

SYSTEM AND METHOD OF CHEMICAL-FREE ALKALINITY/pH CONTROL

The present application claims priority to the Singapore patent application no. 10202108038X, the entire disclosure of which is incorporated herein by reference.

TECHNICAL FIELD

[0001] The present disclosure relates to the treatment of water and other solutions, and more particularly to an electrochemical system and method of alkalinity/pH control.

BACKGROUND

[0002] Many essential and industrial processes require monitoring and regulating of the alkalinity and/or pH levels in order to provide environments or solutions with the required chemical reactivity or biological viability. These include processes in the food and beverage industry, the pharmaceutical industry, as well as in the water treatment of industrial wastewater, drinking water, water in irrigation systems, seawater, etc., just to name a few examples. Conventional methods of adjusting the pH of the solution often involve the direct addition of an acid solution or a base solution. At an industrial scale, this requires the dilution of commercial strong acids and alkalis. Considering the entropy generation and irreversible energy loss from the production of strong acids/alkalis, the transportation and storage of the strong acids/alkalis, and the eventual dilution of the strong acids/alkalis for industrial use, there is an urgent need to provide a more environmentally friendly/sustainable process for pH regulation that is also commercially/industrially viable.

SUMMARY

[0003] In one aspect, the present application discloses a system having at least one module, each of the at least one module comprising: a filtration membrane configured to extend along at least one liquid stream, the filtration membrane defining a first membrane side and a second membrane side, the first membrane side and the second membrane side being different membrane sides facing away from one another, the filtration membrane being configured to separate the at least one liquid stream into a first stream on the first membrane side of the filtration membrane and a second stream on the second membrane side of the filtration membrane; a first electrode; and a second electrode, the first electrode and the

second electrode being at respective ones of the different membrane sides of the filtration membrane, wherein the first stream is configured to flow by the first electrode to form a first effluent stream characterized by a first alkalinity/pH, and wherein the second stream is configured to flow by the second electrode to form a second effluent stream characterized by a second alkalinity/pH, and wherein the first alkalinity/pH and the second alkalinity/pH differ from one another in response to a potential difference applied across the first electrode and the second electrode.

[0004] The system above may be one in which the at least one liquid stream is characterized by a corresponding influent alkalinity/pH, and wherein at least one of the first effluent stream and the second effluent stream is characterized by an alkalinity/pH that is different from the corresponding influent alkalinity/pH. The system according to any above, in which one of the first effluent stream and the second effluent stream has a higher alkalinity/pH than a corresponding one of the first stream and the second stream, and wherein another of the first effluent stream and the second effluent stream has a lower alkalinity/pH than another corresponding one of the first stream and the second stream. The system according to any above, in which one of the first effluent stream and the second effluent stream is an alkaline or neutral effluent stream, and wherein another one of the first effluent stream and the second effluent stream is a neutral or acidic effluent stream. The system according to any above, in which the alkaline effluent stream is characterized by a pH in a range, and wherein the pH is greater than 7 and equal to or smaller than 13. The system according to any above, in which the neutral or acidic effluent stream is characterized by a pH in a range of 1 to 7.

[0005] The system according to any above, further comprising at least one pump in a flow path connected to the at least one module, the at least one pump being configured to controllably perform one or concurrently both of the following: (i) deliver at least one of the first stream and the second stream at a respective fluid pressure; and (ii) provide a hydraulic pressure differential across the filtration membrane between the first stream and the second stream. The system according to any above, in which the second effluent stream comprises a permeate drawn across the filtration membrane from the first stream. The system according to any above, in which a pressure differential between the first stream and the second stream is a result of at least one of the hydraulic pressure differential and an osmotic

pressure differential between the first stream and the second stream, in which the pressure differential is configured to enable any one of the following across the filtration membrane: pressure-retarded osmosis, forward osmosis, osmotically assisted reverse osmosis, reverse osmosis, nanofiltration, ultrafiltration, and microfiltration.

[0006] The system according to any above, further comprising at least one recirculation flow path, wherein a respective one of the at least one recirculation flow path is configured to recirculate at least a portion of one of the first effluent stream and the second effluent stream to a corresponding one of the first stream and the second stream.

[0007] The system according to any above, in which the at least one module further comprises: a first spacer, the first spacer being configured to provide a first flow path for the first stream, and wherein at least one hydrodynamic parameter of the first stream is determined by the first spacer. The system according to any above, in which the first spacer is configured as the first electrode. The system according to any above, wherein the at least one module further comprises a second spacer, the second spacer being configured to provide a second flow path for the second stream, and wherein at least one hydrodynamic parameter of the second stream is determined by the second spacer. The system according to any above, in which the second spacer is configured as the second electrode. The system according to any above, in which the first spacer is disposed between and in contact with the filtration membrane and the first electrode, and wherein the second spacer is disposed between and in contact with the filtration membrane and the second electrode.

[0008] The system according to any above, in which the first membrane side of the filtration membrane is configured as the first electrode. The system according to any above, in which the second membrane side of the filtration membrane is configured as the second electrode. The system according to any above, in which the filtration membrane comprises an electrically non-conductive layer, the electrically non-conductive layer being disposed between the first electrode and the second electrode. The system according to any above, in which at least one of the first alkalinity/pH and the second alkalinity/pH is variable and responsive to a change in the potential difference applied across the first electrode and the second electrode and/or a change in a current provided to the first electrode and the second electrode.

[0009] The system according to any above, further comprising: a controller, the controller being configured to: acquire at least one measured alkalinity/pH measured from one or both of the first effluent stream and the second effluent stream; and in response to the at least one measured alkalinity/pH, change the potential difference applied across the first electrode and the second electrode and/or change the current provided to the first electrode and the second electrode.

[0010] The system according to any above, in which the filtration membrane is a non-ion exchange membrane selected from the following: a reverse osmosis (RO) membrane, a nanofiltration (NF) membrane, an ultrafiltration (UF) membrane, a microfiltration (MF) membrane, a forward osmosis (FO) membrane, a pressure-retarded osmosis (PRO) membrane, and a porous filtration paper.

[0011] The system according to any above, in which the at least one module is configured as one of: a spiral wound membrane filtration module, a plate and frame membrane filtration module, a hollow fiber membrane filtration module, and a tubular membrane module.

[0012] In another aspect, the present application discloses a method comprising: providing at least one liquid stream to flow by a filtration membrane, the filtration membrane defining a first membrane side and a second membrane side, the first membrane side and the second membrane side being different membrane sides facing away from one another, the filtration membrane being configured to separate the at least one liquid stream into a first stream on the first membrane side of the filtration membrane and a second stream on the second membrane side of the filtration membrane; and applying a potential difference across a first electrode and a second electrode, the first electrode and the second electrode being at respective ones of the different membrane sides of the filtration membrane, wherein the first stream is configured to flow by the first electrode to form a first effluent stream characterized by a first alkalinity/pH, and wherein the second stream is configured to flow by the second electrode to form a second effluent stream characterized by a second alkalinity/pH, and wherein the first alkalinity/pH and the second alkalinity/pH differ from one another.

[0013] The at least one liquid stream may be characterized by a corresponding influent

alkalinity/pH, and wherein at least one of the first effluent stream and the second effluent stream may be characterized by an alkalinity/pH that is different from the corresponding influent alkalinity/pH. One of the first effluent stream and the second effluent stream may have a higher alkalinity/pH than a corresponding influent stream, and another one of the first effluent stream and the second effluent stream may have a lower alkalinity/pH than another corresponding influent stream.

[0014] The method may further comprise applying a pressure differential across the filtration membrane. The second effluent stream may comprise a permeate drawn across the filtration membrane from the first stream. The pressure differential may be a result of at least one of a hydraulic pressure differential and an osmotic pressure differential between the first stream and the second stream, and wherein the pressure differential is configured to enable any one of the following across the filtration membrane: pressure-retarded osmosis, forward osmosis, osmotically assisted reverse osmosis, reverse osmosis, nanofiltration, ultrafiltration, and microfiltration.

