

## **BATCH AND SEMI-BATCH LOW SALT REJECTION REVERSE OSMOSIS DESALINATION**

### **CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application is related to and claims priority to US Provisional Patent Application No. 63/513,985 filed on July 17, 2023 and to US Provisional Patent Application No. 63/515,880 filed on July 27, 2023, which are incorporated by reference herein.

### **FIELD**

[0002] The claimed technology relates generally to freshwater production and more particularly to desalination techniques.

### **BACKGROUND**

[0003] The availability of drinkable fresh water is predicted to distress an increasing portion of the world population. Desalination methods are increasingly becoming a source of freshwater in many parts of the world. Accessing higher water recovery in desalination reduces the potential contamination of the ecosystem by the disposal of rejected brine. Thermal processes, based on which the commercial brine concentrators operate, are energy intensive as they involve evaporation/condensation of water. On the other hand, membrane-based methods are efficient as they operate using hydraulic/osmotic pressure difference across a membrane. Reverse osmosis (RO) is one of these methods that can produce freshwater from seawater. However, due to the limited hydraulic pressure difference the membrane can sustain (approximately 80 bar), the water

recovery is limited and the retentate below 70 g/L. Thus, in order to reduce the carbon footprint of brine concentration, novel methods to dewater the reverse osmosis retentate (>70 g/L) are required.

[0004] There are two modified RO methods: osmotically assisted reverse osmosis (OARO) and low salt rejection reverse osmosis (LSRRO). These methods take advantage of a moderate salinity region in the permeate side of the membrane to achieve higher salinity without exceeding the maximum hydraulic pressure. LSRRO has the same module configuration as RO, but it uses a membrane with low salt rejection that allows a moderately saline stream flux to pass through. The salinity of the permeate channel reduces the osmotic pressure difference across the membrane. LSRRO features some advantages over OARO. According to recent studies, it requires less membrane area than OARO due to lower concentration polarization. The module is simpler to manufacture for LSRRO than for OARO. Furthermore, it can be built to sustain higher pressure by simply increasing the membrane thickness and the supporting permeate spacers. Nonetheless, it has higher energy consumption than OARO due to the passage of salt through the membrane. Thus, there remains a need for an improved desalination process.

## SUMMARY

[0005] In one aspect, a desalination assembly is provided having a pressure vessel with an internal bladder portion positioned therein, a circulating pump connected in hydraulic communication with the pressure vessel, a hydraulic fluid reservoir, a high-pressure hydraulic pump connected in hydraulic communication with the hydraulic reservoir and with the pressure vessel bladder portion, a low salt rejection module connected in

hydraulic communication with the pressure vessel, and a low salt rejection membrane positioned in and bisecting the low salt rejection module into a high salinity inlet portion and a low salinity permeate portion. An inlet water reservoir may be connected in hydraulic communication with the circulation pump and a brine reservoir connected in hydraulic communication with the high-pressure pump. The assembly may further include an inlet water reservoir connected in hydraulic communication with the circulation pump which may optionally be at least two water inlet tanks which may contain water having different salt concentrations. The assembly may also include an inlet water reservoir connected in hydraulic communication with the circulation pump where the pressure vessel further includes an internal piston positioned therein. The hydraulic fluid reservoir may be the inlet reservoir in some assemblies. A pressure exchanger may also be included which is operationally connected between the circulation pump and the pressure vessel and where the circulation pump is connected in hydraulic communication with the low salt rejection module. The pressure exchanger may be a Clark pump and the Clark pump governor may be hydraulically connected to the low salt rejection module.

[0006] In another aspect, a desalination assembly is provided having a pressure vessel, a circulation pump connected in hydraulic communication with the pressure vessel, a hydraulic fluid reservoir, a high-pressure hydraulic pump connected in hydraulic communication with the hydraulic reservoir and the pressure vessel, a low salt rejection module connected in hydraulic communication with the housing, and a low salt rejection membrane positioned in and bisecting the low salt rejection module into a high salinity inlet portion and a low salinity permeate portion. The desalination assembly may further

include an inlet water reservoir connected in hydraulic communication with the circulation pump and a brine reservoir connected in hydraulic communication with the high-pressure pump. Optionally, the desalination assembly pressure vessel may further include an internal bladder positioned therein where the high-pressure hydraulic pump is connected in hydraulic communication with the bladder. The desalination assembly may also include an inlet water reservoir connected in hydraulic communication with the circulation pump where the inlet reservoir comprises at least two inlet tanks. Optionally, the at least two inlet tanks hold water having different saline concentrations. An inlet water reservoir connected in hydraulic communication with the circulation pump where the pressure vessel further includes an internal piston positioned therein may also be included. Optionally, the hydraulic fluid reservoir is the inlet reservoir. A pressure exchanger may also be provided which is operationally connected between the circulation pump and the pressure vessel where the circulation pump is connected in hydraulic communication with the low salt rejection module. This pressure exchanger may be a Clark pump.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0007] FIG. 1 is a schematic diagram of the cyclic process of bladder-type batch

LSRRO, including priming, permeate production, and flushing, according to a first embodiment of the present novel technology.

