Journal of Engg. Research **Vol. 5 No. (1) March 2017 pp.** *46-58*

تعزيز فلترة الحمأة المنشطة
بواسطة الحقل الكهربائي المباشر

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الخلاصة

الغرض من هذه الدراسة هو تعزيز فلترة الحمأة المنشطة عبر تطبيق الحقل الكهربائي المباشر بواسطة أقطاب كهربائية من الألومنيوم، وفى الوقت نفسه توفير تيار كهربائي غير فعال على الحياة البكتيرية. الدراسة أجريت على نطاق مخبري في مستوعب حجم 12 ليتر. وقد تم اخذ الحمأة المنشطة من محطة لمعالجة مياه الصرف بواسطة العلاج البيولوجي المتقدم وواسع النطاق. تم تقييم آثار زمن التعرض (2، 5، 10، 15،و 30 دقيقة)، والتدرج المحتملين (0.2، 0.5، 0.8، و 1 V / سم) من خلال نتائج مقاومة الفلترة. النتائج تدعم ايضا بواسطة فحص التغيرات الفيزائية (درجة الحموضة، الأكسدة والاختزال المحتملة ودرجة الحرارة) والمواد الكيميائية المتحللة (الطلب على الاكسجين الكيميائي، الفوسفات، والنيتروجين والأمونيا للحمأة المنشطة). تم دراسة بعض العوامل الكهربائية (الكثافة الحالية، واستهلاك الطاقة، واستهلاك الألومنيوم النظري)، لتقييم الكلفة الأفضل للحقل الكهربائي الفعال مقابل زمن التعرض. واستناداً إلى تجارب مقاومة الفلترة، إستهلاك الطاقة، إستهلاك الألومنيوم النظري، تم تحديد الظروف المثلى لتعزيز الفلترة بـ 0.2 فولت / سم مطبقة تدريجيا لمدة 5 دقائق.

الكلمات المفاتيح: الحمأة المنشطة، الحقل الكهربائي المباشر، والتدرج المحتمل، فلترة الحمأة، مقاومة الفلترة للحمأة.

Enhancing filterability of activated sludge by DC electric field

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ABSTRACT

The purpose of the current study is to enhance filterability of activated sludge by applying controlled DC electric field via perforated aluminum electrodes while providing an ineffective electric current on bacterial life. The studies were conducted in a 12 L laboratory scale cylindrical reactor. Recirculated activated sludge was provided from a full scale advanced biological wastewater treatment plant. The effects of exposure time (2, 5, 10, 15, and 30 min) and potential gradient (0.2, 0.5, 0.8, and 1 V/cm) are evaluated mainly by the results of specific resistance to filtration (SRF). The results also supported with variations in physical (pH, oxidation-reduction potential (ORP), and temperature) and soluble biochemical (chemical oxygen demand (COD), orthophosphate (PO_4-P), and ammonia nitrogen (NH_3-N)) properties of activated sludge. Electrical parameters (current density, energy consumption, and theoretical aluminum consumption) were studied to evaluate the most cost effective DC field vs. exposure time variation. Based on SRF experiments, energy consumption, and theoretical aluminum generation, optimal condition for enhancing filterability is recommended as 0.2 V/cm potential gradient applied for 5 min.

Keywords: Activated sludge; DC electric field; potential gradient; sludge filterability; SRF.

INTRODUCTION

The membrane bioreactor (MBR) is one of the most attractive treatment technologies for both industrial and municipal wastewater treatment on account of many advantages such as higher mixed liquor suspended solid (MLSS), longer sludge retention time (SRT), less space/tank size, and much higher quality effluent (Metcalf & Eddy, 2002; Judd, 2011; Krzeminski *et al*., 2012). Membrane fouling and prevention of membrane fouling are the most remarkable and investigated topic in the literature. Although the particle size, surface charge of floc, extra-cellular polymeric substances (EPS), and MLSS concentration are mentioned as activated sludge biomass characteristics effecting membrane fouling in the previous publications, specifically the particle size of MLSS has the greatest impact on fouling (Huang & Wu, 2008; Judd, 2011). Coagulants or adsorbents addition (Wu *et al*., 2006), ozone oxidation (Huang & Wu, 2008), and electrocoagulation (EC) (Chen *et al*., 2007) are some of the methods applied in the literature in order to enhance filterability and particle size. However, the key point in filterability enhancement is to avoid any possible negative/toxic effect on microbial activity. On the other hand, adopting high intensity and/or high voltage electric field is effective in fouling reduction, but the energy consumption involved is high and must be reduced. At this point much more remains to be investigated both in respect to filterability enhancement, energy consumption, and avoiding negative/toxic effect on microbial activity.

