponding aluminum or iron hydroxides and/or polyhydroxides, which act as reacting or adsorbent agents for most pollutants. EC has been used for removal of all kind of pollutants, with different grades of success. EC has also been combined with many other non-conventional treatments. For example with: flotation for removal of phenol and linear alkylbenzene sulfonate from automotive service station wastewater [3], microwaves for the removal of heavy metals suffused with organic matter [4], and ultra-sonication for remediation of concrete plants' effluents [5].

It is well known that EC using aluminum electrodes remove silica easily, and that removal of small quantities of suspended solids is not a problem for EC. For these reasons precipitation of calcium, and simultaneous removal of suspended solids and silica using EC with Al electrodes was chosen.

Some background for the project is shown in Table 1. Three references are related to total and/or calcium hardness, and the rest for silica. These result are questionable because, they used laboratory prepared solutions instead of using real samples, or pH and conductivity adjustments were made. Laboratory made solutions do not correspond to reality, they do not have the chemicals used for water treatment that can affect the performance of EC. pH and conductivity adjustments are made with the addition of more chemicals that imply cost, safety risks, and wastes.

Through the use of a 2^3 experimental design, this project aims to develop a raw water continuous treatment system, that combines physicochemical processes and EC to remove the two more problematic components of water in cooling systems, calcium and silica, to reduce water consumption, use of energy, use of chemicals, generation of wastes, to increase concentration cycles, and to be competitive with conventional treatments.

2. Methodology

Equipment and materials required for experimental tests are: a beaker size reactor for preliminary tests and a Kaselco continuous reactor of 700 W DC model RC4545050711, with 5 Al electrodes of 11.4 × 9.5 cm and a separation between electrodes of 0.65 cm; a Kaselco Rectifier of 0–50 VDC and 0–10 A, with voltage or current regulator, current invertor, with a peristaltic pump 0–4 lpm, with flow controller, a Talboys Enginering Corp mechanical stirrer model T-line 101; a Thermolyne Cimarec 2 magnetic stirrer; a Mini pump Brushless DC Pump 2415–01 3 M of

Table 1
Background for removal of Ca and SiO_2 with electrocoagulation

Reference	Initial total hardness (TH), calcium hardness (Ca-H) ppm	Removal (%)	Electrodes			Residence time (Rt) (min)	I (Å)	Reactor	Adjustments	Observations
			Dimensions	Material	Separation					
[6]		60–70 60		Fe Al				4 parallel plates		Brine reject from RO. Laboratory prepared solution. Presence of As favors hardness removal, when it is not present only 15% of hardness removal is achieved
[7]	CT ~21–29 RO ~38–47	10–20 15–20	3.2 cm × 34 cm × 0.32 cm	Fe Al	0.4 cm	1	0.3 and 0.9 mA/cm^2	Lab, 9 parallel plates (3.5 l) Pilot 73 Electrodes 20.3 cm × 50.8 cm × 0.32 cm	pH with NaOH or HCl	For purge water from cooling systems and reject from RO
[8]	RW = 12 CT = 140	up to 70	76 cm × 20 cm × 0.3 cm tubular continuous 5 cm diameter, helicoidal, length 360 cm, 0.6 cm	Al	0.5 cm	5–20 18	3	Laboratory tubular continuous	Conductivity with NaCl, pH with NaOH and HCl	
Reference	**Initial silica (ppm)**	**Removal (%)**	**Electrodes**			**Rt (min)**	**I (Å)**	**Reactor**	**Adjustments**	**Observations**
[7]	CT ~40–50 RO ~60–75	60 90	3.2 cm × 34 cm × 0.32 cm	Fe Al	0.4 cm		0.65–2	Lab, 9 parallel plates (3.5 l) Pilot 73 Electrodes 20.3 × 50.8 × 0.32	pH with NaOH or HCl	For purge water from cooling systems and reject from RO
[8]	RW = 12 CT = 140	up to 95	76 cm × 20 cm × 0.3 cm tubular continuous 5 cm diameter, helicoidal, length 360 cm, 0.6 cm	Al	0.5 cm	5–20 18	3	Laboratory tubular continuous	Conductivity with NaCl, pH with NaOH or HCl	
[9]	1,000	70–85 60–75	3.4 cm × 32 cm × 3.2 cm	Fe		10 20	0.322	Concentric	pH with NaOH or H_2SO_4	Reject from RO. Laboratory prepared solution. Maximal removal, pH between 6 and 8
[4]	98.2	42–54	34 of 10 cm × 5 cm × 0.45 cm	Fe	0.5 cm	2	7–15 Å	Descendent flow, laberynth, 43, 63 and 71 lps	pH from 10–11 with $Ca(OH)_2$, cationic polyelectrolyte	
[10]	20–100	60–100	2 of 18 cm × 18 cm	Al	0.5–2.5 cm	15–75		Cylindrical	pH 4.5–10.5	Artificially prepared water
[11]	RW ~50–83 CT ~164–195	RW ~75–88 PP ~39–46	60 plates of 8 cm × 4 cm × 0.5 cm	Al	0.6 cm	>>120	71 A/m^2	Continuous	pH	
[12]	RW = 48	Average 66.5	60 plates of 8 cm × 4 cm × 0.5 cm	Al	0.6 cm		0.0048 A/cm^2	Continuous	Conductivity with NaCl	RW raw water, CT cooling tower, RO reverse osmosis, Å Amperes

