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Electrokinetically Assisted Oil-Water Phase Separation in Oily Sludge with Implementing Novel Controller System

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Highlights

- Novel controller has been employed to an electrokinetic system for demulsification of hazardous oil sludge.
- Percolation theory is applied to control an electrical system for treatment of water-in-oil emulsions.
- Controller secures the four-phase separation during extended exposure time.
- Novel controller enhances the mobility of phases to increase oil to water volumetric ratio.

Abstract

Upstream and downstream petroleum industry generate of significant amounts of oily sludge per day. On the other hand, a disposal of such sludge requires expensive pre-treatments following local regulations. Conventional processes, like centrifugal separation provide sludge volume reduction and water extraction. However, water-in-oil emulsion requires extra stages for phase separation, which overall increases the costs. Therefore, electrokinetically (EK) assisted oil-water phase separation method was considered. In this study, a novel implemented controller, installed into the EK system, permitted to increase the length of exposure time to electrical field, while a significant decrease of energy consumption was observed. The controller, implemented based on Percolation Theory and applied to a linear horizontal EK system, showed enhanced sludge demulsification and improvement the quality of separated fractions. TGA analysis showed a superior quality of liquids extracted by EK with controller comparing to liquids without controller or generated by centrifuging process. A reaction rate with respect to temperature to assess the presence of

water in the oil was also defined. The method, shown in this paper, advances the oil-water phase separation and permits for better oil recovery and sludge volume reduction .

Keywords: Oily sludge, Electrokinetics, Controller theory, Oil-water phase separation, Percolation Theory

1. Introduction

Based on US EPA, oily sludge generated downstream by petroleum industry is classified as a hazardous material [1] and its treatment is mandatory before the final disposal. Since annual average production of sludge is huge (e.g. 30 000 tons per refinery [2] in USA and 3 million tons overall in China [3]) sludge disposal emerges as a critical global issue. Upstream waste sludge might originate from slop oil at oil wells, tailing ponds, crude oil bottom tanks, drilling mud remains, etc. [4] Such refractory residue is characterized as a stable water-in-oil emulsion of water, solids, PHCs, metals, and other impurities [5].

Hydrocarbon-reach sludge presents a potential source of energy. Multitudinous methods are investigated and applied for oil and water recovery from oily sludge. Solvent extraction, centrifugation, surfactant enhanced oil recovery (surfactant EOR), freeze/thaw treatment, pyrolysis, microwave or ultrasonic exposure, and froth floatation are applied at full or experimental bench scale [6]. Solvent extraction and hydrothermal processing are among these technologies, which are not economical at an industrial scale and mostly do not comply with current regulations. Centrifuging is the most common method of sludge treatment at full scale. However, it also has operational problems and often produces low-quality solids. Production of high-quality solids is costly and often uneconomical [7]. The expected issues related to centrifugation treatment are: i) high energy consumption to generate strong enough centrifugation force in order to separate oil from petroleum sludge [8], ii) high equipment investment, iii) limitations of its application at small scale [9], iv) frequent damage of parts, v) noise, vi) heating of sludge to decrease viscosity, and vii) a necessity of using demulsifying agents and surfactants, which leads to increasing of processing costs and bringing environmental concerns [6].

Life cycle analysis conducted by Elektorowicz and Habibi [10] proved that the use of electrokinetically extracted fuel from oil sludge (instead of conventionally produced fuel) might reduce emissions of major greenhouse gases such as CO_2, CH_4, and N_2O by 40 026 000, 1057, and 566 kg, respectively, per refinery per year.

Yang et al. [11] experimental study showed that the array of electrodes significantly influenced the dewatering efficiency of the oily sludge; while vertical configuration was optimal. Their research showed that the water removal was predominantly controlled by electroosmosis and the hydraulic pressure in the

sludge bed, while the role of evaporation was negligible. Yang et al. [12] presented an experimental roadmap in which different electric potentials (10, 20, 30 V) at the bed height of 4.5 cm, where the removal of 52.8% and 4.5% of water and oil, respectively, was achieved at the highest electric potential of 30 V. An investigation of the sludge bed impact showed that the highest initial sludge bed (5.2 cm at 20 V) reached the highest removal efficiency of 49.3% and 3.0% for water and oil, respectively. However, Habibi et al. [7], based on an investigation of oil sludge properties, concluded that lower voltage gradient (0.5 V/cm) and longer exposure time gave better environmental conditions for sludge electro-dewatering.

Glendinning et al. [13] presented a design framework for electrokinetically enhanced dewatering of sewage sludge. The derived equations and experimental results demonstrated that electroosmotic flowrate declined with time once constant voltage was implemented into the electrokinetic cell. In contrast, constant current conditions gave a constant flow rate throughout the same time interval. Obtaining a linear relationship between flow and time, EK dewatering with constant current not only enhances the sludge dewatering efficacy but also makes the designing procedure simpler. However, the wettability alteration of oily sludge under the exposure of the electrical field, the distinctive viscosity of immiscible phases, strong water-in-oil emulsion and discontinuity of an oily sludge system limits the application of such approach in oily sludge medium.

