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Stackable forward osmosis membrane vessel with side ports

Abstract

Forward osmosis membrane vessels, and particularly stackable forward osmosis membrane vessels, are provided as well as systems and methods thereof. The forward osmosis membrane vessel has a body, a strong draw solution chamber, a first and a second semipermeable membrane, and a brine chamber. The first and second semipermeable membranes each are disposed within the cavity of the body. The first and second semipermeable membranes are configured to produce diluted draw solution streams and brine streams. The brine chamber is disposed at least partially between the first semipermeable membrane and the second semipermeable membrane. The forward osmosis membrane vessel may be configured such that in a stacked configuration the brine chamber and the strong draw solution chamber of the forward osmosis membrane vessel aligns with a brine chamber and a strong draw solution chamber of an adjacent second forward osmosis membrane vessel.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS
(1) This application is a U.S. National Phase Application of PCT/US2020/045457, filed Aug. 7, 2020, which claims the benefit of priority to U.S. Provisional Application Ser. No. 62,885,100, filed Aug. 9, 2019, the entire contents of which are each hereby incorporated by reference, for all purposes, in their entirety.
FIELD OF TECHNOLOGY
(2) The present disclosure relates to forward osmosis membrane vessels and, particularly to stackable forward osmosis membrane vessels, for efficient and easy assembly of two or more forward osmosis membrane vessels. Additional aspects of the disclosure relate to methods and systems using such forward osmosis membrane vessels.
BACKGROUND
(3) Fluid purification and treatment is widely used in industrial applications. Fluids suitable for fluid purification may include solutions having both dissolved solids (solutes) and liquid components (solvents), and sometimes containing suspended solid particles. A fluid may be an inorganic, organic, ionic, and/or polymeric solution, or a mixture of the above. Often the solute in a solvent is sought after for its industrial and consumer value, but in many cases the solvent is the product of use. With industry and society becoming more conscious of conservation and environmental issues, the separation, concentration, and recovery of both solute and solvent in a cost and energy efficient way is an important field of endeavor.
(4) Forward osmosis has been used for separation and/or recovery of a solute and/or solvent from a solution. Forward osmosis uses semipermeable membranes that typically allow solvent molecules, but not solute molecules, to pass through the semipermeable membrane from the feed side to the draw side of the semipermeable membrane. To draw the solvent molecules through the semipermeable membrane, a draw solution having an osmotic pressure greater than that of the feed solution is provided to the draw side of the membrane. Forward osmosis process relies upon the

natural phenomenon of diffusion of a solvent where there is a concentration gradient. The diffusion flux is sometimes approximated using Fick's Law of diffusion. The transport of the solvent from the low osmotic pressure feed side of the membrane to the high osmotic pressure draw side of the membrane generally continues until equilibrium in osmotic pressure is reached.

(5) Forward osmosis has drawn interest due to the likelihood of future water shortage and a corresponding increase in demand for cost effective fluid purification technologies. Sea water, brackish water or otherwise contaminated water may be purified by causing water (solvent) to be transported through a semipermeable membrane that rejects the dissolved salts and other contaminates (the solutes) by using the osmotic pressure of the draw solution to pull the solvent through the membrane.

SUMMARY

(6) Aspects of the present disclosure are directed to forward osmosis membrane vessels and, particularly to stackable forward osmosis membrane vessels. Additional aspects of the disclosure relate to methods and systems using forward osmosis membrane vessels and forward osmosis membrane vessel stacks.

(7) In accordance with one aspect of the disclosure provided is a forward osmosis membrane vessel having a body, a strong draw solution chamber, a first and a second semipermeable membrane and a brine chamber. The body has a proximal end portion and a distal end portion spaced from the proximal end portion. The body defines a cavity therein and delineates a draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, and a brine outlet. The strong draw solution chamber is disposed within the cavity. The strong draw solution chamber is in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream. The first and second semipermeable membranes each are disposed within the cavity of the body. The first and the second semipermeable membranes each comprise a feed side for receiving a feed stream comprising a feed solute, and a draw side for receiving the strong draw solution stream comprising a draw solute. The first and second semipermeable membranes are configured to produce a diluted draw solution stream. Additionally, the first semipermeable membrane is configured to produce a first brine stream and the second semipermeable membrane is configured to produce a second brine stream. The brine chamber is disposed at least partially between the first semipermeable membrane and the second semipermeable membrane. The brine chamber is in fluid communication with the first semipermeable membrane for receiving the first brine stream and in fluid communication with the second semipermeable membrane for receiving the second brine stream.

(8) According to another aspect of the disclosure, a forward osmosis membrane vessel is provided having a body, a strong draw solution, and a plurality of semipermeable membranes, and a brine chamber. The body has a proximal end portion and a distal end portion spaced from the proximal end portion. The body delineates a strong draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, and a brine outlet. The body also has an inner surface defining a cavity therein. The strong draw solution chamber is disposed within the cavity at one of the proximal end portion or the distal end portion and is in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream. The plurality of semipermeable membranes are each disposed within the cavity of the body. The plurality of semipermeable membranes each have a first end, a second end spaced from the first end, and an inner surface delineating a passageway extending from the first end to the second end. Each of the plurality of semipermeable membranes has a draw side along the inner surface of semipermeable membrane for receiving the strong draw solution stream comprising a draw solute and a feed side at the first base end for receiving a feed stream comprising a feed solute. The plurality of semipermeable membranes are configured to permit water and the draw solute to transfer therethrough, such that the draw solute has a cross flow direction with respect to the feed stream and each of the plurality of semipermeable membranes produces a brine stream. Further, the plurality of semipermeable

