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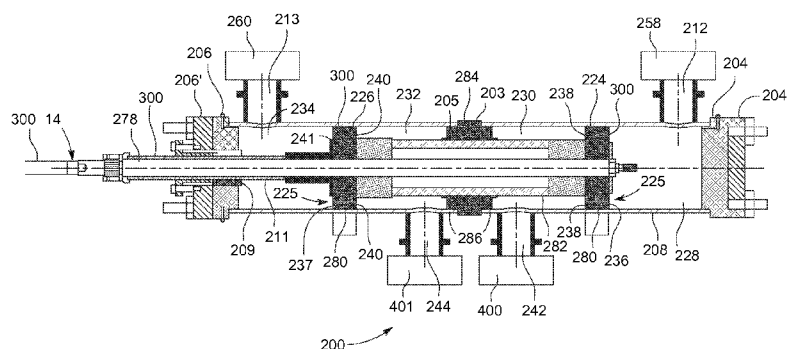


FIG. 3

(57) Abstract: A fluid pumping system with energy recovery provides feed water to a reverse osmosis unit. An actuator drives a feed water piston inside of a cylinder. Concentrate is directed from the reverse osmosis unit to the back side of the piston to reduce the work required from the actuator. The piston has a higher active surface area on its feed water face relative to its concentrate face. The piston also has an opening providing a fluid passageway from one face to other face. Between strokes, the cylinder must transition from having relatively high pressures on both sides of the piston to having relatively low pressures on both sides of the piston, or from low pressures to high pressures. These pressure transitions are at least partially attained by bumping the piston in the direction of the next stroke while concentrate valves in communication with the concentrate face are closed.

ENERGY RECOVERY PUMP WITH PRESSURE BALANCING HOLE AND PRESSURE TRANSITIONING STEP

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 **[0001]** This application claims the benefit of priority of U.S. Provisional Patent Application No. 61/985,144 filed April 28, 2014, which is hereby incorporated herein by reference in its entirety.

FIELD

- 10 **[0002]** This specification relates to pumping systems with energy recovery.

BACKGROUND

- 15 **[0003]** To desalinate seawater by reverse osmosis (RO), the feed water must be pressurized above the osmotic pressure of the feed water. Energy costs, primarily resulting from electrical consumption by the feed water pumps, are the largest component of the operating cost of a seawater reverse osmosis (SWRO) plant. However, energy costs can be reduced by recovering energy from the pressurized brine leaving an RO unit.

- 20 **[0004]** Childs et al. described a piston based pumping and energy recovery system in US Patent Number 6,017,200, entitled Integrated Pumping and/or Energy Recovery System. This system uses a piston driven by a hydraulic pump to provide pressurized feed water to an RO membrane module. The front face of the piston drives the feed water to the RO module. The back face of the piston receives brine from the RO module. The pressure of the brine acting on the back face of the piston reduces the power required from the hydraulic pump to move the piston.

- 25 **[0005]** In the Childs et al. system, "energy recovery" valves admit brine to the back face of the piston on a forward stroke. Additional valves allow the brine to leave the piston on a backward stroke. The energy recovery valves are controlled by a control unit that also operates the hydraulic pump. The control unit synchronizes the movements of the valves with the movement of the piston. Because the piston reciprocates, it must accelerate and
30 decelerate and therefore inherently produces an uneven rate of flow and pressure of the feed

water. However, when a set of pistons are used their output may be synchronized to produce a nearly constant combined output pressure.

[0006] US Patent Application Publication No. US 2013/0082000, entitled Desalination System with Energy Recovery and Related Pumps, Valves and Controller, describes various improvements to a piston based pumping and energy recovery system. According to one improvement, the energy recovery valves are designed to begin closing when the velocity of an associated piston decreases.

SUMMARY

[0007] The following paragraphs are intended to introduce the reader to the detailed description to follow and not to limit or define any claimed invention.

[0008] This specification describes a pump having a piston inside of a cylinder. The cylinder is closed at both ends but for one or more ports on either side of the stroke of the piston. The piston has a higher active surface area on one of its faces relative to its other face. The piston also has a hole or other opening providing a fluid passageway from one face to the other face.

[0009] This specification also describes a process for altering pressures inside a pump as described above. Pressures inside the cylinder are increased or decreased by moving the piston. Advancing the larger piston face increases pressures inside the cylinder. Advancing the smaller piston face decreases pressures inside the cylinder.

[0010] The pump may be used, for example, in a system and process to provide pressurized feed water to an RO unit. During a forward stroke, the larger face of the piston advances and drives the feed water to the RO unit through a one way valve. Also during the forward stroke, a brine inlet valve admits brine to the smaller face of the piston. The pressure of the brine acting on the smaller face of the piston reduces the power required to move the piston. During a backward stroke, a brine outlet valve allows the brine to leave the piston and another one way valve admits more feed water to the larger face of the piston.