Potential gradient (V/cm), which is defined as the potential difference between two electrical fields, is addressed as an indicator parameter in the literature (Alshawabkeh *et al*., 2004; Bani-Melhem & Electorowicz, 2010; Bani-Melhem & Electorowicz, 2011; Liu *et al*., 2012), where potential gradient varies between 0.036 – 6 V/cm. DC electric field greater than 1.4 V/cm was also reported to be harmful on micro organisms within activated sludge in these studies. Exposure time is an another critical parameter in electrochemical applications and previous studies mainly focused on 15 or greater minutes, which lead to higher electricity consumption and therefore higher operational cost in addition to negative effects on microbial activity, even in relatively smaller potential gradient.

In the previous studies, potential gradient range was either too small and not very effective in filterability enhancement or too great and resulted in high electricity consumption and negative/toxic effect on microbial activity. All in all, in the current study, 0.2, 0.5, 0.8, and 1 V/cm potential gradients were exposed for 2, 5, 10, 15, and 30 minutes of DC exposure time to meet expectations for enhancing filterability and particle size meanwhile preserving the microbial activity and providing low energy consumption.

MATERIALS AND METHODS

The main goals of the applying electrical field to activated sludge are to increase floc size, reduce membrane fouling, and enhance filterability while protecting microbial activity. In this study, physicochemical properties such as pH, ORP, SRF, and temperature in addition to soluble biochemical properties such as COD, NH_3-N, and PO_4-P on recirculated activated sludge mixed liquor from Istanbul ISKI (Istanbul Water and Sewerage Administration) Pasakoy Advanced Biological Treatment Plant were investigated in respect of different DC exposure time (2, 5, 10, 15, and 30 minutes) and electric field (0.2, 0.5, 0.8, and 1 V/cm) and optimum conditions were determined through batch tests.

ANALYTICAL METHODS

ORP, pH and temperature values were measured by Eutech pH510 pH meter before and after applying electrical field. SRF experiment was performed right after each experimental set, as described by Sanin et al. (2011). The schematic view of the experimental setup is given in Figure 1. Soluble COD, NH_3-N, and PO_4-P measurements were performed according to APHA Standard Methods (2005) for each experimental, set after filtration of the samples through 0.45 μm pore size filter paper.

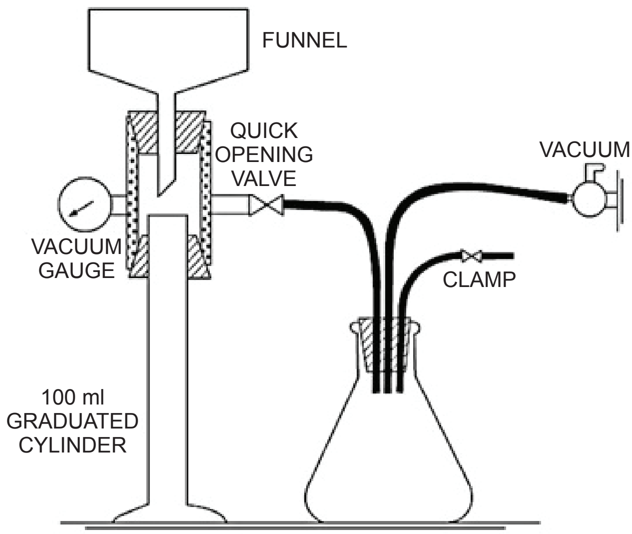

Fig. 1. Schematic view of specific resistance to filtration (SRF) apparatus

REACTOR DESIGN

Laboratory scale cylindrical reactor with 20 cm diameter and 38 cm height, total 12 L volume was designed for experimental work is shown in Figure 2. To avoid possible overflow because of potential foaming problem as a result of electrocoagulation, effective volume of reactor was limited to 6 L. Mesh aluminum anode and cathode electrodes were designed to sustain homogenous circulation inside the reactor. Cathode electrode with an effective surface area of 0.025 m^2 (15.6% of perforation) and anode electrode with an effective surface area of 0.0234 m^2 (73.3% of perforation) were selected for the experimental studies. The electrodes with 4 cm distance to each other were connected to an external DC power supply.