[0015] The method may further comprise recirculating at least one or both of a portion of the second effluent stream to the second stream and a portion of the first effluent stream to the first stream. The first stream may be configured to flow through a first spacer, in which the first spacer is configured to determine at least one hydrodynamic parameter of the first stream. The first electrode may be configured as the first spacer. The second stream may be configured to flow through a second spacer, in which the second spacer is configured to determine at least one hydrodynamic parameter of the second stream. The second electrode may be configured as the second spacer. The first spacer may be disposed between and in contact with the filtration membrane and the first electrode, and the second spacer may be disposed between and in contact with the filtration membrane and the second electrode. The first membrane side of the filtration membrane may be configured as the first electrode. The second membrane side of the filtration membrane may be configured as the second electrode. The filtration membrane may comprise an electrically non-conductive layer, in which the electrically non-conductive layer is disposed between the first electrode and the second electrode.

[0016] The method in which at least one of the first alkalinity/pH and the second

alkalinity/pH is variable and responsive to a change in the potential difference applied across the first electrode and the second electrode and/or a change in a current provided to the first electrode and the second electrode.

[0017] The method may further comprise, in response to at least one measured alkalinity/pH measured from one or both of the first effluent stream and the second effluent stream, changing the potential difference applied across the first electrode and the second electrode and/or changing the current provided to the first electrode and the second electrode.

BRIEF DESCRIPTION OF DRAWINGS

[0018] Fig. 1 is a partial schematic diagram of a system with a module configured to receive one influent stream;

[0019] Fig. 2 is a partial schematic diagram of the system with the module of Fig. 1 configured to receive two separate influent streams;

[0020] Fig. 3A is a schematic cross-sectional diagram illustrating one embodiment of the module of Fig. 1;

[0021] Fig. 3B is a schematic flow diagram of a method according to embodiments of the present disclosure;

[0022] Figs. 4A to 4C are schematic cross-sectional diagrams illustrating the module in which at least one of the spacers is configured to serve as an electrode;

[0023] Fig. 5 is a schematic cross-sectional diagram illustrating yet another embodiment of the module of Fig. 1;

[0024] Fig. 6 is a schematic cross-sectional diagram illustrating another embodiment of the module of Fig. 1;

[0025] Fig. 7 is a partial schematic diagram of the system with a module operable in a filtration mode in accordance with another embodiment of the present disclosure;

[0026] Fig. 8 is a schematic cross-sectional diagram illustrating an embodiment of the

module of Fig. 7;

[0027] Figs. 9A – 9C are schematic cross-sectional diagrams illustrating various embodiments of the module of Fig. 7;

[0028] Figs. 10A – 10F are schematic cross-sectional diagrams illustrating yet further embodiments of the module of Fig. 7;

[0029] Fig. 11A is a schematic cross-sectional diagram illustrating the module of Fig. 1 or Fig. 7 with one of the effluent streams configured to be recirculated;

[0030] Fig. 11B is a schematic cross-sectional diagram illustrating the module of Fig. 1 or Fig. 7 with both of the effluent streams configured to be recirculated;

[0031] Fig. 11C is a partial schematic diagram of the system with multiple units of the modules configured in parallel;

[0032] Fig. 11D is a partial schematic diagram of the system with multiple units of the modules configured in a cascade;

[0033] Fig. 12 shows the experimental results of the pH change in the cathodic and anodic channels of the module of Fig. 1 under 0.6 V, 1.2 V and 2.0 V respectively, with a flowrate of 5 mL/min;

[0034] Fig. 13 shows the experimental results of the pH change in the cathodic and anodic channels of the module of Fig. 1 under 1.2 V with a flowrate of 1.5 and 5 mL/min respectively;

[0035] Fig. 14A shows the experimental results of the pH variation of the permeate over time under different voltages for the module of Fig. 7 with the cathode at the permeate side;

[0036] Fig. 14B shows the experimental results of the pH variation of the feed effluent over time under different voltages for the module of Fig. 7 with the cathode at the permeate side;

[0037] Fig. 14C shows the experimental results of the pH variation of the permeate over time under different voltages for a module of Fig. 7 with the anode at the permeate side;

[0038] Fig. 14D shows the experimental results of the pH variation of the feed effluent over time under different voltages for the module of Fig. 7 with the anode at the permeate side;

[0039] Fig. 15A shows the experimental results of the pH variation of the permeate over a 5-hour test for the module of Fig. 7 under 1.2 V with the cathode at the permeate side;

[0040] Fig. 15B shows the experimental results of the pH variation of the permeate over a 5-hour test for the module of Fig. 7 under 1.2 V with the anode at the permeate side;

[0041] Fig. 16 shows the specific energy consumption of producing alkaline and acidic streams and the corresponding pH levels for the module of Fig. 1 under different voltages;

[0042] Fig. 17A shows the specific energy consumption of producing alkaline and acidic streams and the corresponding pH levels for the module of Fig. 7 under different voltages and with the cathode at the permeate side;

[0043] Fig. 17B shows the specific energy consumption of producing alkaline and acidic streams and the corresponding pH levels for the module of Fig. 7 under different voltages and with the anode at the permeate side; and

[0044] Fig. 18 shows the permeate pH variation with time for the module of Fig. 7 having a seawater reverse osmosis (SWRO) membrane and in which the cathode is at the permeate side.

DETAILED DESCRIPTION

[0045] Reference throughout this specification to “one embodiment”, “another embodiment” or “an embodiment” (or the like) means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” or the like in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided to give a thorough understanding of embodiments. One skilled in the relevant art will recognize, that the

various embodiments may be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, some or all known structures, materials, or operations may not be shown or described in detail to avoid obfuscation.

[0046] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. As used herein, the singular ‘a’ and ‘an’ may be construed as including the plural “one or more” unless apparent from the context to be otherwise.

[0047] Terms such as “first” and “second” are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context. The terms “about” and “approximately” as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms “generally” and “substantially” are to be understood in a similar manner, unless otherwise specified.

[0048] In the present disclosure, reference may be made to an element being on one membrane side of a membrane. Such expressions will be understood in terms of the element being on, at, or in proximity to the referenced membrane side, as opposed to the other membrane side. That is, such expressions do not limit the element to being physically disposed on referenced membrane side or being in direct physical contact with the referenced membrane side.

[0049] In some industrial applications, the regulation of alkalinity may be more critical than the regulation of pH. In other applications, the regulation of pH may be more important. In some solutions (especially in a buffer solution of HCO_3^- or CO_3^{2-}), the pH may remain substantially unchanged even if the alkalinity changes significantly. As will be understood from the various illustrative examples provided below, embodiments of a system 100, a module 200, and/or a method 500 enable regulation or control of the alkalinity as well as the pH of a solution. Therefore, for the sake of brevity and to avoid misunderstanding, the present disclosure uses a term “alkalinity/pH” to mean one or both of the alkalinity of a solution and the pH of the solution, i.e., “alkalinity/pH” refers to one or both of (i) a

buffering capacity of a solution (or a body of water), a measure of the ability of the solution (or the body of water) to neutralize acids and bases and to maintain a fairly stable pH level; and (ii) a measure of how acidic or basic a solution (or the body of water) is. That is, as used herein, the term “alkalinity/pH” may refer to alkalinity, pH, and/or both alkalinity and pH.

[0050] According to one embodiment of the present disclosure, as shown in Fig. 1, the system 100 includes at least one module 200 configured to deliver a first effluent stream 318 and a second effluent stream 328 of different alkalinities or pH. The module 200 includes a pair of electrodes 210 (not shown) connected to a circuit and/or power supply 110 such that a voltage or potential difference may be applied across the pair of electrodes 210. The system 100 may further include a controller 120 configured to be in signal communication 122 with the circuit and/or power supply 110 and to controllably adjust the voltage or potential difference applied across the pair of electrodes 210 and/or to controllably adjust the current supplied to the pair of electrodes 210. In some examples, the voltage across the pair of electrodes may be kept constant. In some examples, the system 100 may be configured to apply a variable current (current density) or a variable voltage to the pair of electrodes 210. In some examples, the system 100 may be configured to provide a constant current (or current density) to the pair of electrodes 210.

[0051] The module 200 is configured to receive a feed stream 301. The feed stream 301 may be provided to the module 200 at a controllable flowrate with the aid of one or more pumps, pressure exchangers, valves, etc. For the sake of brevity, such one or more pumps, pressure exchangers, etc., will be referred to generally as a pump 140. The controller 120 is configured to be in signal communication 124 with the pump 140 and to controllably adjust the flowrate of the feed stream 301.

