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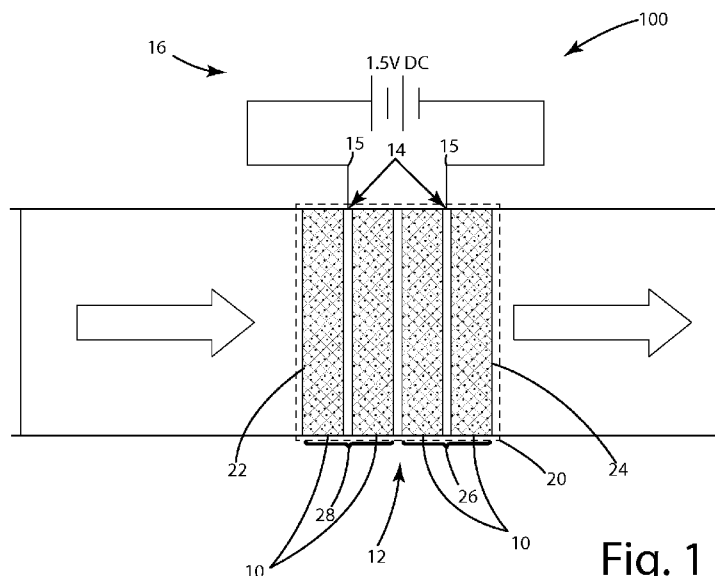
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(54) **Title:** CAPACITIVE DEIONIZATION SYSTEM AND METHOD FOR OPERATING THE SYSTEM

**Fig. 1**

(57) **Abstract:** A capacitive deionization (CDI) reactor for a CDI system including at least two electrodes formed with porous material and a plurality of conductive elements. The plurality of conductive elements in each electrode may be separate from each other. By incorporating a plurality of conductive elements in the electrodes, a CDI reactor according to one embodiment may enable substantially uniform charge distribution throughout the electrodes, irrespective of the size and shape of the electrodes. A method according to one embodiment may include regenerating the CDI system by successively reversing a polarity of voltage applied to electrodes of a CDI reactor, and reducing a magnitude of the applied voltage over time.



# **CAPACITIVE DEIONIZATION SYSTEM AND METHOD FOR OPERATING THE SYSTEM**

## **FIELD OF INVENTION**

[0001] The present invention relates to systems for removing contaminants from water or water purification, and more particularly to a capacitive deionization system for removing contaminants from water.

## **BACKGROUND OF THE INVENTION**

[0002] For a variety of reasons, considerable efforts have been directed to developing water treatment systems that remove contaminants, such as organic and inorganic contaminants, from water. In particular, attempts to provide water fit for human consumption have been a driving force in the field of water treatment.

[0003] One type of purification system that has gained exposure in recent times utilizes capacitive deionization (CDI) to remove anions (negatively charged ions) and cations (positively charged ions) from water. In a conventional CDI system, water may be fed between a pair of electrodes, across which a voltage is applied, in an adsorption phase. This configuration is often times described as a flow-between CDI system due to the passage of water between the electrodes. Because the two electrodes in this system are polarized by the applied voltage, cations and anions in the water flowing between the electrodes may tend to move respectively toward the electrodes. That is, cations may tend to move toward the negatively polarized electrode, and anions may tend to move toward the positively polarized electrode. In this way, the cations and anions may be electrostatically adsorbed by the electrodes and removed from the water.

[0004] In order to increase the capacity of the electrodes to adsorb cations and anions, the electrodes in CDI systems are often times formed of porous material having a large surface area. Larger surface areas may allow adsorption of a greater number of ions. Despite such attempts to increase capacity and effectiveness of the electrodes, CDI systems in which

the water flows between the electrodes may be limited by the ability of the ions in the water to effectively migrate and adsorb to the electrodes. To try to address the limitations of the flow-between configuration, another conventional CDI system has been developed in which water is directed through the electrodes so that the water and ions flow directly through gaps within the electrodes themselves. This type of CDI system is often times referred to as a flow-through CDI system. Rather than relying on migration of the ions toward the electrodes, as in the flow-between CDI configuration, the flow-through CDI configuration may actually position the ions in direct proximity to the electrodes, thereby potentially achieving improved effectiveness in removing ions.

[0005] Although the flow-through CDI configuration may address some of the inefficiencies of the flow-between CDI configuration, the conventional flow-through CDI configuration is not without potential drawbacks. In many instances, the electrodes in CDI systems include materials that are insulative, and impede charge distribution throughout the electrodes. To overcome the insulative nature of the electrode material, the electrodes in many conventional flow-through configurations include thin sheets of material coupled to a conductive material. Because the material of the electrodes is thin, the overall surface area of each electrode is small, and therefore the capacity and effectiveness of each electrode in the conventional flow-through CDI configuration may be limited.

[0006] In a conventional CDI system, the ability of the electrodes to effectively electrostatically adsorb ions may become diminished after operating for a period of time in the adsorption phase. In other words, the electrodes may be considered saturated such that their ability to further electrostatically adsorb ions is diminished. To try release the ions from the electrodes and potentially restore the effectiveness of the electrodes, the CDI system may transition to a regeneration mode. Conventionally, regeneration may be achieved by reducing the potential difference between the electrodes to substantially zero, allowing the ions to leave the electrode, and relying on diffusion to remove ions from the CDI system.

The concentration gradient for diffusion may be increased by flushing regeneration water through the CDI system, thereby enhancing the diffusive process and improving regeneration. Regeneration in this manner can be time consuming due to the reliance on water flow to flush out the ions.

[0007] Regeneration may also be achieved by completely reversing the polarity of the electrodes, and holding the reversed polarity nearly constant for the duration of the regeneration phase. By reversing the polarity of the electrodes, the electrodes may be configured to electrostatically repulse the ions adsorbed in the adsorption phase, and allow diffusion of some ions out of the CDI system in the waste effluent stream. The primary downside to reversing the polarity is that many of the ions may migrate to another electrode. For example, a cation that migrated to a negatively polarized electrode during the adsorption phase may be repulsed from that same electrode during the regeneration phase because that electrode is now positively polarized. However, in the regeneration phase, that same cation may migrate and attract to the negatively polarized electrode, which was positively polarized in the adsorption phase, impeding regeneration of the electrodes. As a result, reversing the polarity of electrodes may result in an exchange of ions between electrodes, and prevent substantial regeneration of the electrodes.

### SUMMARY OF THE INVENTION

[0008] The present invention provides a capacitive deionization (CDI) reactor for a CDI system including at least two electrodes formed with porous material and a plurality of conductive elements. The plurality of conductive elements in each electrode may be separate from each other. As an example, the conductive elements may be separate such that porous material fills the space between each of the conductive elements. The conductive electrodes in this example may be electrically coupled together via a connection external to the porous adsorbent material. As another example, the porous material may be doped with separate conductive elements, such as graphite particles or fragments of stainless steel. By

incorporating a plurality of conductive elements in the electrodes, a CDI reactor according to one embodiment may enable substantially uniform charge distribution throughout the electrodes, irrespective of the size and shape of the electrodes.

[0009] In one embodiment, the CDI reactor may be configured such that water is directed through the electrodes, or in a feed-through configuration, which allows ions in the water to flow directly through gaps within the electrodes, themselves. In configurations in which the porous material of the electrodes is activated carbon, the electrodes may remove contaminants by conventional adsorption or electrostatic Coulomb force, or both. Additionally, incorporating activated carbon as the porous material in the electrodes may enable the electrodes to remove both inorganic and organic contaminants from water, including uncharged contaminants.

[0010] In one aspect, the CDI reactor may include an electrode block with a plurality of electrodes and one or more membranes arranged to electrically insulate the plurality of electrodes from each other. The one or more membranes may be constructed of water permeable material, such as glass fiber or ceramic fiber. The interface between a membrane and an electrode may be non-planar. As an example, surfaces of the membrane and the electrode that interface each other may include at least one of depressions and protrusions. As a result, the surface contact between the membrane and the electrode may be greater than would otherwise occur in a planar interface.

[0011] In one aspect, the electrode block of the CDI reactor in one embodiment may include a water inlet through which water enters the electrode block, and a water outlet through which water exits the electrode block. The water inlet and the water outlet may be configured in a variety of ways. For example, the water inlet may form an opening through the electrode block, and the water outlet may include an outer portion of the electrode block, such as the perimeter of the electrode block. Each of the plurality of electrodes in the electrode block may include an electrode inlet coupled to the water inlet, and an electrode

outlet coupled to the water outlet. With this configuration, water may flow from within the electrode block, through the electrode block, to the outer portion. As another example, the water inlet may form a first outer surface of the electrode block, and the water outlet may form a second outer surface, where the first outer surface opposes the second outer surface. In this configuration, water may flow from the first outer surface, through the electrode block, to the second outer surface.

[0012] In one embodiment, the CDI reactor may include a plurality of electrodes arranged to allow water to flow directly through one of the electrodes. As an example, water entering a water inlet of the CDI reactor may flow through at least one of a plurality of separate water channels, each of which may be formed by one of the plurality of the electrodes. Water exiting each of the separate water channels may be directed to a water outlet of the CDI reactor.

[0013] In one aspect, a method for operating the CDI system may regenerate one or more electrodes of the CDI reactor. The method may include providing power to the one or more electrodes in a regeneration phase using an AC source whose voltage magnitude may decrease over time. In other words, the voltage of power applied to the one or more electrodes in the regeneration phase may reverse polarity at least once, where the magnitude of the applied voltage decreases for each successive reversal. By successively reversing the applied voltage, each time decreasing the magnitude of the applied voltage, the CDI system may regenerate by repulsing ions adsorbed to the electrodes, and potentially allowing the repulsed ions to attract to each other. This way, ions shed from an electrode during regeneration may be diffusively flushed from the CDI reactor without substantially migrating to another electrode.

[0014] In one aspect, a CDI system according one embodiment may achieve improved efficiency through use of electrodes having porous adsorbent material and a plurality of conductive elements. Further, by using a plurality of conductive elements in each

electrode, the electrodes may be configured in a variety of sizes and shapes, and may not be limited by the insulative properties of the adsorbent material. Additionally, a method of operating a CDI system according to one embodiment may enable regeneration of electrodes in less time than conventional methods.

[0015] These and other objects, advantages, and features of the invention will be more fully understood and appreciated by reference to the description of the current embodiment and the drawings.

[0016] Before the embodiments of the invention are explained in detail, it is to be understood that the invention is not limited to the details of operation or to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention may be implemented in various other embodiments and of being practiced or being carried out in alternative ways not expressly disclosed herein. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including” and “comprising” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items and equivalents thereof. Further, enumeration may be used in the description of various embodiments. Unless otherwise expressly stated, the use of enumeration should not be construed as limiting the invention to any specific order or number of components. Nor should the use of enumeration be construed as excluding from the scope of the invention any additional steps or components that might be combined with or into the enumerated steps or components.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Fig.1 shows a representative view of a CDI reactor according to one embodiment.

[0018] Fig. 2 is a top view of a CDI reactor according to one embodiment.

[0019] Fig. 3 is a side view of a CDI reactor according to one embodiment.

[0020] Fig. 4 is a performance plot of a CDI reactor according to one embodiment.

[0021] Fig. 5 is a perspective view of an electrode of a CDI reactor according to one embodiment.

[0022] Fig. 6 is a perspective view of an electrode of a CDI reactor according to one embodiment.

[0023] Fig. 7 is a perspective view of an electrode of a CDI reactor according to one embodiment.

[0024] Fig. 8A is a perspective view of an electrode of a CDI reactor according to one embodiment.

[0025] Fig. 8B is a sectional view of the electrode depicted in Fig. 8A.

[0026] Fig. 9 is a sectional view of a CDI reactor according to one embodiment.

[0027] Fig. 10 is a transverse sectional view of a CDI reactor according to one embodiment.

[0028] Fig. 11 is a longitudinal sectional view of the CDI reactor depicted in Fig. 10.

[0029] Fig. 12 is a transverse sectional view of a CDI reactor according to one embodiment.

[0030] Fig. 13 is a representative view of a CDI system according to one embodiment.

[0031] Fig. 14 is a plot of applied voltage against time for a method of regenerating a CDI reactor according to one embodiment.

[0032] Fig. 15 is a plot of applied voltage against time for a method of regenerating a CDI reactor according to one embodiment.

[0033] Fig. 16 shows a representative view of water flowing between two electrodes of a CDI reactor according to one embodiment.

[0034] Fig. 17 shows a representative view of water flowing between two electrodes of a CDI reactor according to one embodiment.

[0035] Fig. 18 shows a representative view of water flowing between two electrodes of a CDI reactor according to one embodiment.

[0036] Fig. 19 shows a representative view of water flowing between two electrodes of a CDI reactor according to one embodiment.

[0037] Fig. 20 shows a representative view of water flowing between two electrodes of a CDI reactor according to one embodiment.

### DETAILED DESCRIPTION

[0038] A capacitive deionization (CDI) system according to one embodiment is described in Fig. 13, and generally designated 600. The CDI system may be utilized to treat water or remove contaminants from water. The CDI system 600 may be configured and operated according to one or more embodiments described herein. For example, the CDI system 600 may include a CDI reactor 610 configured according to any embodiment. It should be understood that the CDI system 600, as well as the CDI reactor 610, may be configured to include some but not all features of one embodiment. Further, one or more features from one embodiment may be incorporated into another embodiment.