membranes are configured to operate in parallel. The brine chamber is configured for receiving the brine stream produced by each of the plurality of semipermeable membranes and is in fluid communication with the brine outlet.
(9) In accordance with a further aspect of the disclosure, provided is a forward osmosis membrane vessel configured for stacking. The forward osmosis membrane vessel includes a body having a having a proximal end portion and a distal end portion spaced from the proximal end portion. The body defines a cavity therein and delineates a strong draw solution inlet, a strong draw solution outlet, a diluted draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, a brine inlet, and a brine outlet. Additionally, the forward osmosis membrane vessel includes a strong draw solution chamber disposed within the cavity at one of the proximal end portion or the distal end portion. The strong draw solution chamber is in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream. A first and a second semipermeable membrane are also each disposed within the cavity of the body and configured for forward osmosis filtration. The forward osmosis membrane vessel has a brine chamber in fluid communication with the first semipermeable membrane for receiving a first brine stream and in fluid communication with the second semipermeable membrane for receiving a second brine stream. The forward osmosis membrane vessel is configured to be stackable, such that in a stacked configuration the brine chamber and the strong draw solution chamber of the forward osmosis membrane vessel aligns with a brine chamber and a strong draw solution chamber of an adjacent second forward osmosis membrane vessel.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The advantages and features of the disclosure will become apparent by reference to specific embodiments thereof, which are illustrated in the appended drawings, with like elements having the same reference numerals. When a plurality of similar elements is present, a single reference numeral may be assigned to the plurality of similar elements with a small letter designation referring to specific elements. When referring to the elements collectively or to a non-specific one or more of the elements, the small letter designation may be dropped. In accordance with common practice, the various features of the drawings are not drawn to scale unless otherwise indicated. On the contrary, the dimensions of the various features may be expanded or reduced for clarity. These drawings are example embodiments of the disclosure and are, therefore, not to be considered to be limiting of its scope. Included in the drawings are the following figures:
(2) FIG. **1** depicts a cross-sectional view of a stackable forward osmosis membrane vessel having a single end inlet through the base end in accordance with an aspect of the disclosure;
(3) FIG. **2** depicts the cross-sectional view of the forward osmosis membrane vessel of FIG. **1** with arrows to indicate an exemplary flow path of the streams therein;
(4) FIG. **3** is a perspective view of a forward osmosis membrane vessel stack assembled from a plurality of the forward osmosis membrane vessels of FIG. **1** according to another aspect of the disclosure;
(5) FIG. **4** depicts a cross-sectional view of the forward osmosis membrane vessel stack of FIG. **3**;
(6) FIG. **5** depicts the cross-sectional view of the forward osmosis membrane vessel stack of FIG. **4** with arrows to indicate an exemplary flow path of the streams therein;
(7) FIG. **6**A is a perspective view of a plurality of the forward osmosis membrane vessel stacks of FIG. **3** coupled together;
(8) FIG. **6**B is a top view of the plurality of the forward osmosis membrane vessel stacks of FIG. **6**A;
(9) FIG. **7** depicts a cross-sectional view of another stackable forward osmosis membrane vessel

having two inlets through the base ends in accordance with a further aspect of the disclosure;
(10) FIG. **8** depicts the cross-sectional view of the forward osmosis membrane vessel of FIG. **7** with arrows to indicate an exemplary flow path of the streams therein;
(11) FIG. **9** is a perspective view of a forward osmosis membrane vessel stack assembled from a plurality of the forward osmosis membrane vessels of FIG. **7** according to an additional aspect of the disclosure;
(12) FIG. **10**A is a perspective view of a plurality of the forward osmosis membrane vessel stacks of FIG. **9** coupled together;
(13) FIG. **10**B is a top view of the plurality of the forward osmosis membrane vessel stacks of FIG. **10**A;
(14) FIG. **11** depicts a cross-sectional view of an additional stackable forward osmosis membrane vessel having inlets and outlets solely through the side wall in accordance with yet another aspect of the disclosure;
(15) FIG. **12** depicts the cross-sectional view of the forward osmosis membrane vessel of FIG. **11** with arrows to indicate an exemplary flow path of the streams therein;
(16) FIG. **13** depicts a cross-sectional view of the forward osmosis membrane vessel of FIG. **1** with arrows to indicate another exemplary flow path of the streams therein; and
(17) FIG. **14** depicts a cross-sectional view of the forward osmosis membrane vessel of FIG. **1** with arrows to indicate a further exemplary flow path of the streams therein.
DETAILED DESCRIPTION
(18) Aspects of the present disclosure relate to forward osmosis membrane vessels and, particularly to stackable forward osmosis membrane vessels. The forward osmosis membrane vessels disclosed herein provide energy efficient separation of a feed stream into, e.g., a water-rich stream and a feed solute-rich stream (hereinafter “brine stream”). Additionally, the forward osmosis membrane vessels may be configured to be stackable to enable easy assembly of a forward osmosis membrane vessel stack. Additional aspects of the disclosure relate to systems and methods for using forward osmosis membrane vessels and forward osmosis membrane vessel stacks.
(19) As used herein, the term “stream,” in its various forms, including its use in the term “feed stream,” refers to a solution that may be flowed to or received in a portion or component of an apparatus or system of the present disclosure, and is not limited to solutions introduced into an apparatus or system, or portion thereof, under continuous flow, but rather, may also include solutions received in an apparatus or system for a period of time, such as that which may be employed in a series of batch processes. The feed stream may be an aqueous or non-aqueous stream containing salts, ions, acids, bases, metals, fertilizers, carbohydrates, proteins, sugars, monomers, polymers, biomaterials, or other pollutants typically treated with forward osmosis systems, such as brackish water, sea water, saline water, polluted water, farm runoff, chemical/manufacturing plant waste, etc. The feed solutes or particles thereof in the feed stream may be a desired product. For example, the feed stream may contain a dairy composition and the feed solute or particles thereof may be desirable for producing a diary concentrate. The feed stream (e.g. feed stream **142**) may, in some instances, be an aqueous solution containing sodium chloride (NaCl), potassium chloride (KCl), magnesium chloride (MgCl.sub.2), magnesium carbonate (MgCO.sub.3), magnesium sulfate (MgSO.sub.4), calcium chloride (CaCl.sub.2), calcium sulfate (CaSO.sub.4), calcium carbonate (CaCO.sub.3), potassium acetate (KAc) calcium magnesium acetate (CaMgAc), transition metals, lanthanides, and actinides, cyanides, nitrates, nitrites, sulfates, sulfites, sulfonates, hydroxides, phosphates, phosphites, halides, acetates, arsenides, amines, carboxylates, nitros and/or sugars. In some instances, the feed steam may have biological particulate or organisms, such as algae, plant matter, animal matter, or the like.
(20) The strong draw solution stream (e.g., strong draw solution stream **140**) may be an aqueous or non-aqueous stream containing an amount of solute to achieve a desirable osmotic pressure for the strong draw solution stream. In some instances, the strong draw solution stream includes a draw