[0008] FIG. 2 is a schematic diagram of the cyclic process shown in FIG. 1.

[0009] FIG. 3 is a schematic diagram of the cyclic process shown in FIG. 1.

[0010] FIG. 4 is a schematic diagram of the cyclic process shown in FIG. 1.

[0011] FIG. 5 is a schematic diagram of the operation of double-acting piston-type batch

LSRRO in one cycle.

[0012] FIG. 6 is a schematic diagram of the batch LSRRO process shown in FIG. 5.

[0013] FIG. 7 is a schematic diagram of the batch LSRRO process shown in FIG. 5.

[0014] FIG. 8 is a schematic diagram of the batch LSRRO process shown in FIG. 5.

[0015] FIG. 9 is a schematic diagram of the batch LSRRO process shown in FIG. 5.

[0016] FIG. 10 is a schematic diagram of the batch LSRRO process shown in FIG. 5.

[0017] FIG. 11 is a schematic diagram the stages of operation for PX-type batch LSRRO

for one cycle.

[0018] FIG. 12 is a schematic diagram of the PX-type batch LSRRO process shown in

FIG. 11.

[0019] FIG. 13 is a schematic diagram of the PX-type batch LSRRO process shown in

FIG. 11.

[0020] FIG. 14 is a schematic diagram of the PX-type batch LSRRO process shown in

FIG. 11.

[0021] FIG. 15 is a schematic diagram of the configuration of values and flow directions of a Clark pump.

[0022] FIG. 16 is a schematic diagram of the Clark pump shown in FIG. 15.

[0023] FIG. 17 is a schematic diagram of the cyclic operation of a Clark pump type batch LSRRO.

[0024] FIG. 18 is a schematic diagram of the Clark pump type batch LSRRO shown in FIG. 17.

[0025] FIG. 19 is a schematic diagram of the Clark pump type batch LSRRO shown in FIG. 17.

[0026] FIG. 20 is a schematic diagram of the Clark pump type batch LSRRO shown in FIG. 17.

[0027] FIG. 21 is a schematic diagram of the cyclic operation of a semi-batch LSRRO.

[0028] FIG. 22 is a schematic diagram of the semi-batch LSRRO shown in FIG. 21.

[0029] FIG. 23 is a schematic diagram of the semi-batch LSRRO shown in FIG. 21.

[0030] FIG. 24A-G is a schematic diagram of a bladder type batch LSRRO configured for multistaging.

[0031] FIG. 25 is a graph showing the salinity profile of a bladder tanks and permeate tanks during the bladder type batch LSRRO shown in FIG. 24A-G.

[0032] FIG. 26 is a schematic diagram of another example of a bladder type batch LSRRO configured for multistaging.

[0033] FIG. 27 is a schematic diagram of the multistaging bladder type batch LSRRO of FIG. 26.

[0034] FIG. 28 is a schematic diagram of the multistaging bladder type batch LSRRO of FIG. 26.

[0035] FIG. 29 shows dependence of maximum salt rejection on brine salinity and applied pressure.

[0036] FIG 30. Effect of salt rejection of BLSRRO stage and the hydraulic pressure on the performance of a two stage BRO-BLSRRO system.

[0037] FIG 31. Effect of salt rejection in the intermediate stages of a 4-stage BRO-BLSRRO system for feed salinity of 0.6 mol/L and brine salinity of 4 mol/L.

## DESCRIPTION

[0039] For the purposes of promoting an understanding of the principles of the claimed technology and presenting its currently understood best mode of operation, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the claimed technology is thereby intended, with such alterations and further modifications in the illustrated device and such further applications of the principles of the claimed technology as illustrated therein being contemplated as would normally occur to one skilled in the art to which the claimed technology relates.

