

## METHOD AND SYSTEM FOR OPERATING A HIGH RECOVERY SEPARATION PROCESS

### RELATED APPLICATION

5           **[0001]**       This application claims priority to U.S. utility patent application no. 16/138,291, filed September 21, 2018 and also claims the benefit of provisional application no. 62/562,694, filed September 25, 2017. The disclosures of both of the above applications are incorporated by reference herein.

### TECHNICAL FIELD

10           **[0002]**       The present disclosure relates generally to fluid separation systems, and, more specifically, to a method and system for using multiple energy recovery device for multiple stages of fluid separation.

### BACKGROUND

15           **[0003]**       The statements in this section merely provide background information related to the present disclosure and may not constitute prior art.

**[0004]**       Reverse osmosis systems typically use one or more membrane housings that have one or more membranes therein that are used to extract an essentially pure fluid from a solution. The desalination reverse osmosis membranes receive feed fluid from brackish or sea water and extract fresh water therefrom. Fresh water is extracted or separated when the pressure of the feed fluid exceeds the osmotic pressure of the fluid which allows permeate or product fluid to cross the semi-permeable reverse osmosis membrane. The fluid that is left on the input side to the membrane becomes higher in salt concentration because fresh water that travels through the membrane does not include the salt. The water that passes through the membrane is referred to as a permeate. The pressure required to produce fresh water is proportional to the concentration of the total dissolved solids (TDS) in this feed solution within the reverse osmosis housing. For typical ocean water, the concentration is about 35,000 parts per million (ppm) and the corresponding osmotic pressure is about 450 pounds per square inch (psi) (3,102 kPa). For 70,000 ppm feed fluid, the osmotic pressure approximately doubles to 900 psi (about 6,205 kPa). A typical seawater reverse osmosis system uses a series of membranes that recover up to about 45% of the fresh water and generate about 55% concentrate brine from the original volume of seawater. The net driving pressure (NDP) equals the feed pressure minus

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the osmotic pressure. The net driving pressure is the pressure energy available to drive pure fluid across the membrane.

5       **[0005]** Referring now to FIG. 1A, a reverse osmosis system 10 according to the prior art includes a membrane array 12 that generates a permeate stream through permeate pipe 14 and a brine stream through a brine pipe 16 from a feed stream in a feed pipe 18. The feed stream originates from a source 19 typically includes brackish or sea water. A feed pump 20 coupled to a motor 22 pressurizes the feed stream 18 to a required pressure, and the feed stream 18 enters the membrane array 12 at the required pressure.

10       **[0006]** The membrane array 12 includes a membrane housing or pressure vessel 24 and a membrane 26. The portion of the feed stream 18 that flows through the membrane 26 before exiting the membrane array 12 forms the permeate stream 14 that exits through the permeate pipe 14. The portion of the feed stream 18 that does not flow through the membrane 26 before exiting the membrane array 12 forms the  
15 brine stream that exits in the brine pipe 16.

**[0007]** The permeate stream 14 is a purified fluid flow at a low pressure that collects in a tank 28 or is piped to a desired location. The brine stream 16 is a higher pressure stream that contains dissolved materials blocked by the membrane 26. The pressure of the brine stream 16 is only slightly lower than the feed stream 18. A control  
20 valve 30 may be used to regulate the flow through and pressure in the membrane array 12. The brine stream 16 may flow through the control valve 30 and into a drain or tank 32.

**[0008]** Referring now to Figure 1B, the membrane 26 of Figure 1A is typically formed of a plurality of elements 40. The elements 40 are typically formed in a  
25 cylindrical shape by rolling a plurality of sheets and spacers together. In this example a first sheet 42 and a second sheet 44 are glued together on three sides with the fourth side being in glued communication with the central collection tube 46 communicates permeate to a desired location as indicated by arrow 48. Brine which may also be referred to as reject 50 does not enter the collection tube 46. The sheets and the  
30 spacers glued between the membrane sheets 42 and 44 to allow the sheet 44 to stay slightly apart and allow permeate to flow to the collection tube 46. A second spacer sheet 54 is used to keep the membrane sheets slightly apart and allow the axial flow through the element and allow brine or reject 50 to flow therethrough.

**[0009]** Referring now to Figure 1C, an inlet pipe 60 fluidically communicates fluid into the pressure vessel 24. A flow distributor 62 distributes fluid to the reverse osmosis elements 40A – 40E rather than around the elements 40A – 40E. The fluid distributor 62 spreads the fluid flow radially across the surface of element 40A. The seal 64 allows fluid from the distributor 62 to not circumvent the first element 40A. The flow continues through the elements 40A – 40E sequentially. Permeate collection tubes 46A, 46B, 46C, 46D and 46E receive the permeate from each respective element 40A-40E. Connectors 66A-66D join successive collection tubes 46A-46E. An anti-telescoping device 68 may be used to maintain the position of the elements 40A – 40E relative to the flow distributor 62. In most applications between three and eight elements are used. Five of which are used in this example. A brine exit pipe 70 is used to emit the brine from the pressure vessel 24. Permeate exit collection tube flows in a direction indicated by the arrow 48.

**[0010]** As the feed progresses from element to element, the amount of total dissolved solids increases until the brine exits the pipe 70. The osmotic pressure is mostly determined by the concentration of the total dissolved solids. Each succeeding element experiences a higher concentration and thus higher osmotic pressure and lower Net Driving Pressure than the preceding element. Consequently, each successful element has lower permeate production than the preceding element. A minimum Net Driving Pressure for sea water in an RO system is about 100 psi (689.5 kPa). An initial feed pressure must be substantially higher than the initial osmotic pressure to ensure sufficient Net Driving Pressure available toward the end of the array. A typical pressure may be about 800 psi (5516 kPa) while the osmotic pressure is about 450 psi (3103 kPa) which yields a Net Driving Pressure of 350 psi (2413 kPa) for the first element. At the end of the array the osmotic pressure may be 700 psi (4826 kPa) which reduces the Net Driving Pressure to 100 psi (689.5 kPa). A high initial Net Driving Pressure is wasteful because the pressure is much higher than needed for an optimal rate of permeate production. In an ideal situation, the feed pressure would steadily increase to compensate for the increasing osmotic pressure resulting in a constant net driving pressure throughout the array.

