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Applications of Electrokinetic Remediation in Environmental Restoration

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Abstract – Electrokinetic remediation (EK) is well developed technique for removing pollutants and remediation of contaminated sites. EK has been utilized in mitigation of contamination with heavy metal (heavy metal mobilization) and hydrocarbon removal (degradation by bioremediation coupled with EK). Recently EK has been introduced in the field of desalination of saline water and remediation of sludge from wastewater. The past decade has seen a remarkable number of innovations in the exponentially growing field of remediation. The principles of the EK remediation in desalination of saline water and remediation of wastewater sludge are outlined and discussed. The contaminant removal mechanisms and the phenomena associated with EK are presented. Also, the challenges facing electrokinetic remediation are reviewed including the development of pH gradient between the electrodes, the corrosion of electrode materials and the power required for EK remediation. This manuscript covers a review on key aspects of application of EK in desalination, wastewater and bioremediation. The discussion includes, various types of EK, the contaminants and their removal mechanisms, challenges and opportunities, electrode materials, applications and theory with a focus on the use of solar power in EK applications. The use of solar panels to generate electricity for EK can result in reducing the cost of the treatment and minimizing the adverse environmental impact of using hydropower. Innovations and techniques used in controlling pH gradient in EK remediation are discussed. In addition, an attempt has been taken to project future advances in the field of EK and facilitate these advances by framing key unsolved problems in EK and potential research areas. This review covers the challenges facing EK application and the advantages and disadvantages of the proposed solutions. Also, evaluation of the current state-of-the-art of EK technology is provided.

***Keywords*: Electrokinetic, remediation, solar panel, desalination, wastewater, iron, phosphorous**

1. Introduction

Electrokinetic remediation is a continuously evolving technology that can effectively be used to mobilize organic and inorganic contaminants from various media, especially fine-grained matters/particles which are difficult to remediate using conventional methods [1]. Also, electrokinetic remediation can be used to enhance the outcome of other remediation methods. For instance, electrokinetic remediation can be coupled with bioremediation to deliver nutrient for bacteria or to increase the bioavailability of the contaminant. Electrokinetic remediation involves the application of low direct current (between two electrodes) and exploits the features and advantages of three transport mechanisms including electroosmosis, electromigration, and electrophoresis to mobilize cations, anions, and organic compounds [2]. Along with the three mechanisms, electrolysis of water occurs at the electrodes where oxidation takes place at the anode producing hydrogen ions and generating oxygen gas, and reduction occurs at the cathode producing hydroxyl ions and liberating hydrogen gas. Electrolysis reactions generate an acid front at the anode and a base front at the cathode, which results in a pH gradient. The low pH environment near the anode can enhance desorption of cation, while the high pH conditions in the vicinity of the cathode result in cation precipitation [3, 4].

In the last few decades, the increase in the demand for drinking water, due to the increase in the world population, has resulted in requirement for improvement in desalination to overcome water scarcity around the globe [5]. On the other hand, the growth in the wastewater treatment industry has resulted in sludge containing high concentration of ferric phosphate [6]. The scientist and researchers are constantly looking for new ways to improve the current practices. Electrokinetic is an emerging technique that can be used in the desalination as well as the enhancement of wastewater treatments. Generally, electrokinetic treatment has been found to be successful in developing low pH environments near the anode, high pH conditions in the vicinity of the cathode, and uniform pH gradient in between the electrodes. The low pH environment can facilitate the dissolution of cations. This concept has been used in desalination to remove cations form saline water [5]. On the other hand, recent studies have shown the possibility of using electrokinetic remediation to recover iron and sulfur from municipal wastewater [7, 8].

This study focuses on the use of electrokinetic remediation in desalination and wastewater treatment. Also, will shad light on the challenges facing the technique and provide and overview of the development of the technique in the area of desalination, wastewater applications and bioremediation.