Most of electrokinetic applications were related to soil contaminated with different products – not to oil suspensions. For example, Pamukcu et al. [14] research on a matrix of oil polluted clay-rich sediment proved that transport, separation, and recovery of non-polar light crude oil from water was possible through the application of DC field. Displacing of non-polar immiscible oil in the opposite direction of the flow was possible by electroosmotically driven flow of saline water in the absence of viscous coupling of oil and water; while the surface tension reduction of the water phase possibly benefits the passage of water by oil phase. Ghazanfari and Pamukcu [15] implied that ionic migration would be possible to take place in all types of soils including sands and gravels. However, the migration mechanism was affected by ionic strength and pH to a smaller degree compared to electroosmotic (EO) flow. Since most crude oils are mixtures of non-polar compounds, it is expected to face the lack of dissolved charged particles. Therefore, unlike water/wastewater direct application of electric field would not create a remarkable electroosmotic force which is necessary to generate flow [16].

Ghazanfari et al. [17] investigated the efficiency of the electrically assisted hydrocarbon recovery and field cores of hydrocarbon bearing formations. They figured out that clay contents would affect the electrically assisted recovery, since it maximized for surrogate core containing 10-15% clay by mass. At lower clay contents, the mechanism of the recovery was influenced by colloidal transport rather than electroosmotic one.

Habibi et al. [7] implied that electrokinetically enhanced coalescence plays an important role in sludge demulsification and subsequently in oil recovery. Mhatre et al. [18] indicated that a number of parameters can have an impact on the attraction forces between the coalescing drops, for example, the inter-drop separation, size of drops, shape distortion and fluid properties such as conductivity, permittivity, viscosity, interfacial tension, etc. However, the most important mechanism of coalescence is based on the coupled function of molecular and electrostatic force which leads to break the interstitial film and allows drops to unify together. If drops have charges, 'migratory coalescence' results due to electrophoresis. [19], [20] Thus, electric field as one of the major associated parameters enhances the thin film breakup. According to Berg et al., [21] when the electric field (E_0) is small, the coalescence rate is proportional to the magnitude of the electric field; in contrast, due to the exposure of high magnitude of the electric field, the rate is proportional to the square of initial electric field (E_0^2).

Subsequently, a continuous control of the process is crucial to maintain a high efficiency of phase separation. However, to authors' knowledge, no controller has been applied to oil sludge electrokinetic low-voltage treatment yet. Nevertheless, a successful use of controllers was observed in some soil remediation works. For example, Roulier et al. [22] developed Lasagna™ technology, applied a controller with a 9kW DC-power supply in a laboratory scale. The controller consisted of an electromagentic coil design using a saturable reactor coil to make setting current adjustable. Contrary to our system, a constant current was considered for Lasagna™ cells while the voltage was changed in response to the variations of the cell resistance in the range between 10 and 40 V/m. Once the size of power supply was scaled up, an electronic silicon-controlled rectifier- type (SCR) power controller was used for the electromagnetic coil. The objectives of such system were: i) reduce the cost by avoiding larger coil, ii) provide a precise control, and iii) add a feature of operating in both constant-potential and constant current mode. SCR functioned as an electrically controlled switch that could turn on/off small or large amount of power. The preferable feature of SCR is its performing as a switcher without a demand of introducing mechanical part.

Hassan et al. [23] stabilized pH during electrokinetic bioremediation of soil with the configuration of anode-cathode compartment (ACC). ACC also improved a nutrient distribution across the soil. An electrokinetic voltage controller (EKVC) was designed to switch the electric potential between two electrical circuits, while only one circuit was functionalized during the experiments. The EKVC consisted of an arrayed of two groups with three outputs, where each output port had four switched voltage points. Three of the voltage points were used to monitor voltage distribution profile across the soil, and one was used to record the electric current. EKVC's function was switching the current between the circuit based on the timer that was set to alternate the voltage between the two electric circuits for intervals from 30s to 6 min in 30s steps.

None of controllers used for soil electro-remediation was built based on percolation theory logic, which has been suggested in this study. The aim of such approach was minimization of the costs related to the energy consumption, while the phase separation with respect to the oil recovery was preserved. Then, electrokinetic system with controller might compete with a conventional oil sludge treatment by centrifuging [24].

2. Material and Methods

To achieve the study objectives, electrokinetic (EK) phase separation in oil sludge was conducted at lab scale using EK reactors with and without the controller. The upstream oily sludge used in this study consisted of 33.5% water, 14.5% light hydrocarbons, 28.0% heavy hydrocarbons and 24.0% of solids.

The major physical parameters like gravity drainage efficiency, drainage exposure area, flow regimes (e.g. linear horizontal flow and radial flow) and voltage gradient are directly influencing the reactor design. Therefore, a linear horizontal reactor was proposed to investigate the efficiency of phase separation and subsequent extraction of oil and water components.

The EK reactor with an exposure zone volume of 226 mL was designed based on US patent 8,329,042 [24]. Design permitted to avoid quick drainage of the water-in-oil emulsion and promoted a fast coagulation. Four mesh stainless steel electrodes were placed with even separation from each other. The anode and cathode side drainage bank zones (64 mL) were equipped with a tubular drainage system, which transported extracted liquids and collected into vials.