**[0011]** Another issue with reverse osmosis systems is polarization. Polarization is the formation of a stagnant boundary layer adjacent to the membrane surface where the concentration of salinity and foulant becomes very high. Polarization occurs when the flow velocity through the membrane elements is reduced to a certain

value. Polarization typically becomes severe when flow velocity drops to below fifty percent relative to the inlet flow velocity of the first element. The typical amount of permeate that can be recovered is about fifty percent or lower and may have a typical range between thirty-eight and forty-five percent.

5           **[0012]**       Referring now to Figure 2A, one way in which to achieve higher permeate recovery is employing a first set of pressure vessels 210A, 210B which feed a second set of pressure vessels 210C. In this example, two pressure vessels are illustrated in a first stage 212 and a single pressure vessel is illustrated in a second stage 214. This type of configuration is referred to as a 2:1 array. Feed fluid enters a  
10 feed manifold 220 which is distributed between the pressure vessels 210A and 210B. The brine exits the pressure vessels 210A and 210B through a brine manifold 224 to pressure vessel 210C in the second stage 214. Permeate exits the pressure vessels 210A and 210B through a permeate manifold 228. The permeate manifold 228 is also in communication with the permeate generated in the pressure vessel 210C. The  
15 higher concentrated brine is removed from the pressure vessel 210C through a brine pipe 230. Of course, other types of array configurations are known such as a 3:2 and 4:3. For three-stage systems 6:4:2 configurations have been used. Two-stage systems have permeate recovery of about fifty percent to seventy-five percent. Three stage systems may also recover up to about eighty-five percent of permeate.

20           **[0013]**       A second example of a two-stage system is illustrated in Figure 2B. In this example, a boost pump 240 is used between the two stages. That is, the boost pump 240 is in communication with the brine manifold 224 and boosts the pressure in the brine manifold 224 to a desirable pressure to compensate the losses in the Net Driving Pressure that occur within the pressure vessels 210A and 210B of the first  
25 stage 212. Energy recovery devices such as turbochargers are known to be used in reverse osmosis systems to recover the hydraulic energy in a brine stream that exit the last stage and boosts the pressure of another stream such as the feed stream.

**[0014]**       In Figure 3A a pressure vessel 310 has a brine stream 312 that is directed to a turbocharger 314 that has a pump portion 316 and a turbine portion 318.  
30 The turbine portion 318 receives the highly pressurized brine stream 312 which in turn is used to drive the pump 316 that receives feed fluid from a high pressure pump 320. The high pressure pump 320 is driven by a motor 322. The turbine 318 may also be connected to a motor 330 through a common shaft 332. The motor 330 is driven by a variable frequency device 334. During operation, the feed fluid is pressurized to an

intermediate level by the high pressure pump 320. The final pressure of the feed fluid is attained by the pump portion 316 of the turbocharger 314. The pump portion 316 provides the feed fluid to the pressure vessel 310 through a feed pipe 340. Permeate leaves the pressure vessel through the permeate pipe 342.

5           **[0015]**       A variable frequency drive 324 is used to drive the pump 320. However, if a motor 330 and variable frequency drive 334 are provided at the turbine 318, the variable frequency drive 324 is not necessary. In some cases, motor 330 may act as a generator should the turbine portion 318 produce more power than needed by pump section 314 to generate the desired feed boost. Fluid that has been  
10       depressurized in the turbine portion 318 is received within a drain 349.

**[0016]**       A reverse osmosis system having a first stage 350 and a second stage 352 is illustrated by Figure 3B. The first stage 350 is illustrated having a first pressure vessel 353 while the second stage is illustrated having a second pressure vessel 354. The permeate from each stage 350, 352 is collected in a permeate  
15       manifold 356. A brine manifold 358 is in communication with a turbocharger 360 that has a pump portion 362 and a turbine portion 364. A turbine portion 364 receives the pressurized brine fluid from the brine manifold 358 and turns the pump portion 362 to pressurize the brine fluid within the brine manifold 366 exiting from the first pressure vessel 353. A motor 370 and variable frequency drive 372 may also be used in this  
20       configuration. The motor 370 is used to adjust the motor speed of the turbine portion 364 which in turn raises the speed and pressure output of the pump portion 362. Thus, the motor 370 may be used to increase or reduce the boost from the pump portion 362.

**[0017]**       Referring now to Figure 4A, a turbocharger 410 is illustrated having a pump portion 412 and a turbine portion 414. The turbine includes a main nozzle 416  
25       and an auxiliary nozzle 418 which is controlled by an auxiliary valve 420. A bypass valve 422 is located outside of the turbocharger 410 and may be used to control the amount of fluid bypassing the turbine portion 414. The entire or nearly the entire amount of fluid directed toward the turbocharger 410 may be communicated to the bypass valve 422. A backpressure valve 424 is in fluid communication with the outlet of  
30       the turbine portion 414 and or the valve 422. The backpressure valve 424 is used to create a backpressure on the turbine portion 414. The flow through the pipe 430 is regulated by the bypass valve 422. The controller 426 controls the operation of the auxiliary valve 420 through control line 432A. The operation of the bypass valve through control line 432B and the control of the back pressure valve 424 through

control line 432C. Typically, a system operator changes the settings to open and enclose the valves in the desired manner.

