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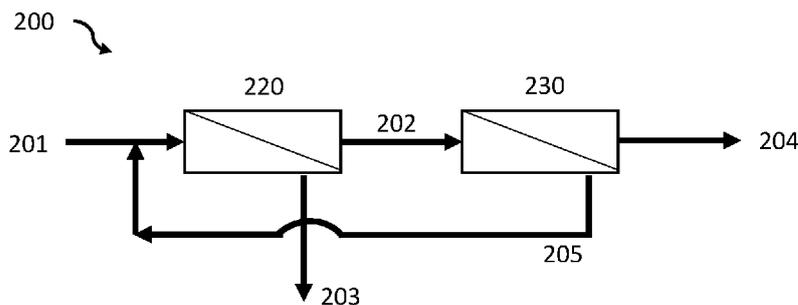


FIG. 2

(57) Abstract: A system and method for increasing the efficiency of a multi-pass nanofiltration system associated with water desalination and mineral extraction. A saline source water is preferably subjected to a first treatment by passage through a first nanofiltration unit, followed by a second treatment by passage through a second nanofiltration unit. At least a portion of the second nanofiltration unit's reject stream is recirculated to the inlet of the first nanofiltration unit, thereby increasing the production of permeate from the first nanofiltration unit, as well as increasing the purity of monovalent ions in the first nanofiltration unit permeate. Further nanofiltration units with one or more recirculated reject streams may be connected in series and/or in parallel with the first and/or second nanofiltration units.



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**SYSTEM AND METHOD FOR MONOVALENT ION PURIFICATION
USING MULTI-PASS NANOFILTRATION WITH RECIRCULATION**

CROSS-REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims priority to U.S. Patent Application Serial No. 17/644,819, filed December 17, 2021, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

10 [0002] The present disclosure relates to design and operation of desalination facilities, and in particular to systems and methods for improving water recovery and mineral byproduct production.

BACKGROUND

15 [0003] In the desalination industry, freshwater is produced via various processes which convert seawater, brackish water, etc., into fresh water. For convenience of reference, at most locations herein reference is made to “seawater,” “saline water” or “feedwater” as the source water. These references are not intended to be limiting, as the source water may be any saline water recognized by those of ordinary skill in the art as possible feed water to a desalination facility.

20 [0004] Most saline water sources contain a large number of minerals in the form of dissolved ions. In desalination, a driving force is applied to remove the minerals from the seawater by means of thermal energy such as MSF (Multi Stage Flash) and MED (Multiple Effect Distillation) or pressure energy such as reverse osmosis (RO), forward osmosis and membrane distillation, or a hybrid system combined between thermal and membrane systems.

25 [0005] Typical desalination plants also have to manage the concentrated brine discharge remaining after separation of potable water (e.g., water with a total dissolved solids (TDS) level of approximately 300 parts per million (ppm) or less). Direct discharge of the brine in its concentrated form may potentially have an adverse impact on the marine environment. Alternative means for disposal of the concentrated brine are costly, due to the relatively large
30 volume of this byproduct and the need to dispose of it in an environmentally safe manner.

[0006] There remains a need for improved systems and methods for generating concentrated and relatively pure ion streams in a more efficient & cost effective manner, such that concentrated brine product(s) can be effectively utilized, rather than disposed of.

SUMMARY

[0007] Described here systems and methods for production of high purity mono-valent ions stream from saline source water. Two or more pass NF systems are considered, where the recirculation of the NF rejects from the second and/or later NF passes are implemented. The recirculation of the NF reject plays a key role to increase the overall recovery rate and/or to increase the purity of mono-valent ions in a final NF permeate.

[0008] In some aspects, described herein are multi-pass nanofiltration systems, comprising: a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium; at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit, wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet.

[0009] In some aspects, the at least one further nanofiltration unit includes a plurality of further nanofiltration units arranged in series; at least a portion of one or more permeate streams from the plurality of further nanofiltration units are feed streams for a respective next downstream one of the plurality of further nanofiltration units; and at least a portion of one or more reject streams from the plurality of further nanofiltration units are configured to be recirculated into the feed stream of at least one upstream one of the plurality of further nanofiltration units, a first nanofiltration unit, or a combination thereof.

[0010] In some aspects, at least a portion of each of the reject streams from the plurality of further nanofiltration units are configured to be recirculated into the feed stream of a respective next upstream one of the plurality of further nanofiltration units. In some aspects, at least a portion of one or more of the reject streams from the plurality of further nanofiltration units are

not configured to be recirculated into a feed stream of another one of the plurality of further nanofiltration units. In some aspects, a multi-pass nanofiltration system further comprises at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of a reject stream from at least one of the plurality of further nanofiltration units, or at least a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units. In some aspects, a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream.

5 [0011] In some aspects, the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being arranged in series; and a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

15 [0012] In some aspects, a multi-pass nanofiltration system further comprises at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of the reject stream from at least one of the plurality of further nanofiltration units, or a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units. In some aspects, a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream. In some aspects, the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being arranged in series, and at least a portion of a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

20 [0013] In some aspects, the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of the first nanofiltration unit and/or an upstream nanofiltration unit. In some aspects, the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of a respective next upstream nanofiltration unit. In some aspects, the multi-pass nanofiltration system

comprises a pump on the permeate stream of one or more nanofiltration units. In some aspects, a reject stream configured to be recirculated into the feed water stream does not comprise a pump before entering the feed water stream. In some aspects, a reject stream is configured to be recirculated into the feed water stream received at a suction side of a pump upstream of the first nanofiltration unit, and/or an upstream nanofiltration unit. In some aspects, a reject stream is configured to be recirculated into the feed water stream received at a pressurized side of a pump upstream of a nanofiltration unit.

[0014] In some aspects, disclosed herein are multi-pass nanofiltration systems, comprising: a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium; at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit, wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet, wherein at least another portion of the first permeate stream is configured to be drawn off to generate a first permeate draw stream, wherein the first permeate draw stream is not configured to be provided to the further nanofiltration unit inlet. In some aspects, at least a portion of the first permeate draw stream and at least a portion of the further permeate stream are configured to be combined to form a combination permeate stream. In some aspects, a flow rate of the first permeate draw stream is configured to be alterable.

[0015] Also disclosed herein are methods of producing a product permeate stream water using one or more systems described herein.

[0016] The use of the word “a” or “an” when used in conjunction with the term “comprising” may mean “one,” but it is also consistent with the meaning of “one or more,” “at least one,” and “one or more than one.”

[0017] The phrase “and/or” means “and” or “or”. To illustrate, A, B, and/or C includes: A alone, B alone, C alone, a combination of A and B, a combination of A and C, a combination of B and C, or a combination of A, B, and C. In other words, “and/or” operates as an inclusive or.

5 [0018] The words “comprising” (and any form of comprising, such as “comprise” and “comprises”), “having” (and any form of having, such as “have” and “has”), “including” (and any form of including, such as “includes” and “include”) or “containing” (and any form of containing, such as “contains” and “contain”) are inclusive or open-ended and do not exclude additional, unrecited elements or method steps.

10 [0019] The systems and methods for their use can “comprise,” “consist essentially of,” or “consist of” any of the components, units, and/or steps disclosed throughout the specification. Systems and methods “consisting essentially of” any of the components, units, and/or steps disclosed limits the scope of the claim to the specified materials or steps which do not materially affect the basic and novel characteristic of the claimed invention.

15 [0020] The term “about” as used herein refers to include the usual error range for the respective value readily known. Reference to “about” a value or parameter herein includes (and describes) embodiments that are directed to that value or parameter per se. For example, description referring to “about X” includes description of “X”. In some embodiments, “about” may refer to $\pm 15\%$, $\pm 10\%$, $\pm 5\%$, or $\pm 1\%$ as understood by a person of skill in the art.

20 [0021] It is specifically contemplated that any limitation discussed with respect to one embodiment of the invention may apply to any other embodiment of the invention. Furthermore, any system of the invention may be used in any method of the invention, and any method of the invention may be used to produce or to utilize any system of the invention. Any embodiment discussed with respect to one aspect of the disclosure applies to other aspects of
25 the disclosure as well and vice versa. For example, any step in a method described herein can apply to any other method. Moreover, any method described herein may have an exclusion of any step or combination of steps. Aspects of an embodiment set forth in one section herein are also embodiments that may be implemented in the context of embodiments discussed elsewhere in the application, such as in the Summary, Detailed Description, Claims, Drawings,
30 Abstract, and Brief Description of the Drawings.

[0022] Other objects, advantages and novel features of the present inventions will become apparent from the following detailed description when considered in conjunction with the accompanying drawings. It should be understood, however, that the detailed description and

the specific embodiments, while indicating specific embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

5

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] Fig. 1 is a schematic illustration of a dual pass nanofiltration system for production of water and high-purity mineral streams.

[0024] Fig. 2 is a schematic illustration of an embodiment of a nanofiltration system in accordance with the present disclosure.

10 [0025] Fig. 3 is a schematic illustration of an embodiment of a nanofiltration system in accordance with the present disclosure.

[0026] Fig. 4 is a schematic illustration of an embodiment of a nanofiltration system in accordance with the present disclosure.

[0027] Fig. 5 is a schematic illustration of an embodiment of a nanofiltration system in
15 accordance with the present disclosure.

[0028] Fig. 6 is a schematic illustration of an embodiment of a nanofiltration system in accordance with the present disclosure.

[0029] Fig. 7 is a schematic illustration of an embodiment of a nanofiltration system in
20 accordance with the present disclosure.

DETAILED DESCRIPTION

[0030] The problems with concentrated brine may be at least partially addressed by extraction of minerals of commercial interest such as sodium, chloride, calcium and magnesium as byproducts which may be used in further applications and/or in to a zero liquid
25 discharge system (membrane or thermal) to minimize environmental impacts. In order to utilize the dissolved ions for various applications, for example using NaCl solution as a raw material for chlor-alkali industry, it is important to increase the content of the ions selected from extraction and beneficial reuse as compared to the other ions in the saline water.