[0052] The module 200 includes a filtration membrane 220 (Fig. 3A) configured to extend along at least one liquid stream from the feed stream 301 (inlet of the module 200) to the effluent streams 318,328 (outlet of the module 200). In operation, the module 200 is configured to separate the at least one liquid stream 302 into substantially parallel and distinct flow paths (first stream 314 and second stream 324) on either side of the filtration membrane 220 (Fig. 3A), such that the first stream 314 develops into the first effluent stream 318, and the second stream 324 develops into the second effluent stream 328.

[0053] Fig. 2 shows a partial schematic diagram of another non-limiting example of the system 100 with some parts of the system 100, e.g., the controller 120, not shown to avoid obfuscation. The module 200 may be configured to receive more than one feed stream 301,301'. The two streams 301 and 301' can be the same solution or different solutions. In some examples, the two streams 301 and 301' can be provided such that there is an osmotic pressure differential between the corresponding first stream 314 and the corresponding second stream 324. Regardless of the number of feed streams 301 received by the module 200, the at least one feed stream 301 forms at least one liquid stream 302 in the module 200. In the module 200, the at least one liquid stream 302 is separated into the first stream 314 and the second stream 324, such that the module 200 provides a corresponding first effluent stream 318 and a corresponding second effluent stream 328. In some examples, the first stream 314 and the second stream 324 are configured to flow in a co-current configuration. In other examples, the first stream 314 and the second stream 324 are configured to flow in opposite directions in a counter-current configuration.

[0054] Fig. 3A is a schematic cross-sectional diagram of a part of the module 200. The filtration membrane 220 is configured to extend along the at least one liquid stream 302 in the module 200. The filtration membrane 220 helps to maintain two distinguishable liquid streams 302 (the first stream 314 and the second stream 324) in substantially different flow paths 230. Each of the flow paths is primarily oriented parallel with an axial direction 202. The two flow paths 230 may be defined by respective channels. The two flow paths 230 are in fluidic communication with one another across the filtration membrane 220. The filtration membrane 220 defines a first membrane side 221 and a second membrane side 222, in which the first membrane side 221 and the second membrane side 222 substantially oppose one another. In other words, the first membrane side 221 and the second membrane side 222 are different membrane sides facing away from one another. The filtration membrane 220 is configured to separate the at least one liquid stream 302 into the first stream 314 and the second stream 324, in which the first stream is on the first membrane side 221 of the filtration membrane 220 and in which the second stream is on the second membrane side 222 of the filtration membrane 220. The pair of electrodes 210 may include a first electrode 211 and a second electrode 212 disposed at respective ones of the different membrane sides 221,222. That is, the first electrode 211 is disposed on one membrane side 221 and the

second electrode 212 is disposed on another membrane side 222 of the same filtration membrane 220. In other words, the filtration membrane 220 is disposed between the pair of electrodes 210 such that each of the two flow paths 230 (or each of the first stream 314 and the second stream 324) is in direct contact with only one of the pair of electrodes 210.

[0055] In operation, a potential difference is applied across the first electrode 211 and the second electrode 212 such and/or a current provided to the first electrode 211 and the second electrode 212 that one of the electrodes 210 serves as a cathode and another of the electrodes 210 serves as the anode. In some examples, the liquid stream 302 is referred to as a cathodic stream if it is in contact with the cathode and spaced apart from the anode by at least the filtration membrane 220. The liquid stream 302 is referred to as an anodic stream if it is in contact with the anode and spaced apart from the cathode by at least the filtration membrane 220. In some examples, the first stream 314 is the cathodic stream, and the second stream 324 is the anodic stream. In other examples, the first stream 314 is the anodic stream, and the second stream 324 is the cathodic stream. The first stream 314 is configured to flow by the first electrode 211 to form a first effluent stream 318 characterized by a first alkalinity/pH, and the second stream 324 is configured to flow by the second electrode 212 to form a second effluent stream 328 characterized by a second alkalinity/pH. The first alkalinity/pH and the second alkalinity/pH differ from one another in response to the potential difference applied across the first electrode 211 and the second electrode 212.

[0056] Each of the electrodes 210 may be formed from one or more materials, including but not limited to any selected from the following: stainless steel, nickel, titanium, platinum, graphite, and any combination thereof. The electrodes 210 may be formed of other advanced materials with or without a catalyst added. Preferably, the electrode to be used as an anode is not made of a non-inert metal such as stainless steel to prevent oxidation of the anode into metal ions. Preferably, one or both of the electrodes 210 are porous carbon electrodes. Examples of porous carbon electrodes include but are not limited to electrodes formed with activated carbon powder, activated carbon cloth, carbon aerogels, mesoporous carbon, carbon nanomaterials, graphene-based materials, carbon nanotube-based materials, and any combination thereof. Carbon materials in the form of sheets (e.g., activated carbon cloth) may be directly attached to current collectors to form the electrodes 210. Alternatively, carbon electrodes may be formed by mixing carbon powder with a polymer binder, followed

by dissolving the carbon-polymer mixture in an organic solvent to form a slurry. The slurry may be dried and coated onto current collectors to form the electrodes 210. Examples of polymer binders that may be used include, but are not limited to, polyvinyl alcohol (PVA), polyvinylidene difluoride (PVDF), polytetrafluoroethylene (PTFE), poly arylene ether sulfone (PAES), polyethylene (PE), polysulfone (PSf), polyethersulfone (PES), and polyvinylpyrrolidone (PVP). Examples of organic solvents that may be used include, but are not limited to, N-Methyl-2-pyrrolidone (NMP) and dimethylformamide (DMF). The current collectors may be made of inert conductive materials, for example, graphite sheets, or titanium plates, or mixed metal oxides containing ruthenium(IV) oxide or iridium(IV) oxide or titanium oxide, but are not limited to such. It will be understood that while porous carbon electrodes are preferred for their ability to enable electrosorption, it is not necessary to select electrode materials that enable or facilitate electrosorption in order to implement any embodiments of the present method or system.

[0057] The filtration membrane may be one selected from a variety of non-ion exchange membranes. Preferably, the filtration membrane 220 is one selected from the following: a reverse osmosis (RO) membrane, a nanofiltration (NF) membrane, an ultrafiltration (UF) membrane, a microfiltration (MF) membrane, a forward osmosis (FO) membrane, a pressure-retarded osmosis (PRO) membrane and a porous filtration paper. The filtration membrane 220 may include a support layer 224 and an active layer 226 (disposed on or supported by the support layer 224). In some embodiments of the present disclosure, the filtration membrane 220 may include more than one active layer 226 and at least one support layer 224 in an interweaving configuration. In various embodiments of the present disclosure, both the support layer 224 and the active layer 226 may be selected from electrically nonconductive materials. In various embodiments of the present disclosure, one of the support layer 224 and the active layer 226 is selected from electrically nonconductive materials, with the other one of the support layer 224 and the active layer 226 being selected from electrically conductive materials and configured to serve as one of the pair of electrodes 210.

[0058] One or both of the flow paths 230 may be defined by a channel or a spacer 240. A spacer 240 may be disposed between the filtration membrane 220 and the electrode 210 to provide or define a flow path 302. For example, a first spacer 240 disposed on one

membrane side 221 provides a flow path 230 for the first stream 314, and a second spacer 240 disposed on the second membrane side 222 provides a flow path for the second stream 324. As illustrated in Fig. 3A, the first spacer 240 may be disposed between and in contact with the filtration membrane 220 and a first electrode 210, and the second spacer 240 may be disposed between and in contact with the filtration membrane 220 and the second electrode 210 of the same module 200. Preferably, the spacer 240 is made of a material such that at least one hydrodynamic parameter of the liquid stream 302 flowing therethrough may be determined by the spacer 240.

[0059] As schematically illustrated by the flow diagram of Fig. 3B, embodiments of a method 500 of treatment of water and other solutions include providing at least one liquid stream 302 to flow by a filtration membrane 220 (510) in which the filtration membrane 220 is configured to separate the at least one liquid stream 302 into a first stream 314 and a second stream 324. The method 500 includes applying a potential difference across a pair of electrodes 210 (520), in which the first stream 314 is configured to flow by the first electrode 211 to form a first effluent stream 318 characterized by a first alkalinity/pH, and the second stream 324 is configured to flow by the second electrode 212 to form a second effluent stream 328 characterized by a second alkalinity/pH. The first alkalinity/pH and the second alkalinity/pH differ from one another. The method 500 is chemical-free in that the alkalinity/pH control is achievable using the system 100 and/or module 200 without the need to use strong acids/alkalis and without the need to dilute strong acids/alkalis.