[0018] Referring now to Figure 4B, the turbine differential versus turbine flow 450 has the auxiliary valve 420 in a closed position. Line 452 illustrates the differential pressure with the auxiliary valve open over a turbine flow range. Curve 454 shows the estimated feed pressure boost with the auxiliary nozzle in the fully opened position. Curve 456 shows the feed boost with the auxiliary nozzle fully closed. The graph illustrates 460, 462, 464 and 466. Area 460 is entirely within the auxiliary nozzle range and has the bypass valve 422 fully closed and the backpressure valve 424 fully opened. Area 462 extends into the region which the turbine cannot create enough flow resistance to achieve the desired  $\Delta P$  at the indicated flow range. Therefore backpressure valve 424 must be partially closed. Area 464 extends into the bypass region that illustrates that the turbine cannot bypass the entire flow. Therefore, the bypass valve 422 and turbine is needed to handle the excess flow. In area 466 a portion is in the backpressure and a portion in the bypass region. Therefore, bypass valve 422 and the backpressure valve 424 are actuated appropriately. That is, the areas 462, 464, 466 are manipulated by the valves 422 and 424 so that the turbine operates between the curves 450 and 452.

[0019] Referring now to Figure 5A, an energy recovery device 510 is illustrated having with a main inlet nozzle 512 that receives a brine stream. The inlet nozzle 512 communicates inlet fluid such as the brine stream to a volute 514. An auxiliary channel 520 is used to communicate fluid through an auxiliary nozzle 522. A valve stem 524 is manually operated to open and close the auxiliary nozzle 522. A seal 526 such as an O-ring or O-rings prevent leaking of brine toward the handle 528 and adjacent to the valve stem 524 from being communicated to the atmosphere. The valve stem 524 in Figure 5A is shown in a closed position. According to Figure 5B, the valve stem 524 is illustrated in an open position to show the valve seat 530 against which the end of the valve stem 524 seals. When additional turbine flow or a reduced differential pressure is required across the turbine the valve stem 524 may be withdrawn to create a flow path from the turbine inlet to the volute through the passage or auxiliary nozzle 522.

## SUMMARY

[0020] The present disclosure provides a method and system for a reverse osmosis system that includes a pump pressurizing a feed stream, a first membrane array generates a first permeate and brine stream from the feed stream. A second membrane array receives the first brine stream and generates a second permeate brine stream from the first brine stream. A first energy recovery device uses first energy from the second brine stream to increase a first pressure of the first brine stream. A first auxiliary and bypass valves are associated with the first energy recovery device. A second energy recovery device uses second energy from the second brine stream to increase a second pressure of the feed stream. A second auxiliary and bypass valves are associated with the second energy recovery device. A first flowmeter generates a first flow signal for the first permeate stream. A second flowmeter generates a second flow signal for of the second permeate stream. A third flowmeter generates a third flow signal for the second brine stream. A motor drives the first energy recovery device. A controller controls the first auxiliary valve, the first bypass valve, the second auxiliary valve and the second bypass in response to the first flow signal, the second flow signal and the third flow signal.

In another aspect of the disclosure, a method of operating a reverse osmosis system includes directing a feed stream to a first membrane array to separate the feed stream into a first permeate stream and a first brine stream, directing the first brine stream to a second membrane array to separate the first brine stream into a second permeate stream and a second brine stream, determining a first flow signal corresponding to a first flow in the first permeate stream, determining a second flow signal corresponding to a second flow in the second permeate stream, determining a third flow signal corresponding to a third flow in the second brine stream, determining a first auxiliary nozzle valve setting and a first bypass valve setting in response to the first flow signal and the third flow signal, determining a second auxiliary nozzle valve setting and a second bypass valve setting in response to the second flow signal and the third flow signal and controlling a torque output of a motor-generator coupled to a first hydraulic pressure booster to adjust an amount by which a first hydraulic booster increases a pressure of at least one of the feed stream and the first brine stream in response to the first flow signal.

[0021] Further areas of applicability will become apparent from the description provided herein. It should be understood that the description and specific

examples are intended for purposes of illustration only and are not intended to limit the scope of the present disclosure.

#### BRIEF DESCRIPTION OF THE DRAWINGS

5           **[0022]**       Figure 1A is a schematic view of a prior art reverse osmosis system.

**[0023]**       Figure 1B is a perspective view of a permeate membrane showing the layers therein of the prior art.

**[0024]**       Figure 1C is a cutaway view of a pressure vessel having a plurality  
10 of membrane elements of the prior art.

**[0025]**       Figure 2A is a block diagrammatic view of a multistage multi-element pressure vessel configuration of the prior art.

**[0026]**       Figure 2B is a schematic view of a multi-element pressure vessel according to the prior art.

15           **[0027]**       Figure 3A is a schematic view of a reverse osmosis system with a motor coupled to a turbocharger of the prior art.

**[0028]**       Figure 3B is a schematic view of a reverse osmosis system according to the prior art.

**[0029]**       Figure 4A is a schematic view of a turbocharger having a bypass  
20 valve and an auxiliary valve according to the prior art.

**[0030]**       Figure 4B is a plot of a method for operating a reverse osmosis system showing a turbine and feed boost differential and turbine flow.

**[0031]**       Figure 5A is a cutaway view of a turbocharger having an auxiliary nozzle of the prior art.

25           **[0032]**       Figure 5B is a cutaway view of the turbine illustrated in Figure 5A in an open position of the prior art.

**[0033]**       Figure 6A is a schematic view of a multistage reverse osmosis system according to the above disclosure.

**[0034]**       Figure 6B is a schematic view of a multistage reverse osmosis  
30 system.

**[0035]**       Figure 6C is a schematic view of a multistage reverse osmosis system according to a third example of the present disclosure.

**[0036]**       Figure 7A is a cross-sectional view of a turbocharger bypass channel and auxiliary channel having a valve stem in a closed position.

[0037] Figure 7B is a cross-sectional view of the turbocharger of Figure 7A having the valve stem in a partially opened position.

[0038] Figure 7C is a cross-sectional view of the turbocharger of Figures 7A and 7B in a fully opened position.