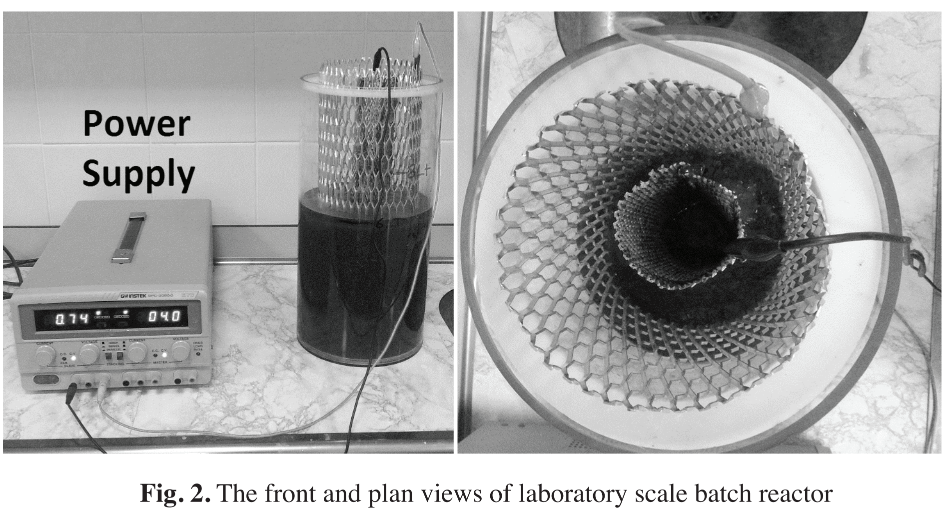

Fig. 2. The front and plan views of laboratory scale batch reactor

SLUDGE SAMPLES

Activated sludge for the studies was provided from Istanbul ISKI Pasakoy Advanced Biological Treatment Plant. The plant collecting the wastewater of 2,500,000 people on Istanbul's Asia Side is in progress since 2000 with a 500,000 m^3/day flow rate. The characteristics of recirculated activated sludge mixed liquor ISKI Pasakoy Advanced Biological Treatment Plant are summarized in Table 1.

Table 1. Characteristics of raw recirculated activated sludge

Parameter	Value
Oxidation-Reduction Potential (ORP) (mV)	-27
pH	6.97
Temperature (T) (^oC)	23.6
Soluble Chemical Oxygen Demand (COD) (mg/L)	164
Soluble Ammonia Nitrogen (NH_3-N) (mg/L)	24.96
Soluble Orthophosphate (PO_4-P) (mg/L)	2.33
Mixed Liquor Suspended Solids (MLSS) (mg/L)	17,150
Specific Resistance to Filtration (SRF) (m/kg)	1.31×10^{13}

RESULTS AND DISCUSSION

pH, Oxidation-reduction potential and temperature

pH, ORP, and temperature are three most critical parameters in biological systems. Baldwin & Campbell (2001) mentioned that optimal pH for activated sludge process range between 6.5 and 8.5. Additionally, Noyes (1994) mentioned neutral or slightly alkaline pH is ideal and promotes biological activity. ORP, on the other hand, is a determinative measurement describing the intensity of oxidation or reduction potential of a solution in millivolt (mV). The ORP data varies in aerobic processes between + 50 and – 200 mV. Decrease in ORP is undesirable and less than – 200 mV is an indicator of anaerobic conditions (Troiani et al., 2011). Temperature is a catalyst, a depressant, an activator, a restrictor, a stimulator, a controller and a killer for biological systems. Even a slightest temperature change outside of limit values might result in a change in dominant bacterial species and affects the process directly (Srinivas, 2008). And under normal circumstances, the biological activity doubles with each temperature increase of 10oC between 5 and 30oC (Mara & Horan, 2003).

pH and ORP values measured at anode and cathode electrodes with DC field and exposure time are given in Table 2 and changes in temperature at the anode and cathode electrodes with the application of different DC electric field and exposure time is given in Figure 3, where no significant increase was observed during the all batch tests.