[0040] The first semi-batch and batch LSRRO systems which improve the LSRRO technology using transient process. The disclosed systems have higher efficiency than the conventional LSRRO. The process includes permeate production step and flushing step. The process may include priming step. During the permeate production step, the process produces permeate by gradually pressurizing the feed. During the flushing step, the remaining brine in the system is replaced by the new feed. During the priming step, the tanks are filled with new feed before the permeate production step. One membrane used for the process consists of an active layer with thickness of around 200 nanometer and pore size of less than 1 nanometer, and the support layer with thickness of 50 micrometer. One method for acquiring the membranes for batch/semi-batch LSRRO is treatment of thin film composite polyamide reverse osmosis modules. In this method, the modules are oxidized using chlorine solutions, and the hydrolysis reaction between polyamide in the active layer and the chlorine reduces the salt rejection of the membrane. Another method is to manufacture the membranes with inherent low rejection. The

process for manufacturing the membranes is similar to that for nanofiltration membranes. A dense woven mesh is also provided for better mechanical strength. Formation of the active layer can be done via phase change processes such as immersion precipitation, and phase separation of the polymer dissolved in solvents. Other methods are interfacial polymerization, and coating a porous support layer with a thin active layer. The membrane can be made from polyamide while the support layer is made from polysulfone. The electrical charge of the active layer plays an important role in determining the rejection of the membrane. The surface charge is controlled by the functional groups deposited in the active layer. The functional groups include carboxylic and amine groups, sulfonic acid, Ethyloxy, and piperazine. These groups are implemented to the membrane via graft polymerization, plasma treatment, and physical pre-adsorption.

[0041] The ratio of salt permeability coefficients and water permeability coefficient indicates how selective the membrane is. For a fixed value for water permeability coefficient, if the salt permeability coefficient is too low, the membrane is unable to produce permeate with moderate salinity, and as a result, it cannot access high salinities. On the other extreme, high salt permeability coefficient leads to high water flux which is expected to reduce the cycling time and increase the capacity of the process, but fouling-related considerations might apply on the upper limit of flux for a zero liquid discharge process. The appropriate salt rejection of the membrane is typically optimized to address the process requirements. Assuming steady state profile for the salinity perpendicular to the membrane, the following equations can be applied in a membrane transport simulation:

$$\frac{C_{c,m} - J_s/J_w}{C_{c,b} - J_s/J_w} = \exp\left(\frac{J_w}{k_c}\right)$$

$$C_{dil} = J_s/J_w$$

$$J_s = B(C_{c,m} - C_{dil})$$

$$J_w = A(\Delta P - \Delta\pi)$$

In the equations above,  $C_{c,b}$  is salinity of the concentrate stream in the bulk region,  $C_{c,m}$  is salinity of the concentrate stream near the membrane active layer,  $C_{dil}$  is salinity of the diluate side,  $J_s$  is salt flux,  $J_w$  is water flux,  $k_c$  is mass transfer coefficient in the concentrate side,  $A$  is water permeability coefficient,  $B$  is salt permeability coefficient,  $\Delta\pi$  is transmembrane osmotic pressure, and  $\Delta P$  is transmembrane hydraulic pressure which is exerted by the high pressure pumps. Based on the definition of salt rejection, different ranges can be defined. Instantaneous salt rejection of the module can be defined as:

$$SR = 1 - \frac{C_{dil}}{C_{c,b}}$$

Using the previous equations, this definition can be rewritten as:

$$SR = \frac{J_w \exp\left(-\frac{J_w}{k_c}\right)}{B + J_w \exp\left(-\frac{J_w}{k_c}\right)}$$

The salt rejection depends on the water flux (which is typically controlled by the high-pressure pump), salt permeability coefficient, and spacer design which controls the mass transfer coefficient. Different strategies regarding the process can be implemented. The

maximum salt rejection is bounded by salinity and applied pressure (FIG. 29). The process can be accomplished using a constant water flux throughout the process, which leads to simpler high pressure pump design, or constant diluate salinity, which requires variable speed for high pressure pump to control the water flux. A primary simulation shows that for the process of dewatering a 70 g/L water with constant diluate salinity of 35 g/L throughout the process and implementing the Clark pump design and with 45% water recovery, and with water permeability of 2.61 L/m<sup>2</sup>/h/bar and salt permeability of 5 L/m<sup>2</sup>/h shows that the required salt rejection of the module starts at 52% in the beginning of the process and reaches 68% at the end of the process. The intrinsic salt rejection of the membrane as shown by:

$$\left(1 - \frac{C_{dH}}{C_{c,in}}\right)$$

varies between 53% and 69%. The water flux varies between 5.6 L/m<sup>2</sup>/h and 11 L/m<sup>2</sup>/h to control the salinity of the diluate stream. In another example, dewatering 100 g/L to produce 70 g/L diluate and with 51% water recovery requires the water flux to vary from 2.6 to 5.3 11 L/m<sup>2</sup>/h from the beginning to the end of the process, which corresponds to 33% and 50% of module salt rejection.

[0042] The tank performs the role of storing the high-pressure feed water and mixing the water inside it with the flow received from the module feed outlet. The tank typically tolerates at least the same pressure the module experiences. The bladder has to push the feed water in the tank and to start the permeate production in the module. It is an inflatable tube that is blown with a hydraulic fluid on its interior. The hydraulic fluid is pumped by the HPP.