2. Electrokinetics Applications in Desalination

Many techniques, based on electrokinetic remediation principles, have been developed and implement to treat seawater including capacitive deionization (CDI), electrodialysis (ED), electrokinetic pretreatment and electrokinetic coupled with reverse osmosis hybrid technique. The capacitive deionization (CDI) is used to remove cations and anions from seawater using electrokinetic treatment principles [5, 9, 10, 11, 12]. In electrokinetic treatment, two pairs of electrodes are used where one pair of electrodes serves as an anode and the other pair of electrodes arranged to serve as a cathode. Ions in solution are attracted to the oppositely charged electrode (the anode is positively charged and the cathode is negatively charged). In CDI technique, the charged ions are removed from seawater by flowing the feed water through a spacer channel with porous electrodes placed on opposite sides of the channel [13]. Due to the application of electric field (1.2 to 1.5 V) and by the effect of electromigration the cations accumulate around the cathode and the anions accumulate near the anode. Adsorption of the cations and anions on the porous cathode and anode is followed by desorption step in which the applied electric field is zero. Adsorption/desorption cycle is repeated several times until dynamic steady state is reached (maximum removal capacity is reached). Therefore, this technique is highly dependent on the adsorption/desportion capacity of the electrode materials. Recent studies proposed the use of alternative electrode materials such as carbide-derived carbon [10, 11]. CDI has seen considerable advances in the last decade including the use of selective membranes, flow electrodes, and flow through electrodes [14, 15]. However, the membrane fouling is considered one of the disadvantages facing the implementation of membrane in this technique [9]. Recently, some studies suggested the use of electric field to reduce membrane biofouling. The results showed that the membrane biofouling was reduced significantly due the electrokinetics processes which reduce bacteria metabolism. For instance, the high pH environment at the cathode and the low near the anode has detrimental effect on the growth of bacteria [9].

Electrodialysis (ED) of seawater is another method that has been developed based on the electrokinetics concept [16]. In electrodialysis, stack of anion exchange membranes and cation exchange membranes is placed between the anode and the cathode to form a number channels through which the salty water is passed [17]. When the electric field is applied the Na^+ ions move through the cation exchange membranes and the Cl^- ions move through the anion exchange membranes therefore diluted water moves through some channels and the concentrated salts move through other channels [16, 17]. ED technique is considered to be energy intensive as it is required around 3.5 kWh per m^3 of treated water produced [16]. Recent studies investigated the use of multistage ED that results in increasing the efficiency of the technique [16, 17]. However, the energy required for ED is estimated to be double the energy required for reverse osmosis.

Electrokinetic pretreatment of seawater has been used to reduce the concentration of certain cations as well as to reduce the presences of microorganisms in the seawater [12]. This technique is developed to overcome the membrane fouling problem which occurs frequently in the reverse osmosis (RO) for sea water desalination. The membrane fouling occurs due to accumulation of inorganic matters (e.g. cations and anions), organic compounds, and growth of bacteria on the service of the membrane. Optimization of the removal of the foulants depend on many factors including the electrode materials, the anode and the cathode positioning arrangement, the electric current intensity, and the length of the treatment [13, 14]. The development of high pH environment at the vicinity of the cathode promotes the removal of cations from solution (at high pH the cations precipitate out of solutions). Moreover, the effect of the electrocoagulation on removal of particulates has been studied and shown to be effective in the pretreatment before reverse osmosis [14].

Electrokinetic can be used to enhance the efficiency of reverse osmosis desalination process of seawater. Two electrokinetic treatment units can be introduced to the conventional reverse osmosis desalination process. Figure 1 shows a diagram that depicts the treatment process with the additional two electrokinetic treatment units (Figure 2 and 3). The first electrokinetic treatment unit (Figure 2) serves as a pre-treatment unit aiming to reduce the ions concentration in the raw seawater. The first electrokinetic treatment unit consists of ions selective membrane and two electrodes which serve as anode and cathode. Proton exchange membrane is used to separate the electrodes solution form the bulk stream. Selective cation and anion exchange membranes is used to separate the cations and anions from the bulk stream. The first electrokinetic treatment unit produces water in the bulk stream characterized with low ion concentrations and electrodes solution contains high ion concentrations. The bulk stream effluent exits the first unit from the middle depth of the unit, while the electrodes solutions effluent exit from the top and bottom parts of the unit. The bulk stream effluent is used as the feed for the reverse osmosis unit, while the electrodes solution effluents are combined and used as feed for the second electrokinetic unit. The reverse osmosis unit is used to desalinate the pretreated seawater. The retentate of the reverse osmosis process is discharged as waste. This technique involves supplementing the drinking water with magnesium to avoid health concerns associated with the deficiency of magnesium in drinking water. The second electrokinetic treatment unit serves as a magnesium separation unit. The second electrokinetic unit composed of graphite electrodes and proton exchange membrane, which is used to separate the electrodes solution form the bulk stream. The feed for the second electrokinetic treatment unit is the electrodes solution effluent from the first unit. The retentate of the second is discharged as waste. The magnesium produced in the second electrokinetic treatment unit is introduced to the desalinated water produced from the reverse osmosis process.