[0031] Nanofiltration (NF) is a well-known membrane-based separation method with
30 permeate and retentate output streams (permeate being the output stream containing ions that have passed through the nanofiltration membrane, and retentate being the output stream that contains ions that have not passed through the membrane). Nanofiltration results in different ion rejections depending on the size and charge of the ions and their salt diffusion coefficient

in water. In general, NF membranes have relatively higher rejection of multivalent ions and lower rejection on monovalent ions, making NF suitable for selectively enhanced separation of monovalent ions to produce NF permeate with target monovalent ions at relatively higher concentrations than multivalent ions in the NF permeate.

5 **[0032]** Examples of differences in rejection observed in testing are illustrated in Table 1, which classes NF membranes by their respective ion rejection performance with a seawater feed source TDS concentration in the range of 35,000-47,000 ppm at approximately 17 bars of feed pressure. In certain implementations, a sea water feed stream may have an initial TDS of about 35,000, 36,000, 37,000, 38,000, 39,000, 40,000, 41,000, 42,000, 43,000, 44,000, 45,000,
 10 46,000, 47,000, 48,000, 49,000, or 50,000, or any range derivable therein. Most of the monovalent ions in the seawater are Sodium (Na⁺), Chloride (Cl⁻) and Potassium (K⁻) ions. Among divalent ions, there typically is a higher rejection of ions such as Sulfate (SO₄⁻), Calcium (Ca⁺⁺), Magnesium (Mg⁺⁺), and Bicarbonate (HCO₃⁻) ions (while bicarbonate (HCO₃⁻) is monovalent, it is included in the divalent portion of Table 1 because its rejection by NF is
 15 similar to that of other multivalent ions).

Table 1: NF membrane ion rejection rates*.

	Group A High rejection NF	Group B Medium rejection NF	Group C Low rejection NF
TDS rejection	45~90%	25~50%	15~40%
Typical monovalent ion rejection**	35~90%	10~45%	<35%
Typical divalent ion rejection***	>80%	>50%	>45%
Sulfate	>95%	>95%	95~100%
Calcium	>80%	60~95%	45~90%
Magnesium	>85%	>80%	70~90%

* Based on pilot test data from NF systems with 4 membrane elements in series. Feed source was seawater with a TDS of about 35,000 ppm to about 47,000 ppm, and the classification of groups A, B and C was based on TDS rejection of 4-element NF membrane system at about
 20 17.2 bar feed pressure.

** Primarily Sodium (Na⁺), Chloride (Cl⁻), Potassium (K⁻), and Bromide (Br⁻) ions in seawater.

*** Primarily Sulfate (SO_4^{-2}), Magnesium (Mg^{+2}) and Calcium (Ca^{+2}) ions in seawater. Note that typical rejection by NF membrane for these ions are: Rejection of Sulfate > Rejection of Magnesium > Rejection of Calcium.

5 [0033] An exemplary Group A - High rejection NF membrane, includes NF90 by Dupont FilmTec™. Exemplary Group B - Medium rejection NF membranes, include NF270 by Dupont FilmTec™ and PRO-XS2 by Hydranautics™. An exemplary Group C - Low rejection NF membrane, includes DL by Veolia (Suez) Osmonics.

10 [0034] Although NF membranes have relatively low rate of rejection of monovalent ions as compared to the higher rejection rate of multivalent ions, Table 1 shows that the purity of monovalent ions in the permeate of the NF system might not be adequate for beneficial use after a single pass through the NF unit, particularly if the target mineral purity level is 98% or more. Accordingly, because the ion rejection rate of divalent ions is not always close to 100%, when the required minimum purity of the monovalent ions of interest is high, or the allowable
15 “impurity level” of certain multivalent ions is very low, a single pass NF system may not be sufficient to obtain the desired product quality. Thus, additional separation processing in two or more passes may be needed to enhance the purity of the monovalent ions and/or lower the content of the multivalent ions in the NF permeate.

[0035] However, when two or more passes are considered, the total recovery of the NF
20 system drops sharply. For example, if the recovery (R) of single pass is 70%, the recovery of a two pass NF system with R=70% of each pass may result in total R of only 49%. Alternatively, in order to maintain the same final NF permeate flow rate, the system may have to be designed for a 43% larger seawater feed to the first NF pass.

[0036] The methods and/or systems of the present disclosure addresses these and other
25 problems, providing for a two or more-unit NF system with recirculation of the NF retentate rejected from the second and/or subsequent passes to the feed entering the first NF unit. The recirculation of the second and/or subsequent NF reject can increase the overall potable water recovery ratio and/or the purity of monovalent ions in a final NF permeate.

[0037] In the following descriptions, calculations of mass and ion balances in the **Fig. 1**
30 and **Fig. 2** embodiments are based on an example 1000 ton seawater feed flow.

[0038] **Fig. 1** shows a simplified schematic illustration of an embodiment of a conventional two-pass nanofiltration system 100. In this simplified illustration, the source saline water 101 received at the inlet 101 in a first nanofiltration unit 120 (NF #1) is seawater with a TDS of

approximately 45,000 ppm, and the individual nanofiltration system recovery fraction (R) is 70%. As also shown in the second column of Table 2, below, the example seawater stream feed TDS includes chloride (Cl^-) at 24,904 ppm, sodium (Na^+) at 13,863 ppm, sulfate (SO_4^{-2}) at 3,414 ppm, magnesium (Mg^{+2}) at 1,657 ppm, calcium (Ca^{+2}) at 502 ppm, potassium (K^+) at 482 ppm, and bicarbonate (HCO_3^-) at 171 ppm.

5 [0039] The effluents from the first nanofiltration unit 120 include a portion of the saline water 101 which entered the nanofiltration unit 120 and passed through the separation membrane 111 (e.g., NF #1 permeate stream 102), and a portion of the saline water 101 which does not pass through the nanofiltration membrane 111 (e.g., NF #1 reject stream 103). As shown in the third column of Table 2 the NF #1 permeate water 102 yield is 70% (e.g., 700 tons), with the NF #1 permeate stream concentrations being TDS at 34,916 ppm, Cl^- at 21,963 ppm, Na^+ at 12,028 ppm, SO_4^{-2} at 35 ppm, Mg^{-2} at 228 ppm, Ca^{+2} at 171 ppm, K^- at 425 ppm, HCO_3^- at 66 ppm. The NF #1 reject stream 103, at 300 tons, has higher concentrations of dissolved solids as shown in the fourth column of Table 2, with the TDS of the NF #1 reject stream 103 having increased to 68,505 ppm and corresponding increases in the constituents, e.g., Cl^- at 31,766 ppm, Na^+ at 18,145 ppm, SO_4^{-2} , at 11,299 ppm, Mg^{+2} at 4,990 ppm, Ca^{+2} at 1,276 ppm, K^+ at 615 ppm, and 415 at ppm HCO_3^- at 415 ppm.

15 [0040] The NF #1 reject stream 103 is removed from the nanofiltration system 100 for subsequent further processing and/or disposal in an environmentally appropriate manner. The NF #1 product stream 102 is introduced to a second nanofiltration unit 130 as the NF #2 feed stream (the NF #2 feed stream contains the same concentrations as the NF #1 permeate stream). Similar to the first nanofiltration unit 120, the second nanofiltration unit 130 includes a separation membrane 121. The sixth column of Table 2 lists an example NF #2 permeate stream 104 concentrations, with a TDS at 30,295 ppm, Cl^- at 19,370 ppm, Na^+ at 10,435 ppm, SO_4^{-2} at 0 ppm, Mg^{+2} at 32 ppm, Ca^{+2} at 58 ppm, K^+ at 375 ppm, and HCO_3^- at 25 ppm. The NF #2 retentate discharge (reject) stream 105 concentrations shown in column 7 of Table 2, are TDS at 45,698 ppm, Cl^- at 28,025 ppm, Na^+ at 15,743 ppm, SO_4^{-2} at 117 ppm, Mg^{+2} at 688 ppm, Ca^{+2} 433 ppm, K^+ at 542 ppm, and HCO_3^- at 160 ppm.

Table 2: Exemplary stream compositions in a two-pass NF arrangement (e.g., as described in Fig. 1).

(unit: ppm)	NF #1 Feed	NF #1 Permeate (R=70%)	NF #1 Reject	NF #2 Feed (= NF #1 Permeate)	NF #2 Permeate (R=70%)	NF #2 Reject
Flow Fraction	100%	70%	30%	70%	49% (overall)	21%
TDS	45,000	34,916	68,505	34,916	30,295	45,698
Cl⁻	24,904	21,963	31,766	21,963	19,370	28,015
Na⁺	13,863	12,028	18,145	12,028	10,435	15,743
SO₄⁻²	3,414	35	11,299	35	0	117
Mg⁺²	1,657	228	4,990	228	32	688
Ca⁺²	502	171	1,276	171	58	433
K⁺	482	425	615	425	375	542
HCO₃⁻	171	66	415	66	25	160
Mg/TDS	3.683%	0.654%	7.284%	0.654%	0.104%	1.506%
CaSO₄ saturation	N/A	N/A	161%	N/A	N/A	N/A

[0041] As the source saline water is processed through the conventional nanofiltration system's first NF subsystem (NF #1 120), the impurity index (Mg/TDS) is lowered from 3.683% to 0.654%, with the impurity level being further lowered to 0.104% after processing through the second NF unit (NF #2 130), as shown in the sixth column of Table 2 (NF #2 permeate). However, the overall recovery of the whole NF system is reduced as an example to only 49%, which means a larger intake system will be needed to meet desired potable water production targets, and/or that a substantial quantity of prepared water (e.g., pumped to site, chemically filtered, dual media filtered, etc.) would not be efficiently utilized.