Table 2. Changes in pH and ORP values at anode and cathode electrodes with the application of different DC electric field and exposure time

	pH				**ORP, mV**			
	Anode/Cathode				Anode – Cathode			
	DC Electric Field, V/cm							
Exposure Time	0.2	0.5	0.8	1.0	0.2	0.5	0.8	1.0
Initial Values	6.97				-27			
2 min	6.98/7.05	6.97/7.01	7.26/7.89	7.45/8.01	-30/-32	-27/-30	-33/-82	-35/-91
5 min	7.02/7.05	7.06/7.23	7.66/8.13	7.74/8.33	-30/-35	-33/-42	-45/-96	-43/-108
10 min	7.08/7.10	7.08/7.31	7.90/8.41	8.50/8.62	-34/-39	-33/-48	-52/-112	-57/-127
15 min	7.05/7.10	7.01/8.34	6.95/8.64	7.15/9.32	-32/-35	-30/-107	-36/-125	-47/-135
30 min	7.02/7.23	7.09/8.65	7.09/8.76	7.06/9.52	-30/-43	-47/-136	-34/-134	-45/-159

OH- ions were released as a result of redox reaction on cathode. On the other hand, pH at the anode was expected to be lower due to the production of H+ ions. However, increase in pH at the anode was observed for higher potential gradient such as 0.8 and 1.0 V/cm. This can be explained by the cathode activity being more dominant and also perforated structure of electrodes providing a homogenous turbulent. Considering the results and literature, 2, 5, 10, and 15 minutes exposure time for 0.5 V/cm and all working periods for 0.2 V/cm are viable in respect of ideal pH range for biological life of activated sludge.

A rapid decrease in ORP values was observed on both anode and cathode electrodes right after application of DC electric field. 0.2 V/cm potential gradient had slightest drop in ORP thereby the least harmful DC electric field on bacteriological life due to negative effects on aerobic bacteria in activated sludge of ORP decrease. ORP decrease with the increase in pH demonstrates the reverse relation between pH and ORP (Table 2).

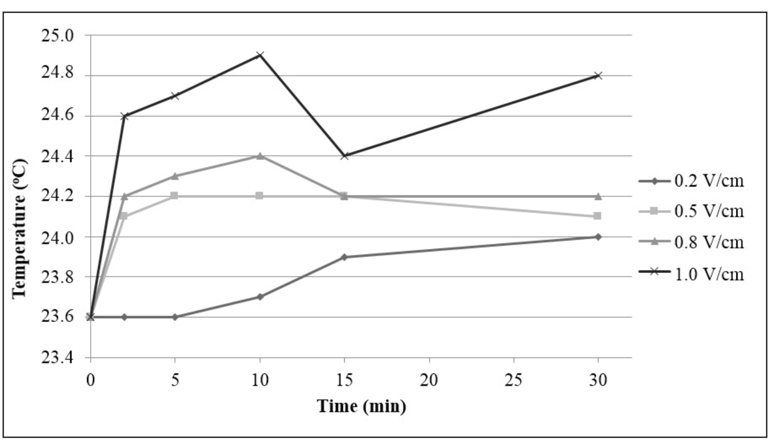

Fig. 3. Changes in temperature at the anode and cathode electrodes with the application of different DC electric field and exposure time

Chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), and orthophosphate (PO_4-P)

COD, NH_3-N, and PO_4-P are some of the primary parameters for water quality measurements, yet these parameters were measured to monitor any potential inhibitory effect of electrical field on aerobic suspended culture. In brief, higher removal efficiencies for soluble COD, NH_3-N, and PO_4-P are considered as undesirable for current application. Figure 4 summarizes the results for soluble biochemical properties.