[0011] Between strokes, the cylinder must transition from having relatively high pressures on both sides of the piston to having relatively low pressures on both sides of the piston, or from low pressures to high pressures. These pressure transitions are at least partially attained by moving the piston in the direction of the next stroke while both brine valves are closed. These motions, as a result of the differential area piston in combination with the hole or other opening through the piston face, alter the pressures in the cylinder.

One of the brine valves is then opened and the stroke continues. Altering the pressures in the cylinder before opening a brine valve reduces the magnitude of any disturbances to the system created when a brine valve is opened.

5 BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 is a schematic drawing of a fluid pumping and energy recovery system in combination with a reverse osmosis system.

[0013] Figure 2 is a schematic, cross-sectional view of a portion of a hydraulic pump used in the system of Figure 1.

10 **[0014]** Figure 3 is a cross-sectional, schematic view of a water cylinder used in the system of Figure 1.

[0015] Figure 4 is a cross-sectional, schematic view of a feed water valve used in the systems of Figure 1.

15 **[0016]** Figure 5 is a cross-sectional, schematic view of an energy recovery valve, alternatively called a brine valve, used in the system of Figure 1.

[0017] Figure 6 is a schematic of inner and outer feedback loops of a control unit used in the system of Figure 1.

[0018] Figure 7 is a graph showing velocity over time and displacement over time profiles used in operating the systems of Figure 1.

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DETAILED DESCRIPTION

[0019] As depicted in Figure 1, a system 10 includes a source of feed water 110, three hydraulic pumps 12, a water cylinder 200 for each hydraulic pump 12, an RO membrane unit 216, and a control unit 100. The system 10 is similar to the system described in US Patent Number 6,017,200, which is incorporated by reference, but will also be described below. The hydraulic pumps 12 are driven by a motor, not shown. Optionally, the three hydraulic pumps 12 may be replaced with a single hydraulic pump and a system of pipes and valves suitable for producing an output associated with each water cylinder 200. The system 10 has three double acting water cylinders 200, which in effect provides six water cylinders, but other numbers and arrangements of water cylinders, and means of powering them, may also be used.

30 **[0020]** Under instruction from the control unit 100, each hydraulic pump 12 controls the movement of a piston rod 14. The piston rod 14 is mechanically coupled to two opposed

pistons 224, 226 (not shown in Figure 1) that are housed within a water cylinder 200. As will be further described below, the hydraulic output of each hydraulic pump 12 causes a piston rod 14 to move. Due to the mechanical coupling, the movement of the piston rod 14 causes the two pistons 224, 226 to move in unison with the movement of the piston rod 14. The piston rod 14 and the pistons 224, 226 may be referred to collectively as a reciprocating assembly 300. For brevity, this specification may at times describe the features of a single hydraulic pump 12, reciprocating assembly 300, water cylinder or other repeated elements of the system 10, but the description similarly applies to the other similar elements. The control unit 100, hydraulic pump 12 and hydraulic cylinder 18 may be referred collectively as an actuating assembly.

[0021] The source of feed water 110, which may provide sea water, brackish water, produced water or any other feed water requiring separation, is connected to the water cylinder 200 by low pressure feed water lines 254, 256. The system 10 also includes high pressure feed water lines 262, 264 to direct a high pressure feed water from the water cylinder 200 to the RO membrane unit 216.

[0022] The RO membrane unit 216 produces a flow of permeate (alternatively called filtrate), for example desalted potable water, which is directed through a permeate line 217 for the desired uses of the permeate. The RO membrane unit 216 also produces a flow of high pressure brine, alternatively called concentrate or retentate. The high pressure brine is directed from the RO membrane unit 216 by high pressure brine lines 218, 219 back to the water cylinder 200.

[0023] The water cylinders 200 also include a low pressure brine outlet that is connected to low pressure brine lines 250, 252. The low pressure brine may be directed to a waste or recycle stream.

[0024] From a simplified perspective, there are four pressures within this system. The first pressure P1 is the pressure that supplies the feed water from the source 110, through low pressure feed water lines 254, 256, to the water cylinder 200. P1 can be provided by gravity or one of a variety of known pumps. The second pressure P2, which is substantially higher than P1, is the pressure exerted on the feed water from the water cylinder 200 and carried through high pressure feed water lines 262, 264, to the RO membrane unit 216. As described below, P2 is provided by the pistons 224, 226 of the water cylinder 200. The third pressure P3 is the pressure of the brine as it leaves the RO membrane unit 216 to return to the water cylinder 200 via high pressure brine lines 218, 219.

P3 is less than P2 because energy is required to filter the feed water and permeate leaves the system 10. The fourth pressure P4 is the pressure of the brine as it leaves the water cylinder 200 via low pressure brine lines 250, 252. P4 is less than P3.