12VDC y 240 lph; a micro pump GOSO D2 of 12 VDC y 180 lpm; a HANNA Instruments pH/ORP &EC/TDS-NaCl meter HI2550; an A&D Company Limited HR-250[a] analytical balance, a JENWAY 7305 spectrophotometer, Steren MUL-285 multimeters, rheostats with breakers for flow control of mini and micro pumps, magnetic bars, Fe and Al electrodes of different dimensions, 100 and 20 l containers, assorted lab materials and equipment, reagent grade chemicals and Whatman filter paper 4. Determination of Ca with EDTA, and SiO_2 with ammonium molybdate, were made following the Standard Methods for the Examination for Water and Wastewater, 2,340 and 4,500 respectively. The raw water used was well water from La Comarca Lagunera, México. Its conductivity is actually in the range of 1,300–1,500 µS, and its calcium and total hardness contents are around 660, and 500 ppm as $CaCO_3$, respectively.

2.1. Ca precipitation tests

For calcium precipitation, different salts were tested, however, the best results were obtained with monosodium, disodium and trisodium phosphates. The followed procedure was: determining the stoichiometric quantities for the reaction of the three different phosphates with calcium carbonate; 2.53 mg of Na_3PO_4 ($12H_2O$), 1.79 mg of Na_2HPO_4 ($7H_2O$), and 0.92 mg of NaH_2PO_4 (H_2O) per mg of Ca respectively, determination of Ca hardness (Ca-H) in raw water, weighting of the required amount of phosphates for each of the tests, and grinding to increase the efficiency of the reaction. The test is performed with 1 L of sample in a beaker size reactor, using magnetic agitation for 10 min. Then, the solution is filtered, and the hardness and calcium removal is determined. In fact the total hardness is used for calculation, but results are only presented for Ca hardness.

2.2. SiO_2 removal tests (batch)

The experimental setup for silica removal in batch, using EC, with Fe and Al electrodes, is presented in Fig. 1.

The followed procedure was: determination of silica concentration (ppm) in raw water sample and running of EC with continuous stirring. Four test were run, using different dimensions, material, and separation of electrodes, as well as different voltage and amperage. The EC process is interrupted every 1 or 2 min to get a sample of the treated water, then it is filtered, the sludge is discarded, the filtered treated water is characterized for SiO_2, and the removal efficiency is determined.

Test 1, with 200 mL volume, 26 VDC, and 1 A, using Fe electrodes of 3.1 × 4.4 cm with a separation of 1.4 cm. In test 2, 3,600 mL of sample, 26 VDC, and 1 A, with Al electrodes of 11.4 × 9.5 cm and a separation of 2.1 cm between them, interrupting the process every two min for sampling. Test 3 with 3,600 mL of sample and Al electrodes of 11.4 × 9.5 cm and a separation of 2.1 cm between them, applying 26 VDC and 1 A. Test 3, using the same experimental conditions as in test 2, but with no interruptions of the process for sampling. For test 4, with same volume and dimensions of electrodes but, 0.7 cm of separation between them, 7.5 VDC and 3 A were applied.