5 [0039] Figure 8A is a cross-sectional view of a turbocharger having independent control of a bypass valve stem and an auxiliary nozzle.

[0040] Figure 8B is a cross-sectional view of the turbocharger of Figure 8A having the bypass channel valve stem in an open position.

10 [0041] Figure 9A is a block diagrammatic view of a reverse osmosis system having multiple stages according to the present disclosure.

[0042] Figure 9B is a chart illustrating the operation of the interstage turbo 940 of Figure 9A.

[0043] Figure 9C is a chart illustrating the configuration of the auxiliary valve and bypass valve for the feed turbo 922 of Figure 9A.

15 [0044] Figure 10 is a flowchart of a method for operating the reverse osmosis system of Figure 9A.

[0045] Figure 11 is a flowchart of a method for operating a reverse osmosis system when the brine pressure is insufficient to achieve a desired boost.

## 20 DETAILED DESCRIPTION

[0046] The following description is merely exemplary in nature and is not intended to limit the present disclosure, application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify similar elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a  
25 logical (A or B or C), using a non-exclusive logical or. It should be understood that steps within a method may be executed in different order without altering the principles of the present disclosure.

[0047] Referring now to Figure 6, a reverse osmosis system 610 is having a first stage 612 and a second stage 614. The first stage 612 includes three pressure  
30 vessels 620A, 620B and 620C that are disposed in parallel. The second stage 614 includes 620D and 620E. Various numbers of pressure vessels may be located in each of the stages 612, 614. Further, various numbers of stages may be included in the system. Flow is reduced as the fluid progresses through the stages so subsequent stages have fewer pressure vessels than the previous stages.

**[0048]** A high pressure pump 630 receives sea or brackish water. The high pressure pump 630 supplies an energy recovery device such as a hydraulic turbocharger 632 with highly pressurized fluid. The turbocharger 632 as will be further described below increases the pressure of the fluid provided from the high pressure pump system 630. The turbocharger 632 includes a pump portion 634 and a turbine portion 636. The turbocharger 632 may be in communication with a motor 637 that rotates a common shaft 639 that extends to and rotates the pump portion 634 and the turbine portion 636. The pump portion 634 is in fluid communication with a feed manifold 638 which provides the pressurized fluid to the pressure vessel 620A-620C in parallel. The pressure vessels 620A-620C produce permeate which is directed to a permeate manifold 640. The brine from the pressure vessels 620A-620C are provided to a second turbocharger 642 which includes a pump portion 644 and a turbine portion 646 through a brine manifold 648. The pump portion 644 receives highly pressurized brine fluid from the pressure vessel 620A-620C. The pump portion 644 increases the pressure of the fluid within the brine manifold 648. Thus, the fluid pressure in an inlet manifold 650 to the second stage 614 of pressure vessels 620D-620E is increased. Permeate produced at the pressure vessels 620D and 620E are in communication with the permeate manifold 640. The brine from the pressure vessels 620D and 620E is in communication with brine manifold 654 which is in communication with the turbine portion 646 of the turbocharger 642. The pressurized fluid in the brine manifold 654 drives the turbine portion 644 which in turn drives the pump portion 644.

**[0049]** The turbine portion 646 has an outlet 656 that communicates the entire volume of brine from the turbine portion 646 to the inlet of the turbine portion 636. The outlet of the turbine portion 636 is communicated fluidically to a drain 658.

**[0050]** Referring now to Figure 6B, a three stage multi-stage reverse osmosis system 10' is illustrated. In this example, three stages 612', 614' and 615' are illustrated. Although only one pressure vessel 620A, 620D and 620F are illustrated in each stage, the pressure vessels 620A-620F may represent multiple pressure vessels in parallel. Following the example set forth in Figure 6A, the first stage may have a greater number of pressure vessels than stage 614' and stage 614' may have a greater number of pressure vessels than the stage 615'.

**[0051]** Because of the additional stage, an additional turbocharger 662 having a pump portion 664 and a turbine portion 666 is set forth. In this example, the brine pump manifold 654' is in communication with the third turbocharger 662. The

outlet of each of the three pressure vessels illustrated (or the parallel combination of pressure vessels) is in fluid communication with permeate manifold 640. In this example the pump portion 664 communicates fluid to an inlet pipe 670 of the pressure vessel 620F. The brine outlet 672 of the pressure vessel 620F is fluid communication  
5 with the turbine portion 666. All of the fluid leaving the turbine portion is communicated to the turbine portion 646 through pipe 674. All of the fluid leaving the turbine portion 646 is in communication with the turbine portion 636.

**[0052]** Referring now to Figure 6C, a three stage reverse osmosis system 610" is set forth. In this example the three stages 612", 614" and 615" may also  
10 include a plurality of pressure tanks in parallel. Similar elements are illustrated from that of Figure 6B. In this example, the second stage turbocharger 642 has been removed. In this example a pipe 678 is used to communicate the turbine portion 666 with the turbine portion 636 directly. All of the brine fluid communicated through the turbine portion 666 is communicated to the turbine portion 636.

**[0053]** Referring now to Figures 7A-7C, the turbochargers illustrated in  
15 Figures 6A-6B may be formed according to the following configuration for a turbocharger 710 illustrated below. The turbocharger 710 includes a turbocharger housing 712. The turbocharger housing 712 includes a volute 714 that has a rotating impeller therein. The impeller has been left off for simplicity purposes. The  
20 turbocharger 710 includes an inlet 716 that leads to the volute 714 through a main nozzle 717. A bypass passage 718 is used for bypassing the volute 714. The bypass passage 718 is in fluid communication with the inlet 716 and an outlet 719. An auxiliary nozzle 720 is in fluid communication with an auxiliary channel 722. The auxiliary channel 722 fluidically couples the auxiliary nozzle 720 and the inlet 716. A valve stem  
25 730 is located within a stem channel 732. The stem channel 732 is fluidically isolated from the auxiliary channel 722 and the bypass passage 718 by a pair of seals 736 and 738. The seal 736 is located between the auxiliary channel 722 and the bypass passage 718. The seal 738 is located between the bypass passage 718 and the exterior of the housing 712.