solute or draw solute particles that have a change in solubility based on a change in one or more process conditions, such as temperature, pressure, and/or pH change, and/or the introduction of additives, such as gasses and/or liquids that change the solubility of the draw solute or draw solute particles. For example, the strong draw solution stream may include draw solute or draw solute particles that are less soluble in an aqueous solution as the temperature rises, such that phase separation may be induced in the diluted draw solution stream (e.g., diluted draw solution stream **142**) by increasing the temperature of the diluted draw solution stream to produce a phase rich in water and a phase rich in draw solute or draw solute particles. Suitable draw solutes and/or draw particles include random or sequential copolymer of low molecular weight diols such as 1,2 propanediol, 1,3 propanediol and/or 1,2 ethanediol. In at least some instances, the draw solutes and/or draw particles may be a thermally sensitive oligomers or polymers, which can be heated with waste heat to separate the draw solutes and/or draw particles from the solvent component, thus enabling the reuse of the draw solutes and/or draw particles. The draw solutes and/or draw particles may also be a natural compound, a "green material," and/or a compound produced by green chemistry for health and safety considerations intrinsic to water purification applications. Additional draw solutes and/or draw particles that may be suitable for the strong draw solution stream and the diluted draw solution stream can be found in US Patent Publication Nos.: US 20160039685 and US 20190054421, which are incorporated herein in their entirety for all purposes.
(21) FIG. **1** depicts a first non-limiting, exemplary embodiment of a forward osmosis membrane vessel **100** in accordance with aspects of the disclosure. As a brief overview, forward osmosis membrane vessel **100** includes a body **110** defining a cavity **150** and at least two semipermeable membranes **152** disposed within cavity **150**.
(22) Body **110** of forward osmosis membrane vessel **100** has a proximal end portion **112** and a distal end portion **114** spaced from proximal end portion **112**. Body **110** may form a cylindrical shape having a first base end **116**, a second base end **118**, and a side wall **117** extending between first base end **116** and second base end **118**. Although body **110** of forward osmosis membrane vessel **100** is illustrated in FIGS. **1-6**B as forming a cylindrical shape, in other embodiments, the body of the forward osmosis membrane vessel may be rectangular, square, pentagonal, hexagonal, octagonal, decagonal, or another geometric or non-geometric shape. In at least one embodiment, body **110** has a circumferential side wall **117**.
(23) Body **110** is configured to include a plurality of inlets and outlets, which may be formed by one or more apertures. Body **110** defines at least a strong draw solution inlet **120**, a diluted draw solution outlet **122**, a first feed stream inlet **124**, a second feed stream inlet **126**, and a brine stream outlet **162** that may each be formed by a separate aperture extending from body **110**. As illustrated by the embodiment shown in FIG. **1**, strong draw solution inlet **120**, diluted draw solution outlet **122**, first feed stream inlet **124**, second feed stream inlet **126**, and/or brine stream outlet **162** may extend through side wall **117** or one of base ends **116** or **118**. Preferably, strong draw solution inlet **120**, diluted draw solution outlet **122**, and brine stream outlet **162** extend through side wall **117**. Although forward osmosis membrane vessel **100** is illustrated as having first feed stream inlet **124** formed by an aperture extending through first base end **116** and second feed stream inlet **126** formed by an aperture extending through side wall **117**, in other embodiments the first feed stream inlet extends through the side wall of the body while the second feed stream inlet extends through a base end. In yet further embodiments, first feed stream inlet **124** and second feed stream inlet **126** extend through base ends **116** and **118**.
(24) Body **110** may also include a strong draw solution outlet **132**, a brine stream inlet **164**, a feed stream outlet **128**, and diluted draw solution inlets **123***a* and **123***b*. Preferably, sidewall **117** of body **110** defines strong draw solution outlet **132**, brine stream inlet **164**, feed stream outlet **128**, and diluted draw solution inlets **123**, or includes a plurality of apertures forming the same. In one embodiment, forward osmosis membrane vessel **100** includes a single brine stream outlet **162**.

Additionally or alternatively, forward osmosis membrane vessel **100** may be configured such that first base end **116** and second base end **118**, together, have two or less inlets and/or outlets. In some instances, forward osmosis membrane vessel **100** includes only one inlet and/or outlet (e.g., second feed stream inlet **124**) extending through one of the base ends **116** or **118**.

(25) Body **110** has an inner surface defining a cavity **150** within body **110**. A strong draw solution chamber **130** is disposed within cavity **150**, preferably at one of proximal end portion **112** or the distal end portion **114**. Strong draw solution chamber **130** is in fluid communication with strong draw solution inlet **120** for receiving strong draw solution stream **140**. Strong draw solution chamber **130** is configured to receive strong draw solution stream **140** and to provide and/or direct flow of strong draw solution stream **140** to semipermeable membranes **152**. In some embodiments, strong draw solution chamber **130** is configured to be in fluid communication with strong draw solution outlet **132**, such that a portion of strong draw solution stream **140** may bypass semipermeable membranes **152** to flow out of forward osmosis membrane vessel **100** without contacting feed stream **142**.

(26) Body **110** may also include a feed stream chamber **136** disposed within cavity **150**. Feed stream chamber **136** is, preferably, disposed at one of proximal end portion **112** or distal end portion **114**. For example, feed stream chamber **136** may be disposed within cavity **150** at distal end portion **114** while strong draw solution chamber **130** is disposed at proximal end portion **112** or feed stream chamber **136** may be disposed at proximal end portion **112** while strong draw solution chamber **130** is disposed at distal end portion **114**. Feed stream chamber **136** may be in fluid communication with either the first feed stream inlet **124** or second feed stream inlet **126** and, optionally, in fluid communication with feed stream outlet **128**, such that a portion of feed stream **142** may bypass semipermeable membranes **152** and flow out of forward osmosis membrane vessel **100** without contacting strong draw solution stream **140**.