#### I. CDI REACTOR

[0039] A capacitive deionization (CDI) reactor in accordance with one embodiment is shown in Figs. 1-3, and generally designated 100. As depicted, the CDI reactor 100 includes an electrode block 20, a water inlet 22, and a water outlet 24. The water inlet 22 and the water outlet 22 may be in fluid communication with the electrode block 20 such that water may flow from the water inlet 22, through the electrode block 20, and to the water outlet 24. The electrode block 20 may include (a) a plurality of electrodes, each of which may include porous material 10 and conductive material 14, and (b) one or more membranes 12 configured to electrically insulate one or more electrodes from among the plurality. The conductive material 14, as will be described herein, may be constructed in a variety of ways, including mesh, nets, dopant, and conductive filaments or strands, that allow water to flow

through the electrodes. The porous material 10 may comprise adsorbent material, such as activated carbon or metal oxide material, or both. The conductive material 14 may be non-corrosive, as well as conductive, to avoid substantial degradation of the conductive material 14 over time. Additionally, in configurations in which water flows through one or more of the electrodes, the conductive material 14 may be configured to avoid significantly impeding flow of water through the one or more electrodes, while providing sufficient contact between the conductive material 14 and the porous material 10 to enable charge distribution on the porous material 10. It should be understood that there may be a balance in configuring the conductive material 14 to avoid impeding flow of water while enabling sufficient charge distribution on the porous material 14. For example, in embodiments in which the conductive material 14 is formed of mesh, the aperture size of openings in the mesh may vary depending on the desired performance characteristics.

[0040] In the illustrated embodiment of Figs. 1-3, the electrode block 20 includes first and second electrodes 26, 28 having porous material 10, formed of activated carbon disks, that sandwich the conductive material 14, formed of metal mesh, in each respective electrode 26, 28. The metal mesh may enable distribution of charge on the carbon disks. As depicted, the first and second electrodes 26, 28 are substantially the same construction, and are approximately 2 inches in diameter and 0.50 inches thick. It should be understood that electrodes of the electrode block 20 are not limited a configuration according to the illustrated embodiment of Figs. 1-3. For example, at least one electrode may be constructed the same or differently from other electrodes. And, the one or more electrodes may be any shape or size, or combination thereof. As another example, the porous material 10 and the conductive material 14 may be configured in any manner capable of distributing charge on the porous material 10, including, for example, a plurality of separate portions of conductive material 14 disposed within the porous material 10.

[0041] The electrode block 20 of the CDI reactor 100, as mentioned herein, may include a membrane 12 that electrically insulates at least one electrode from among the plurality. The membrane 12 may be an insulator or a dielectric material, such as glass fiber or ceramic fiber. In the illustrated embodiment of Figs. 1-3, the membrane 12 electrically insulates the first and second electrodes 26, 28 from each other, while being permeable to water so that water may flow from the water inlet 22, through the electrode block 20, to the water outlet 24. The thickness of the membrane 12 may be relatively thin in comparison to the thickness of the electrodes 26, 28. For example, the thickness of the membrane 12 may be about 0.1mm.

[0042] The CDI reactor 100 may include terminals 15 electrically coupled to the electrode block 20. In particular, each terminal 15 may be electrically coupled to one or more electrodes of the electrode block 20, allowing connection of an external power supply 16 to the electrode block 20. Power from the external power supply 16 to the terminals 15 may positively charge at least one electrode of the electrode block 20, and negatively charge at least one other electrode of the electrode block 20.

[0043] In the illustrated embodiment of Fig. 1, one terminal 15 of the CDI reactor 100 is electrically coupled to a first electrode 26 of the plurality of electrodes 26, 28, and another terminal 15 is electrically coupled to a second electrode 28 of the plurality of electrodes 26, 28. The external power supply 16 may provide power to the terminals 15 such that the first electrode 26 becomes negatively charged, while the second electrode 28 becomes positively charged. The external power supply 16 may be a source of voltage and current suitable for energizing the first and second electrodes 26, 28 to remove ions from water flowing through the CDI reactor 100. As an example, a voltage less than 2 V, often times about 1.5 V, provided by the external power supply 16 may be sufficient to respectively charge the first and second electrodes 26, 28, positively and negatively. As another example, the external power supply 16 may provide constant current to the first and second electrodes 26, 28 to

generate electrostatic Coulomb forces that attract ions to the first and second electrodes 26, 28, thereby removing those ions from the water. The amount of current supplied may vary from application to application depending on a variety of factors, such as water conductivity, size and configuration of the electrodes, and water flow rates. In one embodiment, the amount of current supplied may be constant between 4 A and 10 A.

[0044] As water flows from the water inlet 22 to the water outlet 24, ions within the water may be attracted to respective electrodes 26, 28. For example, negatively charged anions within the water may be attracted to the positively charged second electrode 28, and the positively charged cations in the water may be attracted to the negatively charged first electrode 26. In other words, as the water passes through the electrode block 20, the anionic contaminants may first be removed by the positively charged second electrode 28 (a cathode) and the cationic contaminants may be removed by the downstream, negatively charged first electrode 26 (an anode). As a result, ions in the water entering the water inlet 22 may be removed from the water such that the water emerging from the water outlet 24 may be considered purer. For purposes of disclosure, the first electrode 26 is described as being negatively charged, and the second electrode 28 is described as being positively charged, but it should be understood that the external power supply 16 may reverse the polarity of the terminals 15 in the adsorption phase such that the first electrode 26 may become positively charged, while the second electrode 28 may become negatively charged.

[0045] As mentioned above, the first and second electrodes 26, 28 in the illustrated embodiment of Figs. 1-3 may be constructed of a porous material 10, such as activated carbon or metal oxide material, or both. With this configuration, the first and second electrodes 26, 28 may be positively and negatively charged to remove ions, or inorganic contaminants, from water flowing through the first and second electrodes 26, 28. Additionally, the activated carbon, itself, may remove organic contaminants or uncharged contaminants, or both, from the water by adsorption. Accordingly, the CDI reactor 100

according to one embodiment may remove both inorganic and organic contaminants simultaneously, from water.

[0046] Fig. 6 illustrates performance characteristics of a CDI reactor 100 configured according to the illustrated embodiment of Figs. 1-3. As can be seen, the concentration of total dissolved solids (TDS) in water exiting the water outlet 24, e.g., the permeate, may change depending on whether the first and second electrodes 26, 28 are charged. The CDI reactor 100 in this example has been operated at a flow rate of 130 liters per square meter per hour (LMH), which may be comparable to flow rates for a large-scale operation. For purposes of disclosure, the CDI reactor 100 in this embodiment is configured such that the surface area of the electrodes 26, 28 is approximately 0.00185 meters<sup>2</sup>, and the flow path of water through the CDI reactor 100 is approximately 25.4 mm. With a flow rate of 130 LMH, the velocity of water is about 0.036 mm/s, and the contact time between the water and the CDI reactor 100 is about 11.8 min. It should be understood that the configuration of the CDI reactor 100, as well as the flow rate, may vary from application to application.

[0047] To maintain consistency for the duration of the performance test, the water feed provided to the water inlet 22 is deionized water, to which a controlled amount of salt is added to try to maintain a constant TDS concentration of about 32 ppm for the performance test. As can be seen in Fig. 6, in operation, the CDI reactor 100 reduces the TDS concentration of the water feed for a period of time (approximately 250 min) while the electrode block 20 is charged—e.g., during an adsorption phase. After the charge on the electrode block 20 is removed, the TDS concentration of the permeate increases for a period of time because the ions collected during the adsorption phase are being released. This stage of operation in which the ions are released from the electrode block 20 is referred to as regeneration. In operation, a diverter valve of the CDI system may direct water to a waste effluent stream during regeneration so that water having an increased TDS concentration is not mixed with purified water.

## II. ELECTRODE CONFIGURATION

[0048] Turning now to the illustrated embodiments of Figs. 5-8B, an electrode of an electrode block configured for use in a CDI reactor may be configured in a variety of ways, as discussed herein, and is generally designated 200. The electrode 200 may be similar to the plurality of electrodes 26, 28 described in connection with the illustrated embodiment of Figs. 1-3, and may include porous material 210 and conductive material 214, respectively similar to the porous material 10 and conductive material 14 of the electrodes 26, 28. As an example, the porous material 210 may be adsorbent, activated carbon, and the conductive material 214 may be at least one of mesh, dopant, and conductive filaments or strands.

[0049] As can be seen in the illustrated embodiments of Figs. 5-8B, the conductive material 214 of the electrode 200 may include a plurality of conductive elements 216, 218, 220, 222 separate from each other such that the porous material 210 fills the space therebetween. With this configuration, the CDI reactor may be capable of achieving a charge distribution within the electrode 200 that is more uniform. Lack of uniform charge distribution in the CDI reactor may cause rapid declines in inorganic removal performance, and may cause decomposition of the electrode 200 through an electro-redox reaction. By incorporating a plurality of conductive elements 216, 218, 220, 222 within the electrode 200, the size and shape of the electrode 200 may be changed or expanded without resulting in significant variances in charge distribution within the electrode 200. For example, the plurality of conductive elements 216, 218, 220, 222 within the electrode 200 may be positioned such that the distance between portions of the porous material 210 and the conductive material 214 (a) does not significantly vary throughout the electrode 200, and (b) may be maintained to be sufficiently short such that the insulating properties of the porous material 210 do not significantly impede charge distribution. In porous material, such as activated carbon, the porous nature of the material may impede even distribution of charge. Additionally, activated carbon often times includes binder materials to glue or bond the

activated carbon together. These binder materials in many cases are insulative. Due to these insulative binder materials, larger distances between portions of the porous material 210 and the conductive material 214 may result in lack of uniform charge distribution within the electrode 200. The electrode 200 configured according to one embodiment may avoid such larger distances by distributing the conductive elements 216, 218, 220, 222 of the conductive material 314 at various locations within the porous material 210. Thus, a CDI reactor including an electrode 200 according to one embodiment may yield improved performance.

[0050] In one embodiment, the plurality of conductive elements 216, 218, 220, 222 may not be directly electrically connected within electrode 200, itself. To charge the plurality of conductive elements 216, 218, 220, 222 in this configuration, the plurality of conductive elements 216, 218, 220, 222 may be directly connected together external to the porous material 210 of the electrode such that the plurality of conductive elements 216, 218, 220, 222 may be directly connected to an external power supply. In addition to or alternatively, charge may be provided to the plurality of conductive elements 216, 218, 220, 222 indirectly through the porous material 210 without a direct electrical connection between the plurality of conductive elements 216, 218, 220, 222 and without a direct electrical connection to an external power supply.

[0051] In the illustrated embodiment of Fig. 5, the electrode 200 may include a plurality of conductive elements 216, each constructed of a non-planar mesh material. The example non-planar configuration depicted in Fig. 5 includes creased or pleated mesh conductive elements 216. Creasing or pleating of the plurality of conductive elements 216 may be performed prior to being set in the porous material 210, or may occur, at least in part, during manufacture of the electrode 200. For example, the plurality of conductive elements 216 may be formed of a spring-like material that, under compression forces applied during manufacture of the electrode 200, may transition in shape to a final non-planar form within the electrode 200. By constructing the conductive element 216 in a non-planar manner, the

surface area of contact between the porous material 210 and the conductive element 216 may be larger than embodiments in which the conductive element 214 is planar, and therefore may enable more uniform charge distribution within the electrode 200. Although the conductive elements 216 are described in connection with a creased or pleated mesh, it should be understood that embodiments of the invention are not limited to such a configuration, and that any type of non-planar configuration of conductive elements 216 may be implemented. The plurality of conductive elements 216 may be connected together external to the porous material 210 in order to provide charge from an external power source.

[0052] In the illustrated embodiment of Fig. 6, the electrode 200 may include a plurality of conductive elements 218, each constructed of a helical shaped filament. The helical shaped filament may be a single conductive strand, or a plurality of strands electrically coupled together. Similar to the conductive elements 216, the helical shape of the conductive elements 218 may allow for larger surface area contact between the conductive elements 218 and the porous material 210 of the electrode 200. In this way, the conductive elements 218 may allow more uniform charge distribution within the electrode 200. In one embodiment, the conductive elements 218 may be formed of a spring-like material that, under compression forces applied during manufacture of the electrode 200, may allow coils of the helical shaped filament to move into closer proximity with each other. The spring-like characteristic of the conductive elements 218 may avoid potential damage to, or loss in connectivity in, the conductive elements 218 under the compression forces applied during manufacture of the electrode 200. The plurality of conductive elements 218, similar to the conductive elements 216, may be connected together external to the porous material 210 in order to provide charge from an external power source.

[0053] The electrode 200 according to the illustrated embodiment of Fig. 7 may include a plurality of conductive elements 220, constructed similarly to the conductive elements 218, with several exceptions. Rather than being formed of a helical shaped

filament, the plurality of conductive elements 220 may be formed of a sawtooth shaped filament. In one embodiment, the conductive elements 220 may be at least one of spring-like and connected together external to the porous material 210, similar to the conductive elements 218.

[0054] In the illustrated embodiment of Figs. 8A-B, the plurality of conductive elements 230 of the electrode 200 may be constructed of a dopant, such as powdered graphite or stainless steel fragments or shavings, introduced to the porous material 210 in manufacture. The concentration of conductive elements 230 in the porous material 210 may be controlled to enable uniform charge distribution within the porous material 210 in use in the CDI reactor 100. As depicted in Fig. 8A, the conductive elements 230 may be distributed throughout the porous material 210 of the electrode 200. A cross-section of the electrode 200 is shown in Fig. 8B to further illustrate the distribution of conductive elements 213 within the porous material 210.

### III. ELECTRODE INTERFACE

[0055] As described herein, capacitive deionization is a primary technology relied upon to remove contaminants from water flowing through the CDI system. In operation, the electrodes of the CDI reactor may be considered similar to a double layer capacitor whose fundamental removal mechanism in the context of water treatment is electrical double layer adsorption. As a result, enhancing or increasing the capacitance of the CDI reactor may yield improved removal performance. Increased capacitance of the CDI reactor may be achieved through various configurations. A cross-section of one such configuration is depicted in the illustrated embodiment of Fig. 9, which provides an uneven or nonplanar interface between the electrodes. This uneven or nonplanar interface may provide greater contact surface between the electrodes, thereby increasing the total charge capable of being carried by the electrodes.

[0056] The CDI reactor of the illustrated embodiment of Fig. 9 may be similar to the CDI reactor 100 described with respect to the illustrated embodiments of Figs. 1-3, and is generally designated 300. Like the CDI reactor 100, the CDI reactor 300 may include first and second electrodes 326, 328 having porous material 310, and a membrane 312 disposed between the first and second electrodes 326, 328, respectively similar to the first and second electrodes 26, 28 and the membrane 12. The CDI reactor 300 also may include terminals 315 configured to allow electrical connections between the electrodes 326, 328 and an external power supply 316, respectively similar to the terminals 15 and the external power supply 16.