The controller was set on the input value, which was responded from the connection of the electrodes. Initial electrical conditions were adjusted at a constant voltage. Generally, once water is drained from the EK cell and the ratio of oil to water volume in the treated oily sludge increases, the resistivity increases and leads to a sharp current decline. To make the system more efficient, a controller was introduced to the circuit. At a time that current reached minimum threshold, the controller intensified the voltage up to the point when it reached a specific value. The new set value, "maximum threshold current", takes place when the controller allows the system to change its current within the range between minimum threshold and maximum threshold values. It will permit on continuous current supply during the whole treatment process. The concept of the "percolation based controller" is illustrated in Figure 1.

The first stage of the study was designed based on a series of preliminary experiments, which investigated operating parameters like apposite voltage gradient, the distance between electrodes, and exposure time. Consequently, the experiments were run in a horizontal EK reactor while 1 V/cm voltage gradient was applied. Since an optimal exposure time is strongly related to a recovery rate, it was expected that the EK experiments proceeded for total 60 hours of exposure time.

The second stage of the study conducted for an adequate implementing a controller to enhance the oil recovery from separated phases. Since a constant voltage gradient provided best results in the first stage of the study, such approach to controller design was considered. The current variation versus time for both stages of the study was used for assessment of the controller efficiency.

To provide better justification of water-in-oil electro-demulsification, centrifuging (6000 rpm for 30 minutes) of the same sludge was considered.

The quality of recovered oil increases with lower water content. Then, a reaction rate (dX/dt) with respect to temperature helps to assess the presence of water in the catholyte oil near the oil-water contact. The raw data was generated based on thermogravimetric analysis (TGA). A control sample for separated three phases (oil, water, and solids), was obtained from centrifuging raw oil under 6000 rpm for 30 min. Then, a sample was taken from the oil near the oil-water contact. Therefore, the studied samples were: i) after centrifuging (control); ii) after EK treatment without controller; iii) after EK treatment with controller.

Mass conversion was calculated by subtraction of a residual mass fraction of the active reactant (M) from 1. After plotting mass conversion values versus time, the function of mass conversion (X(t)) was obtained by curve fitting. Afterwards, derivation of X(t) with respect to time (dX/dt) gave X´(t). As a result, reaction rate was calculated by substituting time in the function of X´(t). Then, the reaction rate (dX/dt) was plotted versus temperature to explore a behavior of the reaction rate at different temperatures.

3. Results and Discussion

Primary parameters for both research stages were the current and volume of extraction. The system efficiency was evaluated based on the presence of water in oil and fractioning separated phases. The current variation and voltage changes are described in Figure 2a and Figure 2b, respectively.

The most significant parameter in separation mechanism is the electrical potential which has been also proven in previous research [10]. The search for a new constant voltage gradient for the controller is shown in Figure 1. The benefits of using "percolation based controller" might provide not only continuous current in the reactor, but also reduce a demand for activating a mixer in experimental bench scale and decreasing time of pump assisted circulation process in the field scale; finally, it can eliminate the necessity of introducing post-separation units. The extracted volumes versus time are shown in Figure 3a and 3b.

The minimum threshold current (0.003 A) of the second phase was reached in 33.6 hours; while, the minimum threshold current of the first stage was obtained at 35 hours (Fig. 2a). This is probably related to minimal achieved water saturation prior to expected threshold point. A reduction in water saturation increases the resistivity of the system; therefore, the minimum current is expected to reach minimum

possible water saturation. Also, a sharp decrease in current could be proven by tenable justification. The production of water has been proceeded quickly because of lower viscosity of water comparing to light or heavy oils. Its polar characteristics cause water droplets to get charged by the electrical field and proceed with electro-coagulation faster. Thus, the water extraction is expected to happen in the first 24 hours. In the first stage, the sharp decrease of current was observed in the first 12 hours of the exposure time. While the notable sharp decrease of the second stage takes place between 12 and 24 hours. The reason of the sharp increase in current is interpreted by mixing process for the first stage; while the second stage sharp increase was probably due to the controller which reached the maximum threshold current after detecting the minimum threshold value.

In the second stage, the first sharp increase of current was relevant to the increase of voltage. However, the second sharp increase of voltage did not cause the current increase and reach maximum threshold current. The applied voltage gradient was inadequate to increase current and the limitation was initiated from maximum possible applicable voltage by DC power supply; the required voltage to obtain maximum threshold current was higher than the limit of the power supply (60 V). The last 3 hours of exposure time in Fig. 2b is exclusively devoted to the described phenomenon.

The significant differences in both stages are related to light oil recovery and water production. In the first stage (Fig.3a), the water production was consistently increased throughout the process while the variations of the first 24 hours were strongly ascending. Amount of 43.40% of the existed water was extracted within 60 hours, while, 25.20% of the light oil was recovered, simultaneously. Whereas light oil recovery of Stage 2 had outpaced water production at 22.6 hours and kept upward trend meanwhile the remained 37.4 hours. The results of the second stage showed an extraction of 17.12%, and 34.00% of the initial volume of light oil and water after 60 hours respectively. It was observed that once the electric field was increased from 1 V/cm to 11.49 V/cm, the oil recovery rate was increased by 1.56% during the time interval between 43.6 h to 57 h.