[0025] For example, P1 may be in the range of about 5 to 100 psig; P2 may be in the range of about 600 to 1000 psig; P3 may be in the range of 500 to 950 psig; and P4 may be in the range of about 1 to 50 psig. The pressures may fluctuate to some extent over time, and the system 10 may include one or more accumulators, pressure release valves or other components of hydraulic systems effective to compensate for recurring or emergency flow or pressure variations.

[0026] Under the control of the control unit 100, the hydraulic pump 12 imparts a desired velocity or displacement profile upon the piston rod 14. The hydraulic pump 12 is driven by a motor and translates the rotational energy of the motor into a flow of hydraulic fluid. Therefore, the hydraulic pump 12, on command from the control unit 100, produces a hydraulic output that can range from a maximal hydraulic output to zero hydraulic output to maximal hydraulic output in the opposite direction. The hydraulic output of pump 12 is translated into the reciprocating displacement of the piston rod 14.

[0027] The piston rod 14 is connected to a hydraulic piston 20 within a hydraulic cylinder 18. Attached at one end of hydraulic cylinder is line 26 and attached at the other end of hydraulic cylinder 18 is line 28. The lines 26 and 28 direct the hydraulic output of the pump 12 to either side of the hydraulic piston 20. Optionally, the piston rod 14 may be connected to one face of the hydraulic piston 20 and another rod 30 (shown in Figure 6) may be connected to the opposite face of the hydraulic piston 20.

[0028] As shown in Figure 2, the hydraulic pump 12 is powered by a motor (not shown) that turns a drive shaft 60. The drive shaft 60 preferably turns at a constant number of rotations per minute. The drive shaft 60 is connected, for example by a spline, to a barrel 62 which houses a plurality of axial pistons 64 within piston bores. Each of the pistons 64 terminates in a ball on which is swaged a shoe 66 and the shoe is free to pivot as well as rotate at each piston ball. The shoe 66 bears against a thrust plate 68, alternatively referred to as a creep plate, which in turn bears against a swash plate 70, which is shown angled to the axis of shaft 60. The swash plate 70 does not rotate, but under instruction from the control unit 100, the swash plate 70 can be tilted around an axis perpendicular to the shaft 60.

[0029] When the drive shaft 60 rotates, the thrust plate 68, the barrel 62 and each piston 64 rotate around the drive shaft 60. As the pistons rotate around the drive shaft 60, they follow the angle of the swash plate 70. Following the angle of the swash plate 70 causes the pistons to articulate in and out of the bores in the barrel 62 thereby displacing hydraulic fluid and providing the hydraulic output of pump 12.

[0030] The angle of the swash plate 70 determines the hydraulic output of the hydraulic pump 12. For example, if the swash plate angle is positioned in a first position shown in Figure 2, hydraulic fluid will be pumped into line 28 and discharged from line 26, which causes hydraulic piston 20 of Figure 1 to move in a first direction. When the swash plate angle is substantially perpendicular to the axis of the drive shaft 60, at position N in Figure 2, there is no articulation of the pistons 64, relative to the barrel 62 and there is no displacement of hydraulic fluid into or out of lines 26 and 28, and the hydraulic piston 20 is stationary. When the swash plate angle is changed to the second position shown in Figure 2, line 28 becomes the discharge line and line 26 is the inlet line thereby causing hydraulic piston 20 of Figure 1 to move in a second direction, opposite to the first direction.

[0031] The hydraulic output from the hydraulic pump 12 can be changed from a maximum value in one direction smoothly through zero to a maximum value in the opposite direction as the control unit 100 dictates the angle of the swash plate 70 from one side of center through neutral to the other side.

[0032] In the example illustrated in Figure 1, the actuating assembly comprises a control unit 100, a hydraulic pump 12 and a hydraulic cylinder 18, but the actuating assembly could have different configurations for driving the piston rod 14 in other embodiments. For example, alternative mechanical arrangements such as cams, roller screws or other mechanisms may be used to move the reciprocating assembly 300 back and forth.

[0033] As shown in Figure 3, the water cylinder 200 is generally tubular in shape with two end plates 204, 206 and a lateral wall 208 that extends between the end plates. The water cylinder 200 also includes intermediate plates 203 and 205, which divide the internal bore of the water cylinder 200 into two piston chambers 220 and 222. Within each piston chamber 220 and 222 there is a reciprocating, dual-action piston 224 and 226, each of which defines a feed water working chamber 228, 234 and a concentrate working chamber 230, 232. The dual-action pistons 224, 226 are mechanically coupled by a connection rod 278 which extends through an aperture in both of the intermediate plates 203, 205. The connection rod 278 also extends out of the water cylinder, through a bearing and seal

assembly 209 within the end plate 206 so that no pressure or fluid leaks across the end plate 206 from the feed water working chamber 234.