[0057] In the illustrated embodiment, an interface 330, defined by the physical junction among first and second electrodes 326, 328 and the membrane 312, may be configured to be a nonplanar interface, such as a sawtooth interface. In the example nonplanar interface 330, the first electrode 326 may include a plurality of protrusions 352 and a plurality of depressions 350 that potentially mate with a corresponding plurality of protrusions 362 and plurality of depressions 360 of the second electrode 328. The membrane 312 may be disposed between the protrusions 352, 362 and the depressions 350, 360 to form a dielectric barrier between the electrodes 326, 328. The plurality of protrusions 352, 360 and the plurality of depressions 350, 360 may provide the interface 330 with a greater surface area than a planar interface between the first and second electrodes 326, 328. It should be understood that the size, shape, and number of protrusions and depressions may vary from application to application, depending on a variety of factors, including, for example, TDS removal performance for the CDI reactor 300.

#### IV. ADDITIONAL EMBODIMENTS

[0058] In Figs. 10-11, a CDI reactor in accordance with one embodiment is shown, and generally designated 400. For purposes of disclosure, the CDI reactor 400 in the illustrated embodiment is generally cylindrical, similar to the CDI reactor 100. Fig. 10 illustrates a transverse sectional view of the CDI reactor 400, and Fig. 11 illustrates a

longitudinal sectional view of the CDI reactor 400. It should be understood that the CDI reactor 400 is not limited to this construction, and that the CDI reactor 400 may be configured differently depending on the application.

[0059] In the illustrated embodiment, the CDI reactor 400 may include an electrode block 420, a water inlet 422, and a water outlet 424, similar to the electrode block 20, water inlet 22, and the water outlet 24 described in connection with the illustrated embodiment of Figs. 1-3. The electrode block 420 in the illustrated embodiment may include a plurality of electrodes 426, 428 capable of being energized by an external power source 416, such as a DC power source, to remove contaminants from water flowing from the water inlet 422 to the water outlet 424. The electrodes 426, 428 may include porous material 410, such as adsorbent activated carbon, and conductive material provided according to an embodiment described herein. In this way, the conductive material may be configured to facilitate charge distribution on the porous material 410.

[0060] In the illustrated embodiment of Figs. 10-11, the electrode block 420 of the CDI reactor 400 may define an opening 430 (or space) in direct fluid communication with the water inlet 422 and may be configured to allow water to flow from within the electrode block 420 to an outer portion 432 of the electrode block 420, coupled to the water outlet 424. In one embodiment, each of the plurality of electrodes 426, 428 of the electrode block 420 may include an electrode inlet 448, 446 that defines at least a portion of the opening 430, and is in direct fluid communication with the water inlet 422. And, each of the plurality of electrodes 426, 428 may include an electrode outlet 458, 456, coupled to the water outlet 424. With this configuration, water flowing from the water inlet 422, through the electrode block 420, and to the water outlet 424 may flow through a channel formed by one of the plurality of electrodes 426, 428. In an adsorption phase, depending on whether an electrode 426, 428 from among the plurality is charged positively (cathode) or negatively (anode), either anions or cations may be removed from the water flowing through the electrode 426, 428.

[0061] In a regeneration phase in which the water flow direction remains the same but the polarity of the plurality of electrodes 426, 428 is reversed, the discharge of anions or cations from each of the plurality of electrodes 426, 428 may remain separate or unmixed in the electrode block 420. Mixing between the anions and cations discharged from the plurality of electrodes 426, 428 may occur in the water outlet 424 external to the electrode block 420. In this way, regeneration of the plurality of electrodes 426, 428 by reversing polarity may not result in anions or cations migrating from one electrode to another electrode, potentially avoiding such an adverse effect, and potentially allowing for reversed polarity of an electrode and flushing of that electrode, simultaneously. In other words, the waste stream from the plurality of electrodes 426, 428 may not be mixed such that the ions being released during regeneration may not be taken by an opposite electrode.

[0062] The plurality of electrodes 426, 428 in the illustrated embodiment of Figs. 10-11 may be separated by one or more membranes 412, similar to the membrane 12 described in connection with the illustrated embodiment of Figs. 1-3. For example, the one or more membranes 412 may electrically insulate the plurality of electrodes 426, 428 from each other, and may or may not be water permeable. As depicted in the illustrated embodiment of Figs. 10-11, the electrode block 420 may be separated vertically by the membrane 412, and each electrode 426, 428 of the electrode block 420 may be electrically coupled to the external power source 416. In this configuration, the electrode block 420 may be divided into two oppositely charged electrodes 426, 428. The one or more membranes 412 and the electrode block 420 may be configured differently such that the electrode block 420 includes more than two electrodes 426, 428.

[0063] The electrode block 420 in the illustrated embodiment is depicted as being a tubular cylinder defining an opening 430 along the primary axis of the electrode block 420. However, it should be understood that the electrode block 420 is not limited to this configuration, and that the electrode block 420 may be configured according to any type of

shape or structure. As described above, influent water may enter the opening 430, flow through the charged electrodes 426, 428, and collect outside of the electrode block 420. In other words, influent water may be divided into two paths, passing through an anode or a cathode, respectively, and merging external to the electrode block 420. Water flowing through one electrode 426, 428 of the electrode block 420 in this manner may be treated to remove either anions or cations, but not both. As a result, waste produced during regeneration of the electrode block 420 may be less due to fewer ions being stored in the electrode block 420.

[0064] Turning to the illustrated embodiment of Fig. 12, a CDI reactor in accordance with one embodiment is shown, and generally designated 500. The CDI reactor 500 may include an electrode block 520, a water inlet 522, and a water outlet 524, similar to the electrode block 420, water inlet 422, and the water outlet 424 described in connection with the illustrated embodiments of Figs. 10-11. The electrode block 520 in the illustrated embodiment may include a plurality of electrodes 526, 528 capable of being energized by an external power source 516, such as a DC power source, to remove contaminants from water flowing from the water inlet 522 to the water outlet 524. The electrodes 526, 528 may include porous material 510, such as adsorbent activated carbon, and conductive material 512. Conductive material provided according to an embodiment described herein.

[0065] In the illustrated embodiment of Fig. 12, the electrode block 520 of the CDI reactor 500 may be configured to allow water to flow from an electrode inlet 546 at an outer portion of the electrode block 520, through a plurality of electrodes 526, 528 of the electrode block 520, and to an electrode outlet 556 at an outer portion of the electrode block 520. The electrode inlet 546 and the electrode outlet 556 may be defined at least in part by opposing outer portions of the electrode block 420. As a result, ions in the water flowing from the electrode inlet 546 to the electrode outlet 556 may pass through the plurality of electrodes

526, 528, thereby allowing for removal of both cations and anions from the water flowing through the electrode block 520.

[0066] In one embodiment, the electrode block 520 of the CDI reactor 500 may define an opening 530 (or space) configured to allow water to flow from within the electrode block 520 to the electrode inlet 546 and the electrode outlet 556. The opening 530 may enable the CDI reactor 500 to direct water in a regeneration phase from the opening 530 to the electrode inlet 546 and to the electrode outlet 556. This way, the CDI reactor 500 may achieve regeneration similar to the CDI reactor 400 without mixing the cation and anion waste streams. The CDI reactor 500 may be reconfigurable such that the water inlet 522 of the CDI reactor 500 may be configurable between an adsorption mode and a regeneration mode. More specifically, in the adsorption mode, the water inlet 522 may provide water to be treated to the electrode inlet 546, and, in the regeneration mode, the water inlet 522 may provide water to the opening 530 for regenerating the electrode block 520. In the regeneration mode, a CDI system utilizing the CDI reactor 500 may divert waste from the electrode inlet 546 and the electrode outlet 524 to a waste effluent stream.

[0067] In one embodiment, the CDI reactor 500 may regenerate the electrode block 520 without changing the direction of water flow through the electrode block 520. For example, rather than reconfiguring the electrode inlet 546 to discharge water rather than receive water, the CDI reactor 500 may regenerate by allowing water to flow from the electrode inlet 546 to the electrode outlet 556, the same direction of flow in the adsorption phase, and by controlling the external power supply 516 according to an embodiment described herein.

[0068] As described herein, the external power supply 516 may disconnect the plurality of electrodes 526, 528, releasing collected ions, and allowing water flowing through the system to flush the ions from the electrode block 520. This process may utilize diffusion to achieve regeneration of the plurality of electrodes 526, 528. Alternatively, the external

power supply 516 may be controlled to provide an AC voltage to the plurality of electrodes 526, 528, reversing polarity of the applied voltage a plurality of times, and each time reducing the applied voltage magnitude.

[0069] In one embodiment, the CDI reactor 500 may regenerate the electrode block 520 by reversing the direction of water flow through the electrode block 520. For example, the water inlet 522 may be reconfigured to output water, and the water outlet 524 may be reconfigured to receive water. The external power supply 516 may be controlled to regenerate the electrode block 520 according to any of the embodiments described herein.

[0070] Although described in connection with an opening 530, it should be understood that the electrode block 520 may not include the opening 530. Further, in embodiments in which the electrode block 530 includes an opening 530, the opening 530 may serve as an entry point for water in a regeneration mode, as described above, but in addition to or alternatively, the opening 530 may serve other purposes. For example, the opening 530 may provide a space for water flowing through the electrode block 520 to be treated by UV light. A UV light source (not shown) may be arranged to direct UV light in the opening 530 such that water flowing through the opening 530 may be treated. To direct water through the opening 530 in this embodiment, the membrane 512 may be impermeable to water. As another example, the opening 530 may be filled to direct water flow within the electrode block 520 and to a side of the opening 530.

## V. REGENERATION

[0071] A CDI system according to one embodiment is shown in Fig. 13, and generally designated 600. The CDI system 600 may include a CDI reactor 610 configured according to one or more of the CDI reactors described herein, including, for example, a feed-through reactor or a feed-between reactor. For purposes of disclosure, the CDI reactor 610 in the illustrated embodiment of Fig. 13 is configured to operate in a feed-between manner. That is, the CDI reactor 610 is configured to direct water between at least two

electrodes rather than through the electrodes, themselves. Again, the CDI system 600 and the CDI reactor 610 are not limited to this configuration.

[0072] In the illustrated embodiment, the CDI reactor 610 may include a water inlet 614 through which water to be treated or regeneration water may be provided to the CDI reactor 610, and may include a water outlet 616 through which treated water or waste effluent may be output from the CDI reactor 610. The CDI reactor 610 may also include a first terminal 660 and a second terminal 662 in electrical communication with electrodes of the CDI reactor 610. Depending on the timing and polarity of power applied to the first and second terminals 660, 662, the CDI reactor 610 may be operated (a) in an adsorption mode in which ions are removed from water to be treated, or (b) in a regeneration mode in which ions adsorbed by the electrodes are discharged.

[0073] The CDI system 600 may include a control system 620 capable of controlling operation of one or more components of the CDI system 600, including the CDI reactor 610. As depicted, the CDI system 600 may include a water inlet control valve 612 fluidly coupled to the water inlet 614, and capable of controlling whether a water feed stream 630 or a regeneration stream 632 is provided to the water inlet 614 of the CDI reactor 610. The CDI system 600 may also include a water outlet control valve 618 fluidly coupled to the water outlet 616, and capable of controlling whether water flowing from the water outlet 616 of the CDI reactor 610 is directed to a purified water stream 640 or a waste effluent stream 642. The control system 620 may be operably coupled to the water inlet control valve 612 and the water outlet control valve 618 to direct water in and out of the CDI reactor 610 depending on the mode of operation. For example, in an adsorption mode of operation, the control system 620 may direct the water inlet control valve 612 to provide water from the water feed stream 630, and may direct the water outlet control valve 618 to fluidly couple the water outlet 616 to the purified water stream 640. In a regeneration mode of operation, the control system 620 may direct the water inlet control valve 612 to provide water from the regeneration stream

632, and may direct the water outlet control valve 618 to fluidly couple to the water outlet 618 to the waste effluent stream 642. Although the CDI system 600 is described in connection with the water inlet control valve 612, the water outlet control valve 616, the water feed stream 630, the regeneration stream 632, the purified water stream 640, and the waste effluent stream 642, it should be understood that the CDI system 600 may be configured differently such that the CDI system 600 includes some but not all of these features, or includes additional features. For example, the CDI system 600 may not include a regeneration stream 632 and a water inlet control valve 612; the water feed stream 630 may be fluidly coupled to the water inlet 614 and serve to provide both water to be treated and regeneration water to the CDI reactor 610.

[0074] The control system 620 may include a control unit 624 and a power supply 622. The control unit 624 may be a processor having memory, and capable of directing operation of the CDI system 600, as described above, as well as the power supply 622. In the illustrated embodiment, the power supply 622 may be configured to be electrically connected to the terminals 660, 662 of the CDI reactor 610, and, based on input from the control unit 624, may control one or more characteristics of power applied to the terminals 660, 662. For example, the control unit 624 may direct the power supply 622 to control at least one of the voltage and current supplied to the terminals 660, 662 of the CDI reactor 610. By controlling the power supplied to the CDI reactor 610, the control unit 624 may operate the CDI reactor 610 in one or more modes of operation, including an adsorption mode and a regeneration mode.

[0075] In the adsorption mode of operation, the control unit 624 may direct the power supply 622 to maintain a substantially constant voltage across the terminals 660, 662 in a first polarity. Alternatively, the control unit 624 may direct the power supply 622 to supply constant current through the terminals 660, 662 in the first polarity. By using a constant current source instead of constant voltage, further control may be achieved over each

adsorption cycle, including, for example, the amount of time before reaching saturation during adsorption. In a constant voltage configuration, current may peak at the beginning of a filtration or adsorption cycle and decrease as the electrodes become saturated with ions. This variance in current may be indicative of an inconsistent ion removal rate throughout the adsorption cycle. The constant current source may limit the peak current, and therefore may achieve a more consistent ion removal rate throughout the adsorption cycle. Regardless of whether the power supply 622 is operated in a constant voltage mode or a constant current mode, the voltage supplied by the power supply 622 may be maintained below a threshold to potentially avoid electrolysis in the water path.