The desalination process required high energy; therefore, the it is recommended to enhance the efficiency of the desalination process using renewable energy [15, 16]. The author has investigated the use of solar power for electrokinetic remediation of heavy metals and for electrokinetic bioremediation of diesel fuel. The study concerning the removal of heavy metals was conducted in the summer at Thunder Bay, Ontario, Canada and the electrokinetic bioremediation study was conducted during the winter at London, Ontario, Canada. The results from both studies have confirmed that the solar panels can generate enough power for electrokinetic remediation. Therefore, the solar cells can be an excellent candidate for power supply in electrokinetics per-treatment of sea water. The use of solar power in electrokinetic pre-treatment of sea water can significantly reduce the cost of desalination process. More studies are required to investigate the integrated solar electrokinetic remediation in various areas including pretreatment of seawater, capacitive deionization, dewatering of sludge and iron removal from sludge.

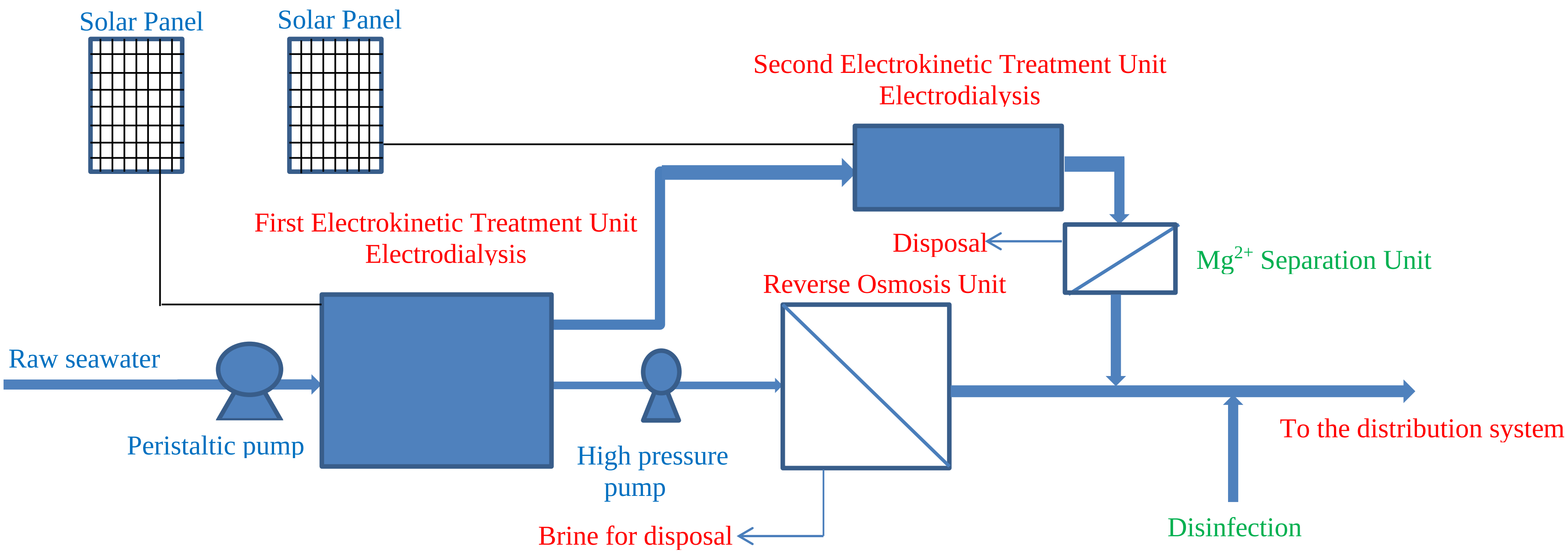

Figure 1 Schematic diagram for hybrid electrokinetic- reverse osmosis distillation process

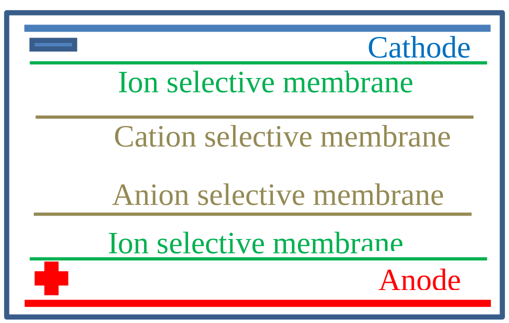

Figure 2: First electrokinetic treatment unit (Electrodialysis)