[0034] The feed water working chamber 228 is defined by the inner surface of end plate 204, the inner surface of lateral wall 208 and the front face 236, also called the feed water face, of the piston 224. The feed water working chamber 234 is defined by the inner surface of end plate 206, the inner surface of lateral wall 208 and the front face 237, also called the feed water face, of the piston 226. The feed water chambers 228, 234 each have a feed water access port 212, 213 to provide fluid communication across the lateral wall 208 of the feed water working chambers 228, 234, for example to allow the inlet and outlet of feed water.

[0035] The concentrate working chamber 230 is defined by the inner surface of the intermediate plate 203, the inner surface of the lateral wall 208 and the back face 238, also called the concentrate face, of piston 224. The concentrate working chamber 232 is defined by the inner surface of the intermediate plate 205, the inner surface of the lateral wall 208 and the back face 240, also called the concentrate face, of piston 226. The feed water face 236, 237 is positioned opposite to the back face 238, 240 of the pistons. The concentrate working chambers 230, 232 each have a concentrate access port 242, 244 to provide fluid communication across the lateral wall 208 of the concentrate working chambers 230, 232, for example to allow the inlet and outlet of concentrate.

[0036] The dual-action pistons 224, 226 include one or more seals 280 between the perimeter of the dual-action pistons 224, 226 and the lateral wall 208 to prevent the movement of fluid between the feed water working chambers 228, 234 and the concentrate working chambers 230, 232 so that there is no fluidic communication across the dual-action pistons 224, 226. The one or more seals 280 are sufficiently resilient to withstand the differential pressure across the pistons 224, 226 caused by different hydrostatic pressures within the feed water working chambers 228, 234 and the respective concentrate working chambers 230, 232.

[0037] As described above, the dual-action pistons 224 and 226 are mechanically coupled by a connection rod 278. The connection rod 278 is also mechanically coupled to the piston rod 14 so that both dual-action pistons 224 and 226 move in unison with the piston rod 14. As described above, the piston rod 14, the connection rod 278 and the dual-action pistons 224 and 226 are collectively referred to as the reciprocating assembly 300.

[0038] As described herein below, the movement of the reciprocating assembly 300, including the actual stroke distance of the dual-action pistons 224, 226 within the water cylinder 200 can change. Therefore, the volume of the feed water working chambers 228, 234 and the volume of the concentrate working chambers 230, 232 can also be defined by the cross-sectional area of the dual-action pistons 224, 226 multiplied by the differential position of the dual-action pistons 224, 226 at the beginning and the end of a stroke of the reciprocating assembly 300.

[0039] In the water cylinder 200 shown, the ports 212, 213, 242 and 244 are each connected to valve bodies that are in turn each connected to a low pressure and a high pressure valve. Optionally, the water cylinder 200 may have twice as many ports, with each port connected to a single low pressure or high pressure valve.

[0040] Referring back to Figure 1, the RO membrane unit 216 includes a set of RO modules each having one or more selectively permeable membranes. The feed water, at pressure P2, enters the RO unit 216 and permeate crosses the selectively permeable membranes to enter into a permeate line 217. Effectively, the RO unit 216 removes a volume of permeate from every input volume of feed water. This causes a decrease in the flow of water that enters the high pressure brine lines 218, 219 and ultimately enters the concentrate working chambers 230 and 232. This difference is referred to as the recovery ratio.

[0041] To compensate for the recovery ratio, a ratio sleeve 282 is placed around the connection rod 278, between the back faces 238, 240 of the dual-action pistons 224, 226. The ratio sleeve 282, also referred to as a ratio rod, is of greater diameter than the connection rod 278 and this decreases the working volume of the concentrate working chamber 230, 232, in comparison to the volume of the feed water working chambers 228, 234. For example, if the recovery ratio of the RO membrane unit 216 is 30%, then the diameter of the ratio sleeve 282 is such that the volume of concentrate pumped out of the concentrate working chamber 230, 232 is 30% smaller than the volume of feed water pumped out of the feed water working chambers 228, 232.

[0042] As shown in Figure 3, the ratio sleeve 282 is part of the reciprocating assembly 300 and the ratio sleeve 282 moves through both the intermediate plates 203, 205. To prevent the communication of fluid or pressure between the concentrate working chambers 230, 232, a ratio sleeve seal assembly 284 is positioned on the inner surface of

the lateral wall 208 at the apertures to provide one or more seals 286 against the outer surface of the ratio sleeve 282.