(27) Forward osmosis membrane vessel **100** includes at least two semipermeable membranes **152** (e.g., first semipermeable membrane **152***a* and second semipermeable membrane **152***b*) disposed within the cavity of body **110**. Although the embodiment of forward osmosis membrane vessel **100** depicted in FIG. **1** includes only two semipermeable membranes, forward osmosis membrane vessel **100** may be configured to include more than two semipermeable membranes, such as three semipermeable membranes, four semipermeable membranes, five semipermeable membranes, or at least six semipermeable membranes. The semipermeable membranes **152** include a feed side for receiving feed stream **142** comprising a feed solute and a draw side for receiving strong draw solution stream **140** comprising a draw solute. Strong draw solution stream **140** may have an osmotic pressure that is equal to or greater than the osmotic pressure of feed stream **142**. In some embodiments, however, strong draw solution stream **140** has an osmotic pressure that is less than that of the feed stream **142**, such that diffusion of solvent (e.g., water) from feed stream **142** through semipermeable membrane **152** is assisted with a pressure that is greater on the feed side than on the draw side. In one embodiment, the osmotic pressure of strong draw solution stream **140** is substantially equal to or equal to the osmotic pressure of feed stream **142**.

(28) Semipermeable membranes **152** are configured to produce diluted draw solution stream **144** and brine stream **146**. In the embodiment illustrated by FIG. **2**, first semipermeable membrane **152***a* produces a first diluted draw solution stream **144***a* and a first brine stream **146***a* while second semipermeable membrane **152***b* produces a second diluted draw solution stream **144***b* and a second brine stream **146***b*. Semipermeable membranes **152** may be configured to have a first end **154**, a second end **155** spaced from the first end **154**, and an inner surface **156** delineating a passageway **158** extending from first end **154** to second end **155**. As illustrated in FIG. **1**, passageway **158***a* of first semipermeable membrane **152***a* may form a single continuous passageway with passageway **158***b* of second semipermeable membrane **152***b*. Preferably, passageway **158***a* of first semipermeable membrane **152***a* aligns with passageway **158***b* of second semipermeable membrane **152***b*. In at least one embodiment, passageway **158***a* of first semipermeable membrane **152***a*

coaxially aligns with passageway **158***b* of second semipermeable membrane **152***b*. In embodiments where strong draw solution stream **140** flows through passageway **158**, inner surface **156** of semipermeable membranes **152** may operate as the draw side.

(29) Semipermeable membranes **152** may be configured to have a shape that corresponds to the inner surface defining cavity **150** and/or to body **110**. For example, semipermeable membranes **152** may each be configured to be cylindrical. A space extends between the inner surface defining cavity **150** of body **110** and an outer surface of semipermeable membranes **152**. The space may be configured for receiving and/or collecting diluted draw solution stream **144**. Additionally the space is in fluid communication with diluted draw solution outlet(s) **122**.

(30) Forward osmosis membrane vessel **100** includes a brine chamber **160** in fluid communication with brine stream outlet **162** and configured for receiving brine stream **146**. Brine chamber **160** receives brine streams **146** produced from each of semipermeable membranes **152** directly or indirectly. For example, as illustrated in FIGS. **1** and **2**, brine chamber **160** is disposed at least partially between first semipermeable membrane **152***a* and second semipermeable membrane **152***b* to directly receive brine stream **146***a* produced from first semipermeable membrane **152***a* and second brine stream **146***b* produced from second semipermeable membrane **152***b*. In one embodiment, forward osmosis membrane vessel **100** includes solely one brine stream outlet **162**. Additionally or alternatively, forward osmosis membrane vessel **100** may include a brine inlet **164** that is in fluid communication with brine chamber **160**.

(31) A central core manifold **134** is positioned within brine chamber **160**. Central core manifold **134** extends from passageway **158***a* of first semipermeable membrane **152***a* to second passageway **158***b* of second semipermeable membrane **152***b*, such that strong draw solution stream **140** may flow through brine chamber **160** without mixing with brine stream **146** therein.

(32) The semipermeable membranes **152** may be adapted for cross-flow filtration, whereby strong draw solution stream **140** flows in a radial direction from inner surface **156** to the outer surface of semipermeable membrane **152**, while feed stream **140** flows in an axial direction from first end **154** to second end **155** of semipermeable membranes **152**. For example, the feed solute and/or feed particles (e.g., salt, ion, metal, etc.) of feed stream **140** may pass through semipermeable membrane **152** in an axial direction, while the draw solute and/or draw solute particles of strong draw solution stream **140** pass through semipermeable membrane **152** in a radial direction.

(33) Forward osmosis membrane vessel **100** is configured such that semipermeable membranes **152** operate in parallel. As illustrated in FIG. **2**, feed stream **142** may enter forward osmosis membrane vessel **100** through first feed stream inlet **124** located at proximal end portion **112** and second feed stream inlet **126** located at distal end portion **114**. Feed stream **142***b* flowing through second stream inlet **126** may flow to feed stream chamber **136** and subsequently second semipermeable membrane **152***b*. Feed stream **142***a* flowing through first feed stream inlet **124** flows through an aperture that extends through strong draw solution chamber **130**, such that feed stream **142***a* flows into first semipermeable membrane **152***a* without mixing with strong draw solution stream **140** within strong draw solution chamber **130**. Strong draw solution stream **140** may enter forward osmosis membrane vessel **100** by way of strong draw solution inlet **120** and flow into strong draw solution chamber **130** and subsequently to passageway **158** extending through semipermeable membranes **152**. Central core manifold **134** is disposed within brine chamber **160** to transfer strong draw solution stream **140** flowing through passageway **158***a* of first semipermeable membrane **152***a* to second passageway **158***b* of second semipermeable membrane **152***b*. By employing central manifold **134**, first and second semipermeable membranes **152***a* and **152***b* may operate in parallel and receive strong draw solution stream **140** from a continuous passageway **158** that flows through brine chamber **160**, which is positioned between first semipermeable membrane **152** and second permeable membrane **152***b*.