**[0054]** In Figure 7A, the valve stem 730 is located in a closed position in  
30 that the bypass passage 718 and the auxiliary channel 722 are not communicating fluid therethrough. All of the brine flow from the inlet 716 reaches the volute 714 through main nozzle 717. In Figure 7B, the valve stem 730 is partially withdrawn to allow flow into the auxiliary nozzle 720. Brine flow is not communicated through the bypass

passage 718. By positioning the valve stem 730 in the location illustrated in Figure 7B, additional turbine flow or reduced pressure differential across the turbine is achieved. No flow exits through the outlet 719.

[0055] The valve stem 730 includes a plurality of ports 740A, 740B, 740C and 740D. The ports 740A-D may be within the bypass passage 718 in which they are present during some of the positions of the valve stem 730. In Figure 7A the ports 740 are not passing fluid therethrough and are between the bypass passage 718 and the auxiliary channel 722. In Figure 7B, the ports 740A-740D are also not communicating fluid therethrough. In Figure 7C the ports 740A-740D are all communicating a portion of the bypass fluid therethrough so that the bypass passage 718 has flow of fluid therethrough. The size and number of the ports 740A-740D may vary depending upon the desired flow characteristics through the bypass passage 718. Of course, a partial position is possible whereby fewer than all of the ports 740A-740D are exposed to and communicate fluid through the bypass passage 718 toward the outlet 719. Again, the number of ports and the number of exposed ports may vary depending upon the various operating conditions of the valve stem 730. It should be noted that the valve stem 730 is perpendicular to a portion of the bypass passage 718 and the auxiliary channel 722 to which it is inserted. The valve stem 730 is coaxial with the auxiliary nozzle 720. The valve stem 730 allows simultaneous control of both the bypass passage 718 and the auxiliary nozzle 720 through the auxiliary channel 722. A single valve actuator 750 may be used to move the valve. The valve actuator may be hydraulic or electrical or manual.

[0056] Referring now to Figures 8A-8B, a turbocharger 810 is illustrated having a housing 812. The same parts are labeled the same from that set forth in Figure 7A-7B. In this example, the auxiliary channel 722 and the inlet 716 are configured in the same manner. However, in this example a bypass passage 816 is illustrated having a different configuration than that set forth in Figure 7A-7C. In this example the bypass passage 816 passes through an outer wall 817 but does not cross the path of the valve stem 830. The valve stem 830 is modified from that is set forth in Figures 7A-7C by not including the ports 740A-740D. One of the seals 736, 738 may also be removed. In this example the valve actuator 750 actuates the valve stem 830 to open and close the auxiliary nozzle 720 without regard to the bypass channel 718.

[0057] In this example, a second valve stem 860 is illustrated within the bypass passage 816. That is, the valve stem 860 under movement of the actuator 862

opens and closes the bypass passage 816 independently from that of the valve stem 830. The valve stems 830 and 860 are perpendicular to each other in this example. The valve stems 830 and 860 do not cross paths. A seal 864 seals the bypass passage 816 from the environment through the housing 812. The valve stem 860 seals  
5 against a valve seat 866 when closed.

**[0058]** In Figure 8B, the valve stem 860 is shown in a withdrawn manner to allow flow to flow through the bypass passage 816 to an outlet 818. Valve stem 830 may be in any position relative to the position of the valve stem 860.

**[0059]** Valve seat 870 seals valve stem 830 against the opening of the auxiliary nozzle 720 to seal flow from entering the auxiliary nozzle 720.  
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**[0060]** Referring now to Figure 9A, a separation system such as reverse osmosis system 910 is set forth. To achieve a maximum benefit, each interstage energy recovery device should produce the desired amount of feed pressure boost to attain the permeate production requirement and uphold the brine flow at a set value.  
15 Further, each pressure vessel in each stage should have approximately the same feed flow, brine flow and permeate flow. All or nearly all of the brine hydraulic energy may be recovered regardless of the amount of pressure boost required by the energy recovery devices. In seawater reverse osmosis systems, the hydraulic energy required for optimal interstage pressure boosting is significantly lower than the amount of  
20 available energy so a means is needed to recover the remaining energy. In brackish reverse osmosis systems, insufficient brine energy may be available thus requiring means to add energy to the interstage boosting process. The reverse osmosis system 910 illustrated in Figure 9A obtains these improved results.

**[0061]** The reverse osmosis 910 has a high pressure pump 920 that acts  
25 as a feed pump. The high pressure pump 920 communicates high pressure fluid to the turbocharger 922. The turbocharger 922 has a pump portion 924 and a turbine portion 926. The pump portion 924 pressurizes the fluid from the high pressure pump 920 to a higher pressure and communicates the higher pressure fluid through an inlet pipe 928 prior to entry within the pressure vessel 930. Although only one pressure vessel is  
30 illustrated multiple parallel pressure vessels may be provided. The permeate generated from the pressure vessel 930 is communicated to a permeate manifold 932. A second pressure vessel 936 is also provided in the system. Again, the pressure vessel 936 may be one pressure vessel or a plurality of pressure vessels in parallel. The pressure vessel 936 receives brine communicated from the pressure vessel 930. That is, the

pressure vessel 930 has a brine outlet 938 that communicates brine to a second turbocharger 940. A turbocharger 940 has a pump portion 942 and a turbine portion 944. The pump portion 942 increases the pressure of the brine fluid within the pump portion 942. The brine fluid with increased pressure is communicated to an inlet pipe 5 946 of the pressure vessel 936 (or in the case of multiple pressure vessels to each of the pressure vessels).

[0062] The outlet of the pressure vessel 936 is both permeate and brine. The permeate of the pressure vessel 936 is communicated through a pipe 950 to the permeate manifold 932. The brine outlet 954 of the pressure vessel 936 is 10 communicated to the inlet of the turbine portion 944 of the turbocharger 940.