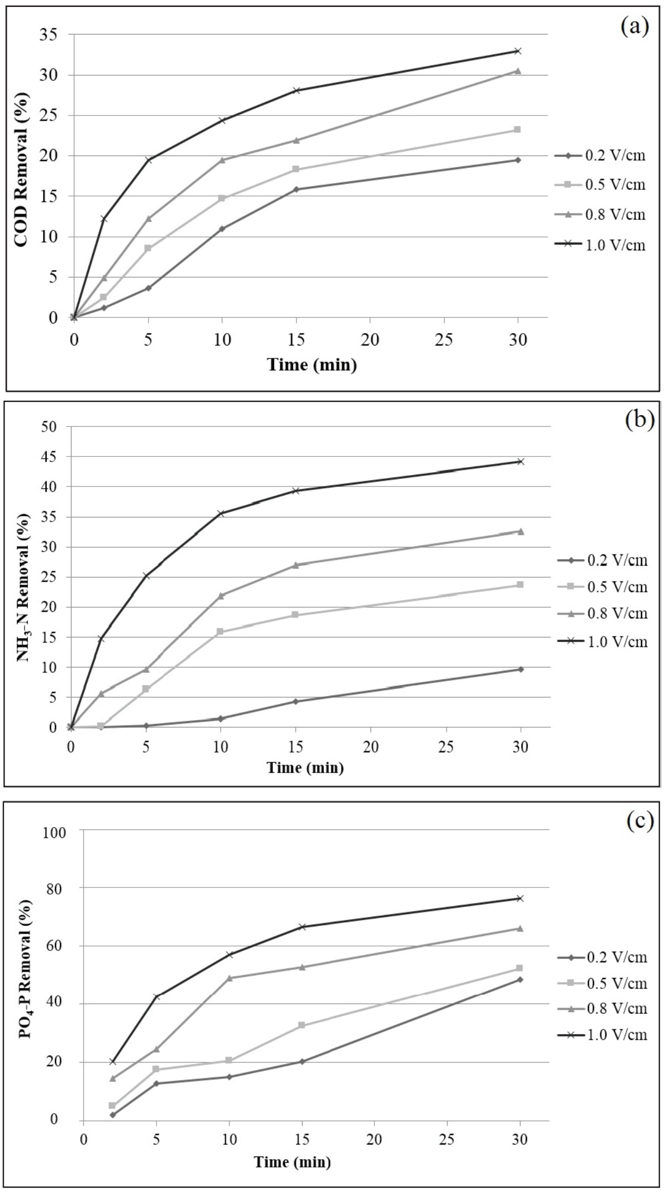

Fig. 4. Removal percentage of soluble biochemical parameters versus exposure time: (a) COD; (b) NH3-N; (c) PO4-P

An increasing removal trend in all soluble COD, NH_3-N, and PO_4-P biochemical parameters was observed for all DC electric fields, especially at 15 and 30 mins exposure times. The negative effect of greater DC electric field was also observed for soluble biochemical parameters similar to ORP and pH parameters (Table 2).

SPECIFIC RESISTANCE TO FILTRATION (SRF)

The flow of a fluid through a porous medium is the description of specific resistance to filtration (SRF, m/kg) and it is based on Darcy's equation. SRF parameter is commonly used to determine optimum chemical dosages to enhance the filterability. Factors like pH, temperature, conductivity, solid concentration properties all affect sludge viscosity so filterability specifications of activated sludge such as SRF. pH values above 5.5 increase the apparent viscosity and increasing viscosity, which also means increasing flocculation, increases SRF value and high temperature decreases viscosity so the SRF sludge filterability (Foladori *et al*., 2010; Sanin *et al*., 2011). The easier to dewater sludge can have SRF values as low as 10^{10}-10^{11} m/kg; whereas the SRF values for difficult to dewater sludge can range as high as 10^{14}-10^{15} m/kg (Sanin *et al*., 2011). To sum up, the previous studies indicates that decrease in SRF results in an increase in the size of sludge flocs and a decrease in resistance to filtration.