[0042] Fig. 2 shows an embodiment 200 of a system of the disclosure that can be utilized in a method of operation according to the present disclosure, in which substantial system performance improvements are achieved relative to Fig. 1, system 100. At least a portion of the reject stream 205 from the second nanofiltration unit 230 is recirculated into the saline water stream 201 entering the first nanofiltration unit 220 (for example, as shown in this embodiment, 100% of the NF #2 reject stream 205).

[0043] Among the advantages resulting from recirculation of the highly concentrated brine of reject stream 205 into the feed stream 201 are increasing of the overall recovery of the nanofiltration system 200, enhanced concentration of divalent ions in the NF #1 reject stream 203, and/or enhanced purity of monovalent ions in the final NF permeate stream. The increase
5 in overall recovery can reduce the required feed water intake volume, and thus result in a substantial increase in system efficiency, e.g., a reduced percentage of feedwater that has been prepared (e.g., pumped to the appropriate site, chemically treated, dual media filtered, etc.) that would be considered as a waste product (e.g., increased potable water production ratio). Moreover, this recirculation process may increase energy efficiency, as little to no additional
10 energy is required to significantly raise the pressure of the recirculated NF #2 reject stream 205 in some instances.

[0044] Table 3 illustrates an example improved concentration performance obtained with methods and/or systems of the present disclosure's reject stream recirculation, using a specific example in which the **Fig. 2** NF #1 feed stream 201's inlet flow is increased by approximately
15 one-quarter (~26.6%) by the introduction of the NF #2 reject stream 205 into the NF #1 feed stream 201 (relative to a system without recirculation).

[0045] As a consequence of the NF #2 reject recirculation, the feed flow rate of NF #1 220 increases, which in turn increases the production of permeate 202 from NF #1 220. The recirculation of the NF #2 reject stream 205 also can lead to a desirable increase in the
20 concentration of monovalent ions in the NF #2 permeate stream 204 relative to the concentration of multivalent ions, thereby increasing the purity of the final permeate and its beneficial use for target applications.

[0046] In certain implementations, a primary consideration is achieving a high monovalent ion relative to multivalent ion purity in the permeate streams, for example, achieving a
25 multivalent ion concentration below a certain percentage of total TDS, such as at or below about 1.5%, 1.4%, 1.3%, 1.2%, 1.1%, 1.0%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1% of total TDS, or any range derivable therein. In certain implementations, a primary consideration is achieving a high monovalent ion relative to Mg^{++} ion concentration in a permeate stream, such as at or below about 1.0%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%,
30 0.2%, or 0.1% of total TDS (Mg/TDS). In certain implementations, a primary consideration is achieving an Mg/TDS ratio at or below a certain ratio, such as at or below about 0.006 (0.6% Mg^{++} of total TDS), 0.005, 0.004, 0.003, 0.002, 0.001. In certain implementations, a primary consideration is achieving a high monovalent ion relative to Ca^{++} ion concentration in a

permeate stream, such as at or below about 1.0%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1% of total TDS (Ca/TDS).

[0047] In certain implementations, utilization of at least a partial permeate stream dual pass nanofiltration system provides for obtaining a target level of monovalent ion relative to multivalent ion purity in a permeate stream when a single pass nanofiltration system does not. Such as for example, but not limited to, a) when ambient temperature conditions are greater than about 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, or 40 °C, or any range derivable therein; b) at NF unit operating pressures at or below about 15 bar, 14 bar, 13 bar, 12 bar, 11 bar, or 10 bar, or any range derivable therein; c) when NF units are aged, such as at least about 1, 1.5, 2.0, 2.5, 3.0, 3.5, 4, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, or 8.5 years of age, or any range derivable therein, and/or d) when the average estimated lifespan of a given NF unit (or system) is at greater than or equal to about 50%, 60%, 70%, 80%, 90%, or 100%, or any range derivable therein, of an average estimated lifespan. In certain embodiments, methods of use of systems described herein are a function of ambient temperatures, NF unit operating pressures, and/or NF unit absolute and/or relative age.

Table 3: Exemplary feed flow rate and ion concentration at NF #1 feed with NF #2 reject recirculation (e.g., as shown in Fig. 2).

(unit: ppm)	NF #1 Feed	NF #1 Feed (with NF #2 reject)	NF #1 Permeate (R=70%)	NF #1 Reject	NF #2 Feed (= NF #1 Permeate)	NF #2 Permeate (R=70%)	NF #2 Reject
Flow Fraction	100%	126.6%	88.6%	38%	88.6%	62%	26.6%
TDS	45,000	45,442	36,090	67,265	36,090	31,357	47,134
Cl⁻	24,904	25,759	22,717	32,857	22,717	20,035	28,977
Na⁺	13,863	14,381	12,477	18,824	12,477	10,825	16,332
SO₄²⁻	3,414	2,717	28	8,990	28	0	93
Mg⁺⁺	1,657	1,434	198	4,319	198	27	595
Ca⁺⁺	502	484	165	1,231	165	56	418
K⁺	482	499	440	636	440	388	561
HCO₃⁻	171	168	65	409	65	25	158
Mg/TDS	3.683%	3.156%	0.548%	6.420%	0.548%	0.087%	1.263%
CaSO₄ saturation	N/A	N/A	N/A	128%	N/A	N/A	N/A

[0048] The effects of the improved system in the **Fig. 2** embodiment may be seen in Table 3, which shows example changes in NF #1 220 feed flow rate and the ion concentrations in the NF #1 feed stream 201 for varying amounts of NF #2 230 reject stream 205 recirculation (columns 2 and 3 respectively). A higher flow feed rate to NF #1 220 results in higher overall recovery because the same saline source water flow rate is augmented by the recirculated flow, increasing the amount of water available to pass through the NF membrane. For example, a higher recovery up to a 33.3% may result from a 33.3% higher feed flow rate to the NF #1 220, depending on the recovery characteristics of the particular type of nanofiltration unit of NF #1 220.

[0049] Additionally, as an example as shown in Table 3, with the recirculation of NF #2 reject to NF #1 feed, the Mg/TDS index at NF #1 feed becomes 3.156% instead of 3.683% in seawater, while a 26.6% higher feed flow rate is calculated in this example. Finally, the overall recovery is increased from 49% to 62%, and the Mg/TDS impurity index is decreased from

0.104% to 0.087%. An additional benefit can be observed in the NF #1 reject, where CaSO_4 saturation index is dropped from 161% to 128%, thus relieving scale deposition risks.

5 [0050] The higher overall recovery may also be accompanied by an increase in the content of monovalent ions and a relatively lower amount of increase in multivalent ion content (content = flow rate times concentration). This is because the modified NF #1 feed stream is a mixture of the fixed flow rate of saline water 201 and the recirculation flow of NF #2 reject stream 205. The ion concentration in the NF #1 feed stream 201 therefore is a function of the efficiencies of the nanofiltration units NF #1 220 and NF #2 230 (e.g., the ion rejection rates as well as the recovery rates) that, combined, result in the ion concentrations of the NF #2 reject stream 205. Thus, because the ion rejection rate of monovalent ions of a typical NF membrane is lower than the rejection rate of multivalent ions, the ratio of multivalent ion concentration to monovalent ion concentration (a measure of impurity of the permeate in terms of content of multivalent ions) in the NF #1 feed stream will be lower with the present disclosure's NF #2 reject stream 205 recirculation (e.g., comparing column 2 to column 3 of Table 3).

15 [0051] This effect is discernable in Table 4, which illustrates an example of the relative ion concentrations in the NF #1 feed stream, and associated relative ion rejection and recovery rates for various amounts of NF #2 reject stream recirculation as compared to no recirculation (e.g., NF #1 feed = 1.000). Table 4 shows that ions which are rejected to a greater degree by nanofiltration membranes (typically, multivalent ions) are concentrated less (left columns), and ions rejected poorly by the NF membranes (typically monovalent ions) are concentrated at a relatively higher rate (right columns). Therefore, the ratio of multivalent ion concentration to monovalent ion concentration in the permeate streams will be proportionally reduced. As an example, when the resultant ion concentration in the NF #1 feed is less than 1 (e.g., 100%, e.g., less than 1.000 in Table 4), then there is benefit to recirculation (in Table 4, the underlined entries). For example, using the example of Table 2 of, $R_{\text{individual}} = 70\%$ (as described herein, wherein $R_{\text{individual}}$ stands for the Recovery (R) of each (individual) NF unit (e.g., NF pass, NF sub-system), where $\text{Recovery} = \text{Permeate Flow} / \text{Feed Flow}$) and rejection of Mg = between 80% and 90%, from Table 3, we can find the relative concentration is 0.845 ~ 0.898 (e.g., less than 1.000), and thus recirculation is desirable. The advantages of the methods and/or systems of the present disclosure are particularly manifested when the recovery of individual NF subsystems (R) is 50% or lower, and/or when R is greater than 50% and the interested ion rejection of an individual NF subsystem (Rej) is between approximately $\text{Rej (in \%)} \geq 1.4 \times R(\%) - 40\%$. For example, where the NF #1 feed comprising at least a portion of an NF #2

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retentate recycle stream / original feed water NF #1 ion concentration ratio is <100% in table 4 (e.g., less than 1.000).

[0052] Accordingly, selection of the amount of recirculation may be used to alter the concentrations in the respective permeate and reject streams to tailor systems and/or methods in the spirit of the present disclosure’s operations to targeted stream output concentrations.

Table 4: Feed flow rate and ion concentration at NF #1 feed with NF #2 reject recirculation.