[0043] The pipes perform the role of delivering streams to and from the modules depending on the stage of operation. All pipes in the circulation loops and downstream of all high-pressure pumps tolerate the high pressure exerted by the high-pressure pumps. Pipes delivering the permeate operate at atmospheric pressure. The diameter of the pipes should be large enough such that the frictional pressure loss would be minimized while the volume of salt water inside them does not make up a significant portion of the circulation loop.

[0044] Typically, a low salt rejection (LSR) module consists of a pressure Bessel, a membrane that divides the vessel volume into concentrate and permeate sides, inlet and outlet ports for the concentrate side, and an outlet port for the permeate side. The membrane has compromised selectivity such that the permeate produced has moderate salinity compared to the high salinity of the concentrate. The membrane active layer can be made from commercial and novel methods and materials. The selectivity of the membrane should be such that the salinity of the permeate is not very low. The support layer typically is configured so as to tolerate the pressure difference across the membrane, and the transient concentration polarization in the support layer would be controlled.

[0045] Bladder-type batch LSRRO typically includes a hydraulic fluid reservoir in hydraulic communication with a high-pressure pump. The high-pressure pump is in hydraulic communication with a bladder inside a bladder tank. The saltwater section in the bladder tank is in hydraulic communication with the high pressure (concentrate) inlet port of the LSR module. The concentrate outlet port of the LSR module is in hydraulic communication with the circulation pump inlet. The circulation pump outlet is hydraulic

communication with the salt water section of the bladder tank. The permeate port of the LSR module produces the stream with lower salinity than the initial salt water in the bladder tank. Flushing is preferably accomplished by a circulation pump, although another pump may be used. Faster flushing with a pump with higher flow rate reduces the flushing downtime and increases the plant capacity.

[0046] Double-acting piston-type batch LSRRO typically includes a high-pressure pump in hydraulic communication with a double acting piston tank on both sides of the tank separated by the piston. The concentrate inlet of the LSR module and the outlet of the circulation pump are in hydraulic communication with the double acting piston tank on both sides of the tank separated by the piston. The concentrate outlet stream of the LSR module is in hydraulic communication with the inlet of the circulation pump. The permeate port of the LSR module produces the stream with lower salinity than the initial salt water in the bladder tank. Flushing is preferably accomplished by a circulation pump although another pump may be used. Faster flushing with a pump with higher flow rate reduces the flushing downtime and increases the plant capacity.

[0047] ERD type batch LSRRO typically includes on or more types of energy recovery devices, such as Clark pump, pressure exchanger (PX), turbines connected to HPP shaft and turbochargers, centrifugal-type ERDs, and isobaric ERDs can be used for ERD type batch LSRRO such as described herein.

[0048] PX batch LSRRO typically includes an atmospheric tank in hydraulic communication with the inlet of a high pressure pump and the feed inlet port of a pressure exchanger. A brine eject port of the pressure exchanger is in hydraulic communication with the atmospheric tank. A feed outlet port of the pressure exchanger is

in hydraulic communication with the inlet of a circulation pump. The outlet of the circulation pump and the high-pressure pump are in hydraulic communication with the concentrate inlet of the module. The concentrate outlet of the module is in hydraulic communication with the brine inlet of the pressure exchanger. The permeate port of the LSR module produces the stream with lower salinity than the initial salt water in the bladder tank. Flushing may be accomplished by a circulation pump although other pumps may also be used. Faster flushing with a pump with higher flow rate reduces the flushing downtime and increases the plant capacity.

[0049] Clark pump type batch LSRRO typically includes an atmospheric tank in hydraulic communication with the inlet of a high-pressure pump. The high-pressure pump outlet is in hydraulic communication with the inlet ports of the pressurizer of a Clark pump. The governor outlet ports of the Clark pump are in hydraulic communication with the atmospheric tank. The pressurizer outlet ports are in hydraulic communication with the concentrate inlet of an LSR module. The concentrate outlet port of the LSR module is in hydraulic communication with the governor inlet port of the Clark pump. The permeate port of the LSR module produces the stream with lower salinity than the initial salt water in the bladder tank. Flushing may be accomplished by the high-pressure pump although other pumps may also be used. Faster flushing with a pump with higher flow rate reduces the flushing downtime and increases the plant capacity.

[0050] Semi-batch LSRRO typically has an outlet of high pressure pump is in hydraulic communication with the outlet of a circulation pump and the concentrate inlet of an LSR module. The concentrate outlet of the LSR module is in hydraulic communication with the inlet of a circulation pump. The permeate port of the LSR module produces the

stream with lower salinity than the initial salt water in a bladder tank. Flushing may be accomplished by a circulation pump although other pumps may also be used. Faster flushing with a pump with higher flow rate reduces the flushing downtime and increases the plant capacity.