In this study, SRF is the most considered parameter, since the main goal of applying electric field is to increase floc size and in this way to enhance the filterability. SRF experiments were conducted as described by Sanin et al. (2011). Changes in SRF are given in Figure 5.

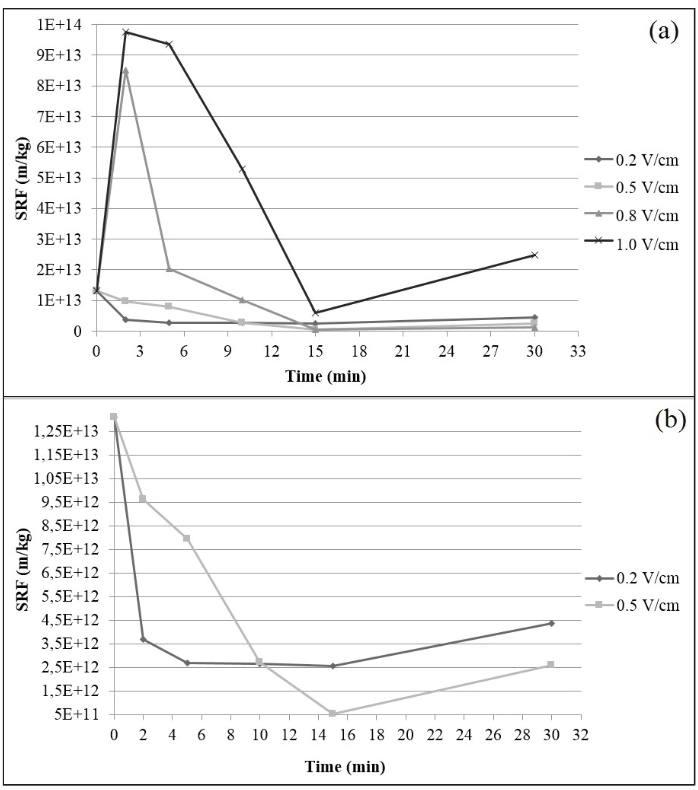

Fig. 5. Results of SRF experiments: (a) SRF trends for all applied DC fields; (b) zoom into applied DC fields with improved SRF

Initial SRF of activated sludge was 1.31 x 10^{13} m/kg. From the Figure 5(a), greater DC fields such as 0.8 and 1.0 V/cm showed a tremendously negative effect on SRF in short exposure (2 mins). This indicates that greater electrical field first meets the activated sludge results in a diverging trend on already formed flocs and turbulence in activated sludge. Later on, aluminum ions released to the water and a quick enhancement was observed, however, longer DC exposure (30 min) showed an unfavorable effect on SRF for both 0.8 and 1.0 V/cm DC field. On the other hand, SRF decreased for 0.2 and 0.5 V/cm DC field, yet 15 minutes was the breaking point and resistance to filtration increased with 30 minute of exposure time for all electrical fields (Figure 5(b)). The highest improvement was obtained at 0.5 V/cm DC field and 15 mins exposure time with 5.31 x 10^{11} m/kg in SRF but even so SRF values for 0.2 V/cm DC field and 5, 10, 15 mins exposure time and 0.5 V/cm DC field and 10 mins exposure time showed a remarkable improvement in SRF value.

Current density, energy consumption, and dissolved aluminum

Besides the benefits of EC process, it is an obligation to take the energy cost and electrode material consumption in consideration. Experiments were carried out via voltages and current values were monitored at the end of each test. Current density expressed as A/m^2 is the parameter in progress for the calculation of energy consumption showed a linear increasing trend after 2 minutes of DC exposure time except for 0.2 V/cm (Figure 6(a)). The electrical consumption results are given in Figure 6(b). The electric consumption was calculated with the following Equation (1) (Akbal & Camcı, 2011):

$$E = \frac{U.I.t}{V} \qquad (1)$$

where E is the energy consumption (kWh/m3), U is the applied voltage (V), I is the current intensity (A), t is the DC exposure time (h), and V is the volume of the treated wastewater (L).