[0060] Figs. 4A-4C are schematic cross-sectional diagrams illustrating various embodiments of the module 200 in which at least one spacer 240 is configured to concurrently provide a flow path and serve as an electrode 210. In the example of Fig. 4A, each of the flow paths 230 is provided or defined by a respective spacer 240 that is also serving as a respective electrode 210. In the example of Fig. 4B, each of the two flow paths 230 is defined by a spacer 240, and in which one of the spacers 240 is also serving as an electrode 210. In the example of Fig. 4C, one of the flow paths 230 is defined by a spacer 240 (which is also serving as an electrode 210) and another of the flow paths 230 is defined by a channel (e.g., a spacing between the filtration membrane 220 and one of the electrodes 210). The spacer 240 may be made of a conductive material so that it can concurrently function as an electrode 210 and define a flow path 230. In some examples, the spacer 240

is a stainless-steel mesh configured with a predetermined thickness to provide a flow path 230 with a corresponding predetermined width w .

[0061] Fig. 5 and Fig. 6 are schematic cross-sectional diagrams illustrating various embodiments of the module 200 in which at least one of the electrodes 210 is integrated with or disposed on a corresponding side or surface of the filtration membrane 220. The filtration membrane 220 is configured to permit fluidic communication between the two liquid streams 302 across the filtration membrane 220, while keeping the two liquid streams substantially separate as the flow paths 302 extend from the feed streams 301 to the effluent streams 308.

[0062] In the example of Fig. 5, the filtration membrane 220 includes a support layer 224 and an active layer 226. The active layer 226 is configured to serve as one of the electrodes 210. The support layer 224 may be configured as electrically non-conductive with the active layer 226 configured as electrically conductive. In some examples, conductive materials are integrated into the filtration membrane such that part of the support layer 224 may be rendered electrically conductive. For example, as shown in Fig. 5, the spacer 240 on the first membrane side 221 may be configured to also serve as the cathode and concurrently provide a flow path 230 for the cathodic stream. The active layer 226 of the filtration membrane 220 may be configured to serve as the anode. The spacer 240 on the second membrane side 222 can act as a current collector to transfer electrically charged ions to the anode, and concurrently provide a flow path 230 for the anodic stream 302. In other words, the first membrane side 221 of the filtration membrane 220 may be configured as the first electrode 210 of the module 200, and the second membrane side 222 of the same filtration membrane 220 may be configured as the second electrode 210 of the same module 200.

[0063] In the example of Fig. 6, the filtration membrane 220 includes a support layer 224 and two active layers 226, one on each of the membrane sides or surfaces 221/222. Each of the active layers 226 is configured to serve as one of the electrodes 210. The support layer 224 may be configured as electrically non-conductive with each of the active layers 226 configured as electrically conductive. In some examples, a layer of conductive material is coated on the filtration membrane 220 to form an active layer 226. In some examples, conductive materials are integrated into the filtration membrane 220 such that part of the

support layer 224 may be rendered electrically conductive. For example, as shown in Fig. 6, one of the active layers 226 of the filtration membrane 220 may be configured to serve as the anode and the other of the active layers 226 of the same filtration membrane 220 may be configured to serve as the cathode. In the various embodiments, the electrically non-conductive layer (the support layer 224) is disposed between the first electrode and the second electrode of the same pair of electrodes 210. In other examples, the filtration membrane 220 may include an electrically conductive active layer 226 (configurable as an electrode 210 in contact with one of the first stream 314 and the second stream 324) and a support layer 224, in which the support layer 224 includes an electrically nonconductive portion integrated or coated with an electrically conductive portion. In such examples, the electrically nonconductive portion is disposed between the active layer 226 and the electrically conductive portion of the support layer 224 to prevent a short circuit therebetween. The electrically conductive portion of the support layer 224 is configured to serve as another electrode 210 that is in contact with the other of the first stream 314 and the second stream 324.

[0064] According to another aspect of the present disclosure, the module 200 is configurable to operate in one of a non-filtration mode as described in the foregoing (also referred to herein as the “electrochemical membrane system non-filtration mode” or “EMS_non-F mode”) and a filtration mode to be described in the following (also referred to herein as the “electrochemical membrane system-filtration mode” or “EMS-F mode”). Fig. 7 is a partial schematic diagram of the system 100 with a module 200 operable in the filtration mode. The system 100 may include at least one pump 140 in a flow path 301 connected to the module 200. The at least one pump 140 is configured to controllably perform one or concurrently both of the following: (i) deliver at least one of the first stream 314 and the second stream 324 at a respective fluid pressure; and (ii) provide a hydraulic pressure differential across the filtration membrane 220 (not shown) between the first stream 314 and the second stream 324. Preferably, the hydraulic pressure differential or osmotic pressure differential across the membrane between the first stream and the second stream is configured to enable any one of the following across the filtration membrane 220: pressure-retarded osmosis, forward osmosis, osmotically assisted reverse osmosis, reverse osmosis, nanofiltration, ultrafiltration, and microfiltration. Referring again to Fig. 3B, the method

500 may include applying a pressure differential across the filtration membrane 220 (530). The module 200 may be configured to implement filtration by the filtration membrane 220 concurrently with the development of two distinguishable streams of effluent 308 with different and controllable levels of alkalinity/pH. In some embodiments, the system 100 may include a sensor 125 configured to measure or sense the alkalinity/pH of one or both of the effluent streams and to provide a feedback to the controller 120. The controller 120 may be configured to change the potential difference or voltage applied across the electrodes 210 in response to the measured alkalinity/pH. That is, the alkalinity/pH of at least one of the effluent streams 308 can be variable and responsive to a change in the potential difference applied across the pair of electrodes 210, and the method 500 can vary the alkalinity/pH of one or both of the effluent streams 308 accordingly.

[0065] As illustrated schematically in Fig. 8, in the filtration mode, a part of the first stream 314 passes through the filtration membrane 220 to form the second stream 324. The second stream 324 is directed along a flow path 302 that flows by one of the pair of electrodes 210 and exits the module 200 as the permeate stream 348 or the second effluent stream 348. The first stream 314 is directed along a flow path 302 that flows by another of the pair of electrodes 210 to form the feed effluent stream 338 or the first effluent stream 318. That is, the second effluent stream 348 of the filtration mode includes a solution 303 drawn across the filtration membrane 220 from the first stream 314. In the present disclosure, references to the first stream and the second stream being the feed stream and the permeate stream respectively are interchangeable. That is, while the examples herein refer to the first stream 314 as the feed and the second stream 324 as the permeate, it will be understood that the system 100 and/or the module 200 may be configured such that the second stream 324 is the feed and the first stream 314 is the permeate. For example, the orientation of the filtration membrane 220 may be changed. Preferably, the filtration membrane is oriented with the active layer 226 facing or in contact with the feed stream 338, and with the support layer 224 facing or in contact with the permeate stream 348. The present system 100 does not preclude the option of having the active layer 226 facing or in contact with the permeate stream 348, and having the support layer 224 facing or in contact with the feed stream 338. The filtration membrane 220 of the present disclosure is preferably one selected to block particulates (e.g., microorganisms, colloidal particles, microorganic molecules, soil

particles, other suspended particles, and/or salt ions, etc.). In some embodiments, it is preferred not to use an ion exchange membrane as the filtration membrane 220. Advantageously, the polarities of the pair of electrodes are interchangeable or can be switched for the same physical set-up.

[0066] The various embodiments of the system 100 and/or the module 200 illustrated in Figs. 1 to 6 in the non-filtration mode are also operable in the filtration mode. To aid understanding, various embodiments in the filtration mode are shown in the schematic diagrams of Figs. 9A-9C and Figs. 10A-10E. In each of Figs. 9A-9C and in each of Figs. 10A-10E, the module 200 is configured such that each of the feed stream 338 and the permeate stream 348 follows a respective flow path 230 that extends along either side of the filtration membrane 220. In the module 200, the feed stream 338 is in contact with only one of the pair of electrodes 210 and the permeate stream 348 is in contact with only the other one of the same pair of electrodes 210. In operation, filtration across the filtration membrane from one liquid stream 302 to another liquid stream 302 occurs concurrently with electrochemical processes at the electrodes 210, such that one of the feed stream 338 and the permeate stream 348 is a cathodic stream, and such that the other one of the feed stream 338 and the permeate stream 348 is an anodic stream.