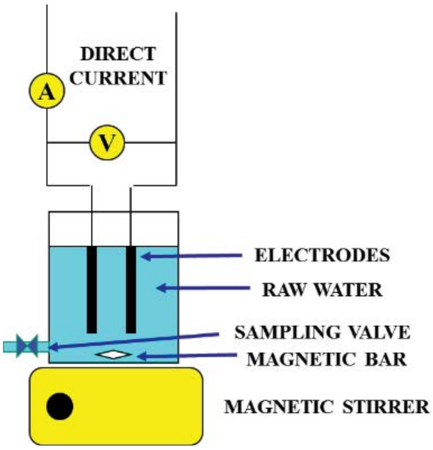


Fig. 1. Experimental set up for silica removal using electrocoagulation.

2.3. Verification test for Ca and SiO_2 removal in batch

After testing the effectiveness of calcium precipitation, and silica removal via EC, and based on the used parameters, it was decided to adjust the method, performing batch tests for the combined removal of calcium and silica.

First, an analysis of calcium and silica in the water to be treated was made, then determination of the stoichiometric quantity of a 50–50, trisodium – disodium phosphate mixture for 900 mL of sample was done, and the reactants weighted, next the precipitation process is carried out with 5 min of residence time. Once the time has elapsed, without filtering the solution the, EC is run for silica removal. Two Al electrodes were used, of 11.4 × 9.5 cm and separated 2.1 cm, applying 26 VDC – 1 A, with 10 min of reaction time, inverting the current every minute. For the second test, EC is done first, followed by precipitation. In the last test, the run was made in the following order, precipitation, filtering of treated water, EC, and again filtration. At the end of each test, the filtered treated water is characterized, and removal efficiency is determined.

With the same experimental conditions and the best results, another run was made, getting a sample from the treated water every 2 min.

2.4. Continuous Ca and SiO_2 removal test, using a 2^3 experimental design

According to the preliminary tests and the fact that the aluminum poly-hydroxide formation during EC occurs at the cathode [13], it was decided to study the effect of three factors using a 2^3 experimental design, with two replicates. The factors and levels are presented in Table 2. All treatments were carried out at random.

The experimental setup is devised to treat up to 100 L of raw water for the tests at constant flow, with a flow of 1 and 2 lpm. The corresponding diagram and image are presented in Figs. 2 and 3.

In order to synchronize flows, the mini-pump for feeding raw water, the micro-pump for phosphates dosification, and the Kaselco peristaltic pump for EC, were characterized. Ca and SiO_2 concentrations (ppm) were

Table 2
Factors and levels for the 2^3 experimental design

Factor	Low level (–1)	High level (+1)
Applied voltage (DC)	20	30
Flow (lpm)	1	2
Reactor configuration	Ending cathode	Ending anode

determined in raw water, and the required phosphates quantities were weighted according to the volume and flow. A mixture of disodium and trisodium phosphates (50–50) was used for Ca precipitation with a constant stirring for 5 min, as well as the Kaselco EC reactor for the SiO_2 removal, with five Al electrodes of 11.4 × 9.5 cm, and a separation of 0.65 cm between them, inverting the current every minute, for 10 min. Two replicates of every experimental condition were run randomly. Once the time for the run is over, the treated water is filtered, solids are discarded and water is characterized (Ca and SiO_2), the removal efficiency is determined, and last, statistical analysis of data is performed using MINITAB 18 software, for the 3 factors, and the 3 responses: Ca removal (%), SiO_2 removal (%), and Ca-SiO_2 combined removal (%).

2.5. Verification test for continuous removal of Ca and SiO_2

Following the same procedure along with the same conditions of the previous test, two more tests were performed; the first one with the values of the parameters that demonstrated to be the best, 20 VCD, 1 lpm, and reactor ending in cathode. The second one with the same conditions for flow and reactor configuration, but applying 25 VDC.

3. Results and discussion

3.1. Ca precipitation test

With the required stoichiometric quantity of phosphates, the average efficiency of calcium removal was 92%. However, the monosodium phosphate lowers the pH of water; while trisodium phosphate increases it, both conditions might favor corrosion or incrustation in the cooling system. It was