Theoretical dissolved electrode amount was calculated by using Equation (2) of Faraday's law (Akbal & Camcı, 2011) and the results are given in Figure 6 (c).

$$C = \frac{I.t.M}{Z.F.V} \qquad (2)$$

where C (g/L) is the theoretical aluminum concentration in the test cell, I is the current intensity (A), *t* is the electrocoagulation time (s), *M* is the molecular weight of the aluminum anode (g/mol), *Z* is the chemical equivalence, *F* is the Faraday constant (96,500 C/mol) and *V* is the volume of the treated wastewater (L).

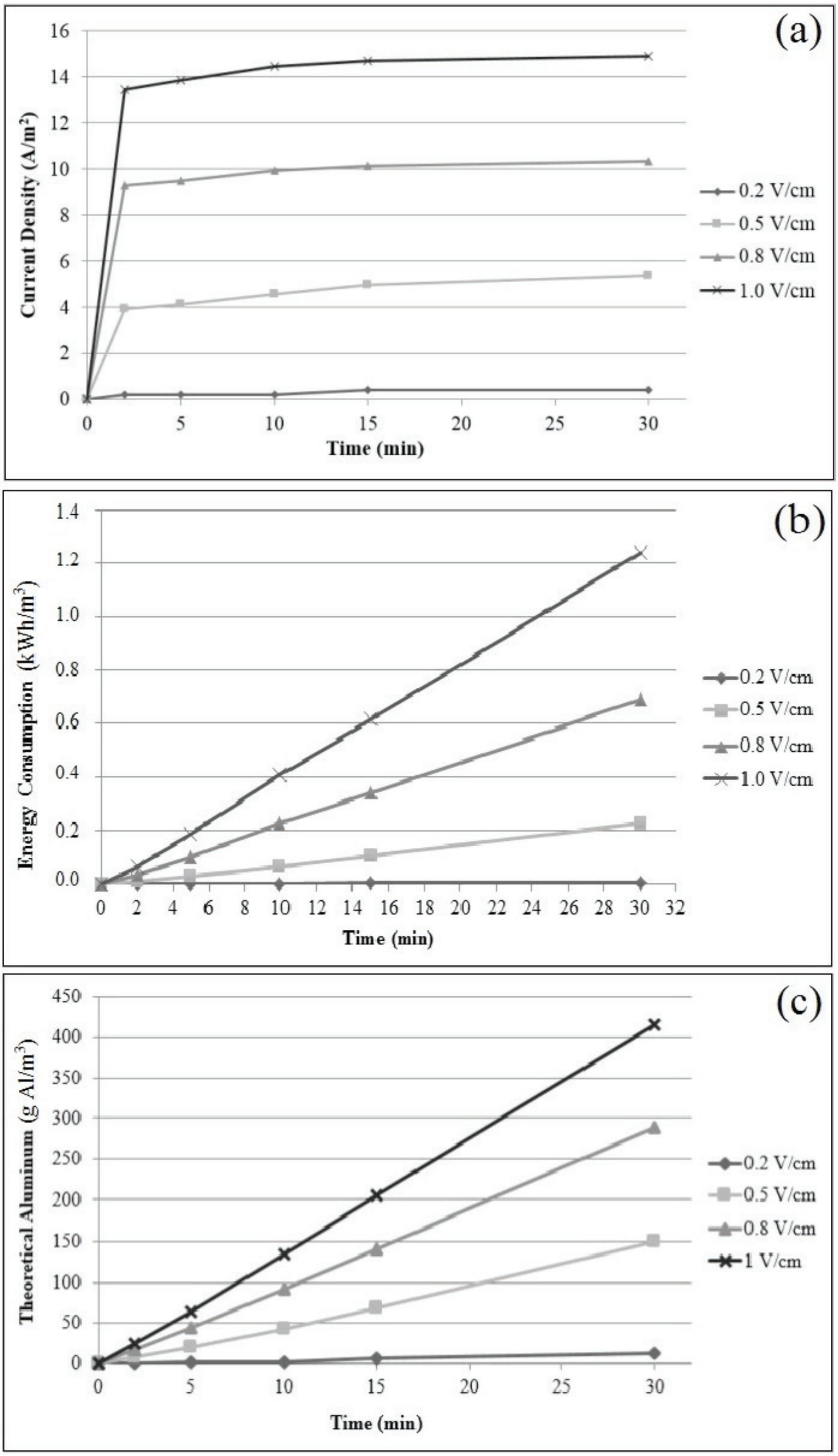

Fig. 6. Variations in electrical parameters: (a) current density; (b) energy consumption; (c) dissolved aluminum