[0051] Multistage systems may include any type of the standalone batch and/or semi-batch LSRRO used as the dewatering unit. The batch or semi-batch LSRRO is in hydraulic communication with several atmospheric tanks the number of which depends on the level of total water recovery. The intermediate diluate volumes produced in the stages can be tuned to have the same salinity with the initial concentrate tank salinity of the next step so that the tank would be recycled to the concentrate tank. The multistage system may be combined with RO or batch RO which has a high rejection system similar to the LSRRO process, but it produces fresh water. The RO/BRO unit produces fresh water from the atmospheric tank with the least salinity. The brine of the RO/BRO is headed to the next atmospheric tank. The inlet to the system can be seawater which would be fed to a first atmospheric tank, or it can be the brine retentate of an RO plant which may be fed to a second atmospheric tank. Such multistage designs as described herein may have a recirculation stream which increases in salinity as the system operates during which time new feed may be continuously or semi-continuously added to the recirculating loop. After a desired concentration is reached the saline water is rejected and the cycle repeated.

[0052] The batch system runs based on a repeated cycle. Lines of higher hydraulic pressure are shown as thicker than lines of lower hydraulic pressure in FIG. 1-4. The process starts by priming the tank with the feed stream, which can be the RO retentate at

the salinity of, for example, 70 g/L (FIG. 1). The circulation pump (CP) 40 primes the tank 42 as its high flow rate minimizes the priming time. As the tank 42 is primed, the hydraulic fluid in the bladder 44 is returned to its reservoir 46. In the next step, permeate production starts with high-pressure pump (HPP) 48 pumping hydraulic fluid to the bladder at high pressure (FIG. 2). As the pressure of the concentrate side of the module increases, a salty permeate stream passes through the membrane 50. The concentrate outlet of the module is returned to the tank 42 via the CP 40, and the tank 42 salinity increases over time. Assuming constant membrane salt rejection, the salinity of the permeate increases over time. At the end of permeate production (FIG. 3), the tank 42 volume is reduced to its designed value, which can be zero if the tank 42 sizing is calculated based on the water recovery and module volume and if the permeate volume is equal to the tank 42 volume at the beginning of permeate production. The final step is flushing (FIG. 4), in which the tank 42 volume is fixed, and the feed stream replaces the remaining brine volume in the tank and membrane which is ejected from the system. The circulation pump flushes the system. When appropriate design considerations are applied, the system can produce a permeate with cumulative salinity of 35 g/L which can be sent back to a reverse osmosis system in which freshwater with high quality and salinity less than 0.5 g/L is produced, as well as retentate with salinity of 70 g/L is produced. The latter stream can be mixed with incoming feed stream to form the priming for the next cycle.

[0053] In double acting piston type (FIG.5-10), a piston 60 divides the tank 62, and the incoming feed 64 is pushed to the opposite side of the piston 60 rather than a hydraulic fluid. This merit reduces the downtime compared to the bladder type system as the

opposite side 66 of the tank 62 is already filled with the feed stream in the precursing cycle and thus the priming step is mitigated.

[0054] In this configuration, the cycle includes two strokes of the piston 62. The system includes either side of the tank 62, pipes, and the module 68 is filled with the feed water. At first, the HPP 70 pumps high pressure feed stream 64 to the bottom section 72 of the tank 62, causing the pressure of the top section 66 to increase, resulting in permeate production of the low-salt-rejection module 68 (FIG. 5). The concentrate outlet of the module 68 is returned to the top side of the tank 62 and increases the tank 62 salinity. When the desired tank 62 salinity is reached or the piston 60 reaches the top of the tank 62 (FIG. 6), the first flushing step starts in which the HPP 70 stops and fixes the position of the piston 60 while the CP 74 pumps feed water to the tank 62 and ejects the remaining brine in the system (FIG. 7). Although the configuration could be designed such that the high-pressure pump 70 would flush the system, as the circulation pump 74 has higher flow rate, the flushing is faster with CP 74 and the downtime is shorter. The second stroke of the system follows the same procedure as the first stroke but the position of the pipes to the tank 62 reverses. The HPP 70 pumps the feed 64 to the top section of the piston 60 (FIG. 8) and the module produces permeate until the end of the cycle (FIG. 9) after which the CP 4 flushes the remaining brine in the system with feed water (FIG. 10). Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 5-10.

[0055] It is possible to use an energy recovery device (ERD) so that the tank may remain at atmospheric pressure. Different ERD types can be used for this configuration including centrifugal-type ERDs such as turbines connected to HPP shaft and turbochargers, and

isobaric ERDs such as Clark pump and pressure exchanger. Energy recovery devices pump the concentrate inlet stream by harnessing the pressure of the concentrate outlet stream.