(34) Pursuant to the exemplary flow path illustrated in FIG. **2**, as feed stream **142** passes through semipermeable membranes **152** in a radial direction, strong draw solution stream **140** passes

through semipermeable membrane **152** in an axial direction and pulls water from feed stream **142** to form diluted draw solution stream **144** and to produce brine stream **146** from feed stream **142**. Diluted draw solution stream **144***a* produced from semipermeable membrane **152***a* may pass through diluted draw solution outlet **122***a*, while diluted draw solution stream **144***b* produced from semipermeable membrane **152***b* may exit diluted draw solution outlet **122***b*. Brine stream **146***a* produced from semipermeable membrane **152***a* and brine stream **146***b* produce from semipermeable membrane **152***b* flow into a single brine chamber **160** and may flow out of forward osmosis membrane vessel **100** via brine stream outlet **162**.

(35) Forward osmosis membrane vessel **100** may be configured to be stackable, such that that a plurality of forward osmosis membrane vessels **100** may be assembled to form a forward osmosis membrane vessel stack, as further discussed below. In the stacked configuration, brine chamber **160** and strong draw solution chamber **130** of first forward osmosis membrane vessel **100** aligns with brine chamber **160** and strong draw solution chamber **130** of an adjacent second forward osmosis membrane vessel **100**.

(36) FIGS. **3-5** depict a forward osmosis membrane vessel stack **200** according to another aspect of the disclosure. Forward osmosis membrane vessel stack **200** includes a plurality of at least two forward osmosis membrane vessels **100** in a stacked configuration. Although FIG. **3** illustrates a plurality of five forward osmosis membrane vessels **100***a*-**100***e* in a stacked configuration, forward osmosis membrane vessel stack **200** may include three, four, six, seven, eight, nine, or at least ten forward osmosis membrane vessels **100**. Forward osmosis membrane vessel stack **200** may also include one or more support brackets **210** to stabilize and/or couple a first forward osmosis membrane vessels **100***a* to an adjacent second forward osmosis membrane vessel **100***b*.

(37) As seen in FIG. **4**, the plurality of forward osmosis membrane vessels **100** of forward osmosis membrane vessel stack **200** may be assembled such that brine chamber **160** and strong draw solution chamber **130** of a first forward osmosis membrane vessel **100***a* align with brine chamber **160** and strong draw solution chamber **130**, respectively, of an adjacent second forward osmosis membrane vessel **100***b*. Forward osmosis membrane vessel stack **200** may also be assembled such that feed chamber **136** of first forward osmosis membrane vessel **100***a* aligns with feed chamber **136** of adjacent second forward osmosis membrane vessel **100***b*. Additionally or alternatively, one or more of strong draw solution outlet **132**, brine stream outlet **162**, diluted draw solution outlet **122**, and feed stream outlet **128** of first forward osmosis membrane vessel **100***a* may align with strong draw solution inlet **120**, brine stream inlet **164**, diluted draw solution inlet **123**, and feed stream inlet **124**, respectively, of adjacent second forward osmosis membrane vessel **100***b*.

(38) Forward osmosis membrane vessel stack **200** may be configured such that the plurality of forward osmosis membrane vessels **100** may be in fluid communication and/or coupled. Each of the plurality of forward osmosis membrane vessels **100** may be coupled directly (e.g., an aperture of first forward osmosis membrane vessel **100***a* may be attached to an aperture of adjacent second forward osmosis membrane vessel **100***b*) or indirectly (e.g., an outlet of first forward osmosis membrane vessel **100***a* may be coupled to an inlet of adjacent second forward osmosis membrane vessel **100***b* via tubes, pipes, etc.) to an adjacent forward osmosis membrane vessel **100**.

(39) For example, brine stream outlet **162** of first forward osmosis membrane vessel **100***a* may be in fluid communication with brine stream inlet **164** of adjacent second forward osmosis membrane vessel **100***b*. In some embodiments, brine stream outlet **162** of first forward osmosis membrane vessel **100***a* is connected (e.g., by attachment of adjacent apertures) to brine stream inlet **164** of adjacent second forward osmosis membrane vessel **100***b*. Strong draw solution outlet **132** of first forward osmosis membrane vessel **100***a* may be in fluid communication with strong draw solution inlet **120** of adjacent second forward osmosis membrane vessel **100***b*. In at least one embodiment, strong draw solution outlet **132** of first forward osmosis membrane vessel **100***a* is connected (e.g., by attachment of adjacent apertures) to strong draw solution inlet **120** of adjacent second forward osmosis membrane vessel **100***b*. Diluted draw solution outlet **122** of first osmosis vessel **100***a* may

be in fluid communication with diluted draw solution inlets **123** of second adjacent forward osmosis membrane vessel **100***b*. For instance, diluted draw solution outlet **122** of first osmosis vessel **100***a* may be connected (e.g., by attachment of adjacent apertures) to diluted draw solution inlets **123** of second adjacent forward osmosis membrane vessel **100***b*. In at least one embodiment, the apertures forming strong draw solution outlet **132**, brine stream outlet **162**, diluted draw solution outlet **122**, and feed stream outlet **128** of first forward osmosis membrane vessel **100***a* are be configured to directly connect (e.g., by attachment of adjacent apertures) to the strong draw solution inlet **120**, brine stream inlet **164**, diluted draw solution inlet **123**, and feed stream inlet **124** of adjacent second forward osmosis membrane vessel **100***b*, respectively.