[0063] The turbine portion 926 of the turbocharger 922 may also be in communication with a motor 960. The motor 960 has a shaft 961 that rotates with the pump portion 924 and the turbine portion 926. The motor may be in electrical communication with a power supply 962. The power supply 962 may provide power to 15 the motor or receive power when the motor 960 acts as a generator.

[0064] Each turbine portion 926 and 944 may be configured with a respective bypass valve 964, 966. As illustrated in Figures 7 and 8, both bypass valves and auxiliary nozzles may be included within the turbines 926 and 944. The external bypass valve 964 and 966 may pass fluid around the turbine portions 926 and 944 20 respectively. The bypass valves 964 and 966 may be internal to the turbine portions 926, 944.

[0065] A controller 970 is in communication with a first flowmeter FM1 and second flowmeter FM2 through a data line 972. The flowmeter FM1 is disposed to receive the permeate outlet flow of the first pressure vessel 930 and generate a first 25 permeate flow signal. The second flowmeter FM2 is disposed to receive the permeate outlet of the second pressure vessel 936 and generate a second permeate flow signal. A controller 970 may monitor the flow signals of the outputs of both of the pressure vessels 930, 936 individually.

[0066] As was the case above with respect to Figure 6A, the turbine 30 portion 944 communicates the brine flow from the second pressure vessel 936 to the turbine 926 through a pipe 963. That is, all of the flow from the second pressure vessel 954 is communicated through both the turbine portion 944 and the turbine portion 926. Ultimately, the turbine outlet 974 is measured by a flowmeter FM3 which is in communication with the controller 970 through the control line 976 the flowmeter FM3

generates a third flow signal corresponding to brine flow through the system. The turbine 926 ultimately communicates the brine fluid to drain 978. Preferably, most of the energy of the brine fluid has been recovered within the series formation of the turbines 926 and 944.

5           **[0067]**       The controller 970 is also in electrical communication with the control lines 981 and 983. Further, the bypass valve actuators (not specifically illustrated) associated with valves 964, 966, 980 and 982 may also be controlled by the controller 970 using the control lines 981, 983 in response to the flow signals.

10           **[0068]**       A control line 983 may be used to control the motor 960 in response to the flow signals. It is also known that various other sensors such as pressure indicators, salinity meters, temperature indicators may all be used to monitor the membrane performance within the pressure vessels 930, 936. However, for clarity, they have been omitted from Figure 9A.

15           **[0069]**       In operation, adjusted auxiliary and bypass valves as well as any backpressure valves, if they are used, are used to obtain the brine flow requirements and generate the desired amount of pressure boost is desirable according to Equation 1:

$$P_{tc} = n * (Q_t / Q_f) * (P_t - P_{ex}) \quad [1]$$

20            $P_{tc}$  = turbocharger feed pressure boost  
 $n$  = transfer efficiency  
 $Q_t$  = turbine flow  
 $Q_f$  = feed flow  
 $P_t$  = turbine inlet pressure  
 $P_{ex}$  = turbine outlet pressure

25           Also  
 $Q_b$  = brine flow from final stage  
 $Q_{by}$  = brine bypass flow  
 $Q_t = Q_b - Q_{by}$

30           The value  $P_t$  for the final pressure boosters established by the brine pressure of the final stage. For each successive energy recovery device  $P_t = P_{ex}$  of the recovery device of the next higher stage. It is, in Figure 6B, for example,  $P_t$  for the energy recovery device 662 equals the brine pressure in the pipe 672. The energy recovery device 642 has a turbine inlet pressure  $P_t$  equal to the turbine outlet pressure from the turbine portion 666. The turbocharger 632 has a turbine inlet pressure equal to the turbine

outlet pressure of the turbine portion 646. The outlet pressure of the turbine portion 636 is about 15-20 psi or about 1.0-1.4 bar.

[0070] From the above Equation [1] reducing the turbine flow or increasing the turbine outlet pressure reduces the turbocharger feed pressure boost. The turbine flow can be reduced by closing the auxiliary nozzle while opening the bypass valve to increase the bypass flow to maintain the brine flow for the final stage. In Figure 9A, for example, boost may decrease without changing the brine flow. The auxiliary nozzle valve 980 may be closed to reduce the turbine flow and hence reduce the pressure boost per the above equation but keep the brine flow constant. The bypass valve 966 may be opened to increase the bypass flow. Thus, simultaneous control of the brine flow as well as the feed pressure boost may be controlled. From analysis of membrane array performance, the permeate flow through a given area of a membrane, which may be referred to as flux or flux rate may be held constant along the entire membrane array of every stage. This can be approximated in a multistage system by keeping the average flux rate of each stage the same. Each pressure vessel in every state may have approximately the same feed flow, brine flow and permeate flow while increasing pressures from stage to stage to keep the net driving pressure approximately constant. Various process requirements may require a different permeate production. In such a case, every stage may be adjusted to maintain uniformity and feed flow, brine flow and permeate flow from each of the pressure vessels in each stage.

[0071] Referring now to Figures 9B and 9C a control scheme for a two stage system is illustrated. In Figure 9B, the control of the interstage turbocharger 940 is set forth if the (second in example) stage permeate flow rate  $Q_p$  (from FM2) is too high (above a first threshold), a pressure boost from the turbocharger 940 may be reduced by closing the auxiliary valve as indicated by the down arrow in Figure 9B in the top row. As well, the bypass valve 966 may be opened. If the permeate flow is too low (below a second threshold) as indicated by the flowmeter FM2, the auxiliary valve is opened and the bypass valve is closed to increase boost. In the third row of Figure 9B, if the brine flow is too high as indicated by FM3 (above a third threshold), the auxiliary nozzle valve 980 is closed and the bypass valve 966 is also closed. If the brine flow is too low (below a fourth threshold), the auxiliary nozzle valve 980 and the bypass valve 966 is opened to reduce the brine flow restriction.