Considering anolyte composition, the recovery of heavy oil reached 15.10% in the first stage and 5.00% in the second stage. A difference of the heavy oil recovery in the second stage can be explained by: i) lack of a mixing process (used for a uniform water distribution in cell); ii) high current in the second phase, permitting on faster electro-osmotic transport of water leading to a decrease of conductivity in the anode area, and subsequent decrease in heavy oil recovery.

Dynamic viscosity of the liquid phase of raw oily sludge was 88.2 mPa.s at 22 °C. At a level of current and potential of 0.007 A (7 mA) and 60 V, respectively, the system faced a decrease in final dynamic viscosity of the cathode extracted oily liquid to 73.8 mPa.s at 27.4 °C. Lower dynamic viscosity might be exposed to

a thermal enhancement resulted by controlled continuous flow within the system. Furthermore, dynamic viscosity of the extracted catholyte without controller was 76.5 mPa.s at 25.3 ℃.

Reduction in the water production rate (Fig. 3b) started after 33.6 hours of exposure time. As it was shown by Pamukcu et al. [14], the surface tension could be reduced with the application of current, which would cause water displacement by oil in the transport direction. Based on this study, an increase in temperature, which maximized at 7 mA and 60 V, led to decline in dynamic viscosity. Therefore, it would be speculated that an enhancement in water displacement by thermal effect would be possible at a high voltage gradient at a full scale in the future.

A significant offset between procedure with and without the controller with respect to the volumetric ratio between oil and water (O:W) can be seen in Figure 4. Also, the fluctuations of the second stage (with controller) are relatively strong while the O:W is gradually evolved up to the limit of 0.6 in the first stage (without controller). The highest offset (1.28) was obtained at 43.6 hours, which demonstrates that the boost in O:W was attained by controller functionalizing throughout the time period between 33.6 and 43.6 hours. Then, the final O:W of Stage 1 was 0.58, contrary to Stage 2, where an increase in light oil recovery led to achieve final O:W = 1.83. A higher O:W value is a good indicator to prove that light oil is recovered faster than water due to minimization of the mobility ratio of water to oil and decrease in oil saturation.

Thermogravimetric analysis (TGA) assessed the water, light, and heavy oil fractions in three samples: i) centrifuged raw oily sludge (6000 rpm for 30 minutes); ii) catholyte in system without controller (oil extracted near oil-water phase contact ; iii) catholyte in system with controller (oil extracted near oil-water phase contact). Based on initial analysis of oily sludge properties, fractions of water, light and heavy oils were 33.5%, 14.46%, and 27.98% respectively. Figure 5a illustrates weight percentage (weight fraction) gradual decline in the temperature range between 302.9 K and 857.5 K for all three described samples. For zero water-in-oil emulsion scenario, it is expected to observe 33.50% decline in weight fraction at 100˚C (402.9 K).

For centrifuged raw oily sludge, the obtained TGA weight fraction at 402.9 K showed only 12.27% mass reduction (Fig.5a). It can be speculated that water-in-oil emulsion was functionalized as an inhibitor in raw oily sludge to restrain water from evaporation. Then, 33.50% weight reduction was achieved at 635.2 K proving the existence of inhibitory function of the water-in-oil emulsion. The final achieved weight fraction at 857.5 K for centrifuged oily sludge was approximately 44.00%.

To construe the breakage of water-in-emulsion by EK treatment without the controller, it is noteworthy to draw attention to the point in which 33.50% weight fraction decrease is observed (Fig.5a) at the temperature of 490.4 K which demonstrates the partial breakage of the water-in-oil emulsion. Finally, application of

controller leads to achieve significant improvement with respect to demulsification by obtaining 33.50% weight fraction reduction at 441.6 K (Fig. 5a).

A residual mass fraction of active reactant, M (Fig. 5b), proved a significant decrease in EK cell with and without controller comparing to centrifuging. The estimated offset between curves representing systems without and with controller is 0.13 for the temperature ranging between 385.5 K and 575.5 K.

Following method of analysis proposed by Shie et al. [25], mass conversion, X, which is calculated with X=1-M, also supports the residual mass conversion of active reactant results by giving elevated time dependent curve for EK cell with controller in the time interval of 5.5 min to 41.7 min (Fig. 5c). To determine the reaction rate, dX/dt, it is crucial to find an apposite fitted curve with high R-squared (R^2) value for X(t). Three equations are given in Table 1 with the R-squared higher than 0.99 based on analyzed TGA samples in the time interval of 0.004 min to 57 min.

An exponential increase in reaction rate with temperature surge shows the strong dependency of centrifuged oily sludge kinetics to temperature (Fig.5d). To interpret the described phenomenon, responsible reactants in chemical reaction kinetics are considered. Confidently, hydroxide ions which are existed in the aqueous medium are placed on the top of the list. Therefore, the significant contribution of water in reaction rate at the temperature range between 302.9 K and 635.2 K leads to obtain strong increase with increasing temperature.

Whereas, the significant lower water content in EK cell without and with controller leads to obtain a reaction rate in the range between 0.01 1/min to 0.03 1/min and 0.01 1/min to 0.033 1/min, respectively.

Qualitative juxtaposition of demulsification is illustrated in Figure 6, where Figure 6b visualizes the separation of oil and water significantly enhanced by using the controller in the electrokinetic process. In this case, water clarity was high and ready to be reused; furthermore, the volume of remained in EK cell solids decreases by 44.30%.