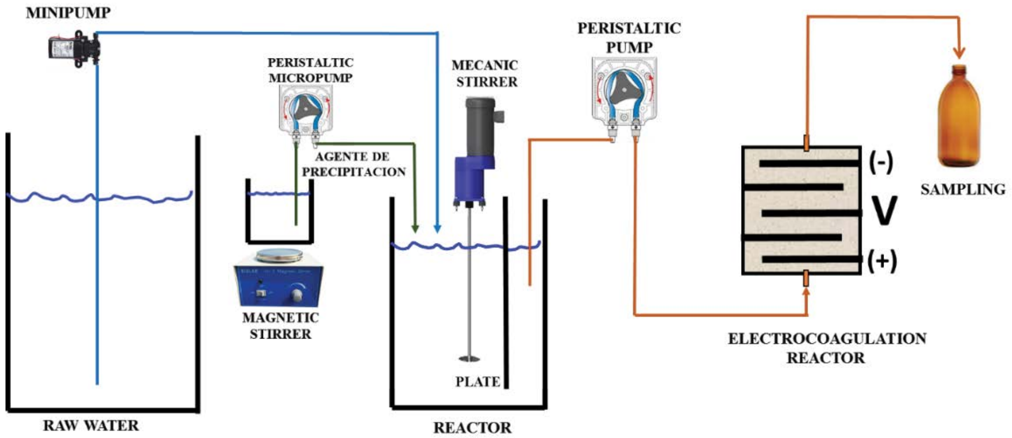


Fig. 2. Diagram of the experimental setup for continuous removal of Ca and SiO_2.

Fig. 3. Image of the experimental setup for continuous removal of Ca and SiO_2.

decided to use a 50–50 mixture of both, which does not affect pH significantly, nor the incrustation–corrosion characteristics of the water, obtaining the same results.

3.2. SiO_2 removal tests via EC

In test 1, a 48.46% silica removal was accomplished in 6 min. However, a yellowish color developed in the water sample due to the presence of ferric ions, which gives water an unpleasant appearance. Because of the low removal efficiency and the developed hue, the use of Fe electrodes was discarded. In test 2, a removal efficiency of 81.73% of the SiO_2 present in raw water was achieved. Even though, in test 2 a removal of 81.73% of silica was achieved, it took 10 min. Larger residence times increase the cost of the process. Possibly, interruption of the EC process every 2 min for sampling, affected its performance. Test 3, using the same experimental conditions as in test 2, but with no interruptions of the process, achieved a SiO_2 removal efficiency of 96.74%, in just 5 min.

For test 4, taking into consideration the results obtained from tests 1 to 3, and that the EC follows Faraday's first law of electrolysis, "The mass of an element liberated or deposited due to the flow of current through an electrolyte is directly proportional to the quantity of electricity (coulombs) passed through it", instead of 26 VDC and 1 A, 7.5 VDC and 3 A were applied. Also, in order to reduce the electrical resistance of the circuit, the separation between electrodes was shortened from 2.1 to 0.7 cm. The results were encouraging, 98.74% of removal in just 2 min of residence time, and up to 99.8% in 10 min. The main cost in EC is energy, hence 98.74% of removal in 2 min is highly convenient.

3.3. Verification of removal of Ca and SiO_2, in batch

Results of the test of precipitation and EC combined in batch, are presented in Table 3. Results show that the first one in being carried out, EC for SiO_2, or precipitation for Ca, exhibits the best results. The third run, with an intermediate filtration, lowers the removal efficiency of SiO_2.

The second test is the one that has equilibrated results for removal. For this reason, using the same experimental conditions, another test was run, sampling treated water every 2 min. Results of this precipitation and EC test are presented in Table 4.

These are excellent results for removal of Ca and SiO_2, even from the first sample at 2 min and they get better with residence time for Ca, but not significantly for SiO_2. It is verified that the process and parameters are adequate.

3.4. Continuous removal of Ca and SiO_2 test, using a 2^3 experimental design

The results of this test are shown in Table 5.

Statistical analysis was made with MINITAB 18 software. Results of the analysis of variance (ANOVA), model summary, equation of the model, Pareto chart of the standardized effects, and residual plot of the model and the adjusted model, are shown only for Ca in Figs. 4 and 5. Adjustment of models, does not change the conclusions of the unadjusted models. In all cases ANOVA assumptions are fulfilled, approximately normal distribution of data, a zero mean, homogeneity of variance, and independent observations; so, the model is considerate adequate, with 95% confidence level. In Table 6, the analysis of results and preliminary conclusions of the test are presented.

3.5. Verification test, continuous Ca and SiO_2 removal

Results are shown in Table 7.