[0067] Fig. 9A illustrates an example in which both of the electrodes 210 are configured as spacers providing respective flow paths 230 for the feed stream 338 and the permeate stream 348. Fig. 9B illustrates an example in which the electrode 210 in contact with the permeate stream 348 is configured as a plate electrode and the electrode 210 in contact with the feed stream 338 is configured as a spacer. Fig. 9C illustrates another example in which the electrode 210 in contact with the feed stream 338 is configured as a plate electrode and the electrode 210 in contact with the permeate stream 348 is configured as a spacer. In a module 200 having a first spacer 240 configured to provide a flow path 230 for a first stream 314 and a second spacer 240 configured to provide another flow path 230 for a second stream 324, either of the first spacer 240 and the second spacer 240 may be configured as one of the pair of electrodes 210. For different applications, the first stream 314 may be the permeate stream or the feed stream, and the first stream 314 may be the cathodic stream or the anodic stream. Similarly, the same is to be understood with respect to the second stream 324.

[0068] Fig. 10A illustrates an example in which both of the electrodes 210 are integrated/disposed/coated on different membrane sides of the filtration membrane 220 in the form of active layers 226. That is, the filtration membrane 220 has two active layers 226 on both of its membrane sides such that each active layer 226 is in contact with a different liquid stream 302 or a different flow path 230 (on either side of the filtration membrane 220). The filtration membrane 220 includes a support layer 224 which is a non-reactive or electrically insulative (i.e., electrically non-conducting) layer between the two active layers 226. Fig. 10B illustrates an example in which the electrode 210 in contact with the feed stream 338 is configured as a spacer and the electrode in contact with the permeate stream 348 is configured as an active layer 226. Fig. 10C illustrates an example in which the electrode in contact with the permeate stream 348 is configured as a plate electrode 210 and the electrode in contact with the feed stream 338 is configured as an active layer 226. Fig. 10D illustrates an example in which the electrode in contact with the feed stream 338 is configured as an active layer 226 and the electrode 210 in contact with the permeate stream 348 is configured as a spacer. Fig. 10E illustrates an example in which the electrode in contact with the permeate stream 348 is configured as an active layer 226 and the electrode 210 in contact with the feed stream 338 is configured as a plate electrode. Either one of the active layer 226 or the support layer 224 of the filtration membrane 220 may be configured to be electrically conductive and to serve as one of the electrodes 210. The other of the active layer 226 or the support layer 224 may be correspondingly configured to be electrically non-conductive. For example, as shown in Fig. 10F, the support layer 224 is in contact with the permeate stream 348, and the support layer 224 is also configured as the electrode 210 in contact with the permeate stream 348. The spacer 240 in contact with the feed stream 338 is configured as another of the electrodes 210, i.e., as the electrode 210 in contact with the feed stream 338.

[0069] One or more units of the module 200 may be implemented in various ways depending on the specific applications. As non-limiting examples, Figs. 11A and 11B schematically show the module 200 of either of the non-filtration mode or the filtration mode, in which either one or both of the liquid streams can be recirculated. That is, the system 100 may include at least one recirculation loop or recirculation flow path 307 configured to recirculate at least a portion of one of the first effluent stream and the second

effluent stream to a corresponding one of the first stream and the second stream. Fig. 11C schematically illustrates an example of the system 100 in which multiple modules 200 are coupled in parallel to a common feed stream 301. The resulting effluent are two separate effluent streams 318,328 of different alkalinity/pH. Fig. 11D schematically illustrates another example of the system 100 in which multiple modules 200 are coupled in series or in a cascading configuration. Each module 200 or multiple units of the module 200 may be configured as one or more of a spiral wound membrane filtration module, a plate and frame membrane filtration module, and a hollow fiber membrane filtration module. These are just a few non-limiting examples to illustrate the flexibility and applicability of the module 200 as a “building block” such that different systems 100 may be configured for a wide variety of practical applications.

[0070] Experiments were conducted on various prototypes of the system 100 and module 200, and the results are presented below with the aid of the data plots of Figs. 12-17B. The vertical line at 9 minutes indicates the time instant when the voltage is first applied. That is, before time = 9 minutes, no voltage was applied across the pair of electrodes 210, and after time = 9 minutes, a potential difference (voltage) was applied across the pair of electrodes 210. Fig. 12 shows the pH variation in a one-pass open-loop system 100. In this example, the pair of carbon electrodes 210 were fabricated with activated carbon powder and PVDF as a binder in a ratio of 4:1, and the mixture was dissolved in NMP. Each electrode 210 is about 2 cm (centimeters) by about 15 cm, and the surface area of each membrane side 221/222 is about 30 cm². The filtration membrane 220 is a piece of ultrafiltration membrane. One influent stream (feed stream 301) of 2 mM (milli-Mole) sodium chloride (NaCl) solution is fed into both channels/flow paths 230 on either side of the filtration membrane 220. The liquid streams 302 in both channels are provided at a constant flowrate of about 5 mL/min (milli-liters per second) and at a depth of about 2 mm (millimeters). Constant voltages of 0.6 V (volts), 1.2 V, and 2.0 V are applied for 45 minutes in each experiment. As shown in the data plot of Fig. 12, compared to the influent stream (feed stream 301) that is characterized by a circumneutral pH of 5.6, the pH of cathodic effluent stream could be increased to 9.8, 10.0, and 10.3 and the pH of anodic effluent stream could be decreased to 5.1, 4.0, and 3.2 under applied potential difference of 0.6 V, 1.2 V, and 2.0 V, respectively. In other words, the method 500 provides a chemical-free method to controllably adjust the

alkalinity/pH of one or both of the effluent streams of the module 200.

[0071] The increase in pH in the cathodic stream upon the application of an electrical field is initiated by a reduction of ubiquitous dissolved oxygen (DO) in the influent solution occurring at cathode. As a result, hydrogen peroxide (H_2O_2) and water molecules are produced via the oxygen reduction reaction. When the applied voltage is sufficiently high, the H_2O_2 produced is further reduced to water molecules. To compensate for the asymmetric distribution of potential between two electrodes caused by the reduction reactions taking place at cathode, the oxidation reactions at anode occur. The anodic oxidation reactions include the oxidation of carbon into the oxygen-containing functional groups, and eventually into carbon dioxide (CO_2), the splitting of water molecules into protons (H^+) and the oxidation of chloride ion (Cl^-). A higher applied voltage will result in a larger pH change in the cathodic channel and the anodic channel. A lower flow rate of the liquid streams will give rise to a larger pH change under the same voltage, as shown in Figure 13. Fig. 13 shows the experimental results of the pH change in the cathodic stream and the anodic stream under 1.2 V with a flowrate of 1.5 and 5 mL/min respectively. The experiments thus demonstrate that the present system and method enable on-the-fly regulation over a solution's alkalinity/pH. In the context of the present disclosure, on-the-fly regulation over the alkalinity/pH refers to a method of controlling or changing the alkalinity/pH of at least one of the effluent streams obtained concurrently with the system 100 or the module 200 in a normal operating mode. The experiments also demonstrate that by regulating or determining one or any combination of the flow rate, the applied voltage (potential difference), the electrode area, the electrode properties, the membrane properties, the feed solution characteristics, etc., the system 100 can be configured to deliver solutions of various alkalinity/pH. In this manner, the system 100 enables greater flexibility and control over a solution's alkalinity/pH.