This outcome was compared to centrifuging results (Fig. 6a); which showed minimal water-oil separation. It seems that centrifuging transformed water-in-oil emulsion to oil-in-water emulsion system; such water requires further treatment. In spite of phase separation, the collected catholyte from EK cell without the controller showed a low clarity of water (Fig. 6c). Detectable solids particles in both experiments without and with controller permitted to conclude that electrophoresis was also involved due to viscous forces prevailed in sludge medium.

The second stage of study necessitated a new development considering larger minimum threshold current value while logically reducing the maximum threshold current; i.e. narrowing the difference between minimum and maximum threshold current. A smaller difference between maximum and minimum threshold current requires less voltage gradient once the controller is functionalized and elevates the minimum threshold current. The reason is to persist higher magnitude of current in EK cell in a shorter time interval.

An important advantage of the controller application was twice lower energy consumption (Tab. 2) at a lower cost (calculated based on Hydro-Quebec price of $0.035/kWh for industrial facilities). Nevertheless, provided costs are based on small-scale tests; true costs should be assessed at a bigger scale only. Thus, longer treatment makes the EK sludge treatment per metric ton cheaper when the newly developed control system is applied. Such lower cost per metric ton provides economical forthcoming for upscaling.

4. Conclusions

Application of electrokinetic (EK) phenomena to sludge treatment confirmed four-phase separation (patent 8,329,042). Using percolation based controller, which was introduced in this research permitted on a complete separation of oil and water in oil sludge after 60-hour exposure to electrokinetics only. The results showed that water production was strongly dependent on exposure time and voltage gradient; the recovery rate of water without using controller was higher at a short period. Majority of water was produced in the first 33.5 h for EK cell without controller and 35 hours with controller. As far as the voltage gradient remained constant, the water production increased continuously. The light oil recovery was significantly higher than water production when the controller was used. A high light oil recovery was related to higher O:W ratio which led to simultaneous lower mobility of water. Using controller permits to increase O:W ratio while reducing W:O ratio. A relationship of reaction rate and temperature, which defined the presence of water, supported above conclusions. Furthermore, the controller application permitted to decreases twice the costs of phase separation.

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Figure captions

Figure 1 Flowchart of the designed controller based on percolation theory logic

Figure 2 Electrical parameters measured in EK oil sludge separation cell with and without controller: a) current variation vs. time b) voltage variation vs. time.

Figure 3 Recovery of light, heavy oil, and water based on their initial volumes of 32.12 mL, 40.28 mL, 48.2 mL, respectively: a) EK system without controller; b) EK system with controller

Figure 4 Cathode side light oil to water ratio vs. exposure time for EK cells with and without controller

Figure 5 Thermogravimetric analysis of centrifuged raw oily sludge and collected catholyte liquids from EK cell with and without controller at temperature ranged between 302.9 K to 857.5 K at time interval of 0.004 min to 57 min: a) weight fraction vs. temperature; b) residual mass fraction of active reactant vs. temperature; c) mass conversion vs. time; d) reaction rate vs temperature.

Figure 6 Qualitative assessment of separated liquids and solids in three scenarios; a) centrifuged oily sludge; b) complete separation of light oil and water using EK cell with controller; c) low clarity of water using EK cell without controller.