The best results for continuous Ca and SiO_2 removal were achieved when applying 25 VDC, 2 min of retention time and reactor configuration ending in cathode.

Table 3
Results of verification of removal of Ca and SiO_2 tests, in batch

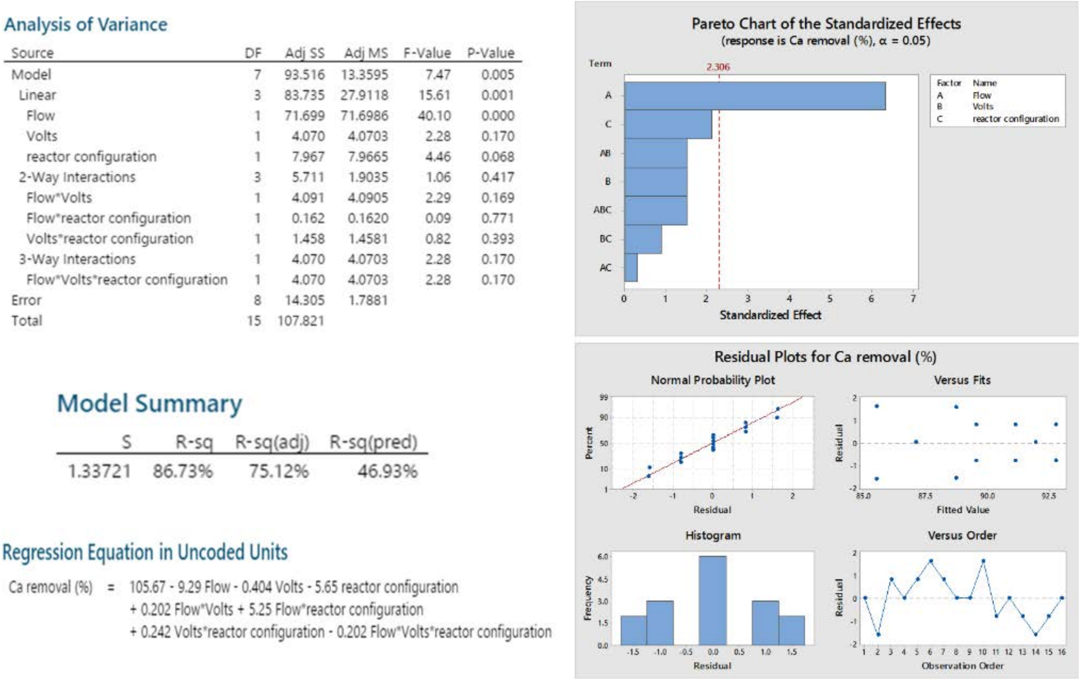
	Initial (ppm)		Final (ppm)		% Removal		
	Ca-H	SiO_2	Ca-H	SiO_2	Ca-H	SiO_2	Average
EC – PPT	580	34.6	190	1.3	67.2	96.2	81.7
PPT – EC	580	34.6	80	9	86.2	74.0	80.1
PPT – Filter – EC	580	34.6	70	13.2	87.9	61.8	74.9

Table 4
Results of the combined precipitation and electrocoagulation test, in batch

	Initial			Final			% Removal		
	Ca-H	Silica	pH	Ca-H	Silica	pH	Ca-H	Silica	Average
2 min	690	34.95	7.1	165	0.44	7.2	76.1	98.7	87.4
4 min	690	34.95	7.1	170	0.4	7.3	75.4	98.9	87.1
6 min	690	34.95	7.1	160	0.23	7.3	76.8	99.3	88.1
8 min	690	34.95	7.1	140	0.19	7.4	79.7	99.5	89.6
10 min	690	34.95	7.1	40	0.07	7.5	94.2	99.8	97.0

Table 5
Results for the 2^3 test, for continuous combined precipitation and electrocoagulation

		Ca-H (ppm)	SiO_2 (ppm)	Ca removal (%)	SiO_2 removal (%)
Replicate	Run/Initial	310	33.204	0.00	0.00
1	1	25	0.581	91.94	98.25
	2	20	0.703	93.55	97.88
	3	30	0.622	90.32	98.13
	4	35	0.541	88.71	98.37
	5	35	0.581	88.71	98.25
	6	25	0.948	91.94	97.14
	7	25	0.5	91.94	98.49
	8	25	0.907	91.94	97.27
2	9	40	0.663	87.10	97.76
	10	30	0.744	90.32	97.76
	11	40	0.744	87.10	97.76
	12	50	0.866	83.87	97.39
	13	40	0.988	87.10	97.02
	14	40	0.825	87.10	97.52
	15	40	0.825	87.10	97.52
	16	40	0.785	87.10	97.64