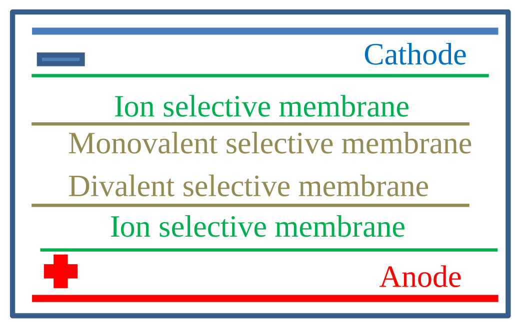

Figure 3: Second electrokinetic treatment unit (Mg^{2+} separation)

3. Electrokinetics Application in Wastewater Treatment

Iron has been used in wastewater treatment industry around the globe for removal of phosphorous. The addition of iron to wastewater results in the formation of a sludge rich in a ferric phosphate [6, 7]. The current practice is to dispose of the sludge containing high concentration of ferric phosphate which has an economical value. Phosphorus, which can be used as fertilizers, is a non-renewable resource diminishing in many parts of the world. Recently, the recovery of phosphorus from wastewater has gained global attention. In the last decade, there is increasing interest in replacing the traditional wastewater treatment processes. For example, addition of chemical compounds that can lower the pH of wastewater is used to facilitate the recovery of phosphorous and iron. Also, some studies suggested the use economical techniques that contribute to sustainability and characterized as environmentally friendly [8]. Recently, the need for finding sustainable alternatives for iron recovery from ferric phosphate sludge generated in wastewater treatment has become more urgent. The growing need for sustainable, economical, and environmentally friendly wastewater treatment processes drives, researchers and engineers to look for ways to extract iron from sludge and reuse it in phosphorous removal [8]. Sulfide can be added to ferric phosphate sludge to separate iron from phosphate [7].

Recent studies have shown the possibility of using electrokinetic remediation to recover iron and sulfur from municipal wastewater [7,8]. However, the technology is under development and the recovery of iron and sulfur is around 60%. Before field applications of the proposed technique the challenges facing the technique should be address including maximize the recovery of phosphorous, enhance the recovery of iron and sulfur, and identification of the effect of the volatile suspended solids on the electrochemical process.

The available literature provides information about iron recovery from ferric phosphate sludge generated in wastewater using electrokinetics [7, 8]. The technique involves two steps, the first step is the isolation of phosphate and the second step is the separation of iron. In the first step sulfide is added to the sludge in sedimentation tank to form iron sulfide precipitate and recover phosphate from the supernatant. Phosphate can be used as additive to produce fertilizers in the agriculture industry. In the second step, the sludge containing iron sulfide is transferred to an electrokinetic cell. Electrokinetic can be used to isolate and recover iron in the anode compartment and sulfide in the cathode compartment from iron sulfide sludge. The underlying hypothesis is that as electroosmosis transports water from the anode to the cathode, the proposed setup will result in transport of sulfide to the cathode compartment. Therefore, iron will be isolated in the sludge sample undergoing treatment.

The current study proposes the develop of cost-effective solutions/technologies to enable the iron recovery from ferric phosphate sludge generated in wastewater using electrokinetics, turning sludge into a valuable product while reducing the need for disposal. The system includes four approaches (solutions/techniques). First, acid mine drainage (AMD) bacteria to is proposed to be used to lower the pH of wastewater to facilitate the separation and recovery of phosphorous from ferric phosphate sludge [18, 19]. AMD bacteria can be cost effective alternative to chemical compounds, which can be used to lower pH of the ferric phosphorus sludge to recover iron and phosphorus. The effluent, in case of addition of chemical compounds, contains high concentration of undesirable by-products that would complicate and interfere with the subsequence processes [20, 21]. Moreover, the high cost of the traditional chemical compounds makes the whole process uneconomical. Therefore, AMD bacteria can be cost effective alternative to chemical compounds. On the other hand, sodium sulfide (Na2S*9H2O) can be added to ferric phosphate wastewater to form iron sulfide (Equation 1) precipitate and separate phosphorous from ferric phosphate sludge. The concentration of sulfide in the wastewater will be determine and the optimum molar ratio S:Fe to achieve maximum recovery of phosphorus will be determined.

$$FePO_4 + nH_2S \rightarrow FeS + xS^o + (n - x - 1)\, H_2S + H_2PO_4^- + H^+ \tag{1}$$