[0043] Each piston 224, 226 also has a hole 225 extending between its faces: between feed water face 237 and back face 240 for piston 226 and between feed water face 236 and back face 238 for piston 224. These holes 225 allow water to move through the pistons 224, 226, in particular when all valves associated with concentrate access ports 242, 244 are closed. Because of the differential area of the pistons 224, 226 (or because the ratio sleeve 282 is present and larger than connection rod 278), moving the reciprocating assembly 300 to the right in Figure 3 causes a decrease in the total volume of right side feed water working chamber 228 and concentrate working chamber 230. The hole 225 allows some liquid to flow from feed water working chamber 228 to concentrate working chamber 230. However, the decrease in total volume causes the pressure in both the feed water working chamber 228 and the concentrate working chamber 230 to rise. Conversely, the pressures in the left side feed water working chamber 234 and concentrate working chamber 232 decreases. When the reciprocating assembly 300 moves to the left, the pressure in left side chambers 232, 234 increases while the pressure in right side chambers 228, 230 decreases.

[0044] Optionally, the holes 225 could be replaced by another type of opening that provides a fluid passageway between feed water face 237 and back face 240 for piston 226 or between feed water face 236 and back face 238 for piston 224. For example, the holes 225 could be replaced by a notch in the side of a piston 226, 224. A hole 225 or other opening can pass through either the main body of a piston 226, 224 or through a seal 280 of the piston 226, 224. Alternatively, the opening can be provided in the lateral wall 208 of the water cylinder 300. Such an opening only needs to provide a fluid passageway while a piston 226, 224 is at its fully extended or retracted position (but preferably at both of these positions), plus the length of a bump. The length of a bump is optionally about 2 to 5% of the stroke of a piston 226, 224. An opening in the lateral wall 208 does not need to be provided at intermediate positions. This would reduce salt leakage through the opening but the lateral wall 208 might then need to be strengthened to allow the water cylinder 300 to withstand its operating pressures. In another alternative, the opening might be provided by way of a loose tolerance between one or more of the seal 280, the rest of a piston 226, 224, and the lateral wall 208. However, an opening preferably has an area of at least 0.02%, or at least 0.04%, of a feed water face 236, 237 and it would be difficult to provide a selected size of opening

and have a smoothly operating piston 226, 224 with an opening of that size provided by loose tolerances alone.

[0045] As will be described further below, these motions occur in an exemplary process while all inlet valves 402 and outlet valves 502 (see Figure 5) connected to concentrate access ports 242, 244 are closed and the reciprocating assembly 300 is starting a transition from movement in one direction to movement in another direction. Further, feed water access ports 212, 213 are each connected to a feed water valve assembly 258, 260 which provide feed water inlet and outlet one way check valves. The one way valves allow water to enter or leave the feed water working chambers 228, 234, but only when the pressure inside each of the feed water working chambers 228 and 234 is near to the pressure on the opposite side of the check valve within a feed water valve assembly 258, 260 that is capable of opening. Accordingly, when moving the reciprocating assembly 300 causes the pressure inside either of the feed water working chambers 228, 234 to increase, it increases only to about, or slightly above, the high feed water pressure P2. When the movement causes the pressure inside of either of feed water working chambers 228, 234 to decrease, it decreases to about, or slightly below, the low feed water pressure P1. The size of the holes 225 and the timing and size of the movement can be adjusted to cause similar or different pressure variations in the concentrate working chambers 230, 232. In particular, the pressure in concentrate working chambers 230, 232 is preferably increased to near, but not above, the high brine pressure P3. Although it is a lesser concern, the pressure in concentrate working chambers 230, 232 is preferably decreased to near, but not below, the low brine pressure P4.

[0046] The water cylinder 200 and other parts of the system 10 may use the materials and other details of construction described in US Patent Application Publication No. US 2013/0082000, Desalination System with Energy Recovery and Related Pumps, Valves and Controller. US Patent Application Publication No. US 2013/0082000 is incorporated by reference.

[0047] As shown in Figure 3, the piston chambers 220, 222 include a feed water valve assembly 258, 260 which regulate the flow of feed water through the feed water access ports 212, 213 to the feed water working chambers 228, 234. For example, when feed water is desired to be supplied to feed water working chamber 228, feed water valve assembly 258 is open to line 254 so that feed water can flow from the source 110, through line 254, and into the feed water working chamber 228 via feed water access port 212. If the feed water

valve assembly 258 is closed to line 254, no feed water will flow into the feed water working chamber 228. To supply feed water to the feed water working chamber 234, feed water valve assembly 260 can open to line 256 so that feed water flows from the source 110, through line 256 to the working chamber 234, via feed water access port 213. If feed water
5 valve assembly 260 is closed to line 256 then no feed water will flow into the feed water working chamber 234.

[0048] For feed water to exit the feed water working chambers 228, 234 the feed water valve assembly 258, 260 are closed to lines 254, 256 and open to lines 262, 264.