(40) Forward osmosis membrane vessel stack **200** may be configured such that each of the plurality of forward osmosis membrane vessels **100** operate in parallel. Forward osmosis membrane vessel stack **200** may include a single distribution pipe **212** for distributing feed stream **142***a* to first feed stream inlet **124** of each of the plurality of forward osmosis membrane vessels **100**. Additionally, forward osmosis membrane vessel stack **200** may be configured such that providing a single one of the plurality of forward osmosis membrane vessels **100** with a strong draw stream **140** provides each of the plurality of forward osmosis membrane vessels **100** with strong draw stream **140** and enables the plurality of forward osmosis membrane vessels **100**, and semipermeable membranes **152** therein, to operate in parallel. Diluted draw solution stream **144** and brine stream **146** produced from all of the plurality of forward osmosis membrane vessels **100** may be removed and/or collected from outlets (e.g., diluted draw solution outlet **122** and/or brine outlet **162**) of a single forward osmosis membrane vessel **100***e*.

(41) FIGS. **6**A and **6**B depict a plurality of forward osmosis membrane vessel stacks **200** coupled together. Although the embodiments illustrated in FIGS. **6**A and **6**B include four forward osmosis membrane vessel stacks **200**, more than four or less than four forward osmosis membrane vessel stacks **200** may be included. One of ordinary skill in the art would understand how to affix two or more forward osmosis membrane vessel stacks **200** adjacent to each other, e.g., using one or more straps, saddles, support frames, and hardware. For example, a support frame **214** may be used for securing the forward osmosis membrane vessel stacks **200** in a relative position with respect to each other.

(42) FIG. **7** depicts another exemplary, non-limiting embodiment of a forward osmosis membrane vessel **300** in accordance with aspects of the disclosure. Forward osmosis membrane vessel **300** operates similar to forward osmosis membrane vessel **100** and includes similar features and/or elements, which may be omitted for brevity from the description below. It should be understood that although similar features and/or elements may be employed, various aspects of forward osmosis membrane vessel **300**, e.g., size, shape, material, etc., may be different than those described with respect to forward osmosis membrane vessel **100**.

(43) As a brief overview, forward osmosis membrane vessel **300** includes a body **310** defining a cavity **350** and at least two semipermeable membranes **352** disposed within cavity **350**. Unlike forward osmosis membrane vessel **100**, forward osmosis membrane vessel **300** includes a first feed stream inlet **324** and a second feed stream inlet **326** that extend through end bases **316** and **318** of body **310**.

(44) Body **310** has a proximal end portion **312** and a distal end portion **314** spaced from proximal end portion **312**. Body **310** may form a cylindrical shape having a first base end **316**, a second base end **318**, and a side wall **317** extending between first base end **316** and second base end **318**. Body **310** is configured to include a plurality of inlets and outlets, which may be formed by one or more apertures. Body **310** defines at least a strong draw solution inlet **320**, a diluted draw solution outlet **322**, a first feed stream inlet **324**, a second feed stream inlet **326**, and a brine stream outlet **362** each formed by a separate aperture extending through body **310**. As illustrated by the embodiment shown in FIG. **7**, strong draw solution inlet **320**, diluted draw solution outlet **322**, and brine stream outlet **362** extend through side wall **317**, while first feed stream inlet **324** and second feed stream

inlet **326** extend through base ends **316** and **318**, respectively. As depicted by FIGS. **7** and **8**, forward osmosis membrane vessel **300** does not include a feed stream chamber or a feed stream outlet.

(45) FIG. **9** depicts a forward osmosis membrane vessel stack **400** according to another aspect of the disclosure. Forward osmosis membrane vessel stack **400** is similar to forward osmosis membrane vessel stack **200**, but includes a plurality of at least two forward osmosis membrane vessels **300** in a stacked configuration. Although FIG. **9** illustrates a plurality of five forward osmosis membrane vessels **300***a*-**300***e* in a stacked configuration, forward osmosis membrane vessel stack **400** may include three, four, six, seven, eight, nine, or at least ten forward osmosis membrane vessels **300** in a stacked configuration. Forward osmosis membrane vessel stack **400** includes two distribution pipes **412***a* and **412***b* for distributing a feed stream to first and second feed stream inlets **324** and **326** of each of the plurality of forward osmosis membrane vessels **300**.

(46) FIGS. **10**A and **10**B depict a plurality of forward osmosis membrane vessel stacks **400** coupled together. Although the embodiments illustrated in FIGS. **10**A and **10**B include four forward osmosis membrane vessel stacks **400**, more than four or less than four forward osmosis membrane vessel stacks **400** may be included. One of ordinary skill in the art would understand how to affix two or more forward osmosis membrane vessel stacks **400** adjacent to each other, e.g., using one or more straps, saddles, support frames, and hardware. For example, a support frame **214** may be used for securing the forward osmosis membrane vessel stacks **400** in a relative position with respect to each other.

(47) FIGS. **11** and **12** depict yet a further non-limiting, exemplary embodiment of a forward osmosis membrane vessel **500** in accordance with an aspect of the disclosure. Forward osmosis membrane vessel **500** operates similar to forward osmosis membrane vessels **100** and **300** and includes similar features and/or elements, which may be omitted for brevity from the description below. It should be understood that although similar features and/or elements may be employed, various aspects of forward osmosis membrane vessel **500**, e.g., size, shape, material, etc., may be different than those described with respect to forward osmosis membrane vessels **100** and/or **300**.

(48) As a brief overview, forward osmosis membrane vessel **500** includes a body **510** defining a cavity **550** and at least two semipermeable membranes **552** disposed within cavity **550**. Unlike forward osmosis membrane vessels **100** and **300**, forward osmosis membrane vessel **500** includes a first feed stream inlet **524** and a second feed stream inlet **526** that extend through side wall **517** of body **510**. Additionally, forward osmosis membrane vessel **500** may have all inlets and outlets for receiving a stream extending through side wall **517** of body **510**. For instance, forward osmosis membrane vessel **500** may be configured to not have any inlets or outlet extending through base end **516** or **518**.