Oxidation reaction at anode

$$FeS \rightarrow Fe^{2+} + S^o + 2e^- \tag{2}$$

Reduction reaction at the cathode

$$S^o + 2e^- \rightarrow S^{2-} \tag{3}$$

The addition of sulfide to the ferric phosphate results in reduction of ferric iron to ferrous iron and formation of iron sulfide precipitates. This step results in formation of iron sulfide precipitate and liberation of phosphate in solution. Therefore, phosphate can be recovered and recycled to produce phosphorus fertilizers for agricultural purposes [19]. The ferrous sulfide (FeS) can be transferred to electrokinetic remediation cell (Step 1 in Figure 4) in order to separate and recover iron in the anode compartment (Equation 2). Using polarity exchange (Step 2 Figure 4), the sulfide is recovered at the new cathode compartment [6]. The underlying hypothesis is that the oxidation of sulfide (in the formation of FeS) at the anode side results in formation of elemental sulfur, which precipitates on the anode surface. Then polarity exchange (Step 2 in Figure 4) can be used to reduce elemental sulfur back to sulfide (Equation 3) and recover the sulfide in at the 'new' cathode side. Therefore, iron and sulfide will be isolated from the sludge sample undergoing treatment. In this technique optimum sulfur reducing bacteria (SRB) should be used coupled with electrokinetics to recover phosphorous, iron, and sulphur. Iron will be transported by electromigration and accumulated at the cathode, while sulfur will be recovered from the anode compartment [19, 20, 21].