[0056] Among energy recovery devices, positive displacement ERDs, also known as pressure exchanger (PX) 80, have higher efficiency than centrifugal types. PX 80 devices contain several cylinders with free pistons that divide the two streams (FIG. 11-14). An alternative type of PX 80 has two cylinders with actuated valves that recover the pressure step by step. In compression step, the concentrate inlet stream is pushed by the concentrate outlet stream which is then ejected in the discharge step. The PX-type batch LSRRO configuration combines HPP 82 and CP 84 with PX 80. Like the previous configurations, HPP 82 flow rate is equal to permeate flow rate as the volumetric flow rates of streams exchanging energy in the PX 80 are equal. The process starts by filling the tank 86 with feed water 88 (FIG. 11). The permeate production starts by HPP 82 delivering high pressure concentrate inlet stream to the LSR module 90 (FIG. 12). The partially dewatered concentrate outlet stream is then fed to the PX 80 in which the pressure of the concentrate outlet stream 92 is recovered and is given to the concentrate inlet stream. The concentrate outlet stream 92 is then released in atmospheric pressure and is mixed with the tank. The tank salinity increases over time until the desired salinity is reached (FIG. 13). Then, a feed stream 88 flushes the remaining brine in the module 90, and the brine in the tank 86 is ejected as well (FIG. 14). Although the configuration could be designed such that the high-pressure pump 82 would flush the system, as the circulation pump 84 has higher flow rate, the flushing is faster with CP 84 and the

downtime is shorter. Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 11-14.

[0057] A Clark pump type batch LSRRO configuration is similar to the PX type batch LSRRO but uses a Clark pump 102 to recover energy from the concentrate outlet stream 100 instead. Circulation pumps operating at high pressure might encounter technical problems for the sealing at the pump inlet. This configuration eliminates the circulation pumps.

[0058] A Clark pump 102 consists of two cylinders called pressurizer 106 and governor 104 (FIG. 15-16). The two cylinders are interconnected and the governor 104 switches the chambers for the concentrate outlet stream received from the module and the one delivered to the tank. A feeding pump 108 supplies the Clark pump 102 with the concentrate inlet stream 110 at moderate pressure. The operation includes two strokes based on the position of the governor 104 which changes the direction of pressurizer's piston 112. Raising the pressure of the concentrate inlet stream is assisted by the back pressure of concentrate outlet stream. This reduces the required pressure supplied by the feeding pump 108. The ratio of the radii of the central rod 116 and the cylinder 114 in the pressurizer 106 determines the ratio between the volumetric flow rate of the concentrate inlet and concentrate outlet streams, and in turn, the recovery ratio per pass, which is the ratio of volumetric flow rate of the permeate and that of concentrate inlet. Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 15-16.

[0059] The implementation of Clark pump for the batch LSRRO process is shown in FIG. 17-20. For simplicity, only one state of the Clark pump 120 is shown. The process

starts by filling the tank 122 with feed 124 (FIG. 17). During this step, the high pressure pump 126 is off and all lines are at atmospheric pressure. Permeate production starts by operating the high pressure pump 126 (FIG. 18). During permeate production, the tank 122 volume is decreased as the flow is dewatered, and the permeate salinity increases. After finishing the permeate production (FIG. 19) flushing is initiated (FIG. 20). For flushing, the remaining brine in the tank 122, the module 128, and the Clark pump 120 should be washed with the fresh feed 124. As the ratio of flows in the Clark pump 120 is fixed due to fixed ratio of radii of rod 132 and cylinder 130 in the pressurizer section 134 of the Clark pump 120, the concentrate outlet flow rate corresponding to the recovery ratio per pass during the permeate production is fed to the governor 136 of the Clark pump 120. The rest of the flow at the concentrate outlet of the module 128 is ejected as brine. Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 17-20.

[0060] In semi-batch LSRRO, there is no storage tank, and the returning concentrate outlet stream is directly mixed with the HPP 140 outlet stream 142 to form the concentrate inlet stream 144. Permeate production starts as the HPP 140 pumps feed water to the circulation loop 146, and the module produces permeate (FIG. 21). The concentrate outlet stream of the module is mixed via CP 150 with the HPP 140 stream to form the concentrate inlet stream 144. The salinity in the circulation loop 146 increases over time until it reaches the desired salinity. (FIG. 22). Then, the CP 150 flushes the circulation loop 146 with freshwater and ejects the remaining brine in the system (FIG. 23). Although the configuration could be designed such that the high pressure pump 140 would flush the system, as the circulation pump 150 has higher flow rate, the flushing is

faster with CP 150 and the downtime is shorter. As the feed stream is in atmospheric pressure, this configuration enables variation in feed salinity. Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 21-23.