[0049] The feed water valve assemblies 258, 260 both comprise the same features
10 and functions. Therefore, the present disclosure will only describe the features of feed water valve assembly 258; however, it is understood that this description similarly describes the features of feed water valve assembly 260. The feed water valve assembly 258 may include an inlet end 302, a central chamber 304, a connection 306 and an outlet end 309. The inlet end 302 is connected to feed water line 254. The feed water valve assembly 258 is
15 connected to the feed water access port 212 via connection 306 which is in fluid communication with the central chamber 304. The outlet end 308 is connected to high pressure feed water supply lines 262.

[0050] The feed water valve assembly 258 also includes a first pressure check valve 308 and a second pressure check valve 310. The first pressure check valve 308 is
20 positioned between the inlet end 302 and the central chamber 304. A second pressure check valve 310 is positioned between the central chamber 304 and the outlet end 309. The pressure check valves 308, 310 generally both comprise the same features and function, therefore the present disclosure will describe the first pressure check valve 308 and it is understood that this described is inclusive of the second pressure check valve 310.

[0051] The first pressure check valve 308 includes a valve piston 312 and a valve
25 seat 314. The valve piston 312 actuates between a closed position, when the valve piston 312 is in direct contact with the valve seat 314 and an open position where the valve piston 312 is not in contact with the valve seat 314. The valve piston 312 actuates between these two positions in response to the greater of a differential hydrostatic pressure acting across
30 the valve piston 312 or a physical force, such as a biasing force. The valve seat 314 includes an extension stem 316 that extends away from the valve seat 314 terminating in an extension plate 318. A spring 320, for example a cylindrical compression spring, is positioned between the extension plate 318 and the valve seat 314 and the spring 320

provides a biasing force to physically direct the valve piston 312 against the valve seat 314 and into the closed position. The biasing force of the spring 316 is slightly greater than the hydrostatic pressure (P1) of the feed water in lines 254 and 260, as the feed water is delivered from the source 316. When valve piston 312 is in the closed position, there is no fluid communication between the contact surfaces of the valve piston 312 and the valve seat 314. When the valve piston 312 is displaced from the valve seat 314, for example by a differential hydrostatic pressure that is greater than the biasing force of the spring 320, a fluid path is created between the valve piston 312 and the valve seat 314.

[0052] In an additional optional feature, feed water access ports 212, 213 are each replaced with separate high pressure and low pressure feed water ports, each port connected to a valve similar to one of the valves from feed water valve assemblies 258, 260.

[0053] As shown in Figure 5, the water cylinder 200 also includes two concentrate (or brine) valve bodies 400, 401, alternatively called energy recovery valves. The concentrate valve bodies 400, 401 are positioned between lines 218, 219, and the concentrate access ports 242, 244 and the respective concentrate working chambers 230, 232 and lines 250, 252 (see Figure 1). The specific features and functions of the concentrate valve bodies 400 and 401 are the same, with the exception of the specific connections between the concentrate working chamber and the high pressure concentrate lines, as described above. Therefore the present disclosure will describe the concentrate valve body 400 and it is understood that this described is inclusive of the concentrate valve body 401.

[0054] As shown in Figure 5, the concentrate valve body 400 includes concentrate flow control valves 402, 502 to control the flow of concentrate into and out of the concentrate working chamber 230. The concentrate valve body 400 has a first end 404, also referred to as the high pressure input end, that is in fluid communication with the high pressure concentrate line 218. The concentrate valve body 400 also has a second end 406, also referred to as the low pressure output end, that is in fluid communication with the low pressure discharge line 250. Between the two ends there is a central chamber 414 that is in fluid communication with the concentrate working chamber 230, through the lateral wall 208, via the concentrate access port 242.

[0055] The concentrate valve body 400, includes concentrate flow control valves 402, 502. The concentrate control valves 402, 502 are also referred to as the inlet valve 402 and the outlet valve 502. The inlet valve 402 is positioned between the first end 404 and the

central chamber 414 of the concentrate valve body 400. The outlet valve 502 is located between the central chamber 414 and the second end 406.

[0056] The inlet valve 402 includes a manifold plate 427, an inlet valve seat 418 and an inlet valve piston 416. The manifold plate 427 is positioned between the first end 404 and the central chamber 414. The manifold plate 427 extends across the inner surface of the concentrate valve body 400 and includes a high pressure port 430 to provide fluid communication between the first end 404 and a high pressure chamber 432. The high pressure chamber 432 is located between the manifold plate 427 and the inlet valve seat 418. The inlet valve seat 418 is located between the manifold plate 427 and the central chamber 414. The inlet valve seat 418 includes a central aperture or a series of apertures so that when the inlet valve piston 416 is displaced from the inlet valve set 418, as further described below, fluid may flow from the high pressure chamber 432, past the inlet valve seat 418 into the central chamber 414.