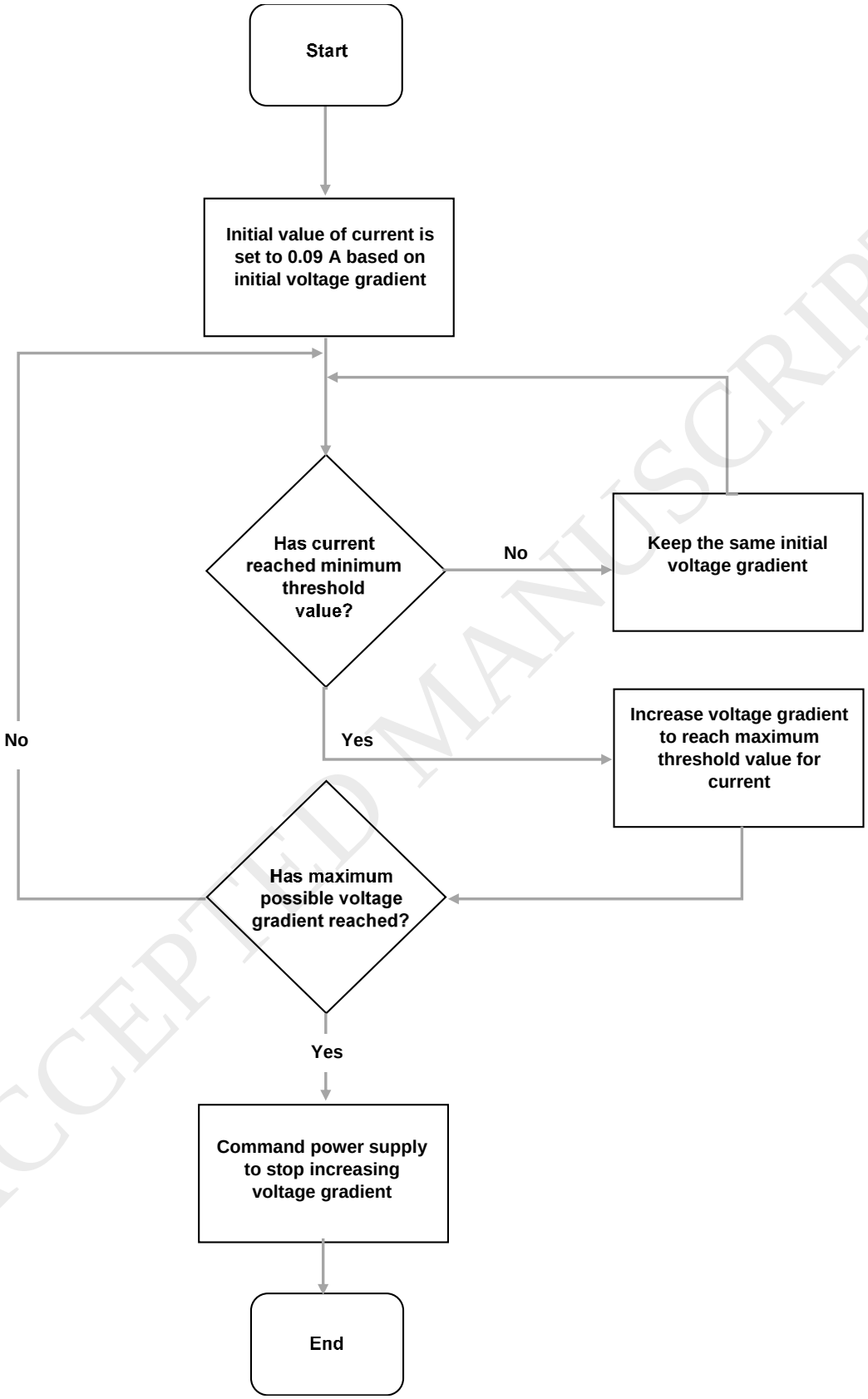

Figure 1 Flowchart of the designed controller based on percolation theory logic

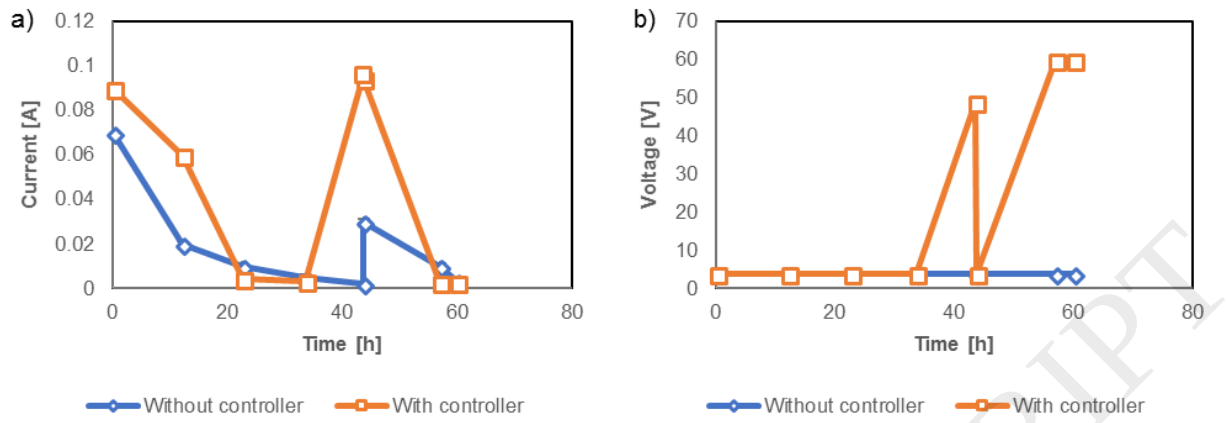

Figure 2 Electrical parameters measured in EK oil sludge separation cell with and without controller: a) current variation vs. time b) voltage variation vs. time.

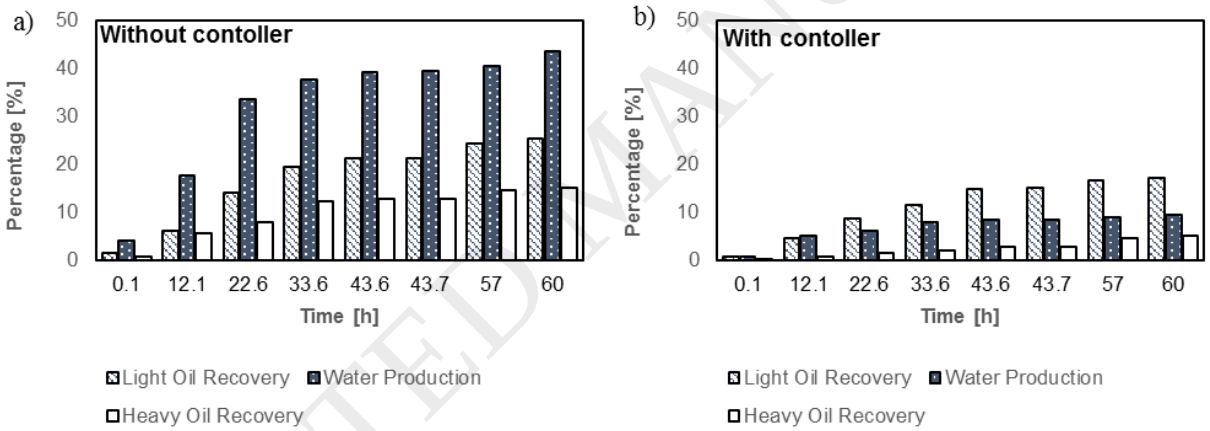

Figure 3 Recovery of light, heavy oil, and water based on their initial volumes of 32.12 mL, 40.28 mL, 48.2 mL, respectively: a) EK system without controller; b) EK system with controller