[0061] It has been explained above how batch and semi-batch LSRRO can dewater the feed stream. If the feed stream has to be dewatered up to very high salinities such as the saturation level while production of freshwater with low salinity ( $\sim 0.5$  g/L) is intended, one step of operation is not enough as the salinity difference between the brine and the permeate is still limited by the membrane's bursting pressure. Here, a multi-staging process is introduced for reaching very high salinities. The process is implemented such that the feed water is concentrated in several steps using only one stage of batch LSRRO to produce the hypersaline effluent while the eventual permeate is dilute enough such that it could be dewatered in a reverse osmosis system for freshwater production. The desired operation is typically cyclic. Thus, the intermediate permeates produced in the cycles is typically fed to the concentrate tank at appropriate step of the proceeding cycle. For the process, any type of batch LSRRO configuration, including bladder type, double acting piston type, or PX type can be used. For the sake of accuracy, we focus on the operation of the system using bladder-type batch LSRRO.

[0062] For the process, we assume that the feed water is the retentate of reverse osmosis plants at the salinity of 70 g/L. Each cycle can yield brine and permeate with brine salinity to be 70 g/L higher than the cumulative permeate salinity to account for membrane's hydraulic pressure limit. Intended effluent salinity is 175 g/L.

[0063] The system 200 shown in FIG. 24A-G includes a bladder type batch LSRRO with 4 open tanks. The required number of tanks depends on the degree of dewatering and typically increases with increasing the total water recovery of the system. The process starts by priming the bladder tank 202 with 70 g/L tank 212 (Step 1, FIG. 24A). The HPP 204 pumps the hydraulic fluid 206 in the bladder 208 and starts permeate production (Step 2, FIG. 24B). The permeate increases salinity such that when the bladder 208 reaches 105 g/L, the cumulative permeate salinity is 35 g/L. Once the bladder tank 202 reaches the salinity of 105 g/L, the tank 210 containing water with salinity of 105 g/L from the previous cycle is added to the bladder tank 202 (Step 3, FIG. 24C). The permeate production resumes, and the permeate with cumulative salinity of 70 g/L is collected in the 70 g/L tank (Step 4, FIG. 24D). Once the salinity in the bladder tank 202 reaches 140 g/L, the permeate stream is switched to the 105 g/L tank 210 (Step 5, FIG. 24E). This tank is used for the proceeding cycle at step 3. The process continues until the bladder tank 202 reaches the salinity of 175 g/L, after which the brine remained in the system is flushed with the 70 g/L tank 212 (Step 6, FIG. 24F). In the end, the produced 35 g/L salt water is dewatered in a reverse osmosis or batch reverse osmosis unit 214 (Step 7, FIG. 24G). This step can use the HPP 204 and CP 216 of the bladder- type batch LSRRO to reduce initial costs. However, as the bladder tank 202 is used for hypersaline brine, a separate tank should be used if reverse osmosis is designed for bladder-type batch mode. FIG. 25 shows the salinity profile along each step. Darker shading indicates areas of higher salinity and thicker lines denote higher hydraulic pressure than thinner lines in FIG. 24A-G.

[0064] A multistage system with simultaneous freshwater production and brine concentration is realized for seawater feed stream when the batch/semi-batch LSRRO is combined with semi-batch RO with high salt rejection. While any batch/semi-batch configuration LSRRO can be used for this purpose, the present example focuses on the bladder type batch LSRRO 300. The diluate salinity from batch/semi-batch LSRRO which fluctuates over the repeated cycle is fed to the semi-batch RO (FIG26-28). A tank filled with hydraulic fluid 302 is connected to the bladder tube 304 inside the bladder tank 306 via the high-pressure pump 308. An on/off valve 310 makes a direct connection from the tank 302 to the bladder 312 as well. The chamber 314 of the tank 306 is fed to feed inlet port 316 of LSRRO module 318 via the valves 320 and 322. The feed outlet stream 324 of LSRRO module 318 is returned to the bladder tank 306 via circulation pump 326. The diluate stream 328 of LSRRO module 318 is fed to HPP2 330 via the valve 332. The HPP2 330 feeds the stream to the circulation loop 334 of the RO module 336. The returning stream 338 of the module 336 is mixed with the feed inlet stream 340 via the circulation pump 342. During the permeate production (FIG. 26); valve 320 is closed, and HPP1 308 pressurizes the bladder tank 306 and causes diluate production in LSRRO module 318. The stream 328 is then pressurized by HPP2 330 and causes permeation of freshwater in RO module 336. The process continues until the desired water recovery is achieved. Then, the flushing step starts (FIG. 27) by opening valve 320 to the brine tank 344 via stream 346 and redirect the valve 348 to connect stream 338 to the valve 322. The stream 350 of the feed tank 352 serves two purposes: replacing the remaining brine in the RO module 336 with the new feed and replacing the remaining brine in the LSRRO module 318 by the brine from RO module 336. During the priming

step (FIG. 28) the valve 320 closes the stream 346 and the valve 310 opens. Pushing flow by HPP2 330 causes the bladder 312 to shrink and return the hydraulic fluid to back to the hydraulic fluid tank 302. The cycle repeats from the permeate production step.