[0076] To achieve regeneration of the CDI connector 610 in a regeneration mode, the control unit 624 may direct the power supply 622 to operate in a variety of ways. For example, the power supply 622 may electrically isolate the terminals 660, 662, thereby isolating the electrodes of the CDI reactor 610, and enabling ions collected by the electrodes to be discharged through a diffusion process. As another example, the power supply 622 may apply voltage across the terminals 660, 662 in a second polarity, opposite from the first polarity provided during the adsorption mode. In other words, the power supply 622 may reverse the voltage applied across terminals 660, 662. By reversing the voltage, the electrodes of the CDI reactor 610 may repulse ions collected in the adsorption phase to potentially enhance diffusion.

[0077] In one embodiment, the control unit 624 may operate the CDI system 600 in a regeneration mode by controlling the power supply 622 to successively reverse the voltage applied to the electrodes 660, 662, as illustrated in Figs. 14-15. The voltage applied to the electrode 660, 662 may be reversed a plurality of times, and each time the applied voltage is reversed, the magnitude of the voltage may be decreased. For example, the power supply 622 may be directed to reverse the voltage applied to the electrodes 660, 662 to a second polarity, opposite or reverse from the first polarity provided during the adsorption mode.

After a period of time, the power supply 622 may be directed to again reverse the voltage applied to the electrodes 660, 662, returning the applied voltage to the first polarity, but at a magnitude less than the magnitude applied previously. Put differently, the control unit 624 may achieve regeneration of the CDI reactor 610 by reversing the polarity of the voltage applied to the electrodes 660, 662 a plurality of times, each time decreasing the magnitude of the applied voltage. The successively alternating voltage applied to the electrodes 660, 662 may be visualized as a convergent oscillation, or regarded as an AC voltage source having a decreasing root-mean-square (RMS) voltage over time. By regenerating the CDI reactor 610 in this manner, the CDI system 600 may quickly desorb or release ions, potentially even ions that have been adsorbed deeply within the electrodes, or potentially ions that may be inefficient to flush using diffusion due to their longer diffusion distance compared to ions attached to an outer surface of an electrode.

[0078] As depicted in Figs. 14-15, the voltage applied to the terminals 660, 662 of the CDI reactor 610 is successively reversed a plurality of times until the voltage is substantially zero, potentially on a scale of a few minutes. At this stage, the control unit 624 may direct the power supply 622 to maintain a substantially zero voltage across the terminal 660, 662, as shown in Fig. 14. Alternatively, the power supply 622 may be controlled to disconnect the terminals 660, 662 such that the voltage across the terminals 660, 662 is allowed to float. In another alternative, the power supply 622 may be controlled to provide a low magnitude alternating voltage VAC to the terminals 660, 662, as shown in Fig. 15.

[0079] Although regeneration according to this embodiment is described in connection with successively reducing the magnitude of the voltage until it reaches substantially zero, it should be understood that the voltage applied to the terminals 660, 662 may not be reduced to zero, and that the number of times the voltage is successively reversed may vary from application to application. The timing and amplitude for the pulses (e.g., application of the voltage at a particular magnitude) may vary from application to

application, as well. For example, the pulse width of each pulse and the amplitude of each pulse used for regeneration may depend on factors such as the flow rate of the feed water, the TDS concentration of the feed water, or the dimensions of the CDI reactor 610, or a combination thereof.

[0080] The interaction between ions and electrodes during adsorption and regeneration according to one embodiment is depicted in Figs. 16-20. For purposes of disclosure, the illustrated embodiment of Figs. 16-20 is described in connection with a water feed 714 that flows between a first electrode 710 and a second electrode 712. This arrangement of the electrodes 710, 712 and the water feed 714 may be considered a feed-between configuration. It should be understood, however, that a feed-through configuration (such as the CDI reactor 100 described in connection with the illustrated embodiments of Figs. 1-3) may be implemented instead, and that such a configuration may be operated in a similar manner. Similar to embodiments described herein, the first electrode 710 and the second electrode 712 may include porous material capable of being charged by application of a voltage across the first and second electrodes 710, 712.

[0081] Starting with Fig. 16, a voltage  $V_1$  may be applied across the first electrode 710 and the second electrode 712 such that they form a capacitor in which the first electrode 710 is a cathode and the second electrode 712 is an anode. In other words, with the voltage  $V_1$  applied across the first electrode 710 and a second electrode 712, charge may accumulate on the first and second electrodes 710, 712 based on the following relationship between charge ( $Q$ ), capacitance ( $C$ ) of the electrodes, and applied voltage ( $V$ ):

$$[0082] \quad Q = C \cdot V$$

[0083] As water in the water feed 714 flows between the first and second electrode 710, 712, charged particles within the water may be attracted to and held by the first and second electrodes 710, 712. In accordance with Coulomb's law, a charged particle within the water may experience electrostatic force proportional to the product of a charge of the charge

particle and the charge on a respective electrode 710, 712, and inversely proportional to the distance between the charged particle and the respective electrode 710, 712. Specifically, using Coulomb's law, the relationship between two charges ( $q_1$  and  $q_2$ ), electrostatic force ( $F$ ), and distance ( $d$ ) may be generally expressed as follows:

$$[0084] \quad F \approx \frac{(q_1 \cdot q_2)}{d^2}$$

[0085] The effect of Coulomb's law on charged particles within the water feed 714 is shown in Fig. 17, where a negatively charged particle 720 is attracted to and held by the positively charged electrode 710, and a positively charged particle 722 is attracted to and held by the negatively charged electrode 712. Accordingly, applying a voltage on the first and second electrode 710, 712 may cause accumulation of negatively and positively charged particles within the water feed 714, thereby removing the charged particles from the water feed 714 to purify the water.

[0086] As mentioned above, the first and second electrodes 710, 712 may become saturated over time such that their ability to attract and hold charged particles is diminished. To regenerate the first and second electrode 710, 712, a CDI system may initiate steps to discharge the charged particles that have been attracted to and held by the electrodes 710, 712. According to one embodiment, a CDI system may regenerate electrodes by reversing the polarity of the voltage applied to the electrodes a plurality of times, each time reducing the magnitude of the applied voltage. For example, the electrodes may be regenerated by applying voltage in accordance with the illustrated embodiment of Fig. 15. Fig. 18 is a representative illustration of the effect of an initial reversal according to this embodiment. During a first time period T1, the voltage V2 applied to the first and second electrode 710, 712 may be reversed in polarity from the voltage V1 applied during the adsorption phase. The magnitude of the voltage V2 may be the similar or less than the voltage V1.

[0087] By applying voltage V2 during the first time period T1, the charged particles 720, 722 held by the first and second electrode 710, 712 may be shed, and may become

attracted toward each other. As can be seen in Fig. 18, reversing the polarity on the first and second electrode 710, 712 may reverse their respective charge such that the first electrode 710 may become an anode, and the second electrode 712 may become a cathode. In embodiments in which the magnitude of the voltage V2 is less than the magnitude of the voltage V1, there may be less charge on the first and second electrode 710, 712 such that an electrostatic force between the charged particles 720, 722 may be greater than an electrostatic force between the charged particles and the first and second electrodes 710, 712. In other words, the first and second electrodes 710, 712 may not attract the charged particles 720, 722 as tightly, thereby potentially allowing the charged particles 720, 722 to become attracted toward each other.

[0088] During a second time period T2, following the first time period T1, the voltage applied to the first and second electrodes 710, 712 may be reversed again. That is, a voltage V3, with a polarity opposite the voltage V2 or the same as the voltage V1, may be applied to the first and second electrodes 710, 712 during the second time period T2. The magnitude of the voltage V3 may be less than the magnitude of the voltage V2. As a result, the migration of the charged particles 720, 722 may again reverse course but with less force due to a lower electrostatic force applied by the first and second electrodes 710, 712, as shown in Fig. 19.

[0089] During a third time period T3, following the second time period T2, the voltage applied to the first and second electrode 710, 712 may be reversed yet again. That is, a voltage V4, with a polarity opposite the voltage V3 or the same as the voltage V2, may be applied to the first and second electrodes 710, 712 during the third time period T3. The pressure of the water feed 714 during the first, second, and third time period T1, T2, T3 may operate to diffusively flush the charged particles 720, 722 from the electrodes 710, 712 of the CDI reactor, ultimately removing the charged particles 720, 722 from the CDI reactor. Although described in connection with reversing the polarity multiple times, it should be

understood that a method of regeneration according to one embodiment may reverse the polarity applied to the electrodes any number of times, including, for example, once or twice.

[0090] In addition to or alternatively, the regeneration process utilized for the CDI reactor may include applying a low magnitude alternating voltage, such as the alternating voltage VAC depicted in Fig. 15, during any time period. This low magnitude alternating voltage may provide alternating charge on the first and second electrodes 710, 712 that may suspend the charged particles 720, 722 within the water feed 714, allowing the flow of water to carry the charged particles away from the first and second electrode 710, 712 to a discharge stream.

[0091] Directional terms, such as “vertical,” “horizontal,” “top,” “bottom,” “upper,” “lower,” “inner,” “inwardly,” “outer” and “outwardly,” are used to assist in describing the invention based on the orientation of the embodiments shown in the illustrations. The use of directional terms should not be interpreted to limit the invention to any specific orientation(s).

[0092] The above description is that of current embodiments of the invention. Various alterations and changes can be made without departing from the spirit and broader aspects of the invention as defined in the appended claims, which are to be interpreted in accordance with the principles of patent law including the doctrine of equivalents. This disclosure is presented for illustrative purposes and should not be interpreted as an exhaustive description of all embodiments of the invention or to limit the scope of the claims to the specific elements illustrated or described in connection with these embodiments. For example, and without limitation, any individual element(s) of the described invention may be replaced by alternative elements that provide substantially similar functionality or otherwise provide adequate operation. This includes, for example, presently known alternative elements, such as those that might be currently known to one skilled in the art, and alternative elements that may be developed in the future, such as those that one skilled in the art might,

upon development, recognize as an alternative. Further, the disclosed embodiments include a plurality of features that are described in concert and that might cooperatively provide a collection of benefits. The present invention is not limited to only those embodiments that include all of these features or that provide all of the stated benefits, except to the extent otherwise expressly set forth in the issued claims. Any reference to claim elements in the singular, for example, using the articles “a,” “an,” “the” or “said,” is not to be construed as limiting the element to the singular.

CLAIMS

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A reactor for a capacitive deionization system, the capacitive deionization system being configured to remove contaminants from water, said reactor comprising:

a water inlet capable of receiving feed water;

a plurality of electrodes in fluid communication with said water inlet, said plurality of electrodes configured to adsorb ions from the feed water to provide purified water, each of said plurality of electrodes including porous material and a plurality of conductive elements, wherein said plurality of conductive elements are separate from each other;

a plurality of terminals configured to provide power to said plurality of electrodes, wherein, in response to being provided power from said plurality of terminals, each of said plurality of electrodes forms an electrode charge that is positive or negative, wherein said plurality of electrodes are configured to adsorb ions having a charge opposite to said electrode charge; and

a water outlet in fluid communication with said water inlet, said water outlet being capable of providing the purified water from said reactor.

2. The reactor of claim 1 wherein the feed water is at least one of water to be treated and regeneration water.

3. The reactor of claim 1 wherein said plurality of electrodes are disposed in fluid communication with said water inlet such that the feed water is directed through one or more of said plurality of electrodes.

4. The reactor of claim 1 wherein said porous material is at least one of activated carbon and metal oxide material.

5. The reactor of claim 4 wherein said porous material includes activated carbon, and wherein, in response to being provided power, said activated carbon forms said electrode charge such that said activated carbon adsorbs ions from the feed water.

6. The reactor of claim 4 wherein said activated carbon removes organic contaminants from the feed water.

7. The reactor of claim 1 wherein said plurality of conductive elements are separate from each other such that said porous material separates each of said plurality of conductive elements.

8. The reactor of claim 1 wherein each of said plurality of conductive elements is directly electrically connected to one or more of said plurality of terminals external to said porous material.

9. The reactor of claim 1 wherein said plurality of conductive elements are a dopant within said porous material.

10. The reactor of claim 9 wherein said dopant is at least one of stainless steel fragments and graphite particles.

11. The reactor of claim 1 further comprising at least one membrane arranged to electrically insulate a first electrode from a second electrode, wherein said first electrode and said second electrode are oppositely charged, and wherein said plurality of electrodes includes said first electrode and said second electrode.

12. The reactor of claim 1 wherein in response to reversing said power provided to said plurality of terminals, said plurality of electrodes electrostatically repulse one or more adsorbed ions, wherein said power is reversed a plurality of times in a regeneration mode, and wherein a magnitude of said power is successively decreased each of said plurality of times said power is reversed in said regeneration mode.

13. An electrode block for a reactor of a capacitive deionization system, the capacitive deionization system being configured to remove contaminants from feed water, said electrode block comprising:

a plurality of electrodes configured to adsorb ions from feed water to provide purified water, each of said plurality of electrodes including porous material and conductive material;

a plurality of terminals configured to provide power to said plurality of electrodes, wherein, in response to being provided power from said plurality of terminals, each of said plurality of electrodes forms an electrode charge that is positive or negative, wherein said plurality of electrodes are configured to adsorb ions having a charge opposite to said electrode charge; and

one or more membranes arranged to electrically insulate said plurality of electrodes from each other, wherein at least one of said membranes defines an interface between a first electrode from among said plurality and a second electrode from among said plurality, wherein said interface is a non-planar interface.

14. The electrode block of claim 13 wherein each of said first electrode and said second electrode includes an interface surface in contact with said at least one membrane, wherein said interface surface of said first electrode and said interface surface of said second electrode includes at least one protrusion.

15. The electrode block of claim 14 wherein said interface surface of said first electrode and said surface interface of said second electrode includes at least one depression, wherein said at least one protrusion and said at least one depression interface with each other to form said non-planar interface.