Recovery of Individual NF Subsystem	Flow Rate of NF #1 Feed*	Ion Rejection Rate** of Individual NF Sub-system										
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
		<u>Ion Concentration in NF #1 Feed</u>										
0%	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.0
10%	1.099	<u>0.910</u>	<u>0.919</u>	<u>0.928</u>	<u>0.937</u>	<u>0.946</u>	<u>0.955</u>	<u>0.964</u>	<u>0.973</u>	<u>0.982</u>	<u>0.991</u>	1.0
20%	1.190	<u>0.840</u>	<u>0.857</u>	<u>0.874</u>	<u>0.890</u>	<u>0.907</u>	<u>0.923</u>	<u>0.939</u>	<u>0.955</u>	<u>0.970</u>	<u>0.985</u>	1.0
30%	1.266	<u>0.790</u>	<u>0.814</u>	<u>0.837</u>	<u>0.860</u>	<u>0.883</u>	<u>0.905</u>	<u>0.927</u>	<u>0.947</u>	<u>0.966</u>	<u>0.984</u>	1.0
40%	1.316	<u>0.760</u>	<u>0.790</u>	<u>0.820</u>	<u>0.850</u>	<u>0.878</u>	<u>0.905</u>	<u>0.930</u>	<u>0.952</u>	<u>0.971</u>	<u>0.988</u>	1.0
50%	1.333	<u>0.750</u>	<u>0.787</u>	<u>0.824</u>	<u>0.860</u>	<u>0.893</u>	<u>0.923</u>	<u>0.949</u>	<u>0.971</u>	<u>0.987</u>	<u>0.997</u>	1.0
60%	1.316	<u>0.760</u>	<u>0.805</u>	<u>0.850</u>	<u>0.892</u>	<u>0.930</u>	<u>0.962</u>	<u>0.988</u>	1.005	1.013	1.011	1.0
70%	1.266	<u>0.790</u>	<u>0.845</u>	<u>0.898</u>	<u>0.947</u>	<u>0.989</u>	1.023	1.044	1.053	1.048	1.030	1.0
80%	1.190	<u>0.840</u>	<u>0.907</u>	<u>0.970</u>	1.027	1.074	1.105	1.119	1.115	1.091	1.052	1.0
90%	1.099	<u>0.910</u>	<u>0.991</u>	1.068	1.133	1.182	1.209	1.211	1.187	1.140	1.076	1.0
100%	1.000	1.000	1.099	1.190	1.266	1.316	1.333	1.316	1.266	1.190	1.099	1.0

* Combination initial feed with recycling from NF #2 reject stream, shown as a ratio compared to the values found in a non-recirculation case.

** The ion rejection rate may be the rejection rate for any ion of interest when passed through a single NF unit. In general, due to the preferential rejection of multivalent/divalent ions by NF membranes, the table is most readily applicable to removal of multivalent/divalent ions and/or increase of monovalent ions in a permeate stream.

[0053] The increase in overall recovery achieved by the methods and/or systems of the present disclosure also permits cost and energy efficiency improvements. For example, the

recirculation of the NF #2 reject stream 205 may permit the size of the seawater intake and pumping station to be reduced, as more of the prepared water is utilized, achieving overall greater system efficiencies when compared to a system without any NF #2 reject stream recirculation. Further, in certain aspects, because the reject stream 205 from NF #2 is typically pressurized, the recirculation of the NF #2 reject stream 205 may require little or no boosting of its pressure to be introduced into the seawater feed stream 201, where the feed pressure to NF #1 220 is lower than the feed pressure to NF #2 230. Furthermore, where the NF #2 reject stream is introduced to the suction side of the NF #1 feed water pump, an energy recovery device may be employed on the NF #2 reject line, capturing what may otherwise be wasted energy and further increasing system efficiencies. Thus, the NF #2 recirculation approach may recover pressure energy in the NF #2 reject stream 205 to increase system efficiency. In certain aspects disclosed in Table 4, where the ion concentration in NF #1 combination feed is found to be greater than a value of 1, it may not be necessary and/or efficient to conduct an NF #2 recirculation, as there would be no further increase in monovalent ion purity (and potentially a decrease in monovalent ion purity). In certain aspects, disclosed herein are methods of producing product streams with target ion concentrations through utilization of systems described herein in light of the data provided in Table 4.

[0054] The amount of benefit from systems and/or methods of the present disclosure are dependent on the specific recovery and ion rejection capacities of the particular NF subsystems, which in turn are a function of NF membrane type and operating conditions (e.g., rejection rates, maximum pressures, ambient temperatures, water temperatures, etc.). Such selective concentration of desirable ions allows for designing the NF systems and/or methods of use of the present disclosure in a manner that it suitable for a large number of practical applications. For example, Table 1 illustrates the results of testing of various nanofiltration units, which were found to fall within three broad categories (Group A, high rejection NF; Group B, medium rejection NF; and Group C, low rejection NF) based on their separation performance.

[0055] The highly concentrated brine from the NF permeate streams, enriched with sodium and chloride and of low content of calcium and magnesium impurity, may be generated as a raw source material for various industrial uses in which calcium and magnesium impurities must be reduced below an allowable target concentration (e.g., such as chlor-alkali).

[0056] Systems and methods of the present disclosure may also be used with reverse osmosis (RO) and brine concentrator systems installed downstream (e.g., on the permeate line) of the present disclosure's NF subsystem arrangements. As most commercially available RO

and brine concentrator systems remove (reject) both the monovalent and the divalent ions with similar high rejection rates from the NF permeate, it is important to minimize the content of impurities in the NF permeate to be fed to these downstream subsystems, in order to minimize these impurities in the concentrated brine (RO and/or brine concentrator system reject streams) and minimize further processing costs (e.g., associated with further brine purification) before the brine is suitable for use in industrial production processes. In the example of chlor-alkali industry, magnesium is considered the main impurity that requires removal before the use of the brine in the downstream industrial chemical production processes, and therefore, minimization of this ion in the NF permeate minimizes further purification needs, improving overall system efficiency relative to systems that do not comprise embodiments of the immediate disclosure.

[0057] Systems and/or methods of use according to the present disclosure are not limited to the use of only two nanofiltration units, but may include multiple nanofiltration units arranged with one or more of the downstream reject streams being recirculated to the first nanofiltration inlet and/or to the inlets of one or more upstream nanofiltration units, depending on the target permeate stream quality and/or quantity targets, target reject stream quality and/or quantity targets, and/or factors such as cost and suitability of the component arrangements to a particular installation environment.

[0058] **Fig. 3** shows an exemplary embodiment 300, where multiple nanofiltration units are arranged with the first two units 320, 330 being arranged in the manner shown in **Fig. 2**, with the recirculation of the NF #2 reject stream 305 to the inlet of the NF #1 unit 320. Further nanofiltration units are arranged downstream of NF #2 330, out to n-1 335 and n units 340. In this embodiment, at least a portion of each of the downstream nanofiltration units' reject streams is recirculated to the immediately upstream nanofiltration unit (for example, reject stream 307 from the NF #n nanofiltration unit 340 is recirculated to the inlet of the n-1 nanofiltration unit 335).

[0059] The recirculation of reject streams to solely the immediately upstream nanofiltration unit is not required, and other recirculation routes or combination of routes are possible.

[0060] **Fig. 4** shows another exemplary embodiment 400 in which the reject streams 408 from one or more intermediate nanofiltration units NF #i 435 are diverted from the system for subsequent treatment or use, for example, where a particular nanofiltration unit's reject stream ion concentrations suit a particular industrial application, while other reject streams 409 are recirculated to upstream nanofiltration units (in this example, 407 can become stream 409, which

can be recirculated to before 435 and/or 430). This arrangement may be particularly desirable if one or more of the nanofiltration units is constructed with a separation membrane having different selectivity for ions when compared to other nanofiltration units in the system.

[0061] For example, assuming that a first type of nanofiltration unit (e.g., “NF type-A”) rejects less of certain multivalent ions (e.g., “Z” ions) relative to a second type of nanofiltration unit (e.g., “NF type-B”), (e.g., higher ionic rejection of Z ions for NF type-B than type-A), a system may use a NF type-A unit for the initial pass(es) in an NF #1 to #i-1 (NF # intermediate (i) minus 1 (-1)) sub-system, and use an NF type-B unit for the downstream passes (e.g., NF #i+1 to n sub-system). In such a system the NF #1 unit reject stream would have higher purity of other multivalent ions, but not the multivalent Z ions, while the NF #i unit reject stream would have higher purity of multivalent Z ions (e.g., other multivalent ions having already been removed in the reject streams of the upstream nanofiltration units). Thus, multivalent Z ions may be selectively separated by an appropriate choice and arrangement of separation membranes. Similarly, appropriate NF unit selection choices would allow separation of two or more ion types depending on the NF membrane types and their ion rejection characteristics.

[0062] **Fig. 5** shows additional exemplary embodiments of the present disclosure. In this arrangement of n nanofiltration units in m nanofiltration branches 500, 600, 700, etc. the NF #1 reject stream 503 is routed to a separate one of the m branches (e.g., 600, 700, etc.), specifically in this example figure, to the inlet of a first branch 600 nanofiltration unit 620. Preferably the saline water 601, 701, etc. being fed to the branches 600, 700, etc. comprises a lower salinity than the source saline water 501, for example, a partially purified stream from another process or another nanofiltration branch. In alternative embodiments the reject stream 503 from the nanofiltration unit 520 may be routed to the inlet of a further downstream branch nanofiltration unit in an m branch nanofiltration train (e.g., 503 may feed the inlet of downstream branch 700 nanofiltration unit 720, etc.). Arrangement of the recycled streams results in the ability to tailor the product streams to suit downstream applications. For example, depending on the concentrations of ions in the NF #1 reject stream 503 and the ion content saline water 601 (preferably water with a lower salinity than the source saline water 501, for example, a partially purified stream from another process or another nanofiltration branch) being fed to the inlet of nanofiltration unit 620, specific ions may be selectively further separated to increase the concentration of desired monovalent ions in the branch’s final permeate product stream and/or generation of a nanofiltration product enriched in multivalent ions beyond that otherwise attainable without the addition of the NF #1 reject stream 503. For

example, reject streams 509 are recirculated to upstream nanofiltration units (in this example, 507 can become stream 509, which can be recirculated to before 535 and/or 530).