[0057] The inlet valve piston 416 is located between the manifold plate 427 and the inlet valve seat 418. The inlet valve piston 416 has a first surface 419 that faces towards the manifold plate 427 and a second surface 421 that faces towards the inlet valve seat 418. The second surface 421 includes a stepped region 417 that establishes two effective surface areas, a central area 423 and an outer ring 425. When the second surface 421 is seated in the inlet valve seat 418, as described further below, the central area 423 is in direct contact with the inlet valve seat 418 and the outer ring 425 is recessed from the inlet valve seat 418.

[0058] The manifold plate 427 includes a manifold plate extension 434 that restricts the movement of the inlet valve piston 416 to actuate in a single plane, between an open position and a closed position. The manifold plate extension 434 extends away from the manifold plate 427, towards the central chamber 414. The manifold plate extension 434 extends around the inlet valve piston 416, thereby restricting the movement of the inlet valve piston 416 to move either towards or away from the manifold plate 427 and thereby towards or away from the inlet valve seat 418.

[0059] The high pressure chamber 432 is defined by the inner surface of the concentrate valve body 400, the manifold plate 427, the manifold plate extension 434 and at least partially by the inlet valve piston 416, as will be discussed further below. Via the high pressure port 430, the manifold plate 427 isolates the first surface 419 of the inlet valve piston 416 from the high pressure concentrate fluid flow that enters the concentrate valve body 400 from the first end 404.

[0060] Optionally, an inlet spring 429, for example a compression spring, can be positioned between and in contact with the manifold plate 427 and the first surface 419 of the inlet valve piston 416. The inlet spring 429 provides a physical biasing force that directs the inlet valve piston 416 towards the inlet valve seat 418.

5 **[0061]** The inlet valve piston 416 is moveable, within the confines of the manifold plate extension 434, to position the second surface 421 of the inlet valve piston 416 in direct contact with the inlet seat 418, this is referred to as the closed position. When the inlet valve 402 is in the closed position, there is no fluid communication between the inlet valve piston 416 and the inlet valve seat 418 and therefore there is no fluid communication between the
10 first end 404 and the central chamber 414. Further, when the inlet valve piston 416 is in the closed position it contributes to defining the high pressure chamber 432 (as shown in Figure 5). When the inlet valve piston 416 is in the closed position, the inlet fluid path between the first end 404 and the central chamber 414 terminates in the high pressure chamber 432.

[0062] The inlet valve piston 416 is also moveable to position the second surface 421
15 away from the inlet seat 418, this is referred to as the open position. When the inlet valve piston 416 is in the open position, the inlet fluid flow path is open between the inlet valve piston 416 and the inlet valve seat 418. This inlet fluid flow path provides fluid communication from the first end 404 to the central chamber 414 and ultimately into the concentrate working chamber 230. When the inlet valve piston 416 is in the open position it
20 contributes only partially to defining the high pressure chamber 432 because the inlet fluid path is open between the inlet valve piston 416 and the inlet valve seat 418. When the inlet valve piston 416 is in the open position, an inlet fluid path between the first end 404 and the central chamber passes through the high pressure chamber 432.

[0063] The inlet valve 402 includes an inlet valve actuator 420 that responds to
25 instructions from the control unit 100. Instructions from the control unit 100 cause the inlet valve piston 416 to actuate between the open position and the closed position.

[0064] The inlet valve actuator 420 includes a solenoid 450 that responds to electrical signals from the control unit 100. Based upon the electrical signals received from the control unit 100, the solenoid 450 can activate thereby connecting an air compressor 452 to an air
30 line 454. The air line 454 is connected to one end of a pilot valve body 456. The solenoid 450 can also de-activate thereby connecting the air line 454 to a vent port (not shown) of the solenoid valve 450. The pilot valve body 456 includes a pilot valve piston 458, which has one piston face that faces the pressurized air line 454. The pilot valve piston 458 also has

an opposite piston face that is connected to a pilot valve stem 460. The pilot valve stem 460 extends away from the pilot valve piston 458. The pilot valve stem 460 extends away from the pilot valve piston 458 through a pilot valve chamber 462. The pilot valve stem 460 can move within the pilot valve chamber 462 without creating any pressure or fluid seals therein.

5 **[0065]** Three separate channels branch off of the pilot valve chamber 462: a first pilot chamber 464; a second pilot chamber 466; and a third pilot chamber 468. The first pilot chamber 464 is connected to the first end 404 to provide fluid communication between the first end 404 and the pilot valve chamber 462. The second pilot chamber 466 is connected between the pilot valve chamber 462 and the first surface 419 of the inlet valve piston 416.
10 The second pilot chamber 466 can extend through the manifold plate 427 to provide fluid communication between the first surface 419 of the inlet valve piston 416 and the pilot valve chamber 462. The third pilot chamber 468 is connected between the pilot valve chamber 462 and the central chamber 414, providing fluid communication therebetween.