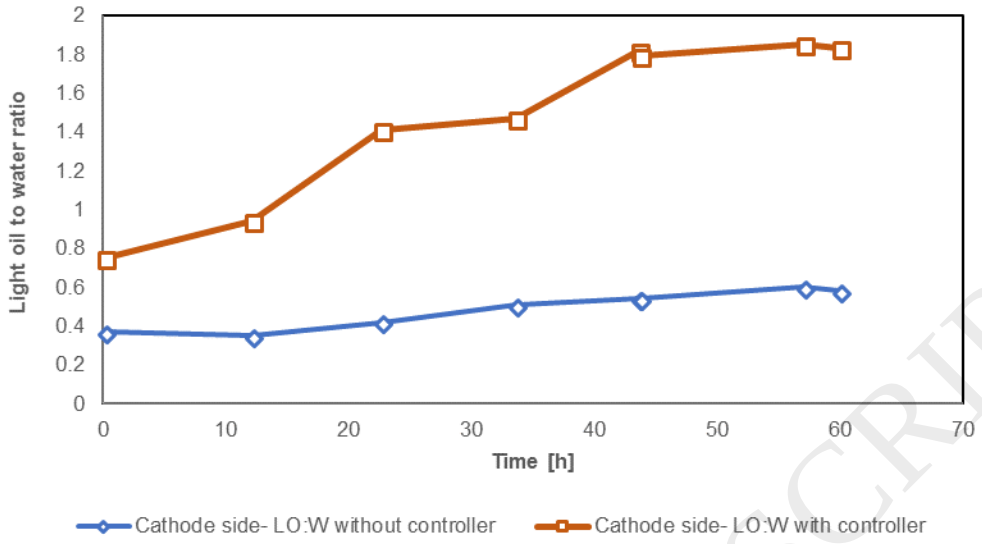

Figure 4. Cathode side light oil to water ratio vs. exposure time for EK cells with and without controller.