5 [0063] With the combination of nanofiltration unit types and arrangements typified by **Fig. 5**, more than one product stream may be obtained from the saline source water, for example, a nanofiltration process reject stream with higher concentration of multivalent ions, such as calcium and magnesium, while minimizing monovalent ions such as sodium and chloride, and a final permeate stream enriched in monovalent ions resulting from combination with the lower salinity source water. It is noted that depending on the needs of a particular application, at least a portion of downstream permeate streams may be returned to other nanofiltration units in the
10 same and/or different ones of the m branches to lower the salinity of the feed stream into these nanofiltration units.

[0064] An example of method for increasing nanofiltration system performance in accordance with the present disclosure includes introducing a saline water source stream to the inlet of a first nanofiltration unit, supply of at least a portion of a permeate stream from the first
15 nanofiltration unit to the inlet of a second nanofiltration unit, and recirculation of at least a portion of a reject stream from the second nanofiltration unit to the inlet of the first nanofiltration unit.

[0065] **Fig. 6** shows a simplified schematic illustration of an embodiment of a two-pass nanofiltration system 800 with an NF unit #1 permeate bypass stream 809 and NF #2 reject stream recirculation 805 (shown as 100% rejection stream recirculation here, in some implementations, the recirculation stream is less than 100%, such as 50%, 60%, 70%, 80%, 90%, etc.). In this simplified illustration, the initial source saline water 801 received at the inlet in a first nanofiltration unit 820 (NF #1) is seawater with a TDS of approximately 45,000 ppm (e.g., about 44,900 to 45,100 ppm), at a flow rate of 100 m³/h, and the individual
20 nanofiltration system recovery fraction (R) is 70%.

[0066] The effluents from the first nanofiltration unit 820 include a portion of the saline water 801 which entered the nanofiltration unit 820 and passed through the NF separation membrane (e.g., NF #1 permeate stream 802), and a portion of the saline water 801 which does not pass through the nanofiltration membrane (e.g., NF #1 reject stream 803). Table 5
30 illustrates the improved concentration performance with the present implementation's reject stream recirculation. Using a specific example in which the **Fig. 6** NF #1 feed stream 801's inlet flow is increased by approximately 15% (relative to a system without recirculation) by the introduction of the NF #2 reject stream 805 into the NF #1 feed stream 801. As a

consequence of the NF #2 reject recirculation, the feed flow rate of NF #1 820 increases, which in turn increases the production of permeate 802 and reject 803 from NF #1 820 (relative to a system without recirculation). The recirculation of the NF #2 reject stream 805 also can lead to a desirable increase in the volume of the NF #1 permeate stream 802 and permeate draw stream 809 (e.g., increasing overall system efficiency by utilizing more of the prepared feed water), and increase in the concentration of monovalent ions in the NF #1 permeate stream 802 and the NF #2 permeate stream 804 relative to the concentration of multivalent ions, thereby increasing the purity of the final permeates, and facilitating methods of beneficial product water stream creation for use in target applications.

10 **[0067]** As shown in Table 5, an exemplary implementation of the system shown in **Fig. 6**, a portion of the NF #1 permeate stream can be drawn off and utilized as a product permeate stream (e.g., for use in a downstream process, not utilized as a feed stream to an NF #2 unit), with the second portion of the NF #1 permeate stream acting as the feed stream for the NF #2 unit. In this exemplary implementation, the final Mg/TDS ratio may be less than or equal to
15 about 0.006 (0.6% Mg/TDS). In this implementation, with an R=70% in each of the NF #1 and NF #2 units, the NF #2 unit receives about 63% of the NF #1 unit permeate stream (e.g., about 50.6% total relative flow fraction when compared to a feed stream of a dual pass NF system that does not comprise recirculation), while about 37% of the NF #1 unit permeate stream (e.g., about 30% total relative flow fraction when compared to a feed stream of a dual
20 pass NF system that does not comprise recirculation), can be drawn off as a product water permeate stream. In this exemplary implementation, two product permeate streams with target ion concentration ratios can be generated, a) 30 m³/h of NF #1 permeate that comprises a final Mg/TDS less than about 0.6%; and b) 35.4 m³/h of NF #2 permeate that comprises a final Mg/TDS less than about 0.1%. This exemplary implementation is applicable for, but not
25 limited to, use with systems that require different downstream ion purity requirements.

Table 5: Exemplary feed flow rate and ion concentrations, with NF #1 feed, partial NF #1 permeate draw (e.g., ~37% of permeate), partial NF #1 feed to NF #2 (e.g., ~63% of permeate), and with NF #2 reject recirculation to NF #1 feed (e.g., as shown in Fig. 6).

(unit: ppm)	NF #1 Feed	NF #1 Feed (with NF #2 reject)	NF #1 Permeate (R=70%)	NF #1 Reject	NF #2 Feed (= ~63% of NF #1 Permeate)	NF #2 Permeate (R=70%)	NF #2 Reject
Flow Fraction	100%	115.2%	80.6%	34.6%	50.6%	35.4%	15.2%
TDS	~45,000	45,192	35,575	67,631	35,575	30,892	46,500
Cl⁻	24,904	25,386	22,388	32,380	22,388	19,744	28,557
Na⁺	13,863	14,155	12,281	18,527	12,281	10,655	16,074
SO₄²⁻	3,414	2,977	31	9,853	31	0	102
Mg⁺⁺	1,657	1,522	210	4,583	310	29	632
Ca⁺⁺	502	492	167	1,250	167	57	424
K⁺	482	491	433	627	433	382	553
HCO₃⁻	171	169	65	411	65	25	159
Mg/TDS	3.683%	3.367%	0.599%	6.776%	0.599%	0.094%	1.359%
CaSO₄ saturation	N/A	N/A	N/A	140.6%	N/A	N/A	N/A

- 5 [0068] Fig. 7 shows a simplified schematic illustration of an embodiment of a two-pass nanofiltration system 900 with an NF unit #1 permeate bypass stream 909 and NF #2 reject stream recirculation 905 (shown as 100% rejection stream recirculation here, in some implementations, the recirculation stream is less than 100%, such as 50%, 60%, 70%, 80%, 90%, etc.). In this simplified illustration, the initial source saline water 901 received at the inlet in a first nanofiltration unit 920 (NF #1) is seawater with a TDS of approximately 45,000 ppm (e.g., about 44,900 to 45,100 ppm). The effluents from the first nanofiltration unit 920 include a portion of the saline water 901 which entered the nanofiltration unit 920 and passed through the NF separation membrane (NF #1 permeate stream 902), and a portion of the saline water 901 which does not pass through the nanofiltration membrane (NF #1 reject stream 903).
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- 15 [0069] Table 6 illustrates an exemplary implementation of the improved concentration performance with system 900 reject stream 905 recirculation. In table 6, an initial flow rate of 100 m³/h is utilized, and the individual nanofiltration system recovery fraction (R) is 70%. The

NF #1 feed stream 901's inlet flow is increased by approximately 2.7% (relative to a system without recirculation) by the introduction of the NF #2 reject stream 905 into the NF #1 feed stream 901. As a consequence of the NF #2 reject recirculation, the feed flow rate of NF #1 920 increases, which in turn increases the production of permeate 902 and reject 903 from NF #1 920 (relative to a system without recirculation). The recirculation of the NF #2 reject stream 905 also can lead to a desirable increase in the volume of the NF #1 permeate stream 902 and permeate draw stream 909 (e.g., increasing overall system efficiency by utilizing more of the prepared feed water), and the concentration of monovalent ions in the NF #1 permeate stream 902 and the NF #2 permeate stream 904 relative to the concentration of multivalent ions, thereby increasing the purity of the final permeates, and facilitating methods of beneficial product water stream creation for use in target applications. In this implementation, the NF #1 permeate draw stream and NF #2 permeate streams are combined into a single combination permeate stream, 910, that meets the desired target ion concentrations.

[0070] As shown in **Table 6**, a portion of the NF #1 permeate stream can be drawn off and utilized as a product permeate stream (e.g., for use in a downstream process, and not for use as a feed stream to an NF #2 unit), with the second portion of the NF #1 permeate stream acting as the feed stream for the NF #2 unit. In this exemplary implementation, a final Mg/TDS ratio of less than or equal to about 0.006 (0.6% Mg/TDS) may be achieved. In this implementation, with an R=70% in each of the NF #1 and NF #2 units, the NF #2 unit receives about 12.4% of the NF #1 unit permeate stream (e.g., about 8.9% total relative flow fraction when compared to a feed stream of a dual pass NF system that does not comprise recirculation), while about 87.6% of the NF #1 unit permeate stream (e.g., about 63% total relative flow fraction when compared to a feed stream of a dual pass NF system that does not comprise recirculation), can be drawn off as a product water permeate stream. In this exemplary implementation, the two product permeate streams are combined to achieve a single permeate stream with a target ion concentration ratio, such as less than about 0.006 (0.6% Mg/TDS). This exemplary implementation is applicable for, but not limited to, use with systems where minimization of the feed flow to NF #2 unit is desired (e.g., to increase overall efficiencies by requiring less pressurization steps and/or reducing equipment/system wear-and-tear).

Table 6: Exemplary feed flow rate and ion concentration at NF #1 feed, partial NF #1 permeate draw (e.g., ~87.6% of permeate), reduced NF #1 permeate feed to NF #2 (e.g., ~12.4% of permeate), NF #2 reject recirculation, and combination of NF #1 permeate draw and NF #2 permeate (e.g., as shown in Fig. 7).