16. The electrode block of claim 13 wherein said one or more membranes are water permeable.

17. The electrode block of claim 13 wherein water to be treated is capable of flowing through one or more of said plurality of electrodes.

18. A reactor for a capacitive deionization system, the capacitive deionization system being configured to remove contaminants from water, said reactor comprising:

a water inlet capable of receiving feed water;

a water outlet capable of providing effluent water;

a plurality of electrodes in fluid communication with said water inlet and said water outlet, said plurality of electrodes configured to adsorb ions, each of said plurality of electrodes including porous material and conductive material; and

wherein each of said plurality of electrodes is arranged to be directly fluidly coupled to said water inlet and said water outlet, wherein water flows through said plurality of electrodes from said water inlet to said water outlet.

19. The reactor of claim 18 wherein said plurality of electrodes form an electrode block having an opening that is directly fluidly coupled to said water inlet.

20. The reactor of claim 19 wherein the feed water is capable of flowing through said opening of said electrode block to an outer surface of said electrode block, wherein said outer surface is directly fluidly coupled to said water outlet.

21. The reactor of claim 18 wherein the feed water is regeneration water and the effluent water is waste water.

22. The reactor of claim 18 wherein the feed water is water to be treated and the effluent water is purified water.

23. The reactor of claim 18 wherein each of said plurality of electrodes forms a separate channel through which water flows from said water inlet to said water outlet.

24. A capacitive deionization system configured to remove contaminants from water, said system comprising:

a reactor having a water inlet, a water outlet, and a plurality of terminals, wherein in response to power being supplied to said plurality of terminals at a first polarity, said reactor is configured to remove ions from feed water provided to said water inlet;

a power supply electrically coupled to said plurality of terminals, said power supply capable of providing power to said reactor in an adsorption mode at said first polarity to remove ions from the feed water, said power supply capable of providing power in a regeneration mode to said reactor to generate said reactor, wherein, in said regeneration mode, said reactor discharges ions adsorbed in said adsorption mode; and

a control unit operably coupled to said power supply, said control unit programmed to direct said power supply to supply power according to at least one of said adsorption mode or said regeneration mode, wherein said control unit is programmed to direct said power supply in a regeneration mode to reverse a polarity of power supplied to said plurality of terminals a plurality of times.

25. The capacitive deionization system of claim 24 wherein said control unit is programmed to direct said power supply in said regeneration mode to reduce a magnitude of a voltage applied to said plurality of terminals for each successive reversal of said polarity.

26. The capacitive deionization system of claim 24 wherein said control unit is programmed to direct said power supply in said regeneration mode to provide an AC voltage to said plurality of terminals, wherein an root-mean-square voltage of said AC voltage decreases over time.

27. A method of regenerating a capacitive deionization system to discharge ions adsorbed during an adsorption phase, the method comprising:

providing a reactor having a water inlet, a water outlet, and a plurality of terminals;

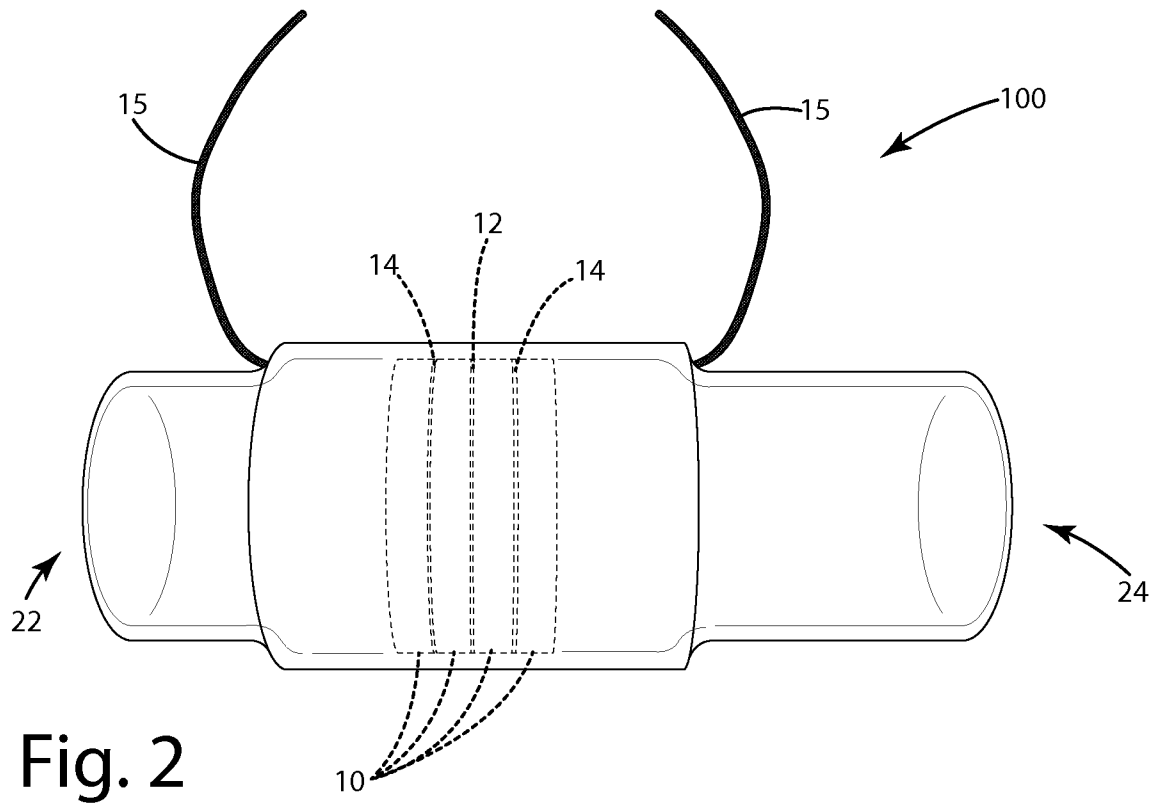
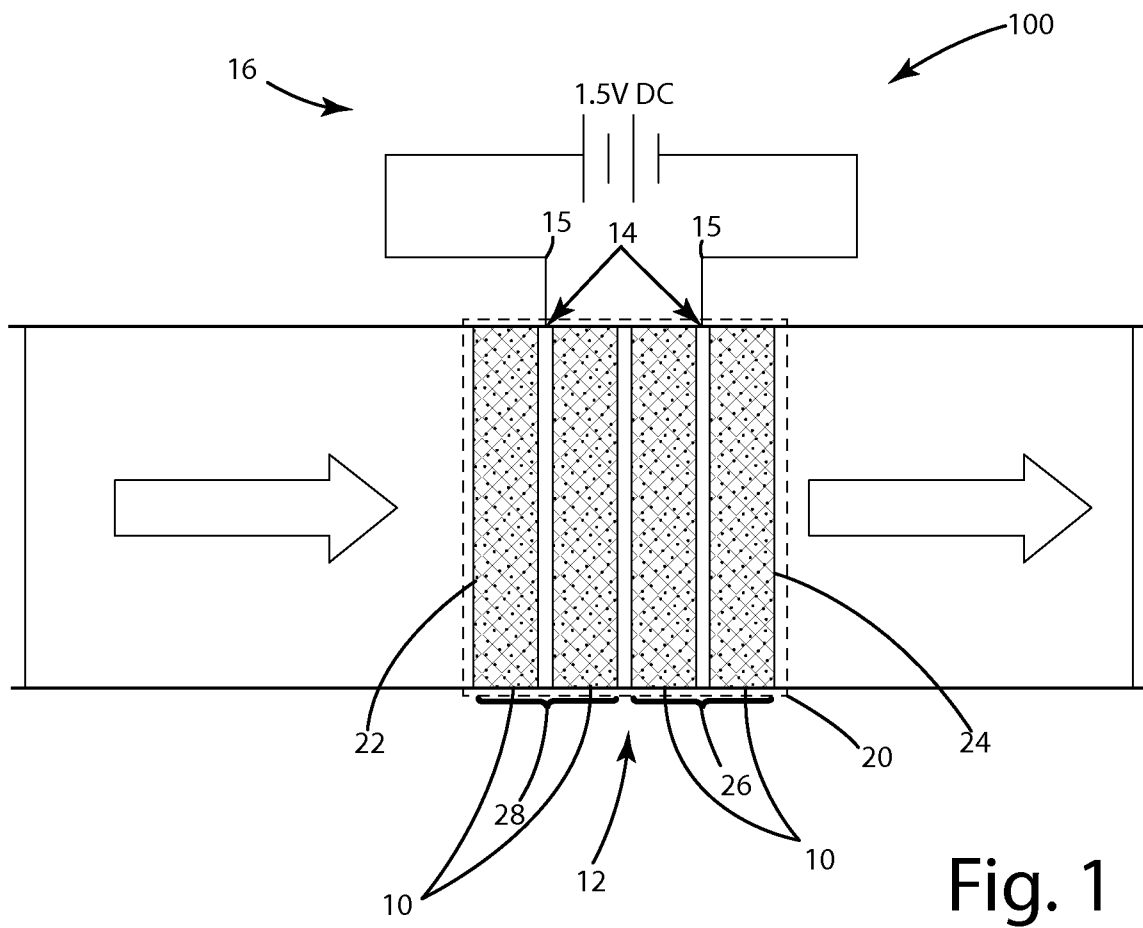
operating the reactor in the adsorption mode by applying power to the plurality of terminals at a first voltage having a first polarity;

applying power to the plurality of terminals at a second voltage having a second polarity reversed from the first polarity; and

applying power to the plurality of terminals at a third voltage having a third polarity reversed from the second polarity.

28. The method of claim 27 wherein a magnitude of the second voltage is less than a magnitude of the first voltage, and wherein a magnitude of the third voltage is less than the magnitude of the second voltage.

29. The method of claim 27 wherein said applying power at the second voltage and the third voltage regenerates the reactor, wherein said applying power at the second voltage and the third voltage provides an AC voltage having an RMS voltage that decreases over time.