[0065] Spatial multistaging of the process requires selection of appropriate membrane salt rejection value for each stage. For a two-stage system consisting one batch RO and one batch LSRRO, the salt rejection in the batch LSRRO stage affects the energy consumption and brine salinity (FIG. 30). For a four stage system containing batch RO as the first stage and three batch LSRRO as the following stages, the last stage determines the final brine salinity while the intermediate stages can be optimized for minimum energy consumption (FIG. 31).

[0066] While the claimed technology has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character. It is understood that the embodiments have been shown and described in the foregoing specification in satisfaction of the best mode and enablement requirements. It is understood that one of ordinary skill in the art could readily make a nigh-infinite number of insubstantial changes and modifications to the above-described embodiments and that it would be impractical to attempt to describe all such embodiment variations in the present specification. Accordingly, it is understood that all changes and modifications that come within the spirit of the claimed technology are desired to be protected.

## CLAIMS

What is claimed is:

1. A desalination assembly comprising:  
a pressure vessel having internal bladder positioned therein;  
a circulation pump connected in hydraulic communication with the pressure vessel;  
a hydraulic fluid reservoir;  
a high-pressure hydraulic pump connected in hydraulic communication with the hydraulic reservoir and the pressure vessel bladder;  
a low salt rejection module connected in hydraulic communication with the pressure vessel; and  
a low salt rejection membrane positioned in and bisecting the low salt rejection module into a high salinity inlet portion and a low salinity permeate portion.
2. The desalination assembly of claim 1 and further comprising:  
an inlet water reservoir connected in hydraulic communication with the circulation pump;  
and  
a brine reservoir connected in hydraulic communication with the high-pressure pump
3. The desalination assembly of claim 1 and further comprising:  
an inlet water reservoir connected in hydraulic communication with the circulation pump.
4. The desalination assembly of claim 3, wherein the inlet reservoir comprises at least two inlet tanks.

5. The desalination assembly of claim 4, wherein the at least two inlet tanks hold water having different saline concentrations.
6. The desalination assembly of claim 1 further comprising an inlet water reservoir connected in hydraulic communication with the circulation pump;  
wherein the pressure vessel further comprises an internal piston positioned therein.
7. The desalination assembly of claim 6 wherein the hydraulic fluid reservoir is the inlet reservoir.
8. The desalination assembly of claim 1 and further comprising a pressure exchanger operationally connected between the circulation pump and the pressure vessel;  
wherein the circulation pump is connected in hydraulic communication with the low salt rejection module.
9. The desalination assembly of claim 8 wherein the pressure exchanger is a Clark pump.
10. The desalination assembly of claim 9 wherein the Clark pump governor is hydraulically connected to the low salt rejection module.
11. A desalination assembly comprising:

a pressure vessel;

a circulation pump connected in hydraulic communication with the pressure vessel;

a hydraulic fluid reservoir;

a high-pressure hydraulic pump connected in hydraulic communication with the hydraulic reservoir and the pressure vessel;

a low salt rejection module connected in hydraulic communication with the housing; and

a low salt rejection membrane positioned in and bisecting the low salt rejection module into a high salinity inlet portion and a low salinity permeate portion.

12. The desalination assembly of claim 11 and further comprising:

an inlet water reservoir connected in hydraulic communication with the circulation pump;

and

a brine reservoir connected in hydraulic communication with the high-pressure pump.

13. The desalination assembly of claim 11 wherein the pressure vessel further comprises an internal bladder positioned therein; and wherein the high-pressure hydraulic pump is connected in hydraulic communication with the bladder.

14. The desalination assembly of claim 13 and further comprising:

an inlet water reservoir connected in hydraulic communication with the circulation pump;

and wherein the inlet reservoir comprises at least two inlet tanks.

15. The desalination assembly of claim 14, wherein the at least two inlet tanks hold water having different saline concentrations.
16. The desalination assembly of claim 11 and further comprising an inlet water reservoir connected in hydraulic communication with the circulation pump; wherein the pressure vessel further comprises an internal piston positioned therein.
17. The desalination assembly of claim 16 wherein the hydraulic fluid reservoir is the inlet reservoir.
18. The desalination assembly of claim 11 and further comprising a pressure exchanger operationally connected between the circulation pump and the pressure vessel; wherein the circulation pump is connected in hydraulic communication with the low salt rejection module.
19. The desalination assembly of claim 20 wherein the pressure exchanger is a Clark pump.