(49) Body **510** has a proximal end portion **512** and a distal end portion **514** spaced from proximal end portion **512**. Body **510** may form a cylindrical shape having a first base end **516**, a second base end **518**, and a side wall **517** extending between first base end **516** and second base end **518**. Body **510** is configured to include a plurality of inlets and outlets, which may be formed by one or more apertures. Body **510** defines at least a strong draw solution inlet **520**, a diluted draw solution outlet **522**, a first feed stream inlet **524**, a second feed stream inlet **526**, and a brine stream outlet **562** each be formed by a separate aperture extending from body **510**. As illustrated by the embodiment shown in FIG. **11**, strong draw solution inlet **520**, diluted draw solution outlet **522**, and brine stream outlet **562**, first feed stream inlet **524**, and second feed stream inlet **526** extend through side wall **517**.

(50) Forward osmosis membrane vessel **500** includes at least two feed stream chambers **536***a* and **536***b*. As depicted by FIG. **12**, feed stream **142** may enter forward osmosis membrane vessel **500** through first feed stream inlet **524** located at proximal end portion **512** and second feed stream inlet **526** located at distal end portion **514**. Feed streams **142***a* and **142***b* flowing through first and second feed stream inlets **524** and **526**, respectively, may flow into feed stream chambers **536***a* and **536***b*,

respectively. From feed stream chambers **536***a* and **536***b*, feed stream **142***a* and **142***b* flow to semipermeable membranes **552***a* and **552***b*, respectively. Feed stream **142***a* flowing through first feed stream inlet **524** flows through a feed stream manifold **538** that extends through draw solution chamber **530**, such that feed stream **142***a* flows into first semipermeable membrane **552***a* without mixing with strong draw solution stream **140** within strong draw solution chamber **530**. Strong draw solution stream **140** may enter forward osmosis membrane vessel **500** by way of strong draw solution inlet **520** and flow into strong draw solution chamber **530** and subsequently to passageway **558** extending through semipermeable membranes **552**. Central core manifold **534** is disposed within brine chamber **560** to transfer strong draw solution stream **140** flowing through passageway **558***a* of first semipermeable membrane **552***a* to second passageway **558***b* of second semipermeable membrane **552***b*.

(51) FIGS. **13** and **14** depict a cross-sectional view of forward osmosis membrane vessel **100** of FIG. **1** with arrows to indicate exemplary flow paths of streams therein. As depicted by FIGS. **13** and **14**, forward osmosis membrane vessel **100** may be operated with stream flow paths that are different from those illustrated in FIG. **2**. For consistency, the elements of forward osmosis membrane vessel **100** have been labeled with the same reference numerals, although the stream flow paths of one or more of the strong draw solution stream **140**, feed stream **142**, diluted draw solution stream **144**, and the brine stream **146** are different from those depicted in FIG. **2**.

(52) Pursuant to the stream flow path depicted in FIG. **13**, feed stream **142** may enter forward osmosis membrane vessel **100** through brine outlet **162** and flow to brine chamber **160**. From brine chamber **160**, feed stream **142** may flow into first and second semipermeable membranes **152***a* and **152***b*. Brine streams **144***a* and **144***b*, produced respectively from first semipermeable membrane **152***a* and second semipermeable membrane **152***b*, may flow out of forward osmosis membrane vessel **100** through first feed inlet **124** and second feed inlet **126**. As shown in FIG. **13**, brine stream **146***b* collects in feed chamber **136** prior to flowing out of forward osmosis membrane vessel **100** through second feed inlet **126**.

(53) Pursuant to the stream flow path depicted in FIG. **14**, strong draw solution stream **140** enters forward osmosis membrane vessel **100** through diluted draw solution inlets **123***a* and **123***b* and flows into the space defined between semipermeable membranes **152** and the inner surface defining cavity **150**. Strong draw solution **140** subsequently flows through semipermeable membranes **152** in a radial direction inward toward passageway **158**. As strong draw solution **140** flows through semipermeable membranes **152**, diluted draw solution stream **144** is produced and collected in passageway **158** defined by the inner surface **156** of semipermeable membranes **152**. Diluted draw solution stream **144** flows to and/or collects in strong draw solution chamber **130** prior to flowing out of forward osmosis membrane vessel **100** through strong draw solution outlet **132**. Feed stream **142** and brine stream **146** may have a flow path through forward osmosis membrane vessel **100** similar to that depicted in FIG. **13**.

(54) Although the invention is illustrated and described herein with reference to specific embodiments, the invention is not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention.

Claims

1. A forward osmosis membrane vessel configured for stacking comprising: a body having a proximal end portion and a distal end portion spaced from the proximal end portion, the body defining a cavity therein and delineating a strong draw solution inlet, a strong draw solution outlet, a diluted draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, a brine inlet, and a brine outlet; a strong draw solution chamber disposed within the cavity at one of the proximal end portion or the distal end portion, the strong draw solution

chamber being in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream; a first and a second semipermeable membrane each disposed within the cavity of the body and configured for forward osmosis filtration; and a brine chamber in fluid communication with the first semipermeable membrane for receiving a first brine stream and in fluid communication with the second semipermeable membrane for receiving a second brine stream, wherein the forward osmosis membrane vessel is configured to be stackable, such that in a stacked configuration the brine chamber and the strong draw solution chamber of the forward osmosis membrane vessel align with a brine chamber and a strong draw solution chamber of an adjacent second forward osmosis membrane vessel.

2. The forward osmosis membrane vessel stack comprising a plurality of forward osmosis membrane vessels of claim 1, wherein the plurality of forward osmosis membrane vessels includes at least a first forward osmosis membrane vessel in the stacked configuration with an adjacent second forward osmosis membrane vessel, wherein the brine chamber and the strong draw solution chamber of the first forward osmosis membrane vessel aligns with the brine chamber and the strong draw solution chamber of the adjacent second forward osmosis membrane vessel.

3. The forward osmosis membrane vessel stack of claim 2, wherein the brine outlet of the first forward osmosis membrane vessel is in fluid communication with the brine inlet of the adjacent second forward osmosis membrane vessel.

4. The forward osmosis membrane vessel stack of claim 3, wherein the brine outlet of the first forward osmosis membrane vessel is connected to the brine inlet of the adjacent second forward osmosis membrane vessel.

5. The forward osmosis membrane vessel stack of claim 2, wherein the strong draw solution outlet of the first forward osmosis membrane vessel is in fluid communication with the strong draw solution inlet of the adjacent second forward osmosis membrane vessel.