[0072] Figs. 14A-14D show the experimental results of pH variation of the feed effluent (effluent arising from the feed stream) and the permeate stream over time in a filtration mode (EMS_F) process in a one-pass open-loop operation. In the experiments of Figs. 14A and 14B, the cathode was placed at the permeate stream. In the experiments of Figs. 14C and 14D, the anode was placed at the permeate stream. The filtration membrane 220 was an ultrafiltration membrane and the feed channel was configured with a depth of 2 mm. A

differential pressure of 0.1 bar was applied across the filtration membrane and the flowrate of feed stream was set at 15 mL/min. A spacer formed by a piece of woven permeate carrier with a thickness of about 0.24 mm was provided in the permeate channel/permeate stream. The effective filtration area of the filtration membrane was 30.04 cm². In the tests conducted, each test involved applying a constant voltage of 0.2 V, 0.4 V, 0.6 V, 0.8 V, 1.0 V, 1.2 V, 2.0 V, or 3.0 V across the electrodes. For each test, the charging stage lasted for 45 minutes if the cathode was placed at the permeate side, and for 81 minutes if the anode was placed at permeate side, respectively. According to the same mechanism, the cathodic stream turns alkaline, and the anodic stream turns acidic. A higher applied voltage resulted in a higher pH in cathodic permeate and a lower pH in anodic permeate caused by more complex Faradaic reactions. When the cathode is located at permeate stream, the permeate pH can reach above 10 upon application of a voltage higher than 0.4 V. When the cathode is located at the permeate stream, the permeate pH can reach above 11 on application of a voltage higher than 2.0 V. In the experiments in which the anode was placed at the permeate stream, the permeate pH can be decreased to a pH lower than 4 if the voltage is higher than 0.8 V. If the anode was placed at the permeate stream and the applied voltage was higher than 2.0 V, the permeate pH could be further decreased to a pH lower than 3. In the experiments conducted, the highest pH of the permeate stream achieved under 3.0 V with the cathode at the permeate stream could be as high as 11.3, and the lowest pH of the permeate stream achieved under 3.0 V with the anode at the permeate stream was as low as 2.6.

[0073] Fig. 15A shows the data plot of pH variation of the cathodic permeate stream and anodic feed stream (cathode at the permeate stream) over a 5-hour test under an applied potential difference of 1.2 V, and Fig. 15B shows the data plot of pH variation of the anodic permeate stream and cathodic feed stream (anode at the permeate stream) over a 5-hour test under 1.2 V. The pH changes illustrated in Figs. 15A and 15B indicate that the pH of the cathodic stream and the anodic permeate stream can be maintained in at a substantially stable level of around 10.7 and 3.3 respectively for at least 5 hours. In other words, the present system 100 provides a viable and industrially applicable method to regulate or control the permeate alkalinity/pH and the feed effluent alkalinity/pH. For a given system with fixed electrodes and membranes, by adjusting the flowrate of the feed stream 301, the permeate flux (through the applied pressure differential across the filtration membrane), and

the voltage (potential difference) applied across the pair of electrodes 210, the alkalinity/pH of either or both of the permeate effluent stream and the feed effluent (feed effluent stream) can be regulated.

[0074] As shown above, the present method 500 can produce a first effluent stream 318 characterized by a first alkalinity/pH and a second effluent stream 328 characterized by a second alkalinity/pH, in which the first alkalinity/pH and the second alkalinity/pH differ from one another. The at least one liquid stream 301/302 may be characterized by a corresponding influent alkalinity/pH, and at least one of the first effluent stream 318/308 and the second effluent stream 328/308 may be characterized by an alkalinity/pH that is different from the corresponding influent alkalinity/pH. For example, the first effluent stream 318 and the second effluent stream 328 may be characterized by a respective alkalinity/pH that is different from that of the corresponding first feed influent stream 312 and the second feed influent stream 322 (Fig. 3A). In another example, each of the feed (effluent) stream 338/308 and the permeate (effluent) stream 348/308 may be characterized by a respective alkalinity/pH that is different from that of the corresponding feed influent stream 301 (e.g., Fig. 8 and Figs. 11A-11B). As shown by the experimental results, one of the first effluent stream 308 and the second effluent stream 308 may have a higher alkalinity/pH than the corresponding influent stream 301, and another one of the first effluent stream 308 and the second effluent stream 308 may have a lower alkalinity/pH than another corresponding influent stream 301.

[0075] The system 100 and method 500 are characterized in that at least one of the first alkalinity/pH and the second alkalinity/pH is variable and responsive to a change in the potential difference applied across the first electrode 210/211 and the second electrode 210/212. The method 500 may further include changing the potential difference applied across the first electrode 210/211 and the second electrode 210/212 in response to at least one measured alkalinity/pH measured from one or both of the first effluent stream 318 and the second effluent stream 328.

[0076] In one aspect, the present system 100 and module 200 provide the ability to produce solutions with the desired alkalinity/pH without the need to handle strong acids/alkalis. Advantageously, this provides a safer system and method. The ability to adjust the

alkalinity/pH by just changing the voltage applied also enables a faster response, i.e., more responsive control of the alkalinity/pH. The range of alkalinity/pH achievable by the present system 100 and/or the method 500 is not limited to any particular range. For the purpose of many industrial applications, the present system 100 and method 500 can produce alkaline effluent streams with pH in a range of about 7 to about 13 (both values inclusive) and acidic effluent streams with pH in a range of about 1 to about 7 (both values inclusive). In some examples, acidic streams with pH below 2 are also achievable using the present system 100 and/or method 500. In some examples, one of the effluent streams may be an alkaline effluent stream characterized by a pH in a range, in which the pH is greater than 7 and equal to or smaller than 13. In some examples, one of the effluent streams may be a neutral or acidic effluent stream characterized by a pH in a range of 1 to 7.

[0077] In addition, the present system 100 and method 500 provide an alternative to the use of chemicals or the dilution of strong acids/alkalis and reduces the overall irreversible energy loss. Experimental results suggest that the present system 100 and method 500 can be described as highly energy efficient. Fig. 16 shows the specific energy consumption (SEC) of producing alkaline streams and acidic streams and the corresponding levels of alkalinity/pH for a module 200 operating in the non-filtration mode under different applied voltages. Figs. 17A and 17B show the SEC of producing alkaline streams and acidic streams and the corresponding levels of alkalinity/pH for a module 200 operating in a filtration mode under different applied voltages. Fig. 17A is based on tests in which the cathode was placed at the permeate stream. Fig. 17B is based on tests in which the anode was placed at the permeate stream. When the voltage applied is under 1.2 V, the SEC for the production of an alkaline permeate stream with pH of 10.7 is 0.0344 kWh/m³ (Fig. 17A) and the SEC for producing an acidic permeate stream with pH of 3.3 is 0.0467 kWh/m³ (Fig. 17B). With higher applied voltages, the SEC increased, indicating that the SEC is inversely proportional to a surface loading rate and the permeate flux respectively. It was observed that the SEC of the non-filtration mode (Fig. 16) was about only one quarter of that in the filtration mode to generate alkaline permeate streams and acidic permeate streams. The SEC for producing alkaline feed effluents (feed effluent streams) and acidic feed effluents (feed effluent streams) in the filtration mode can be as little as about one third of the SEC in the non-filtration mode for the same applied voltage. Although increasing the voltage (e.g., to 2.0 V

or 3.0 V) will consume more energy, the SEC required to achieve relatively large pH changes are still considerably low. Furthermore, the energy required to adjust the permeate pH can be further cut down if the flux can be increased, especially when the practical microfiltration or ultrafiltration (MF/UF) processes possess a higher permeate flux than the average flux in this series of filtration mode tests (29.1 LMH, i.e., 29.1 liter/m²/hour). Therefore, compared to the electrolysis/electrodialysis processes with high voltages applied to stimulate the proton and hydroxyl production, the present system 100 and method 500 only require relatively low energy input to achieve the desired effective elevation or reduction in the level of alkalinity/pH.

[0078] The present system 100 and method 500 find a wide range of practical applications. The following examples are therefore illustrative and not intended to be limiting.

[0079] One exemplary application is in the treatment of water and wastewater. Coagulation, flocculation, and precipitation are processes typically employed prior to the filtration process in the treatment of water and wastewater. Alkalinity/pH regulation is important in order for these processes to be carried out efficiently and effectively. In some examples, it would be preferred to provide an acidic environment so as to facilitate the removal of natural organic matter (NOM) of humic substances through charge neutralization mechanism. In some examples, it would be preferred to provide an alkaline environment to facilitate the precipitation of metal ions such as magnesium and calcium ions. Instead of dosing acids or bases to adjust pH environment, more efficient coagulation, flocculation, and precipitation processes can be carried out by replacing the conventional filtration process with the present method 500 in the filtration mode. The desired alkalinity/pH range can be achieved by applying different voltages, while the sediments and precipitants can be concurrently filtered out without involving costly, complicated, and potentially dangerous chemicals. No acids or bases are required in the present method 500, and the present system 100 advantageously require relatively low energy consumption.