(unit: ppm)	NF #1 Feed	NF #1 Feed (with NF #2 reject)	NF #1 Permeate (R=70%)	NF #1 Reject	NF #2 Feed (= ~12.4% of NF #1 Permeate)	NF #2 Permeate (R=70%)	NF #2 Reject	Combo NF #1 permeate draw and NF #2 permeate
Flow Fraction	100%	102.7%	71.9%	30.8%	8.9%	6.2%	2.7%	69.2%
TDS	~45,000	45,015	35,029	68,314	35,029	30,398	45,835	34,614
Cl⁻	24,904	24,987	22,036	31,872	22,036	19,434	28,108	21,803
Na⁺	13,863	13,913	12,071	18,211	12,071	10,473	15,800	11,928
SO₄⁻	3,414	3,329	34	11,016	34	0	114	31
Mg⁺⁺	1,657	1,632	225	4,914	225	31	678	208
Ca⁺⁺	502	500	170	1,271	170	58	432	160
K⁺	482	484	426	617	426	376	544	422
HCO₃⁻	171	170	66	414	66	25	160	62
Mg/TDS	3.683%	3.625%	0.642%	7.193%	0.642%	0.102%	1.478%	0.599%
CaSO₄ saturation	N/A	N/A	N/A	157.2%	N/A	N/A	N/A	N/A

5

[0071] The following aspects describe certain inventions disclosed herein.

[0072] Aspect 1. A multi-pass nanofiltration system, comprising: a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium; at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further

10

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separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit, wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet.

5 [0073] Aspect 2. The multi-pass nanofiltration system of aspect 1, wherein: the at least one further nanofiltration unit includes a plurality of further nanofiltration units arranged in series; at least a portion of one or more permeate streams from the plurality of further nanofiltration units are feed streams for a respective next downstream one of the plurality of further nanofiltration units; and at least a portion of one or more reject streams from the 10 plurality of further nanofiltration units are configured to be recirculated into the feed stream of at least one upstream one of the plurality of further nanofiltration units, a first nanofiltration unit, or a combination thereof.

[0074] Aspect 3. The multi-pass nanofiltration system of aspect 2, wherein at least a 15 portion of each of the reject streams from the plurality of further nanofiltration units are configured to be recirculated into the feed stream of a respective next upstream one of the plurality of further nanofiltration units.

[0075] Aspect 4. The multi-pass nanofiltration system of aspect 2 or 3, wherein at least a 20 portion of one or more of the reject streams from the plurality of further nanofiltration units are not configured to be recirculated into a feed stream of another one of the plurality of further nanofiltration units.

[0076] Aspect 5. The multi-pass nanofiltration system of any one of aspects 1 to 4, further 25 comprising at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of a reject stream from at least one of the plurality of further nanofiltration units, or at least a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units.

[0077] Aspect 6. The multi-pass nanofiltration system of any one of aspects 2 to 5, wherein 30 a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream.

[0078] Aspect 7. The multi-pass nanofiltration system of aspect 6, wherein: the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being

arranged in series; and a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

[0079] Aspect 8. The multi-pass nanofiltration system of aspect 4, further comprising at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of the reject stream from at least one of the plurality of further nanofiltration units, or a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units.

[0080] Aspect 9. The multi-pass nanofiltration system of aspect 8, wherein a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream.

[0081] Aspect 10. The multi-pass nanofiltration system of aspect 9, wherein the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being arranged in series, and at least a portion of a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

[0082] Aspect 11. The multi-pass nanofiltration system of any one of aspects 1 to 10, wherein the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of the first nanofiltration unit and/or an upstream nanofiltration unit.

[0083] Aspect 12. The multi-pass nanofiltration system of any one of aspects 1 to 11, wherein the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of a respective next upstream nanofiltration unit.

[0084] Aspect 13. The multi-pass nanofiltration system of any one of aspects 1 to 12, comprising a pump on the permeate stream of one or more nanofiltration units.

[0085] Aspect 14. The multi-pass nanofiltration system of any one of aspects 1 to 13, wherein the further reject stream configured to be recirculated into the feed water stream does not comprise a pump before entering the feed water stream.

[0086] Aspect 15. The multi-pass nanofiltration system of any one of aspects 1 to 14, wherein the further reject stream is configured to be recirculated into the feed water stream received at a suction side of a pump upstream of the first nanofiltration unit.

[0087] Aspect 16. A method of producing a product permeate stream water using the system of any one of aspects 1 to 15.

[0088] Aspect 17. A multi-pass nanofiltration system, comprising: a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium; at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit, wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet, wherein at least another portion of the first permeate stream is configured to be drawn off to generate a first permeate draw stream, wherein the first permeate draw stream is not configured to be provided to the further nanofiltration unit inlet.

[0089] Aspect 18. The multi-pass nanofiltration system of aspect 17, wherein at least a portion of the first permeate draw stream and at least a portion of the further permeate stream are configured to be combined to form a combination permeate stream.

[0090] Aspect 19. The multi-pass nanofiltration system of aspect 17 or 18, wherein a flow rate of the first permeate draw stream is configured to be alterable.

[0091] Aspect 20. A method of producing a product permeate stream water using the system of any one of aspects 17 to 19.

[0092] The foregoing disclosure has been set forth merely to illustrate the invention and is not intended to be limiting. Because such modifications of the disclosed embodiments incorporating the spirit and substance of the invention may occur to persons skilled in the art, the invention should be construed to include everything within the scope of the appended claims and equivalents thereof.

[0093] Listing of reference labels:

	100, 200, 300, 400, 500, 800, 900	nanofiltration system
	101, 201, 301, 401, 501, 801, 901	saline water feed stream
	102, 202, 302, 402, 502, 802, 902	nanofiltration unit #1 permeate stream
5	103, 203, 303, 403, 503, 803, 903	nanofiltration unit #1 reject stream
	104, 204, 304, 404, 504, 804, 904	nanofiltration unit #2 permeate stream
	105, 205, 305, 405, 505, 805, 905	nanofiltration unit #2 reject stream
	111, 121	membrane
	120, 220, 320, 420, 520, 820, 920	nanofiltration unit #1 nanofiltration unit
10	130, 230, 330, 430, 530, 830, 930	nanofiltration unit #2 nanofiltration unit
	306, 406, 506	nth nanofiltration unit permeate stream
	307, 407, 507	nth nanofiltration unit reject stream
	335, 435	intermediate nanofiltration unit (NF #i)
	340, 440, 540	nth nanofiltration unit (NF #n)
15	409, 509	recirculated intermediate reject streams
	601, 701	branch stream saline feed stream
	602, 702	branch stream nanofiltration unit #1 permeate stream
	603, 703	branch stream nanofiltration unit #1 reject stream
	620, 720	branch stream nanofiltration unit #1
20	710	branch product stream
	809, 909	nanofiltration unit #1 permeate bypass stream
	910	nanofiltration unit #1 permeate bypass and nanofiltration #2 permeate combination stream

WHAT IS CLAIMED IS:

1. A multi-pass nanofiltration system, comprising:

a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium;

at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit,

wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet.

2. The multi-pass nanofiltration system of claim 1, wherein:

the at least one further nanofiltration unit includes a plurality of further nanofiltration units arranged in series;

at least a portion of one or more permeate streams from the plurality of further nanofiltration units are feed streams for a respective next downstream one of the plurality of further nanofiltration units; and

at least a portion of one or more reject streams from the plurality of further nanofiltration units are configured to be recirculated into the feed stream of at least one upstream one of the plurality of further nanofiltration units, a first nanofiltration unit, or a combination thereof.

3. The multi-pass nanofiltration system of claim 2, wherein at least a portion of each of the reject streams from the plurality of further nanofiltration units are configured to be recirculated into the feed stream of a respective next upstream one of the plurality of further

nanofiltration units.

4. The multi-pass nanofiltration system of claim 2, wherein at least a portion of one or more of the reject streams from the plurality of further nanofiltration units are not configured to be recirculated into a feed stream of another one of the plurality of further nanofiltration units.

5. The multi-pass nanofiltration system of claim 1, further comprising at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of a reject stream from at least one of the plurality of further nanofiltration units, or at least a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units.

6. The multi-pass nanofiltration system of claim 5, wherein a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream.

7. The multi-pass nanofiltration system of claim 6, wherein:

the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being arranged in series; and

a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

8. The multi-pass nanofiltration system of claim 4, further comprising at least one additional plurality of nanofiltration units arranged in series configured to receive at least a portion of the first nanofiltration unit reject stream, at least a portion of the reject stream from at least one of the plurality of further nanofiltration units, or a portion of both the first nanofiltration unit reject stream and the reject stream from at least one of the plurality of nanofiltration units.

9. The multi-pass nanofiltration system of claim 8, wherein a first nanofiltration unit of the at least one additional plurality of nanofiltration units is configured to receive at least a portion of the first nanofiltration unit reject stream.

10. The multi-pass nanofiltration system of claim 9, wherein the at least one additional plurality of nanofiltration units includes at least two additional pluralities of nanofiltration units, each of the at least two additional pluralities of nanofiltration units being arranged in series, and

at least a portion of a reject stream from a first one of the at least two additional pluralities of nanofiltration units is configured to be at least a portion of a feed stream of at least one of a second one of the at least two pluralities of additional nanofiltration units.

11. The multi-pass nanofiltration system of claim 1, wherein the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of the first nanofiltration unit and/or an upstream nanofiltration unit.

12. The multi-pass nanofiltration system of claim 11, wherein the at least one further nanofiltration unit is configured to receive a feed stream at a greater pressure than the feed stream of a respective next upstream nanofiltration unit.

13. The multi-pass nanofiltration system of claim 12, comprising a pump on the permeate stream of one or more nanofiltration units.

14. The multi-pass nanofiltration system of claim 1, wherein the further reject stream configured to be recirculated into the feed water stream does not comprise a pump before entering the feed water stream.

15. The multi-pass nanofiltration system of claim 1, wherein the further reject stream is configured to be recirculated into the feed water stream received at a suction side of a pump upstream of the first nanofiltration unit.