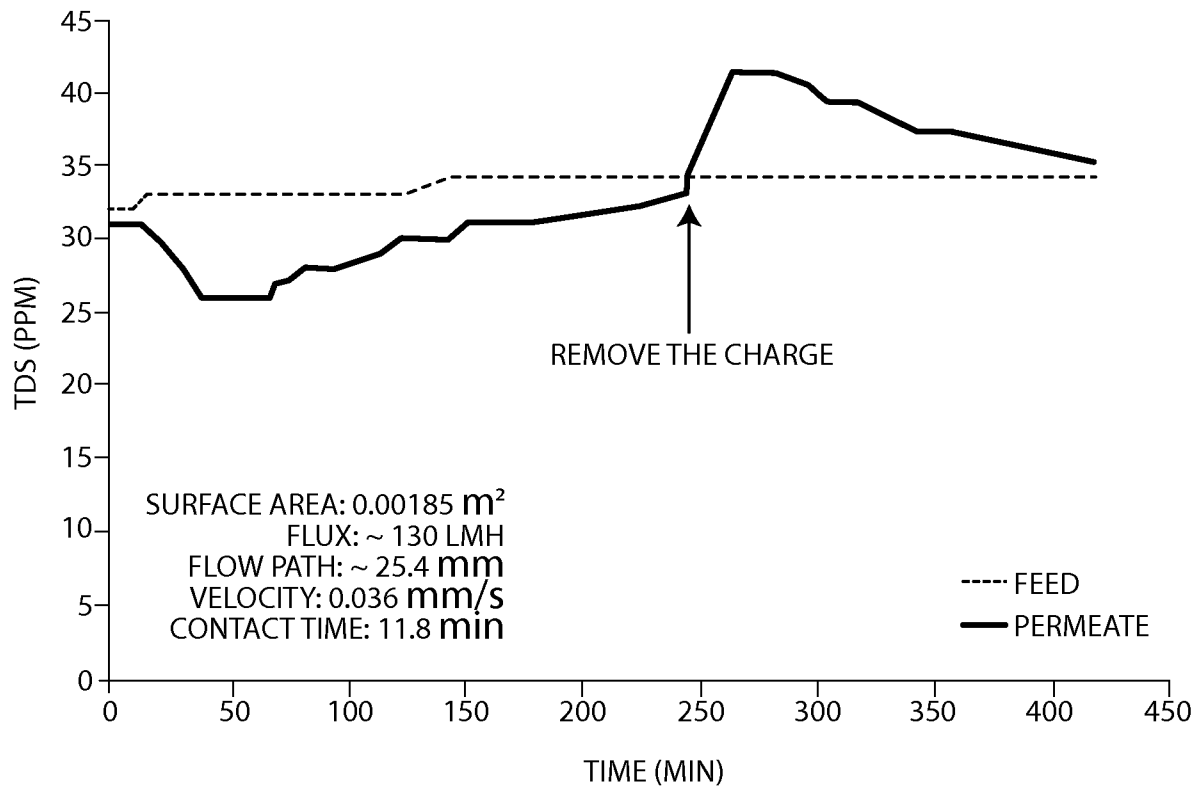
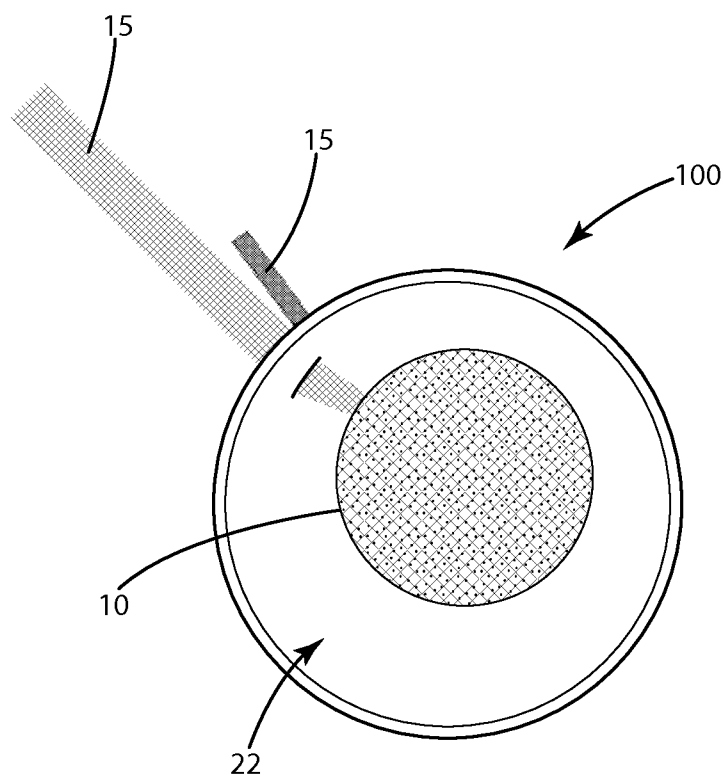
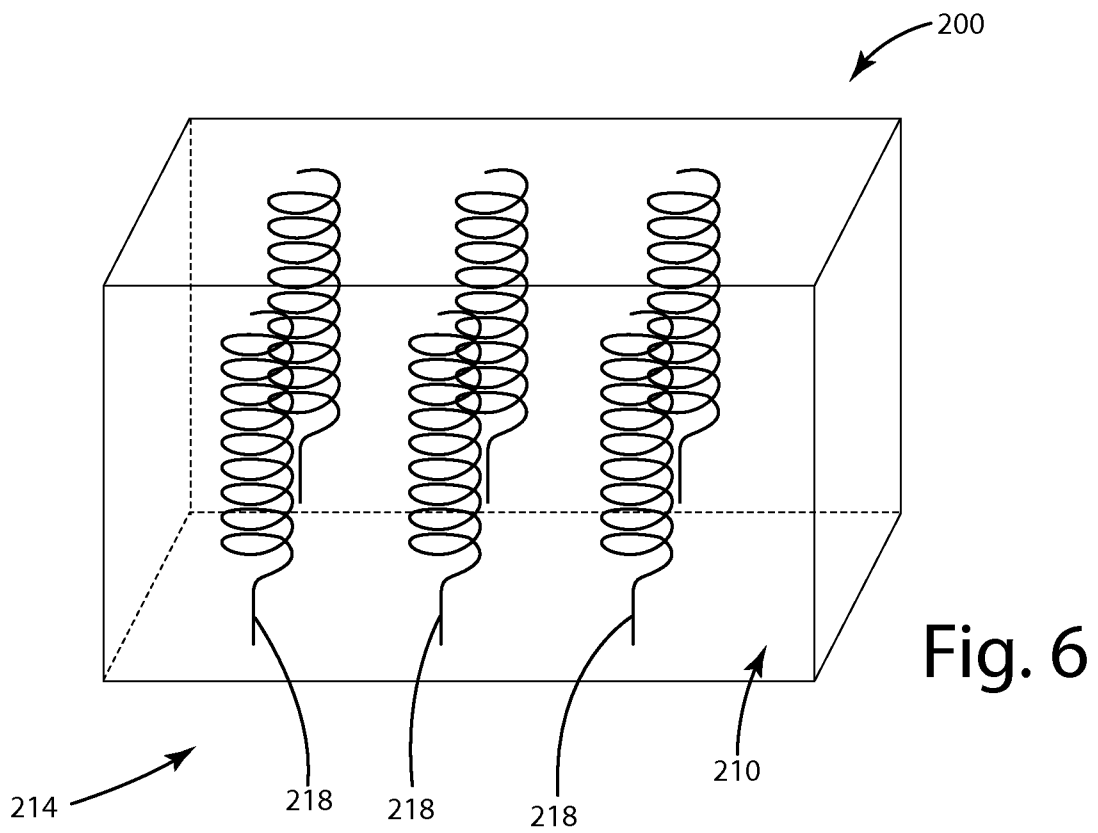
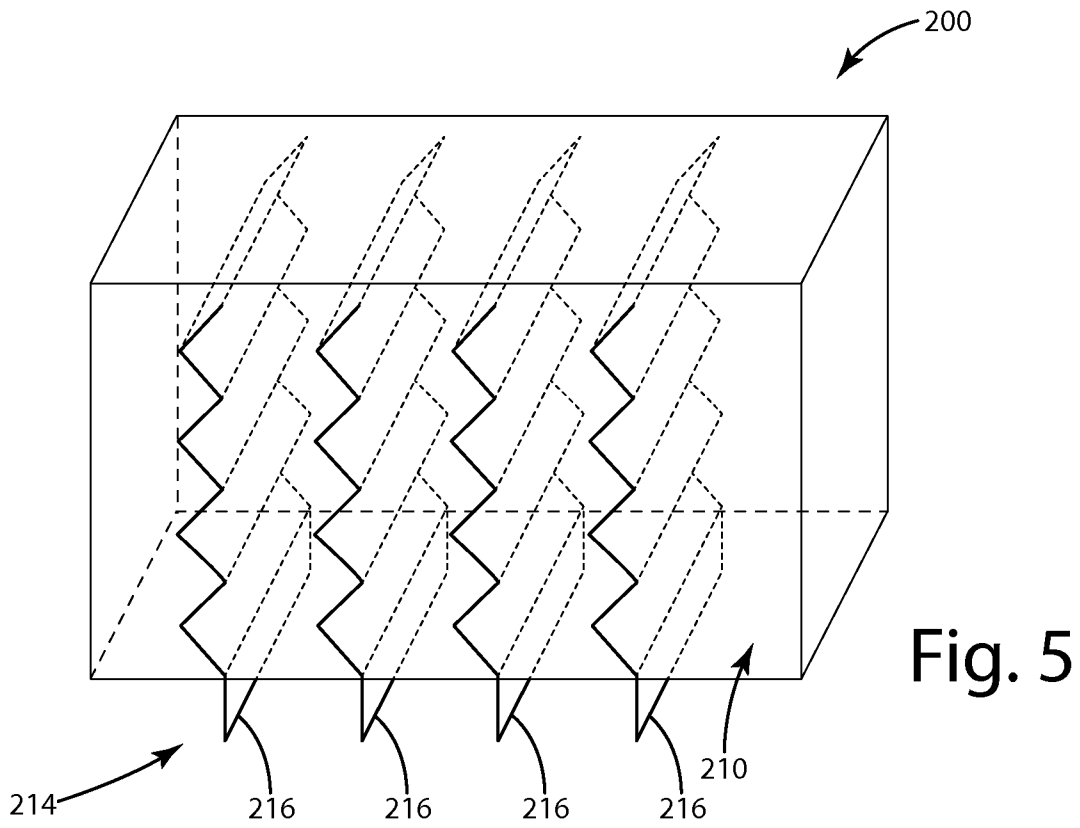
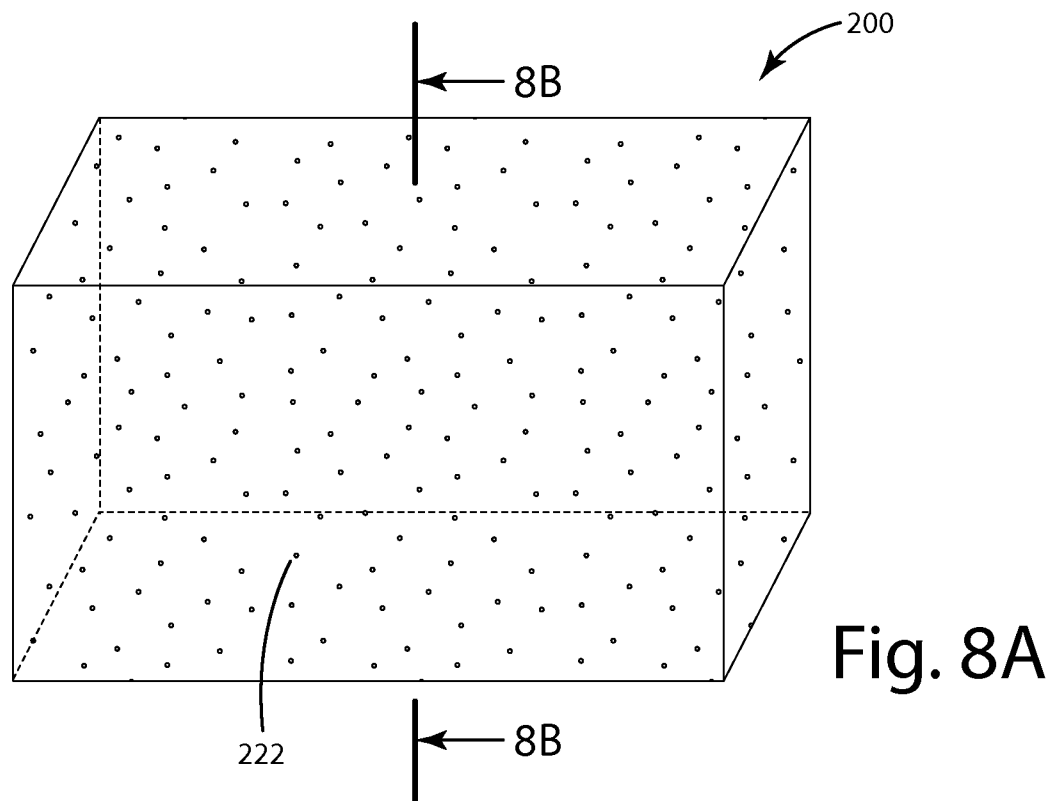
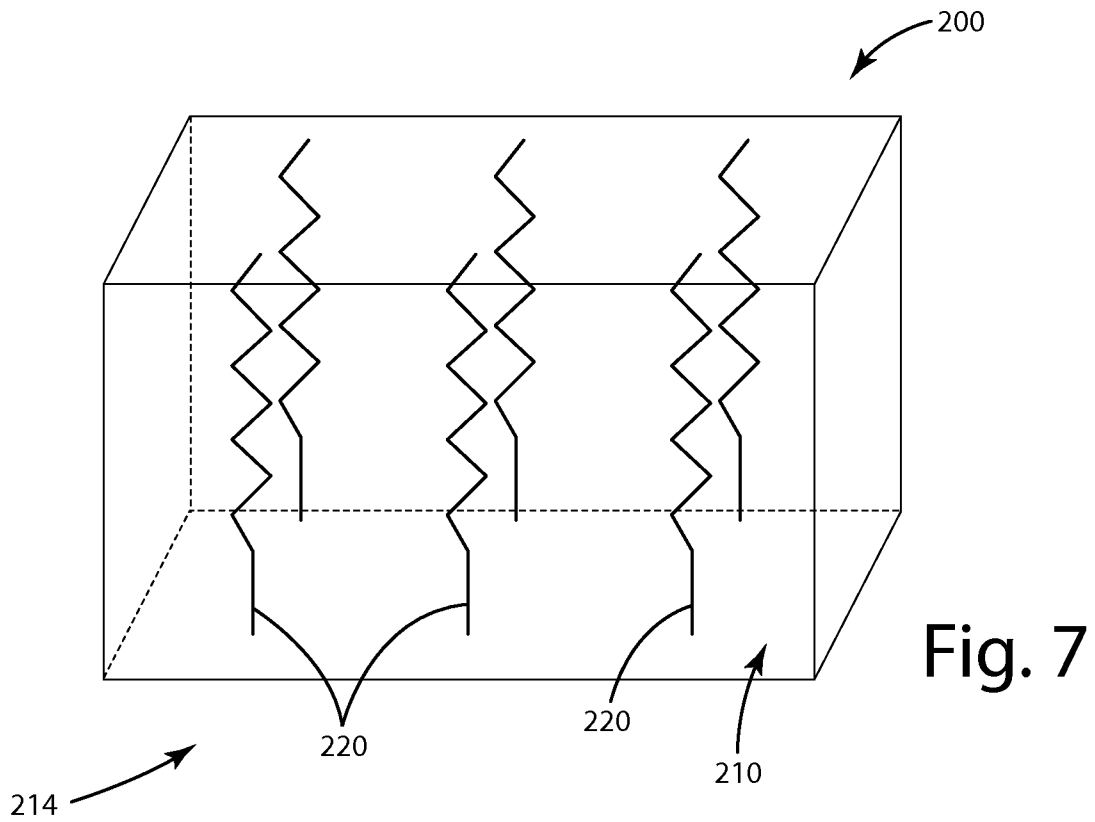