[0080] Another exemplary application is in providing improved filtration processes. In conventional water treatment and desalination, ultrafiltration (UF) processes and microfiltration (MF) processes are employed as pretreatment processes to remove particulates, macromolecules, colloidal particles, etc. Because the conventional UF exhibits

no rejection of salt ions, a secondary purification process is required to remove the unwanted ions in the water. The present system 100 (in the filtration mode and fitted with porous carbon electrodes) is capable of electro-adsorbing ions from the water. The present system 100 is especially effective for water with low to medium salinity. The present method in the filtration mode can be applied to water treatment in which the water has a low to medium level of ion concentration, such that alkalinity/pH control, rejection of ions, and filtering of particles can be carried out concurrently.

[0081] In another exemplary application, the method 500 in the filtration mode can be applied in a sea water reverse osmosis (SWRO) desalination plant. The method 500 in the filtration mode can be employed prior to a second pass of the reverse osmosis (RO) process to achieve greater efficiency in boron removal. The first-pass RO permeate stream (which is also the second-pass RO feed stream) may contain a small amount of sodium chloride (NaCl) and boron (in terms of boric acid under neutral condition). Conventionally, to effectively remove the boron, caustic soda is added to raise the pH of the liquid stream and to convert the boric acid into borate ions. Borate ions are negatively charged and are larger in size, and are intended to be removed by a second-pass RO. Using the present method 500 in the filtration mode, the pH of the first-pass RO permeate can be elevated in the cathodic channel, such that the boron can be effectively converted to borate ions via the produced OH^- ions. The change of permeate pH in the described configuration when different voltages were applied is illustrated in Fig. 18. Fig. 18 shows that when the feed solution contains 32 g/L of NaCl and 5 mg/L of boron (which is equivalent to the salinity and boron content in the seawater), applying only 0.6 V of voltage could contribute to the elevation of permeate pH from 7.3 to 10.3. Applying 1.8 V of voltage could increase the permeate pH to a value or a level higher than 11. The present method 500 as applied to this purpose requires very little energy (e.g., as low as 0.0024 kWh/m³) to achieve a change in the alkalinity/pH to a desired range. In other words, the present method 500 is effective for boron conversion to borate ion without involving any alkaline chemicals dosage. This method further eliminates the transportation and storage cost of caustic soda.

[0082] In yet another example, the present method 500 can also be harnessed for resource recovery such as the recovery of ammonia. The ammonium in the wastewater can be converted to ammonia molecules in the cathodic alkaline stream and then be recovered in

the anodic acidic stream in the form of ammonium fertilizer.

[0083] In another exemplary application, the in situ-generated H_2O_2 and Cl_2 at the cathodic permeate stream and the anodic permeate stream respectively can be potentially harvested for the disinfection of water and degradation of contaminants. For example, the filtration and chlorination/ultraviolet disinfection are commonly utilized together in the shipping industry to filter out the large particles and to kill marine organisms in the ballast water. These combined treatment methods require high investments for the two or more systems. However, the present method 500 can realize the filtration and the chlorination in one system 100. The filtration membrane 220 is selected such that it is able to filter out the sediments and a large portion of organisms in the ballast water, and the generated chlorine gas dissolved as hypochlorous acid can inactivate the remaining microorganisms without the addition of chlorine. The deoxygenation process is another secondary treatment for the ballast water employed in practice to asphyxiate the organisms. The present method 500 can also achieve the same effect because the cathodic reduction reaction to produce H_2O_2 consumes the oxygen existing in the solution. Furthermore, the generated H_2O_2 is also an effective disinfectant and oxidizer to degrade organic impurities in various water treatment processes.

[0084] The ability to control the alkalinity/pH on-the-fly, e.g., via an electrical circuit, facilitates automation and enables greater flexibility in producing the target effluents. The present method enables direct control over the alkalinity/pH of a solution without the need to involve industrial chemicals, and thus advantageously further enables the system 100 to be used in the household or office environment to deliver safer drinking water. As demonstrated experimentally, the system 100 is energy efficient such that it can be provided as a battery-operable mobile device to facilitate use in various outdoor situations or in places without a reliable supply of electricity.

[0085] As described in the foregoing with the aid of various non-limiting examples, the present disclosure provides a chemical-free and energy-efficient electrochemical system and method to adjust the alkalinity/pH of solutions. The present system 100 is an electrochemical membrane system which enables alkalinity/pH adjustment and the separation of alkalized and acidized streams. The present system 100 includes a pair of

electrodes 210 acting as a cathode and an anode respectively, and a filtration membrane 220 disposed between the two electrodes 210. The filtration membrane 220 acts as a separator to segregate the cathodic flow path and anodic flow path. By applying different voltages across the pair of electrodes 210, reduction and oxidation reactions occur on the cathode and anode respectively. A higher voltage can promote a larger change in alkalinity/pH in both channels. The application of a current to the electrodes (application of a potential difference or voltage across the electrodes) results in electrode reactions that produce OH^- and H^+ ions, and concurrently the voltage determines the ion flux of OH^- and H^+ moving across the filtration membrane 220. The change in alkalinity/pH in the solution is a result of a difference in the generation rate of OH^- (or H^+) ions in one liquid stream, and the flux of said ions towards the other liquid stream. Consequently, the solution in the cathodic stream and the solution in the anodic stream become acidic and alkaline respectively.

[0086] Based on the proposed mechanism described, various embodiments of the present system 100 may be differently configured from the examples described herein without going beyond the scope of the claimed invention. For example, the ratio of the flow rate of an liquid stream 302 over an area of an electrode 210 exposed to the liquid stream 302 may be varied to determine the range of alkalinity/pH achievable for one or both of the effluent streams 308. In some embodiments, the distance between the pair of electrodes 210 may be predetermined or adjustable to determine the range of alkalinity/pH achievable for one or both of the effluent streams 308. In some embodiments, the electrodes 210 and/or filtration membrane 220 may be selected from materials according to the resistance of the materials, such that the range of operable or adjustable alkalinity/pH is within the desired/required range. By configuring the relative rate of production of the OH^- and H^+ ions, and the ion flux or the transfer of the OH^- and H^+ ions across the filtration membrane, the operable ranges of alkalinity/pH of one or both of the effluent streams can be configured for any of the various embodiments of the present system 100. The use of electrodes that enable or promote electrosorption is therefore optional and not a requirement for the present method 500 of controlling alkalinity/pH. In some applications, it may be preferred to select electrode materials that do not facilitate electrosorption.

[0087] In addition to embodiments of the system 100 operable in a non-filtration mode as described above, various embodiments of the system 100 are operable in a filtration mode

by employing a hydraulic pressure difference across the filtration membrane. The filtration mode can achieve the concurrent or simultaneous filtration and alkalinity/pH adjustment by applying a pressure on the feed side. During the operation, the impurities such as microorganisms, colloidal particles, microorganic molecules, suspended particles, and/or salt ions, from the feed side can be removed such that only acidized or alkalized clean permeate water can be produced. Similarly, a higher voltage will give rise to a permeate that is more acidic or more alkaline. In such manner, it is possible to achieve both qualitative and quantitative alkalinity/pH adjustment of a solution by exerting different electrical voltages, with no additional chemicals required. Advantageously, the method 500 requires less energy input.

[0088] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding and are not intended to be limiting or exhaustive. Various changes and modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. A system comprising:
 - at least one module, each of the at least one module comprising:
 - a filtration membrane configured to extend along at least one liquid stream, the filtration membrane defining a first membrane side and a second membrane side, the first membrane side and the second membrane side being different membrane sides facing away from one another, the filtration membrane being configured to separate the at least one liquid stream into a first stream on the first membrane side of the filtration membrane and a second stream on the second membrane side of the filtration membrane;
 - a first electrode; and
 - a second electrode, the first electrode and the second electrode being at respective ones of the different membrane sides of the filtration membrane, wherein the first stream is configured to flow by the first electrode to form a first effluent stream characterized by a first alkalinity/pH, and wherein the second stream is configured to flow by the second electrode to form a second effluent stream characterized by a second alkalinity/pH, and wherein the first alkalinity/pH and the second alkalinity/pH differ from one another in response to a potential difference applied across the first electrode and the second electrode.
2. The system of claim 1, wherein the at least one liquid stream is characterized by a corresponding influent alkalinity/pH, and wherein at least one of the first effluent stream and the second effluent stream is characterized by an alkalinity/pH that is different from the corresponding influent alkalinity/pH.
3. The system of claim 1 or claim 2, wherein one of the first effluent stream and the second effluent stream has a higher alkalinity/pH than a corresponding one of the first stream and the second stream, and wherein another of the first effluent stream and the second effluent stream has a lower alkalinity/pH than another corresponding one of the first stream and the second stream.