16. A method of producing a product permeate stream water using the system of claim 1.

17. A multi-pass nanofiltration system, comprising:

a first nanofiltration unit having an inlet configured to receive a feed water stream, a first permeate outlet configured to output a first permeate stream which has passed through a separation medium of the first nanofiltration unit, the separation medium being configured to separate one or more ions from the feed water stream, and a first reject stream outlet configured to output a first reject stream containing ions which have not passed through the separation medium;

at least one further nanofiltration unit downstream of the first nanofiltration unit, the at least one further nanofiltration unit having an inlet configured to receive at least a portion of the first permeate stream, a further permeate outlet configured to output a further permeate stream which has passed through a further separation medium of the further nanofiltration unit, the further separation medium being configured to separate one or more ions from the at least a portion of the first permeate stream, and a further reject stream outlet configured to output a further reject stream containing ions which have not passed through the further separation medium of the further nanofiltration unit,

wherein at least a portion of the further reject stream is configured to be recirculated into the feed water stream received at the first nanofiltration unit inlet,

wherein at least another portion of the first permeate stream is configured to be drawn off to generate a first permeate draw stream, wherein the first permeate draw stream is not configured to be provided to the further nanofiltration unit inlet.

18. The multi-pass nanofiltration system of claim 17, wherein at least a portion of the first permeate draw stream and at least a portion of the further permeate stream are configured to be combined to form a combination permeate stream.

19. The multi-pass nanofiltration system of claim 17, wherein a flow rate of the first permeate draw stream is configured to be alterable.