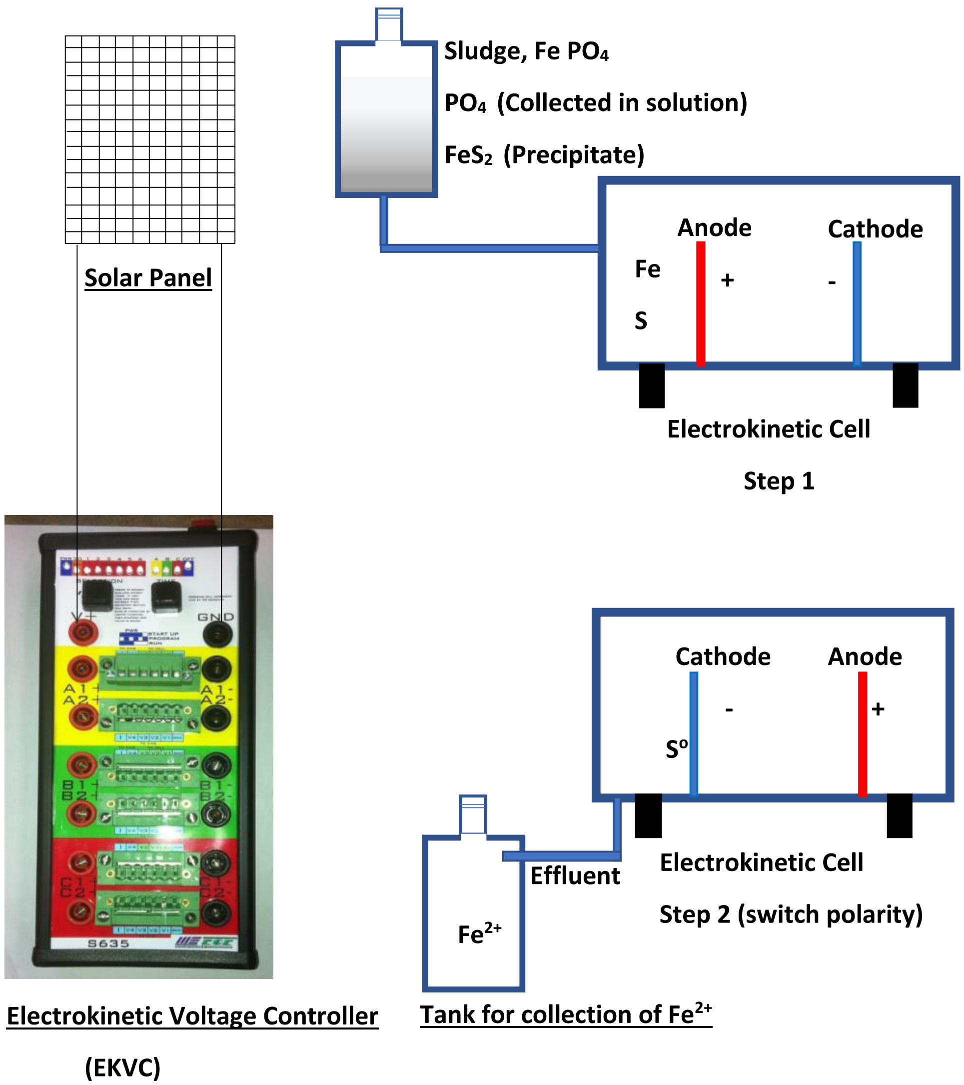

Figure 4: Electrokinetic setup for iron and phosphorous recovery

Figure 4 shows electrokinetic voltage controller (EKVC) device, which was designed and manufactured to switch the electric potential between the two electric circuits such that at any given time there is only one electric current running through either electric circuit in the electrokinetic cell. The EKVC takes an input of dc voltage of up to 60 V and has six output ports and a programmable timer. These output ports are arranged in two groups of three outputs. For each output port, there are four switched voltage points. Three of the voltage points are used to monitor the voltage distribution across the electrokinetic cell and one to record the electric current. These points are switched to three groups of a four data acquisition points. The voltage distribution profile (at three points) across the electrokinetic cell under treatment and the electric current through the soil can be monitored using the voltage points connected to data acquisition terminals. The data acquisition terminals should be connected with a computer to record the current and the volage.

The EKVC alternates the voltage between outputs groups at a set programmable time. The timer can be set to alternate the voltage between the two electric circuits for intervals from thirty seconds to six minutes in thirty second steps. The EKVC can be connected to up to three electrokinetic cells. Also, the EKVC controls the duration time of the electric current delivered through the electric circuits. The EKVC can be set for any desired time setup. Time off can be selected based on preliminary tests to determine the time required for neutralization of hydrogen and hydroxyl ions in the water compartments. The off time needed for pH neutralization may vary depending on the properties of the soil and electrolyte solutions as well as the voltage gradient and electrode material.

4. Challenges Facing Electrokinetic Remediation

During the last three decades electrokinetic remediation application has been developed and used as effective remediation method. However, few challenges face the technique. The challenges can be divided into two parts, general challenges facing the technology and challenges facing field application in particular.

4.1. General Challenges

The general challenges include the decay of the electric current during the remediation process and the corrosion of the electrode material. Many researchers have reported decay in electric current during electrokinetic treatments due to precipitation of cations from pore fluid solution. The precipitation of cations can be attributed to high pH, known as base front, near the cathode. Most of cations precipitates from solution at pHs range from 8 to 12 pH. Also, the low and high pHs directly affect zeta potential and consequently result in a non-uniform electroosmotic flow (Equation 4), which is sensitive to zeta potential.

$$q_e = k_e A E \quad (4)$$

Where qe (m3/s) is the flow rate of water drained by electroosmosis, A (m2) is the cross-sectional area perpendicular to the direction of flow, ke (m2/(sV)) is the electroosmotic permeability, E (V/m) is the electric field intensity defined as E = - ∇U, U (V) is the electric potential, and ∇ is the del vector.

$$k_e = \frac{\zeta \varepsilon n}{\eta} \quad (5)$$

Where η is (N·s/m2) is the dynamic viscosity of the liquid; ε (F/m) is the permittivity (a measure of the ease with which molecules can be polarized and oriented) of the pore fluid; ζ (V) is the zeta potential (the electrical potential at the junction between the fixed and mobile part of the double layer) and n is the porous medium with porosity.

Many researches and scientist have addressed the current decay issue and proposed and implemented different solutions [22, 23, 24, 25]. The proposed solutions can be divided into conventional solutions and innovative approaches. The conventional solutions include separation of electrolyte solution using ion selective membranes and addition of chemical compounds (conditioning agents). Selective membranes are placed in the anode and cathode compartments. The function of the selective membrane is to prevent the advancement of selected ions (e. g. Hydrogen ions form the anode and the hydroxyl ions from the cathode). The addition of chemical compounds includes the use of organic (e.g. Acetic Acid) and inorganic (e. g. Hydrochloric Acid) acids as conditioning agents to compact the advancement of the base front. The acetic acid is characterized by formation of soluble slats and partial disassociation (does not fully dissociate) [22]. On the other hand, hydrochloric acid generates chlorine gas resulting in production of new contamination and exacerbate the problem. Therefore, it is preferred to use acidic acid than hydrochloric acid. Other chemical compounds such as nitric acid can excessive acidification which has an adverse effect on the outcome of the electrokinetic remediation. Also, some compounds can form strong complexes with cations making them unavailable for removal (e. g. EDTA). Thus, it crucial to select a proper enhancement agent and avoid chemical compounds that produce secondary contaminants in the subsurface, propagate waste products due to electrochemical reactions and aggravate the existing contaminant condition. Also, the introduction of chemical compound in the process will increase the remediation cost. Large prototype tests and field trials are required to confirm the available data from small scale laboratory results.