[0072] When reviewing the equation, a combination of low permeate flow and high brine flow may appear contradictory in control action because the auxiliary

valve would be adjusted in opposite directions. However, control logic would iterate the bypass valve to be increasingly closed until both the flow of permeate and the flow of brine have achieved set point values. It should be noted that there are no pairs of permeate flow and brine flow table entries that require exactly the same control valve adjustment thus providing the controller the necessary freedom to set all set points. The auxiliary valve 980 and bypass valve 966 are iteratively increasing opened or closed as the flowmeter signals are monitored.

[0073] Referring now to Figure 9C, a method for controlling the feed turbocharger 922 is set forth. The turbocharger 922 has the motor 960 as included in the control. By controlling the motor the auxiliary nozzle of the turbine portion 926 is allowed to be kept open to the highest degree and the bypass valve 964 of the turbine portion 926 may be closed as much as possible as a set point so that feed boost can be achieved with the motor power by either adding power by rotating the shaft of the pump portion 922 and turbine portion 926 for more boost or extracting power from the rotor of the turbocharger 922 to reduce the amount of boost. That is, in Figure 9C when the permeate flow from FM1 is too high (above a fifth threshold) the auxiliary valve 982 is closed and the bypass valve 964 is open. Boost may be reduced from using the motor 960. When the permeate flow  $Q_p$  is too high as indicated by the flowmeter FM1, the auxiliary valve 982 is closed and the bypass valve 964 of the turbocharger 922 is opened. Boost may be reduced by using the motor 960 to extract power from the rotor of the turbocharger 922. As indicated in the second row of Figure 9C when the permeate flow  $Q_p$  is too low (above a sixth threshold) as indicated by the flowmeter FM1, the auxiliary valve 982 is opened and the bypass valve 964 is closed. Boost may be increased by adding power to the motor 960 which in turn increases the rotational speed of the shaft 961 of the turbocharger 922. When the brine flow  $Q_b$  is too high (above a seventh threshold) as set forth in the third row of Figure 9C, the auxiliary valve 982 is closed and the bypass valve 964 is closed while the brine flow restriction is increased. When the brine flow is low (below an eighth threshold) the auxiliary valve 982 is open and the bypass valve 964 is open. Thus, the brine flow restriction may be reduced.

[0074] Referring now to Figure 10, a summary of the method for controlling the energy recovery devices such as the turbochargers in the various stages are set forth. In step 1010 the bypass valve setting for the final stage turbocharger is determined by its controller. In step 1014 the  $P_{ex}$  for the final stage is determined. This

may be calculated or may use a mathematical model 1016 as an optional input. When a mathematical model 1016 is used the membrane performance may be approximated. The valves may be iteratively moved toward the determined setup in step 1018. Thus, the controller may reduce the number of valve adjustment iterations by saving time for the membrane array to reach the desired operating conditions. In step 1020 the  $P_t$  for the previous turbocharger stages is determined. In the example set forth in Figure 9A this corresponds to turbocharger 922. In the turbine inlet  $P_t$ . In step 1022 if all of the turbocharger valve positions are not done, step 1020 is repeated until all the turbocharger valve positions after all the turbocharger valve positions have been determined step 1022 is again repeated. The valves are continually moved toward the determined settings iteratively.

**[0075]** Referring now to Figure 11, various unanticipated conditions may be presented in which the brine pressure may be insufficient to achieve the desired boost. The controller may change the average flux requirement. In step 1110 it is determined whether the brine pressure is sufficient, to achieve the desired boost. If the brine pressure is sufficient normal operating conditions such as that set forth in Figure 10 are performed. In step 1112 the average flux requirement is reduced by the controller to reduce the brine flow available for each stage. In step 1114 the feed boost for each stage is reduced by the controller. In step 1116 the average flux rate is recalculated by the controller for the system. In step 1118 the valves are adjusted. Step 1110 is then again performed after 1118. Interim adjustments will continue. It should be noted that the unanticipated conditions may reduce the permeate production in rare cases. However, the membrane array will be operating at a minimum energy consumption and the membranes will be protected against excessive fouling.

**[0076]** The energy recovery devices set forth in the above examples may have a customized hydraulic design such that the hydraulic range overlaps as much as possible in the anticipated flow and the pressure ranges. Thus, the maximum energy recovery is obtainable and excepted permeate reduction is achieved under normal operating conditions. For the interstage energy recovery devices when motors are not used, only one combination of auxiliary valve and bypass valve positions for any particular feed boost and brine flow rate suitable. For the feed energy recovery device (the first stage), the required pressure for the first state is assured by use of a motorized energy recovery device or a variable discharge pressure from the high pressure pump. That is, the motor 960 may be coupled to the high pressure pump 920

so that a varied amount of pressure boost may be easily controlled into the first pressure vessel 930.

**[0077]** Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope  
5 of the disclosure should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification and the following claims.

## CLAIMS

What is claimed is:

1. A reverse osmosis system comprising:
  - 5 a pump operable to pressurize a feed stream;
  - a first membrane array configured to receive the feed stream and to generate a first permeate stream and a first brine stream from the feed stream;
  - a second membrane array configured to receive the first brine stream and to generate a second permeate stream and a second brine stream from the first brine stream;
  - 10 a first energy recovery device configured to receive the second brine stream and to use first energy from the second brine stream to increase a first pressure of the first brine stream;
  - a first auxiliary valve and a first bypass valve associated with the first energy recovery device;
  - 15 a second energy recovery device configured to receive the second brine stream after the first energy recovery device and to use second energy from the second brine stream to increase a second pressure of the feed stream;
  - a second auxiliary valve and a second bypass valve associated with the second energy recovery device;
  - 20 a first flowmeter generating a first flow signal corresponding to a first flow of the first permeate stream;
  - a second flowmeter generating a second flow signal corresponding to a second flow of the second permeate stream;
  - 25 a third flowmeter generating a third flow signal corresponding to a third flow of the second brine stream;
  - a motor coupled to the first energy recovery device, operable to use energy from a power supply to drive the first energy recovery device; and
  - a controller in communication with the first flowmeter, the second flowmeter, and
  - 30 the third flowmeter, said controller controlling the first auxiliary valve, the first bypass valve, the second auxiliary valve and the second bypass in response to the first flow signal, the second flow signal and the third flow signal.