4. The system of any one of claims 1 to 3, wherein one of the first effluent stream and the second effluent stream is an alkaline or neutral effluent stream, and wherein another one of the first effluent stream and the second effluent stream is a neutral or acidic effluent stream.
5. The system of claim 4, wherein the alkaline effluent stream is characterized by a pH in a range, and wherein the pH is greater than 7 and equal to or smaller than 13.
6. The system of claim 4, wherein the neutral or acidic effluent stream is characterized by a pH in a range of 1 to 7.
7. The system of any one of claims 1 to 6, further comprising at least one pump in a flow path connected to the at least one module, the at least one pump being configured to controllably perform one or concurrently both of the following: (i) deliver at least one of the first stream and the second stream at a respective fluid pressure; and (ii) provide a hydraulic pressure differential across the filtration membrane between the first stream and the second stream.
8. The system of claim 7, wherein the second effluent stream comprises a permeate drawn across the filtration membrane from the first stream.
9. The system of claim 8, wherein a pressure differential between the first stream and the second stream is a result of at least one of the hydraulic pressure differential and an osmotic pressure differential between the first stream and the second stream, in which the pressure differential is configured to enable any one of the following across the filtration membrane: pressure-retarded osmosis, forward osmosis, osmotically assisted reverse osmosis, reverse osmosis, nanofiltration, ultrafiltration, and microfiltration.
10. The system of any one of claims 1 to 9, further comprising at least one recirculation flow path, wherein a respective one of the at least one recirculation flow path is

configured to recirculate at least a portion of one of the first effluent stream and the second effluent stream to a corresponding one of the first stream and the second stream.

11. The system of any one of claims 1 to 10, wherein the at least one module further comprises:
 - a first spacer, the first spacer being configured to provide a first flow path for the first stream, and wherein at least one hydrodynamic parameter of the first stream is determined by the first spacer.
12. The system of claim 11, wherein the first spacer is configured as the first electrode.
13. The system of claim 11 or claim 12, wherein the at least one module further comprises a second spacer, the second spacer being configured to provide a second flow path for the second stream, and wherein at least one hydrodynamic parameter of the second stream is determined by the second spacer.
14. The system of claim 13, wherein the second spacer is configured as the second electrode.
15. The system of claim 13, wherein the first spacer is disposed between and in contact with the filtration membrane and the first electrode, and wherein the second spacer is disposed between and in contact with the filtration membrane and the second electrode.
16. The system of any one of claims 1 to 10, wherein the first membrane side of the filtration membrane is configured as the first electrode.
17. The system of any one of claims 1 to 10, wherein the second membrane side of the filtration membrane is configured as the second electrode.

18. The system of any one of claims 1 to 17, wherein the filtration membrane comprises an electrically non-conductive layer, the electrically non-conductive layer being disposed between the first electrode and the second electrode.
19. The system of any one of claims 1 to 18, wherein at least one of the first alkalinity/pH and the second alkalinity/pH is variable and responsive to a change in the potential difference applied across the first electrode and the second electrode and/or a change in a current provided to the first electrode and the second electrode.
20. The system of claim 19, further comprising: a controller, the controller being configured to:
 - acquire at least one measured alkalinity/pH measured from one or both of the first effluent stream and the second effluent stream; and
 - in response to the at least one measured alkalinity/pH, change the potential difference applied across the first electrode and the second electrode and/or change the current provided to the first electrode and the second electrode.
21. The system of any one of claims 1 to 20, wherein the filtration membrane is a non-ion exchange membrane selected from the following: a reverse osmosis (RO) membrane, a nanofiltration (NF) membrane, an ultrafiltration (UF) membrane, a microfiltration (MF) membrane, a forward osmosis (FO) membrane, a pressure-retarded osmosis (PRO) membrane, and a porous filtration paper.
22. The system of any one of claims 1 to 21, wherein the at least one module is configured as one of: a spiral wound membrane filtration module, a plate and frame membrane filtration module, a hollow fiber membrane filtration module, and a tubular membrane module.
23. A method comprising:
 - providing at least one liquid stream to flow by a filtration membrane, the filtration membrane defining a first membrane side and a second membrane side, the first membrane side and the second membrane side being different membrane sides

facing away from one another, the filtration membrane being configured to separate the at least one liquid stream into a first stream on the first membrane side of the filtration membrane and a second stream on the second membrane side of the filtration membrane; and

applying a potential difference across a first electrode and a second electrode, the first electrode and the second electrode being at respective ones of the different membrane sides of the filtration membrane, wherein the first stream is configured to flow by the first electrode to form a first effluent stream characterized by a first alkalinity/pH, and wherein the second stream is configured to flow by the second electrode to form a second effluent stream characterized by a second alkalinity/pH, and wherein the first alkalinity/pH and the second alkalinity/pH differ from one another.

24. The method of claim 23, wherein the at least one liquid stream is characterized by a corresponding influent alkalinity/pH, and wherein at least one of the first effluent stream and the second effluent stream is characterized by an alkalinity/pH that is different from the corresponding influent alkalinity/pH.
25. The method of claim 23 or claim 24, wherein one of the first effluent stream and the second effluent stream has a higher alkalinity/pH than a corresponding influent stream, and wherein another one of the first effluent stream and the second effluent stream has a lower alkalinity/pH than another corresponding influent stream.
26. The method of any one of claims 23 to 25, further comprising applying a pressure differential across the filtration membrane.
27. The method of claim 26, wherein the second effluent stream comprises a permeate drawn across the filtration membrane from the first stream.
28. The method of claim 27, wherein the pressure differential is a result of at least one of a hydraulic pressure differential and an osmotic pressure differential between the first stream and the second stream, and wherein the pressure differential is

configured to enable any one of the following across the filtration membrane: pressure-retarded osmosis, forward osmosis, osmotically assisted reverse osmosis, reverse osmosis, nanofiltration, ultrafiltration, and microfiltration.

29. The method of any one of claims 23 to 28, further comprising recirculating at least one or both of a portion of the second effluent stream to the second stream and a portion of the first effluent stream to the first stream.
30. The method of any one of claims 23 to 29, wherein the first stream is configured to flow through a first spacer, and wherein the first spacer is configured to determine at least one hydrodynamic parameter of the first stream.
31. The method of claim 30, wherein the first electrode is configured as the first spacer.
32. The method of claim 30 or claim 31, wherein the second stream is configured to flow through a second spacer, and wherein the second spacer is configured to determine at least one hydrodynamic parameter of the second stream.
33. The method of claim 32, wherein the second electrode is configured as the second spacer.
34. The method of claim 32, wherein the first spacer is disposed between and in contact with the filtration membrane and the first electrode, and wherein the second spacer is disposed between and in contact with the filtration membrane and the second electrode.
35. The method of any one of claims 23 to 29, wherein the first membrane side of the filtration membrane is configured as the first electrode.
36. The method of any one of claims 23 to 29, wherein the second membrane side of the filtration membrane is configured as the second electrode.

37. The method of any one of claims 23 to 36, wherein the filtration membrane comprises an electrically non-conductive layer, the electrically non-conductive layer being disposed between the first electrode and the second electrode.
38. The method of any one of claims 23 to 37, wherein at least one of the first alkalinity/pH and the second alkalinity/pH is variable and responsive to a change in the potential difference applied across the first electrode and the second electrode and/or a change in a current provided to the first electrode and the second electrode.
39. The method of claim 38, further comprising, in response to at least one measured alkalinity/pH measured from one or both of the first effluent stream and the second effluent stream, changing the potential difference applied across the first electrode and the second electrode and/or changing the current provided to the first electrode and the second electrode.