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	93.516	13.3595	7.47	0.005
Linear	3	83.735	27.9118	15.61	0.001
Flow	1	71.699	71.6986	40.10	0.000
Volts	1	4.070	4.0703	2.28	0.170
reactor configuration	1	7.967	7.9665	4.46	0.068
2-Way Interactions	3	5.711	1.9035	1.06	0.417
Flow*Volts	1	4.091	4.0905	2.29	0.169
Flow*reactor configuration	1	0.162	0.1620	0.09	0.771
Volts*reactor configuration	1	1.458	1.4581	0.82	0.393
3-Way Interactions	1	4.070	4.0703	2.28	0.170
Flow*Volts*reactor configuration	1	4.070	4.0703	2.28	0.170
Error	8	14.305	1.7881		
Total	15	107.821			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.33721	86.73%	75.12%	46.93%

Regression Equation in Uncoded Units

Ca removal (%) = 105.67 - 9.29 Flow - 0.404 Volts - 5.65 reactor configuration
+ 0.202 Flow*Volts + 5.25 Flow*reactor configuration
+ 0.242 Volts*reactor configuration - 0.202 Flow*Volts*reactor configuration

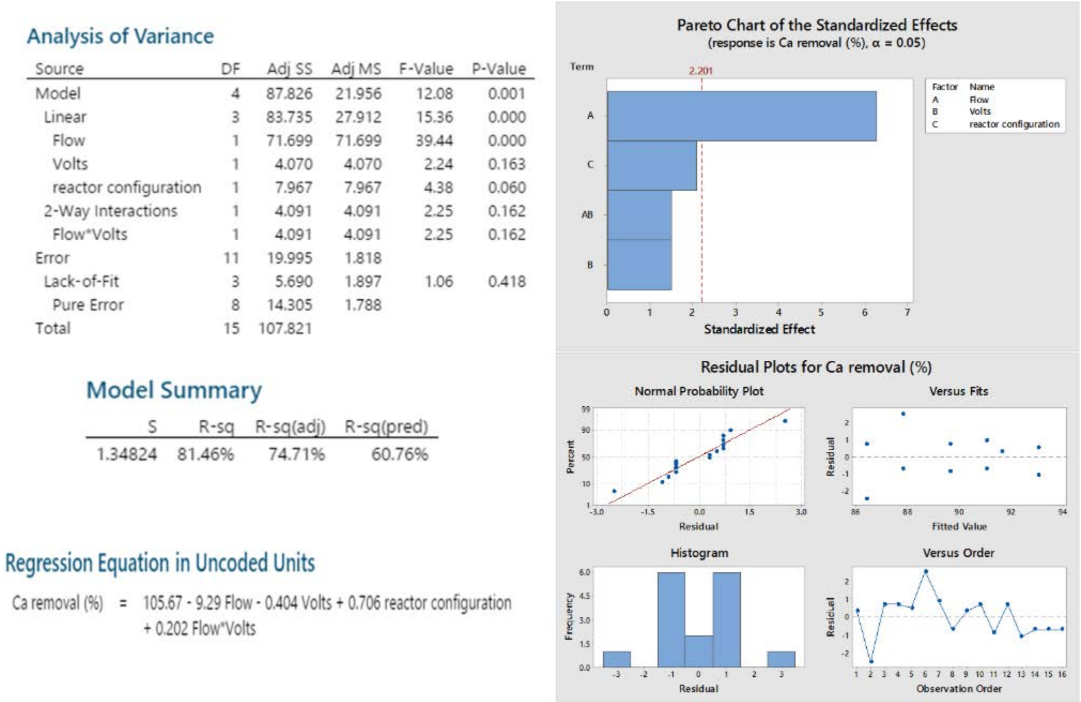
Fig. 4. ANOVA for continuous Ca and SiO_2 removal.