The innovative approaches include step moving anode, exchange polarity technique, two anodes technique and two anodes and two cathodes technique. The step moving anode can be described as the advancement of the anode in the direction of cathode through the electrokinetic cell [23]. The anode produces hydrogen ions and creates low pH environment which can facilitate the dissolution of cations. In this technique cation-exchange membrane was use to control the advancement of the base front. There is increase in the cost associated with the use of the selective membrane and the cost of relocating of the anode. Also, there is a concern about the possibility of electrode (anode) damage during the process.

The corrosion of electrode material during the remediation process results in ceasing of the treatment. Many researchers and scientist discussed the use of different electrode materials. The durability of the electrode is crucial for sustainable remediation process. On the other hand, the by products from the electrode can affect the treatment process. It is preferable to use an inert material for the electrode. The by-products from electrode material can interfere with some electrokinetic remediation application (e. g. electrokinetic desalination). However, few studies investigated the effect of the electrode materials on the electrokinetic desalination. Pervious study investigated the effect of chemical reaction and interaction between the electrode material and the contaminated matrix. The result confirmed the detrimental effect of the electrode material by-products on indigenous microorganisms' metabolisms [24]. However, the biochemical reactions and the by-products were not identified. Previous research provided information about the effectiveness of the use of steel, copper and carbon as electrode material in electrokinetic remediation. Also, the study discussed the combinations between different electrodes materials for the anode and cathode [25]. It was founded that the selection of suitable electrode material for specific electrode (anode or cathode) results in significant improvement of the remediation process. The information about the electrode materials in the current literature need to be supported with more comprehensive in-depth studies.

4.2. Challenges Facing Field Application

The general challenges facing electrokinetic remediation field application can be summarized as:

1- The influence of temperature

2- The availability of power lines near the contamination sites and the cost of electric energy

In the following sections each of the above-mentioned challenges will be discussed.

In the last decade, the need for finding sustainable and economical alternative sources of power to replace the traditional hydropower has become urgent. Recently, solar energy has been considered by scientists as well as the general public as a suitable alternative. The advancement in technology and the production of efficient solar panels resulted in decreasing the initial cost and increasing of the efficiency of the solar panels. The power generated by solar panels is directly affected by the day light, the day time weather conditions (clear sky, clouds and rainfall). During the night no power can be generated by solar panel. Therefore, the electric current generated by solar panel varies during the day depending on the weather and becomes zero during the night resulting in intermittent current. Previous studies show that the pulsed current results in enhancement of electrokinetic remediation by eliminating the adverse effect of the uneven electroosmotic flow [26, 27, 28, 29, 30]. The ions in the double layer orient in a direction against the electric current in response to the application of electric field during electrokinetic remediation. This orientation of ions results in a decay of the electric current and the interruption of electric current can be used to reverse this effect. Therefore, the variation of electric current during the electrokinetic remediation process powered by solar panel excites the electric current. Previous studies investigated the intermittence current and concluded that the fluctuation of current can be beneficial to enhance electrokinetic remediation [26, 31]. The author investigated the use of power generated by solar panel in electorkinetic remediation to mitigate soil contaminated with copper. The results confirmed that the solar panels are effective in generating power for electrokinetic process [31, 32].

The utilization of solar power is widely spread in many countries around the world including US, Japan, Germany and Canada. It is known that the efficiency of solar panels increases at low temperature. Solar panels are considered to be the most suitable alternative for power supply for electrokinetics, However, few areas need to be investigated such as the effect of zero current during the night on the electrokinetic applications. The benefits of using solar panels include the reduction of electricity transmission expenses, the elimination of the power losses in the transmission lines and minimization of the adverse effect of the traditional power plants on the environment. Nevertheless, solar panels generate DC electric current that can be directly used in electrokinetic remediation compared to the AC from the gride that need to be altered to a DC using DC transformer. The prices of the solar panels have been decreasing in the last decade and this trend is expected to continue with the advancement in the technology.