6. The forward osmosis membrane vessel stack of claim 5, wherein the strong draw solution outlet of the first forward osmosis membrane vessel is connected to the strong draw solution inlet of the adjacent second forward osmosis membrane vessel.

7. The forward osmosis membrane vessel stack of claim 2, wherein the diluted draw solution outlet of the first forward osmosis membrane vessel is in fluid communication with the diluted draw solution inlet of the adjacent second forward osmosis membrane vessel.

8. The forward osmosis membrane vessel stack of claim 7, wherein the diluted draw solution outlet of the first forward osmosis membrane vessel is connected to the diluted draw solution inlet of the adjacent second forward osmosis membrane vessel.

9. A forward osmosis membrane vessel comprising: a body having a proximal end portion and a distal end portion spaced from the proximal end portion, the body defining a cavity therein and delineating a strong draw solution inlet, a strong draw solution outlet, a diluted draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, a brine inlet, and a brine outlet; a strong draw solution chamber disposed within the cavity at one of the proximal end portion or the distal end portion, the strong draw solution chamber being in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream; a first and a second semipermeable membrane each disposed within the cavity of the body, the first and the second semipermeable membranes each comprising a feed side for receiving a feed stream comprising a feed solute, and a draw side for receiving the strong draw solution stream comprising a draw solute, wherein the first and second semipermeable membranes are configured to produce a diluted draw solution stream and the first semipermeable membrane is configured to produce a first brine stream and the second semipermeable membrane is configured to produce a second brine stream; and a brine chamber disposed at least partially between the first semipermeable membrane and the second semipermeable membrane, the brine chamber in fluid communication with the first semipermeable membrane for receiving the first brine stream and in fluid communication with the second semipermeable membrane for receiving the second brine stream, wherein the forward

osmosis membrane vessel is configured to be stackable, such that in a stacked configuration the brine chamber and the strong draw solution chamber of the forward osmosis membrane vessel align with a brine chamber and a strong draw solution chamber of an adjacent second forward osmosis membrane vessel.
10. The forward osmosis membrane vessel of claim 9, wherein the first feed stream inlet is delineated by the body at one of the proximal end portion or the distal end portion; wherein the second feed stream inlet is delineated by the body at the other one of the proximal end portion or the distal end portion; and wherein the body has a first base end, a second base end, and a side wall extending between the first base end and the second base end.
11. The forward osmosis membrane vessel of claim 10, wherein the body has a cylindrical configuration with a circumferential side wall extending between the first base end and the second base end.
12. The forward osmosis membrane vessel of claim 10, wherein at least the strong draw solution inlet, the diluted draw solution outlet, the first feed stream inlet, and the brine outlet are delineated by the side wall of the body; and wherein the side wall of the body has a plurality of apertures forming the strong draw solution inlet, the diluted draw solution outlet, the first feed stream inlet, and the brine outlet.
13. The forward osmosis membrane vessel of claim 10, wherein all inlets and outlets for receiving a flow are defined by the side wall of the body.
14. The forward osmosis membrane vessel of claim 9, wherein the vessel has a brine stream outlet.
15. The forward osmosis membrane vessel of claim 9, wherein the first semipermeable membrane and the second semipermeable membrane are each configured to be cylindrical with a passageway extending therethrough; and wherein the passageway of the first semipermeable membrane coaxially aligns with the passageway of the second semipermeable membrane.
16. The forward osmosis membrane vessel of claim 9, further comprising a central core manifold that extends through the brine chamber; wherein the central core manifold is configured to transfer strong draw solution flowing through a passageway of the first semipermeable membrane to the passageway of the second semipermeable membrane.
17. A forward osmosis membrane vessel comprising: a body having a proximal end portion and a distal end portion spaced from the proximal end portion, the body delineating a strong draw solution inlet, a strong draw solution outlet, a diluted draw solution inlet, a diluted draw solution outlet, a first feed stream inlet, a second feed stream inlet, a brine inlet, and a brine outlet, the body having an inner surface defining a cavity therein, a strong draw solution chamber disposed within the cavity at one of the proximal end portion or the distal end portion, the strong draw solution chamber being in fluid communication with the strong draw solution inlet for receiving a strong draw solution stream; a plurality of semipermeable membranes each disposed within the cavity of the body, the plurality of semipermeable membranes each having a first end, a second end spaced from the first end, and an inner surface delineating a passageway extending from the first end to the second end, each of the plurality of semipermeable membranes having a draw side along the inner surface of semipermeable membrane for receiving the strong draw solution stream comprising a draw solute and a feed side at the first end for receiving a feed stream comprising a feed solute, wherein the plurality of semipermeable membranes are configured to permit water and the draw solute to transfer therethrough, such that the draw solute flows in a cross-flow direction with respect to the feed stream and each of the plurality of semipermeable membranes produces a brine stream, wherein the plurality of semipermeable membranes are configured to operate in parallel; and a brine chamber for receiving the brine stream produced by each of the plurality of semipermeable membranes, the brine chamber in fluid communication with the brine outlet, wherein the forward osmosis membrane vessel is configured to be stackable, such that in a stacked configuration the brine chamber and the strong draw solution chamber of the forward osmosis membrane vessel align with a brine chamber and a strong draw solution chamber of an adjacent

second forward osmosis membrane vessel.

18. The forward osmosis membrane vessel of claim 17, wherein the plurality of semipermeable membranes includes two semipermeable membranes configured to operate in parallel.

19. The forward osmosis membrane vessel of claim 17, wherein the plurality of semipermeable membranes includes at least three semipermeable membranes configured to operate in parallel.

20. The forward osmosis membrane vessel of claim 17, wherein the draw solute flows through the semipermeable membrane in a radial direction, wherein the feed stream flows in an axial direction; wherein a space extends between the inner surface of the body and the plurality of semipermeable membranes, the space adapted for receiving the diluted draw solution; and wherein the space extending between the inner surface of the body and the plurality of semipermeable membranes is in fluid communication with the diluted draw solution outlet.