4. Conclusions

The goal of designing a continuous system for removal of Ca y SiO_2 from raw water, for evaporative cooling systems was fulfilled. A removal up to 91% of Ca y SiO_2, was achieved in only five min of retention time for precipitation and 2 min for EC. During the literature review, no studies related to this topic were found for comparison of removal efficiencies. Al electrodes are best suited than Fe electrodes. Fe electrodes leave an unpleasant yellowish color in water and yield a low removal efficiency (barely 46%). The factor that have the more significant effect on EC was flow, followed for the applied voltage, and last the reactor configuration. It is easier to remove Ca and SiO_2 from raw water, than it is to remove them from cooling water, due to amount and diversity of inorganic and organic chemicals

Table 6
Analysis of results for the 2^3 experimental design

Response	Model R^2	Flow (lpm)	DC voltage (V)	Reactor configuration
Calcium removal (%)	0.8673 indicates a strong linear correlation. The difference with the adjusted R^2 indicates that unnecessary factor are considered.	Only factor that has a significant effect on Ca removal. Since its coefficient has (–) sign. It is convenient to manage it at his low level (1 lpm).	It has not a significant effect on Ca removal. Its coefficient has a (–) sign, so it is convenient to manage it at its low level (20 V).	It has not a significant effect on Ca removal. But, it is the second one with the highest effect. Due to the (+) sign of its coefficient, it is convenient to manage it at its high level.
Silica removal (%)	0.7849 indicates a not very strong linear correlation. The difference with the adjusted R^2 indicates that unnecessary factor are considered.	It has a significant effect on SiO_2 removal. Due to the (–) sign of its coefficient, it is convenient to manage it at its low level (1 lpm).	It is the second factor that has a significant effect on silica removal. Due to the (+) sign of its coefficient it is convenient to manage it at its high level (30 V).	It has not a significant effect on silica removal. It is convenient to manage it at its high level (Ending cathode).
Combined removal Ca-SiO_2 (%)	0.8648 indicates a strong linear correlation. The difference with the adjusted R^2 indicates that unnecessary factor are considered.	It has a significant effect on Ca and SiO_2 removal. Due to the (–) sign of its coefficient, it is convenient to manage it at its low level (1 lpm).	It has not a significant effect. Its coefficient has a (–) sign, so it is convenient to manage it at its low level (20 V).	It has not a significant effect on the result. It is the second factor that has a significant effect. Due to the (+) sign of its coefficient, it has not a significant effect on the result.
General		It is the only that has a significant effect on Ca and silica. It is convenient to manage it at his low level (1 lpm).	It has not a significant effect. But, for Ca it is better to manage it at its low level, while for SiO_2 at its high level. 25 V might be a good choice.	It has not a significant effect on the result. But, the results show that it is convenient to manage it at its high level (Ending cathode).



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	87.826	21.956	12.08	0.001
Linear	3	83.735	27.912	15.36	0.000
Flow	1	71.699	71.699	39.44	0.000
Volts	1	4.070	4.070	2.24	0.163
reactor configuration	1	7.967	7.967	4.38	0.060
2-Way Interactions	1	4.091	4.091	2.25	0.162
Flow*Volts	1	4.091	4.091	2.25	0.162
Error	11	19.995	1.818		
Lack-of-Fit	3	5.690	1.897	1.06	0.418
Pure Error	8	14.305	1.788		
Total	15	107.821			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.34824	81.46%	74.71%	60.76%

Regression Equation in Uncoded Units

Ca removal (%) = 105.67 - 9.29 Flow - 0.404 Volts + 0.706 reactor configuration + 0.202 Flow*Volts

Fig. 5. ANOVA for continuous Ca and SiO_2 removal for the adjusted model.

Table 7
Results of the verification test (continuous)

	t (min)	DC (V)	A	Ca-H (ppm)	Silica (ppm)	Ca removal (%)	Silica removal (%)
Test	Initial			449	28.44	0.00	0.00
1	2	20	0.4	87	5.16	80.62	81.86
	4	20	0.4	87	5.20	80.62	81.72
	6	20	0.4	53	4.22	88.20	85.16
	8	20	0.4	24	3.37	94.65	88.16
					Average	86.02	84.23
2	2	25	0.5	38	2.31	91.54	91.88
	4	25	0.5	29	3.16	93.54	88.88
	6	25	0.5	33	1.49	92.65	94.74
	8	25	0.5	48	1.29	89.31	95.46
					Average	91.76	92.74

used in its treatment, and since it is an open system, for the microorganisms and organic matter that get in there.

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