20. A method of producing a product permeate stream water using the system of claim 17.

PRIOR ART

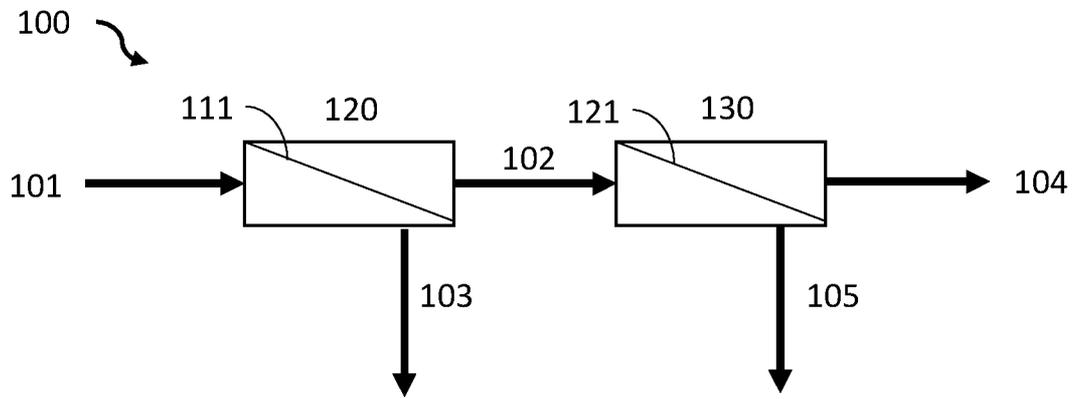


FIG. 1

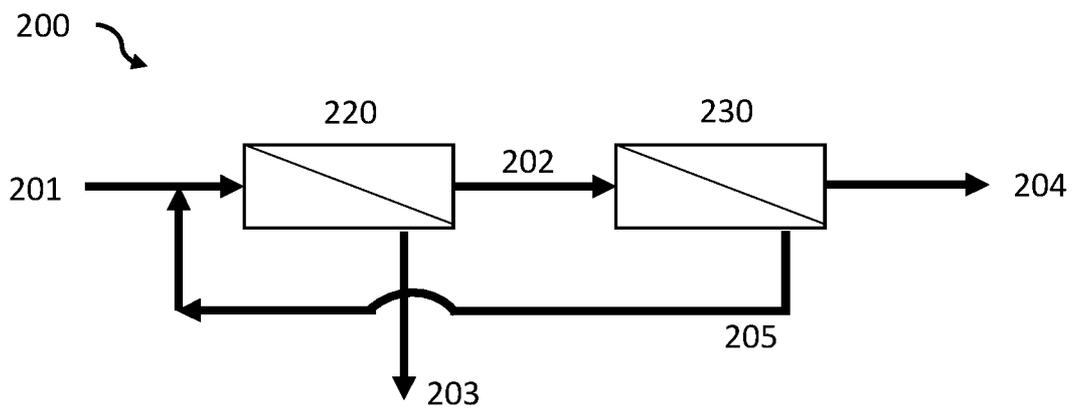


FIG. 2

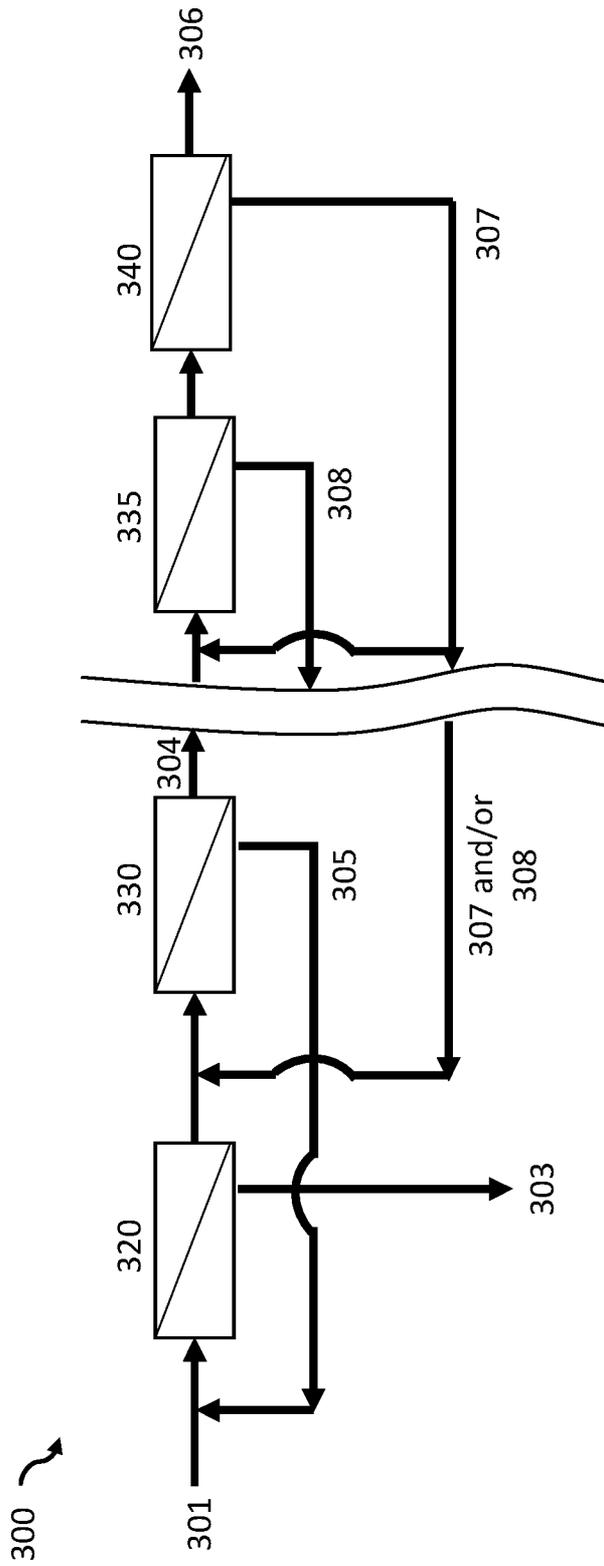


FIG. 3

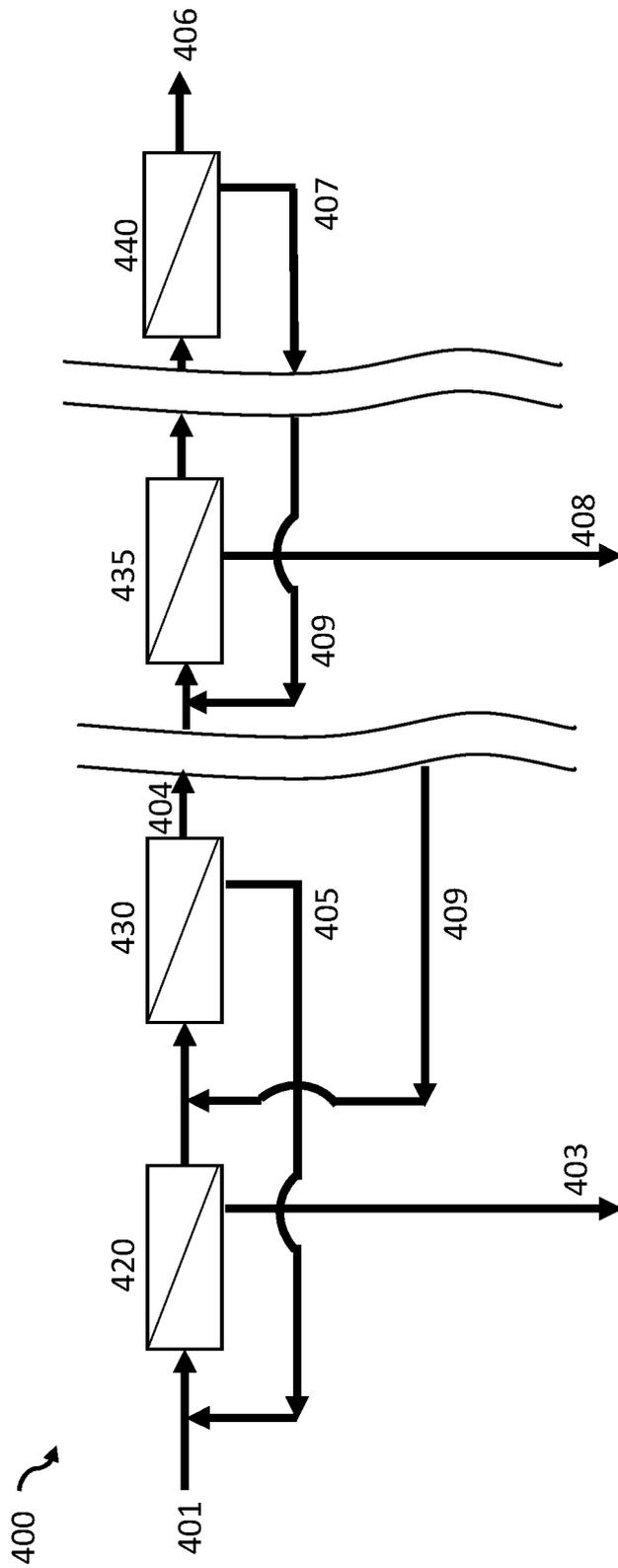


FIG. 4

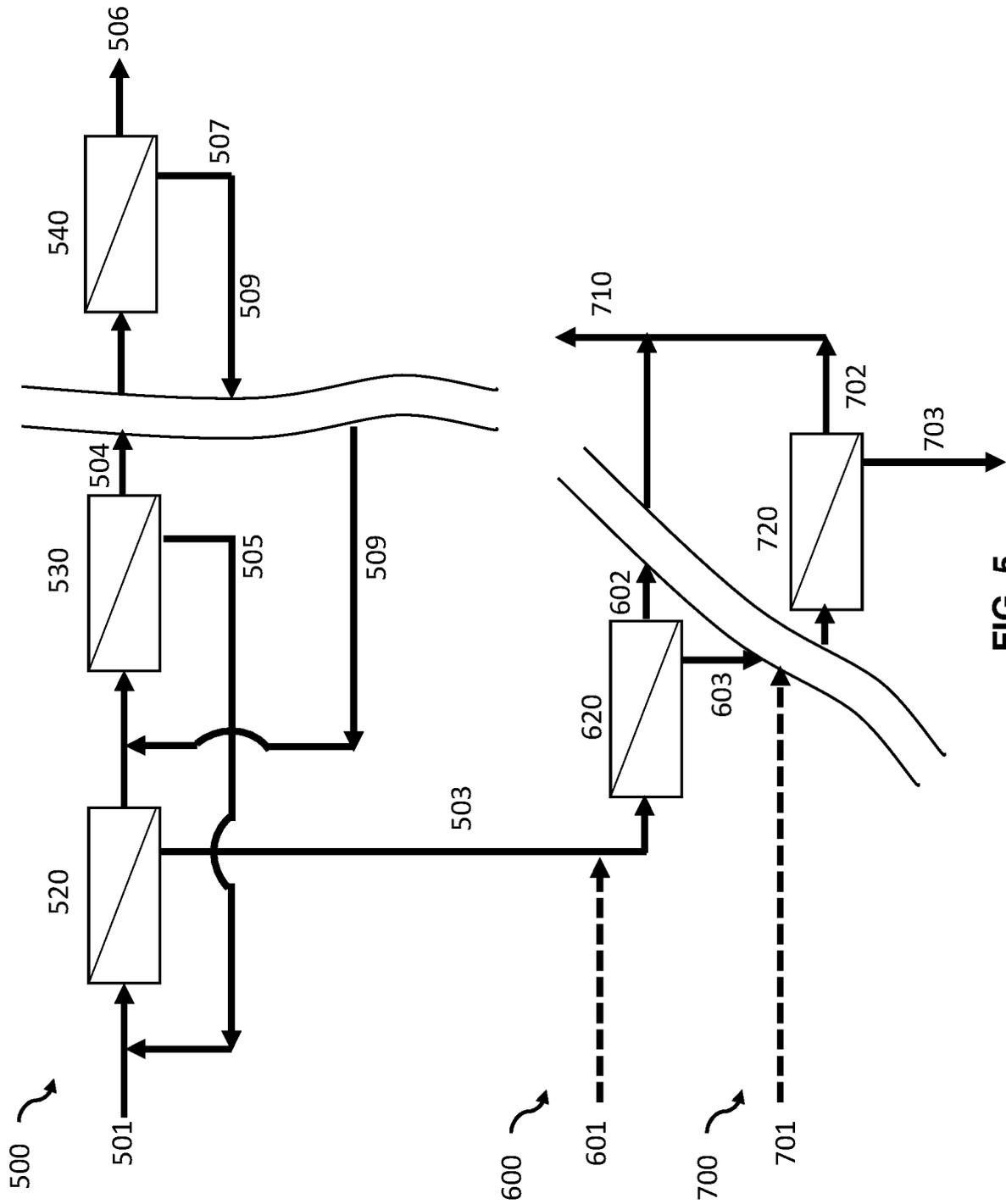


FIG. 5

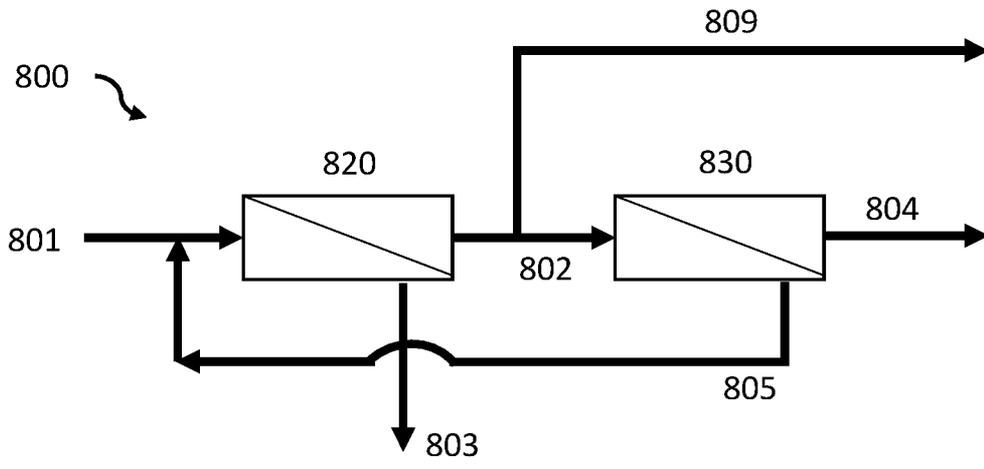


FIG. 6

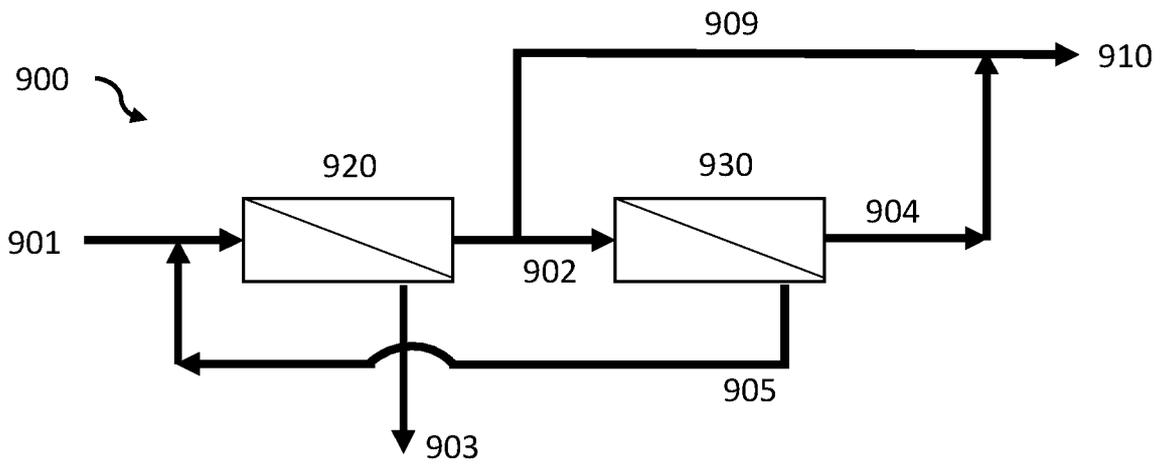


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2022/062404

A. CLASSIFICATION OF SUBJECT MATTER INV. B01D61/02 B01D61/08 C02F1/44 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) B01D C02F		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2020/316526 A1 (NICOLL PETER GEORGE [GB] ET AL) 8 October 2020 (2020-10-08) paragraphs [0011], [0034], [0036], [0042], [0043], [0061], [0062], [0064]; claims 1-10, 15; figures 3,4; examples 1,2; tables 1,2 -----	1, 11-16
X	CN 110 064 305 A (CHENGDU HONGRUN TECH CO LTD) 30 July 2019 (2019-07-30) paragraphs [0010], [0012], [0025], [0028], [0030], [0040]; claims 1,3,4,8; figure 1 ----- -/--	1-10, 14, 16
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
* Special categories of cited documents :		
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family	
Date of the actual completion of the international search	Date of mailing of the international search report	
24 February 2023	03/03/2023	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Williams, Jennifer	

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2022/062404

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>ALTAEE ALI ET AL: "Alternative design to dual stage NF seawater desalination using high rejection brackish water membranes", DESALINATION., vol. 273, no. 2-3, 1 March 2011 (2011-03-01), pages 391-397, XP093020318, NL</p> <p>ISSN: 0011-9164, DOI: 10.1016/j.desal.2011.01.056</p> <p>Fig.1 caption; page 392, left-hand column, paragraph 3; figure 1</p> <p style="text-align: center;">-----</p>	1, 15, 16
X	<p>US 6 162 361 A (ADIGA MAHABALA R [CA]) 19 December 2000 (2000-12-19) paragraphs [0013], [0023] - [0028], [0028] - [0032], [0034]; figure 1</p> <p style="text-align: center;">-----</p>	1, 14, 16-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2022/062404

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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