Challenges facing in-situ application of electrokinetic bioremediation include microorganism related factors such as, availability of nutrient for microorganisms and the capacity of the indigenous microbial consortium in degrading the contaminant [33]. The aim of electrokinetic bioremediation hybrid approach is to enhance the naturally occurring biodegradation process by proving more opportunities for interaction between microorganisms and contaminants. Also, stimulate the metabolism of the existing microbial community in the subsurface by delivering nutrients required to promote microbial growth. Recently, the author investigated the use of solar panels to produce electric current to conduct electrokinetic bioremediation for clay soil artificially contaminated with phenanthrene. Figure 5 shows profile of the voltage generated by the solar panel during the test. The figure shows that the solar panel generate voltage in the range of <1 V/cm in the first hour and a half after the sun rise and at the last hour and a half before the sun set. The solar panel generate 50- 60 V during the rest of the day which enough for electrokinetic bioremediation. The distribution of generated voltage as shown in Figure 5 is in agreement with trapezoidal model where the daylight hours represent the bottom base of the trapezoid and the noon hours represent the upper base of the trapezoid [34]. The height of the trapezoid is the maximum irradiance during the day. The results from this study showed that the power generated by solar energy is not only sufficient for electrokinetic bioremediation, but can also be monitored and evaluated using the trapezoidal model. It was found that the solar panels successfully generate enough power for electrokinetic bioremediation of petroleum hydrocarbons. Nevertheless, the results showed that the zero current during the night decreases the soil temperature which was beneficial for the remediation process. That study also concluded that the combined effect of applied current intensity and duration is the crucial factor affecting living organisms rather than the current intensity alone.

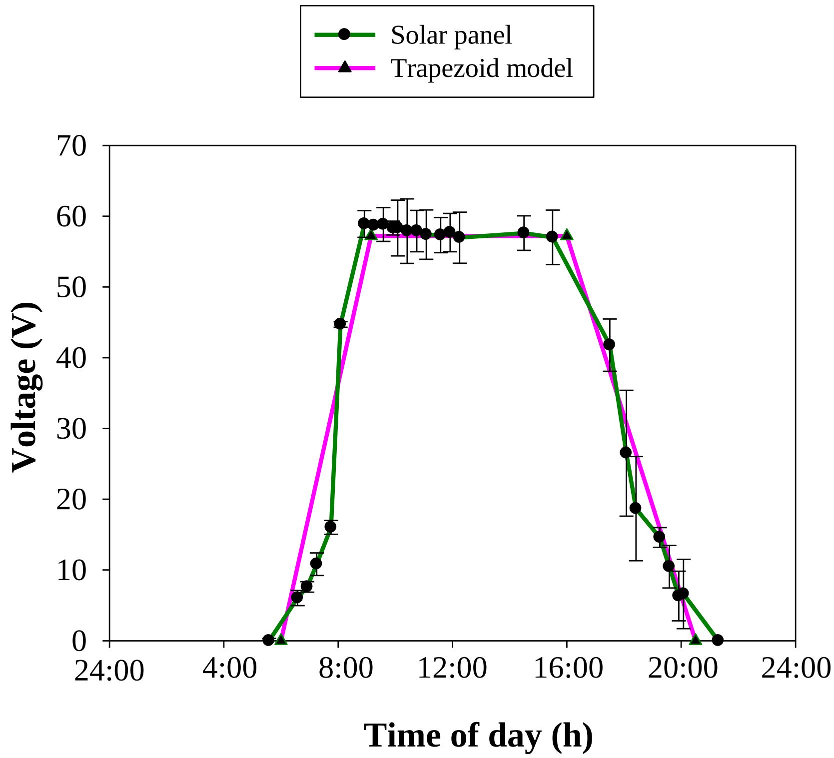

Figure 5: Power generated by solar panel

5. Conclusion

In electrokinetic remediation, electrolysis reactions form a pH gradient between the electrodes. The pH gradient has an adverse effect on the remediation prosses. The success of an electrokinetic remediation treatment relies mainly on the ability to control pH. Therefore, controlling the pH during an electrokinetic remediation treatment is crucial for its success. The Electrokinetic remediation can be an effective remediation technique suitable for various applications, provided that the process cost can be reduced and the pH gradient is controlled. High energy consumption increases the overall cost of the remediation process and may become a major factor restricting the field application of the technology. There are very few studies in the available literature that have investigated the cost of energy in electrokinetic remediation, which is a major contributor to the total cost of the process. Research to date has shown considerable contaminant removal using electrokinetic bioremediation. However, future research should pay more attention to optimize the removal efficiency by electrokinetic remediation. In addition, current research tends to address the pH issue using two different approaches, either by using conventional techniques, in which chemical compounds are added to control the pH, or by innovative techniques, such as step moving anode in an attempt to neutralize the pH. Both techniques can result in a further increase in the overall cost of remediation.

Solar panels can be a source of substantial power for electrokinetic remediation. The use of solar power can reduce the total cost of the process, and the added benefits would include less adverse environmental impact. Advanced technologies, in particular, solar panel production provide great opportunities for enhancing electrokinetic remediation with reduced cost. It is anticipated that, with intense research efforts, electrokinetic remediation would become a viable technology in the near future.

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