Fig. 4





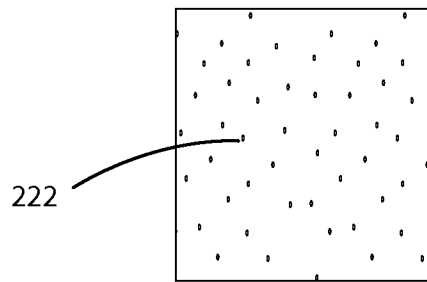


Fig. 8B

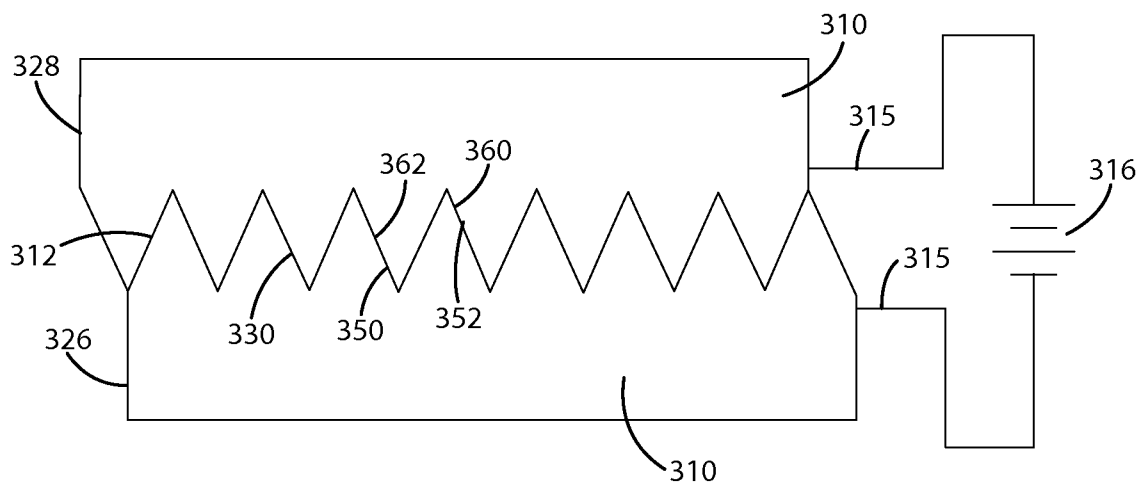


Fig. 9

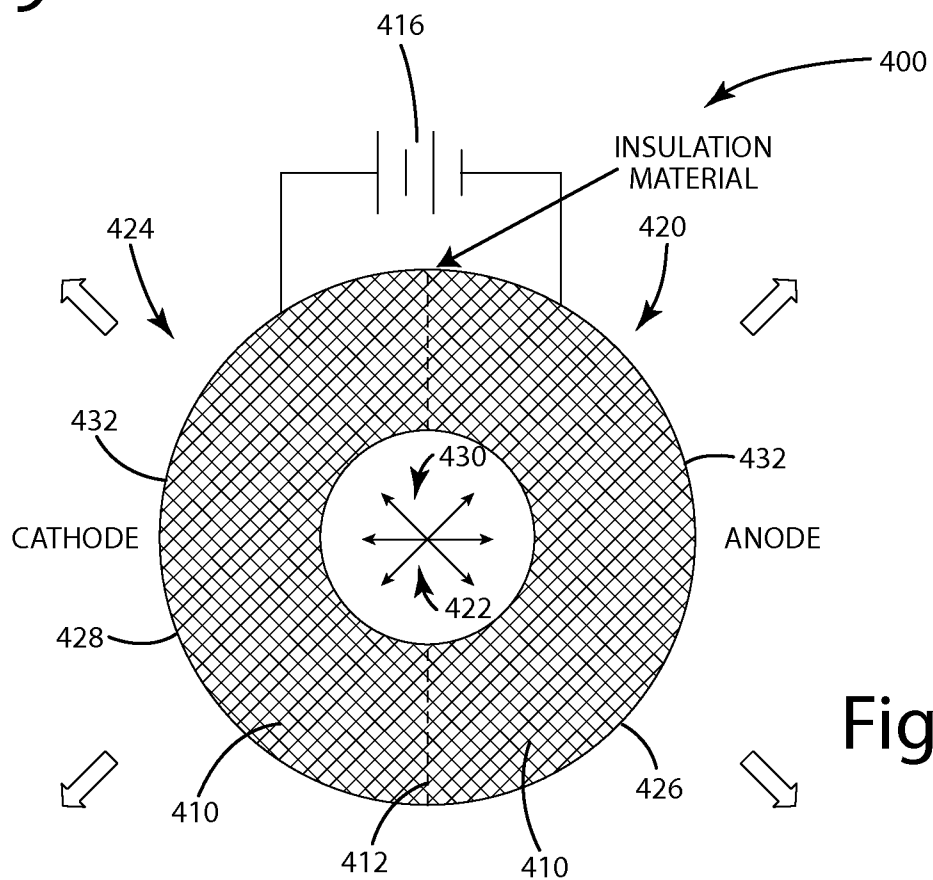
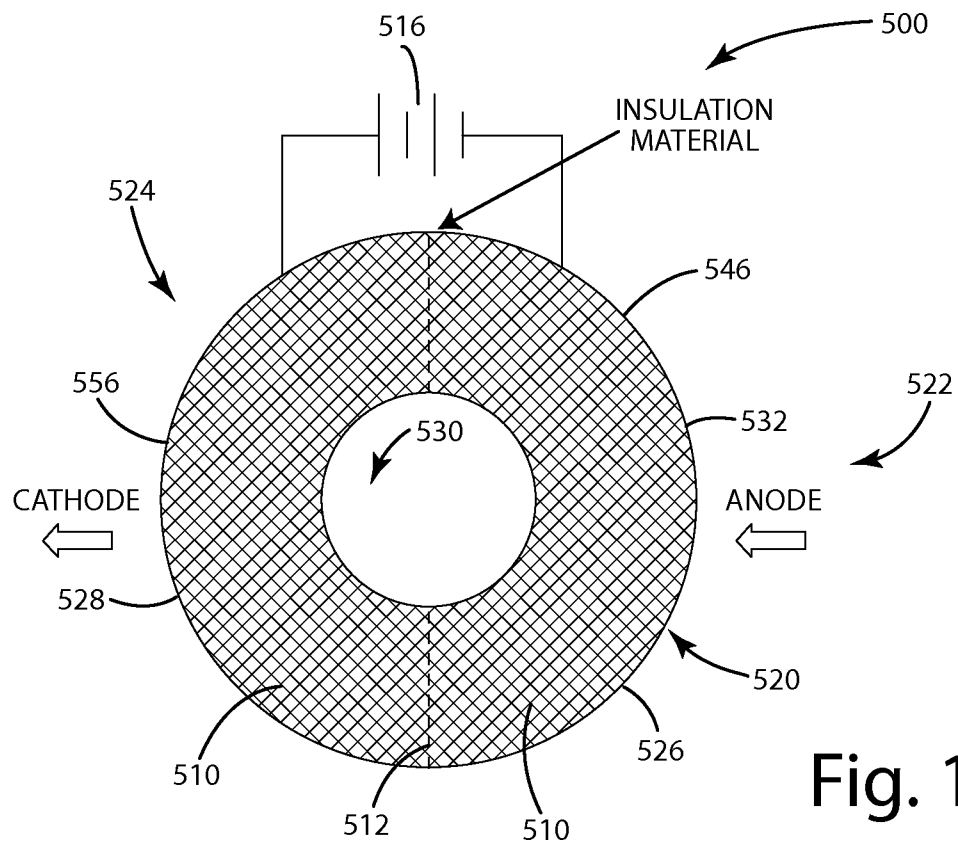
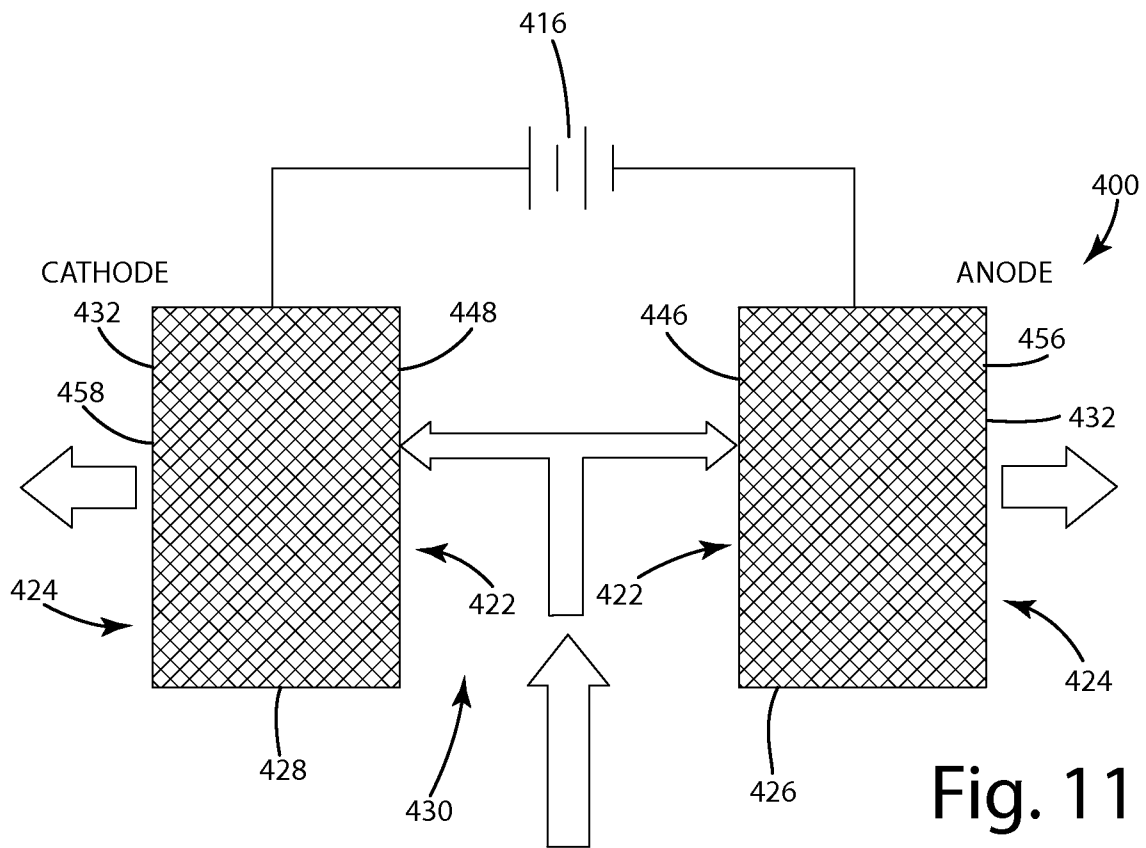