2. The reverse osmosis system of claim 1 wherein the first energy recovery device comprises a first turbocharger comprising a first turbine receiving the second brine stream, and the second energy recovery device comprises a second turbocharger comprising a second turbine receiving the second brine stream after the first turbine.

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3. The reverse osmosis system of claim 2 wherein the first turbine comprises a first main nozzle receiving the second brine stream and a first auxiliary nozzle comprising a first auxiliary valve selectively communicating a first portion of the second brine stream to a first volute, and wherein the second turbine comprises second main  
10 nozzle receiving the second brine stream and a second auxiliary nozzle comprising a second auxiliary valve selectively communicating a second portion of the second brine stream to a second volute.

4. The reverse osmosis system of claim 3 further comprising a first bypass  
15 valve and selectively communicating at least a third portion of the second brine stream bypassing the first turbine and further comprising a fourth bypass valve bypassing at least a fourth portion of the second brine stream around the second turbine.

5. The reverse osmosis system of claim 4 wherein the first turbocharger  
20 comprises a first turbocharger housing comprising a first bypass passage and the first auxiliary nozzle and wherein the second turbocharger comprises a second bypass passage and second auxiliary nozzle.

6. The reverse osmosis system of claim 5 further comprising first valve stem  
25 forming both the first bypass valve and the first auxiliary valve and further comprising second valve stem forming both the second bypass valve and the second auxiliary valve.

7. The reverse osmosis system of claim 6 wherein the first valve stem  
30 comprises a first port coupled therethrough so that when the auxiliary nozzle is partially opened, a portion of bypass fluid bypasses the turbine through the port.

8. The reverse osmosis system of claim 7 wherein the first port comprises a plurality of ports disposed in parallel, said plurality of ports sequentially opening as the first valve stem moves to open the auxiliary nozzle.

5 9. The reverse osmosis system of claim 5 further comprising a first valve stem selectively closing the first auxiliary nozzle and a second valve stem selectively closing the first bypass passage.

10 10. The reverse osmosis system of claim 9 wherein said first valve stem and said second valve stem are independently controllable using the controller.

11. The reverse osmosis system of claim 9 wherein said first valve stem and said second valve stem are perpendicularly disposed.

15 12. The reverse osmosis system of claim 9 further comprising a third valve stem selectively closing the second auxiliary nozzle and a fourth valve stem selectively closing the second bypass passage.

20 13. The reverse osmosis system of claim 12 wherein said third valve stem and said fourth valve stem are independently controllable using the controller.

14. The reverse osmosis system of claim 1 wherein said motor is operable to use second energy from the second brine stream to provide power to the power supply.

25 15. A method for operating a reverse osmosis system, the method comprising:

directing a feed stream to a first membrane array to separate the feed stream into a first permeate stream and a first brine stream;

30 directing the first brine stream to a second membrane array to separate the first brine stream into a second permeate stream and a second brine stream;

determining a first flow signal corresponding to a first flow in the first permeate stream;

determining a second flow signal corresponding to a second flow in the second permeate stream;

- determining a third flow signal corresponding to a third flow in the second brine stream;
- determining a first auxiliary nozzle valve setting and a first bypass valve setting in response to the first flow signal and the third flow signal;
- 5 determining a second auxiliary nozzle valve setting and a second bypass valve setting in response to the second flow signal and the third flow signal; and
- controlling a torque output of a motor-generator coupled to a first hydraulic pressure booster to adjust an amount by which a first hydraulic booster increases a pressure of at least one of the feed stream and the first brine stream in response to the
- 10 first flow signal.
16. The method of claim 15 further comprising independently controlling a first auxiliary nozzle and a first nozzle valve within a controller.
- 15 17. The method of claim 15 simultaneously controlling a first auxiliary nozzle and a first nozzle valve with a controller.
18. The method of claim 15 wherein the step of determining the second auxiliary nozzle valve setting and a second bypass setting comprises iteratively determining the
- 20 second auxiliary valve setting and the second bypass valve setting.
19. The method of claim 15 wherein when the first flow signal is above a first threshold reducing boost of the first hydraulic pressure booster by closing a first auxiliary nozzle valve and opening a first bypass valve.
- 25 20. The method of claim 19 wherein when the first flow signal is below a second threshold increasing boost of the first hydraulic pressure booster by opening the first auxiliary nozzle valve and opening the first bypass valve.
- 30 21. The method of claim 20 wherein when the third flow signal is above a third threshold, increasing brine flow restriction by closing the first auxiliary nozzle valve and closing the first bypass valve.

22. The method of claim 21 wherein when the third flow signal is below a fourth threshold, reducing brine flow restriction opening the first auxiliary valve and opening the first bypass valve.

5 23. The method of claim 22 wherein when the second flow signal is above a fifth threshold, reducing pressure boost of a second hydraulic turbocharger by closing a second auxiliary nozzle and opening a second bypass valve.

10 24. The method of claim 23 wherein when the second flow signal is below a sixth threshold, increasing boost of the second hydraulic turbocharger by opening the second auxiliary valve and closing the second bypass valve.

15 25. The method of claim 24 wherein when the third flow signal is above a seventh threshold, increasing brine flow restriction by closing the second auxiliary valve and closing the second bypass valve.

20 26. The method of claim 25 wherein when the third flow signal is below an eighth threshold, reducing brine flow restriction by opening the second auxiliary valve and opening the second bypass valve.