0.2 V/cm DC field and 2 minutes of exposure time has the minimum energy (0.00021 kWh/m^3) and theoretical aluminum consumption (0.39 g Al/m^3) as expected. Linear increase was observed with the increase in applied DC electric field and time; whereas these values even reached 1.24 kWh/m^3 and 416.08 g Al/m^3 for 1.0 V/cm DC field and 30 minutes exposure time, respectively.

CONCLUSIONS

The present study intended to investigate effects of DC electric field and exposure time on activated suspended sludge by using meshed aluminum electrodes, diversify and improve current studies in the literature. Ozone oxidation and adsorbent/chemical addition are the prominent processes studied in the literature for filterability enhancement with no harm on bacterial activity. Similar efficiencies with regard to filterability enhancement were observed in all these studies within some limits defined. On the other hand, electrocoagulation has been proposed as an alternative method to conventional chemical coagulation because it is environmental friendly and cheap to operate besides its wide range of advantages such as simple equipment, easy operation and automation, a short retention time, low sludge production, no chemical requirement and resulting with more settable sludge (Top *et al*., 2011; Lambert *et al*., 2013; Ukiwe *et al*., 2014). For this purpose, 12 L laboratory scale reactor with 6 L effective volume was designed and batch experiments were performed to determine enhancement in filterability of activated sludge based on SRF.

Surely, SRF parameter has the greatest impact on enhancement on filterability. In the current study, the greatest enhancement in SRF was observed with 5.31 x 10^{11} m/kg for 0.5 V/cm DC field and 15 minutes exposure time, though considering only the SRF would not be feasible and applicable. The water quality parameters as indicator of the effects on microbial activity, energy cost and electrode consumption cannot be ignored at this point. Yet, temperature and pH affect the viscosity and SRF values, no remarkable changes on pH and temperature was observed during all experimental sets (Table 2 and Figure 3) since the process does not run longer exposure time and greater electrical field, and does not target an ultimate dewaterability but enhancement of filterability. So, the current variations in SRF observed are largely due to DC exposure time and electric field. 0.2 V/cm DC field and 5, 10, 15 mins exposure time and 0.5 V/cm DC field and 10 mins exposure time are other experimental sets resulted in sufficient SRF values such as 26.8 x 10^{11} m/kg, 26.5 x 10^{11} m/kg, 25.5 x 10^{11} m/kg, and 27.3 x 10^{11} m/kg, respectively. Considering the highly similar trends in every parameters for all these experimental sets, 0.2 V/cm electric field and 5 minutes exposure time is recommended due to the more stable and desirable physical (-30 mV ORP anode, -35 mV ORP cathode, 7.02 pH anode, 7.10 pH cathode, and 23.6^{o}C temperature) and soluble chemical properties (158 mg/L COD, 2.03 mg/L PO4-P, and 24.88 mg/L NH3-N) of activated sludge as well as 26.8x10^{11}m/kg enhanced SRF and considerably low energy consumption.

In this study, one of the variables is the applied voltage (V/cm) depending on the distance between anode and cathode. For full-scale application, this configuration could be easily applied as long as reactor designed with the consideration of this distance. However, wider reactor design with a wider distance between electrodes could result with high voltage demand following by foaming problem. On the other hand, deeper reactor design could arise settlement and mixing problem throughout the reactor. This problem might be solved with the integration of a non-metallic and non-conductive (plastic, plexiglas, etc.) mixing apparatus. Briefly, keeping the 1.9 height/diameter proportion (half-filled) as in the current application could encourage scaling up the system.

ACKNOWLEDGEMENTS

This research has been supported by The Scientific and Technological Research Council of Turkey (TUBITAK) (Project Number: 113Y391). I would like to thank my friend and my colleague, PhD candidate Noha Bekraki for her valuable time and effort to translate my abstract into Arabic.

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