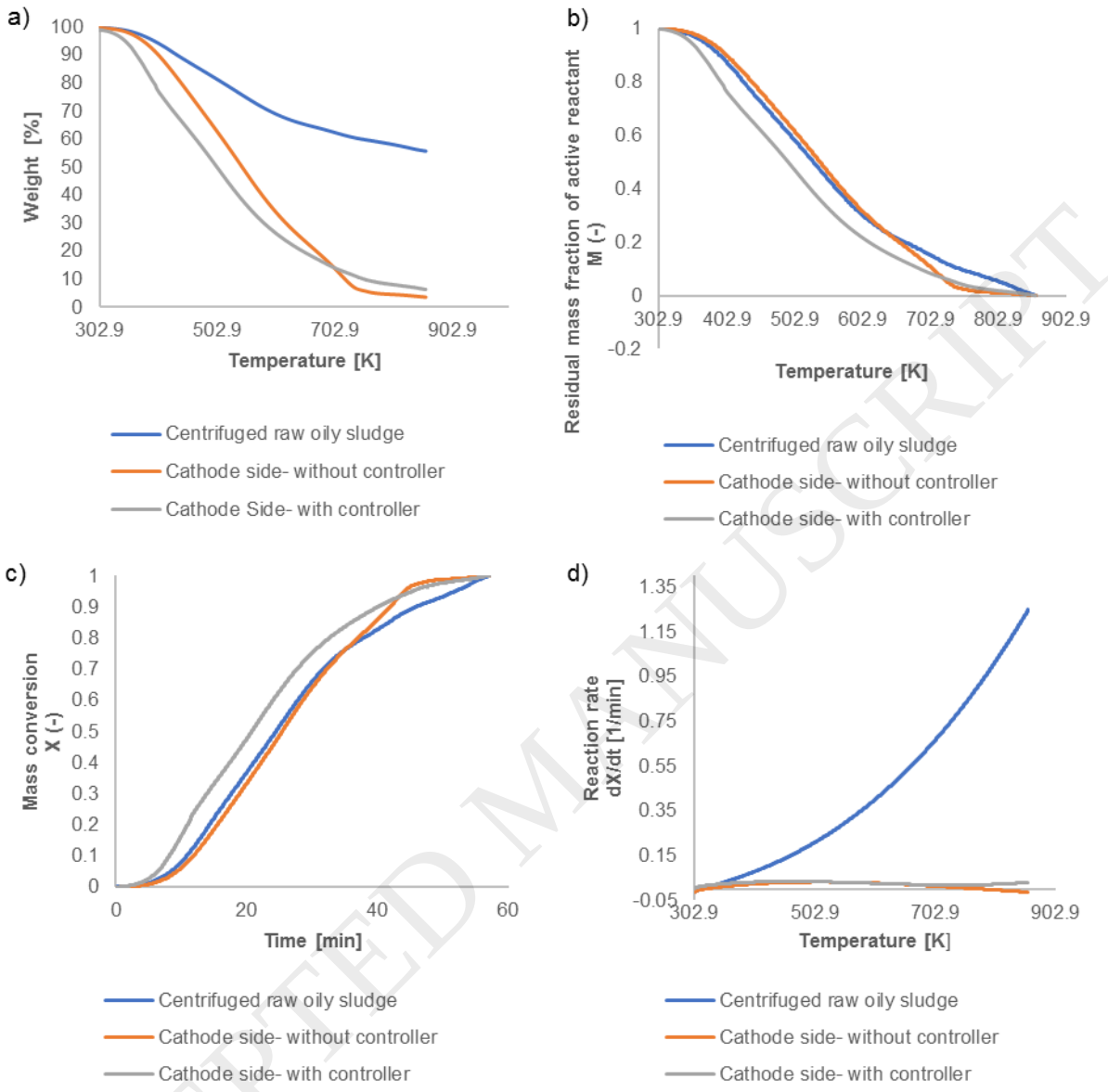

Figure 5 Thermogravimetric analysis of centrifuged raw oily sludge and collected catholyte liquids from EK cell with and without controller at temperature ranged between 302.9 K to 857.5 K at time interval of 0.004 min to 57 min: a) weight fraction vs. temperature; b) residual mass fraction of active reactant vs. temperature; c) mass conversion vs. time; d) reaction rate vs temperature.

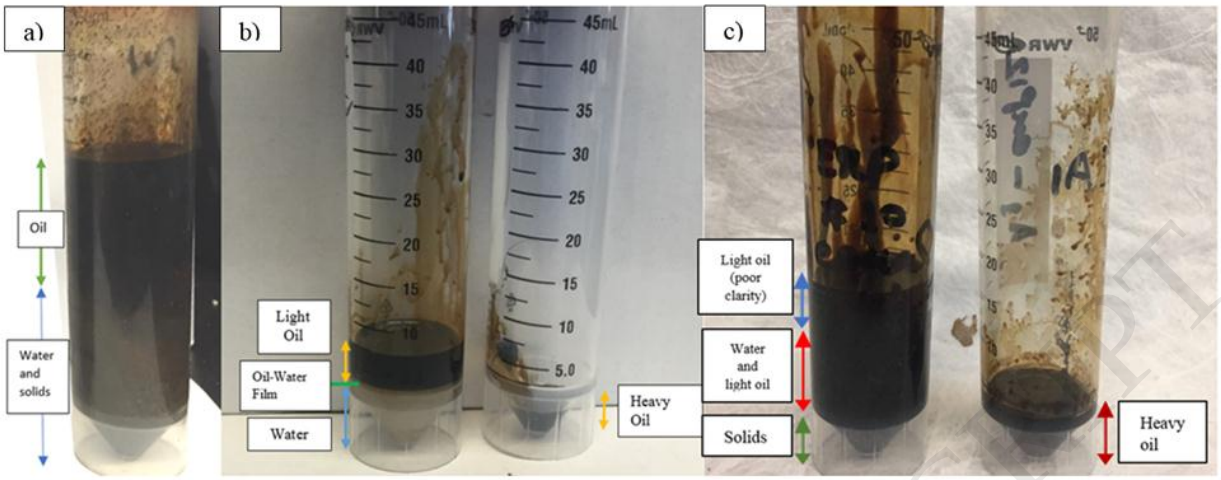

Figure 6 Qualitative assessment of separated liquids and solids in three scenarios; a) centrifuged oily sludge; b) complete separation of light oil and water using EK cell with controller; c) low clarity of water using EK cell without controller.

Table legends

Table 1 Mass conversion equations for centrifuged raw oily sludge, catholyte oil for EK cell without and with controller analyzed TGA samples in the time interval of 0.004 min to 57 min

Table 2 Comparison of power consumption by EK lab batch cells without and with controller

Table 2 Mass conversion equations for centrifuged raw oily sludge, catholyte oil for EK cell without and with controller analyzed TGA samples in the time interval of 0.004 min to 57 min

Type of sample	Mass conversion equation	R-squared
Centrifuged raw oily sludge	$X(t) = 5E\text{-}07\ t^4 - 6E\text{-}05\ t^3 + 0.0027\ t^2 - 0.0136\ t + 0.0171$	0.9998
Catholyte oil (EK without controller)	$X(t) = 2E\text{-}07\ t^4 - 4E\text{-}05\ t^3 + 0.0021\ t^2 - 0.0112\ t + 0.0124$	0.9997
Catholyte oil (EK with controller)	$X(t) = 4E\text{-}07\ t^4 - 5E\text{-}05\ t^3 + 0.0019\ t^2 - 0.0049\ t - 0.0217$	0.9993

Table 2 Comparison of power consumption by EK lab batch cells without and with controller

Type of EK reactor	Power consumption per test [kWh]	Power consumption (at 44 h retention time) [kWh]	Power per tonne [kWh/mt]	Cost per a tonne of oily sludge [CAD]
Without controller	0.0386	0.0256	118	4.13
With controller	0.0144	0.0139	63.5	2.22