Fig. 10



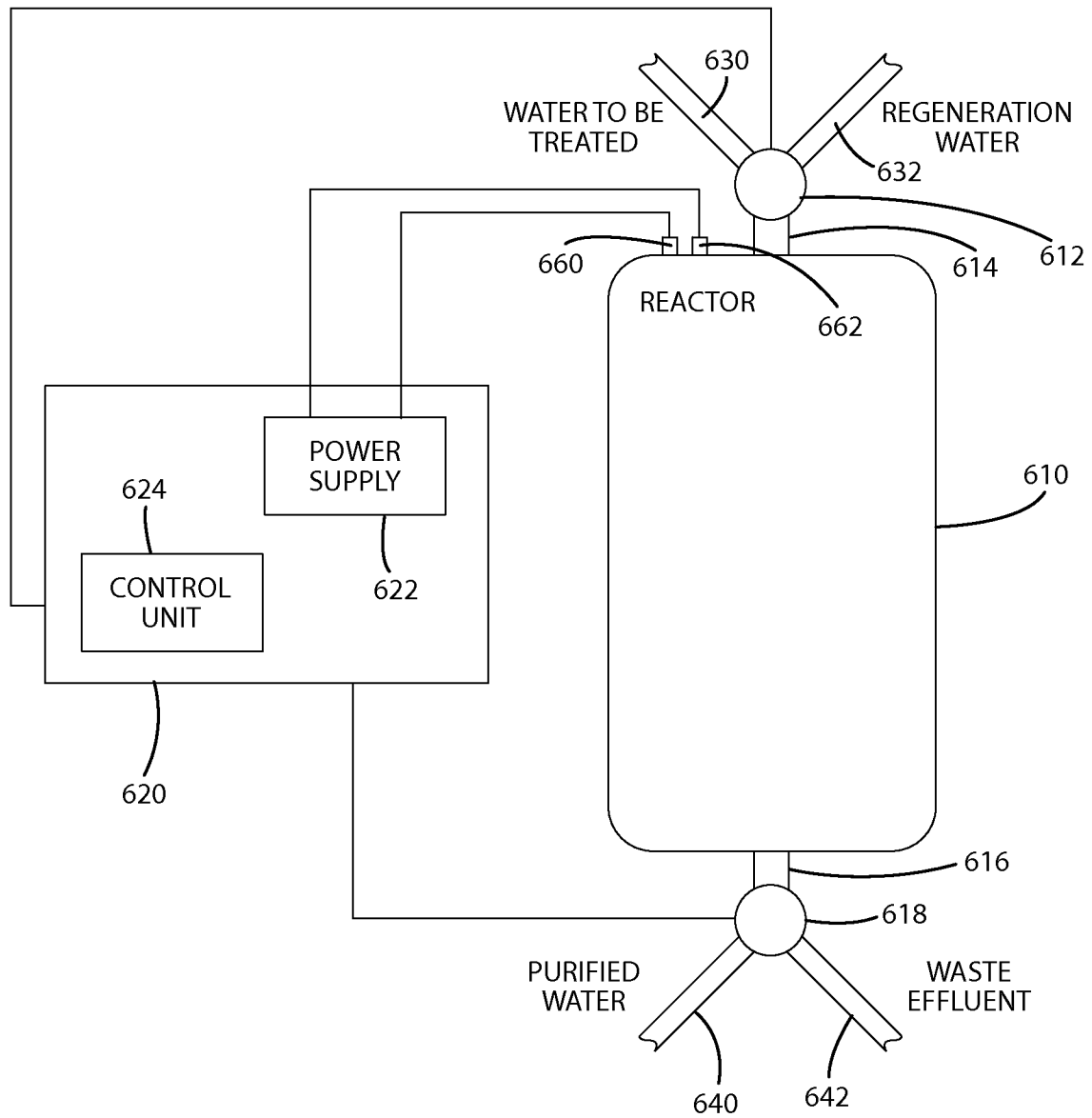


Fig. 13

VOLTAGE V. TIME

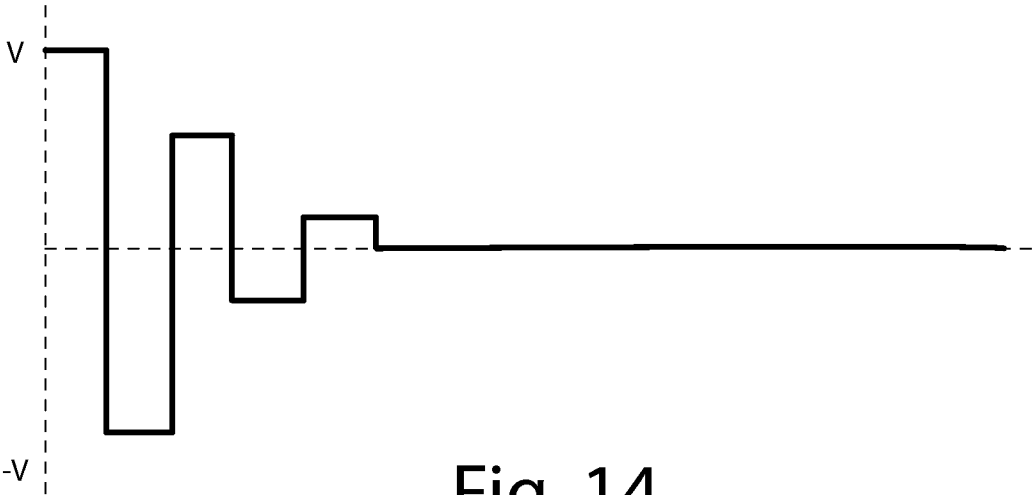


Fig. 14

VOLTAGE V. TIME

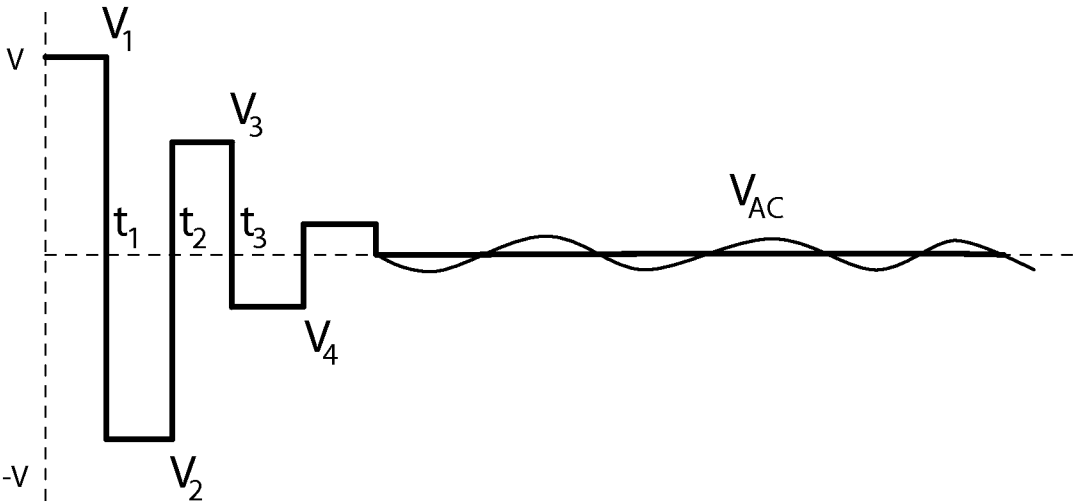


Fig. 15

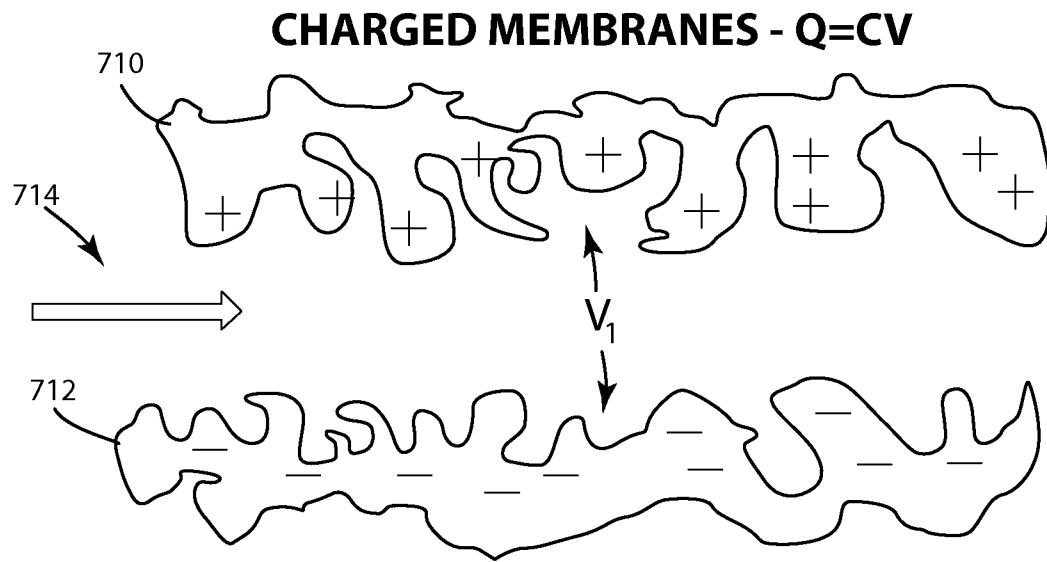


Fig. 16

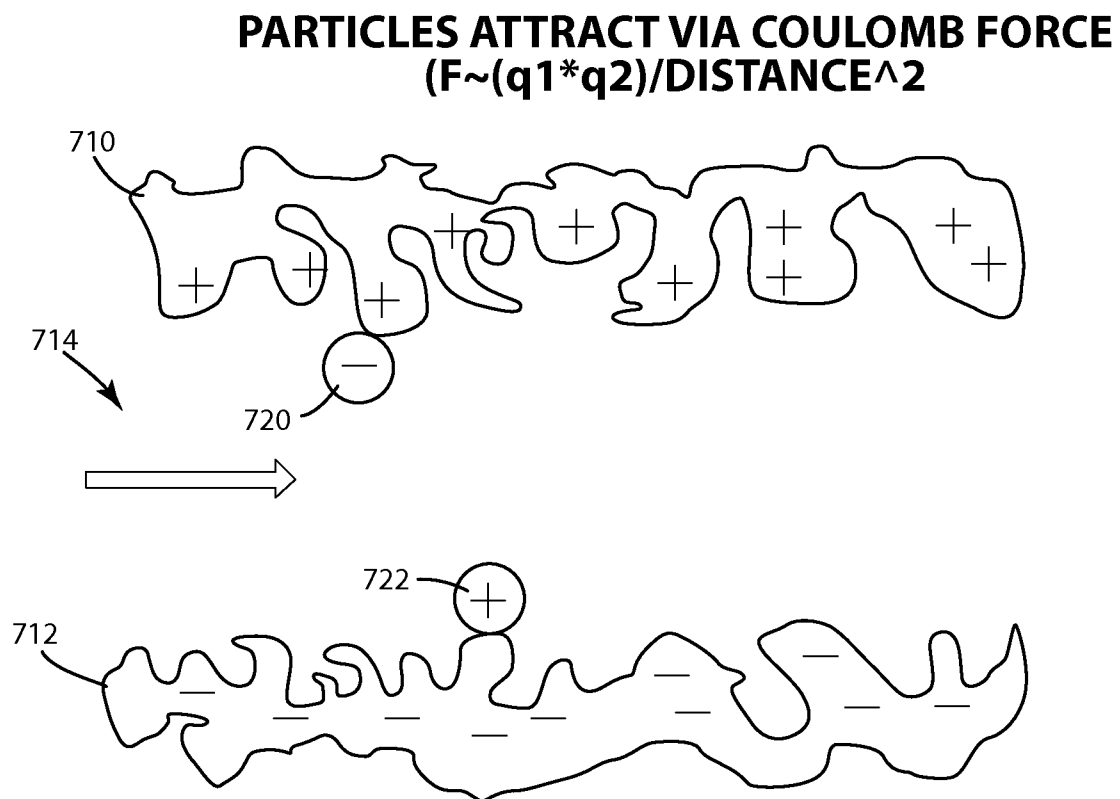


Fig. 17

**REVERSE VOLTAGE, LOWER  $V \rightarrow$  LOWER  $q$ ,**

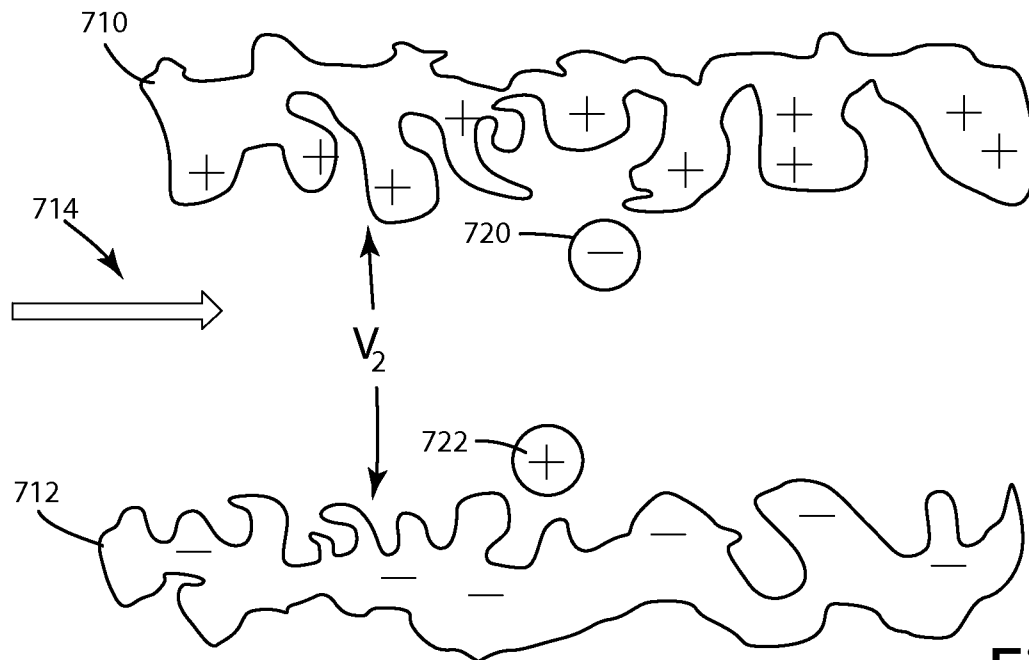


**Fig. 18**

**REVERSE AGAIN**

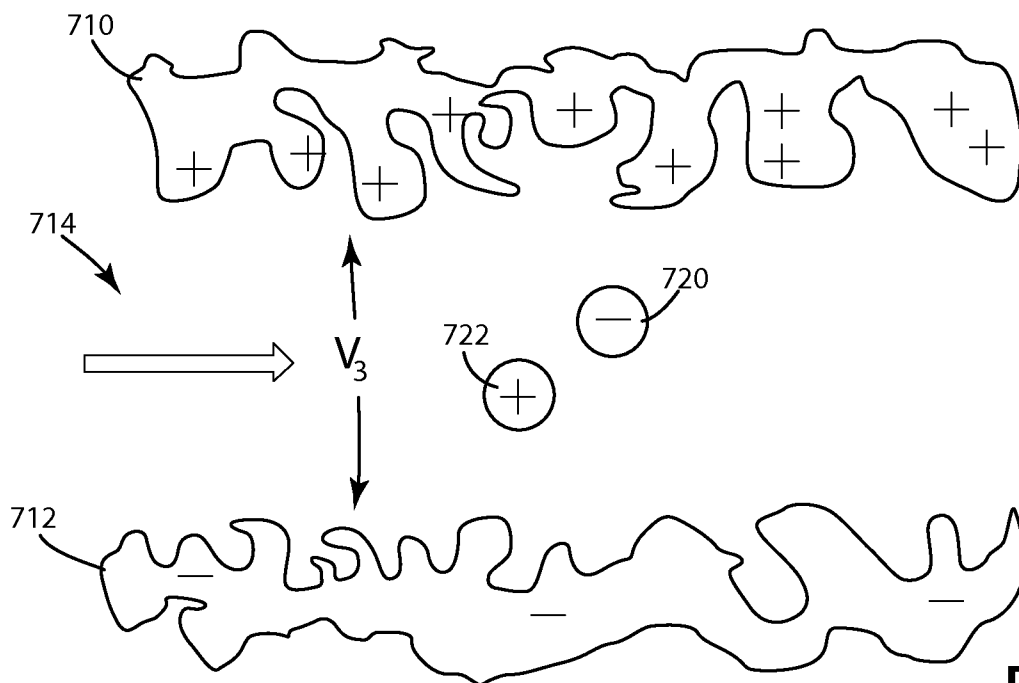


**Fig. 19**

**LOWER VOLTAGE AND REVERSED AGAIN,  
WATER PRESSURE TAKES OUT**

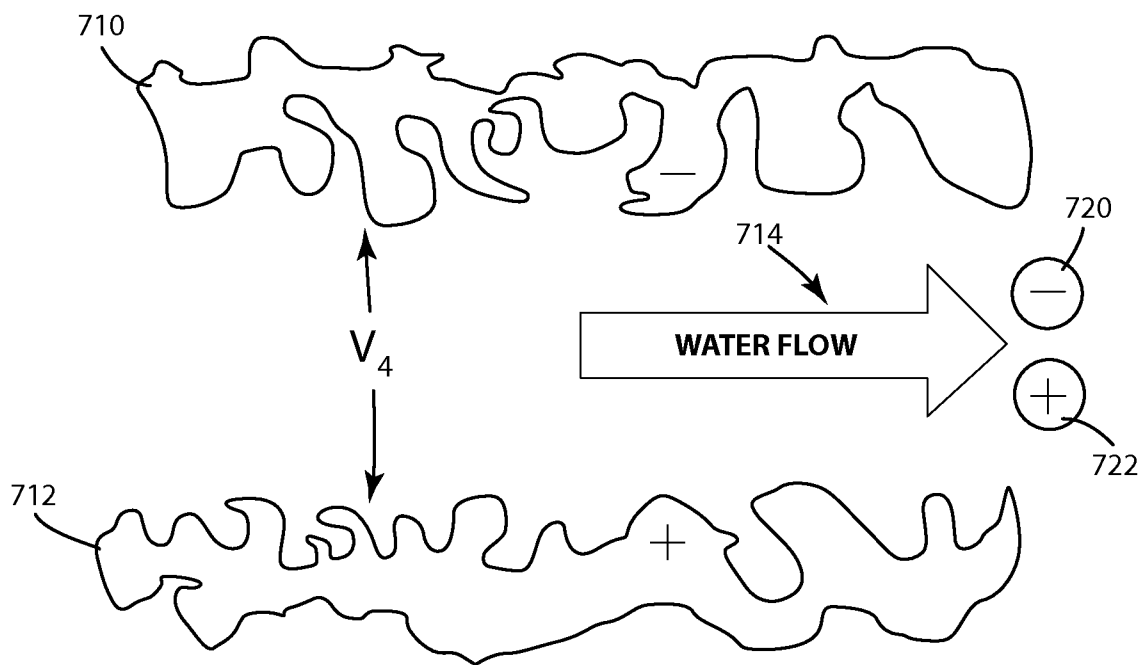


Fig. 20