[0066] The pilot valve chamber 462 also includes a pilot ball valve 470, an inlet pilot
15 ball valve seat 472 and an outlet ball valve seat 474. The pilot ball valve 470 can move between an inlet position and an outlet position. When the pilot ball valve 470 is seated in the inlet pilot ball valve seat 472, this is referred to as the inlet position. When the pilot ball valve 470 is seated in the outlet pilot ball valve seat 474, this is referred to as the outlet position. In Figure 5, the pilot ball valve 470 is shown in the outlet position.

20 **[0067]** When the pilot ball valve 470 is in the inlet position, there is no fluid communication between the first pilot chamber 464 and the second pilot chamber 466. When the pilot ball valve 470 is in the inlet position there is fluid communication between the second pilot chamber 466 and the third pilot chamber 468.

[0068] When the pilot ball valve 470 is in the outlet position, there is fluid
25 communication between the first pilot chamber 464 and the second pilot chamber 466. When the pilot ball valve 470 is in the outlet position, a fluid path is opened from the first end 404, through the first pilot chamber 464 the second pilot chamber 466 to the first surface 419 of the inlet valve piston 416. Pressurized concentrate that follows this fluid path causes the inlet valve piston 416 to move into direct contact with the inlet valve seat 418, the closed
30 position.

[0069] The outlet valve 502 is located within the concentrate valve body 400, between the second end 406 and the central chamber 414. The outlet valve 502 includes a manifold plate 527, an outlet valve seat 518 and an outlet valve piston 516. The manifold

plate 527 is positioned between the second end 406 and the central chamber 414. The manifold plate 527 extends across the inner surface of the concentrate valve body 400 and includes a flow port 530 that provides fluid communication between the central chamber 414 and a pressure chamber 532. The pressure chamber 532 is located between the manifold plate 527 and the outlet valve seat 518. The outlet valve seat 518 is located between the manifold plate 527 and the second end 406. The outlet valve seat 518 is smaller in cross-section than the outlet valve piston 516. The outlet valve seat 518 includes a central aperture or a series of apertures so that when the outlet valve piston 516 is displaced from the outlet valve set 518, as further described below, fluid may flow from the high pressure chamber 532, past the inlet valve seat 518 towards the second end 406.

[0070] The outlet valve piston 516 is located between the manifold plate 527 and the outlet valve seat 418. The outlet valve piston 516 has a first surface 519 that faces towards the manifold plate 527 and a second surface 521 that faces towards the outlet valve seat 518. The second surface 521 includes a stepped region 517 that establishes two effective surface areas, a central area 523 and an outer ring 525. When the second surface 521 is seated in the outlet valve seat 518, as described further below, the central area 523 is in direct contact with the outlet valve seat 518 and the outer ring 525 is recessed from the outlet valve seat 518.

[0071] The movement of the outlet valve piston 516 is restricted by a manifold plate extension 534 to actuation in a single plane, between an open position and a closed position. The manifold plate extension 534 extends away from the manifold plate 534, towards the second end 406 and the manifold plate extension 534 extends around the outlet valve piston 516. The manifold plate extension 534 restricts the movement of the outlet valve piston 516 to move either towards or away from the manifold plate 527 and thereby towards or away from the outlet valve seat 518.

[0072] The pressure chamber 532 is defined by the inner surface of the concentrate valve body 400, the manifold plate 527, the manifold plate extension 534 and at least partially by the outlet valve piston 516, as will be discussed further below. The manifold plate 527 isolates the first surface 519 of the outlet valve piston 516 from the concentrate fluid flow within the central chamber 414.

[0073] Optionally, an outlet spring 529, for example a cylindrical compression spring, may be placed in contact with the manifold plate 527 and the first surface 521 of the outlet

valve piston 516. The outlet spring 529 provides a physical biasing force that drives the outlet valve piston 516 towards the outlet valve seat 518.

[0074] The outlet valve piston 516 is moveable, within the confines of the manifold plate extension 534 to position the second surface 521 of the outlet valve piston 516 in direct contact with the outlet seat 518, this is referred to as the closed position. When the outlet valve 274 is in the closed position, there is no fluid communication between the outlet valve piston 516 and the outlet valve seat 518. When the outlet piston 516 is in the closed position there is no fluid communication between the central chamber 414 and the second end 406. When the outlet valve piston 516 is in the closed position it contributes to defining the pressure chamber 532 (as shown in Figure 5). Therefore, when the outlet valve piston 516 is in the closed position, an outlet fluid path between the central chamber 414 and the second end 406 terminates in the pressure chamber 532.

[0075] The outlet valve piston 516 is moveable to position the second surface 521 away from the outlet seat 518, this is referred to as the open position. When the outlet valve piston 516 is in the open position, the outlet fluid flow path is established between the outlet valve piston 516 and the outlet valve seat 518. This outlet fluid flow path provides fluid communication from the central chamber 414 to the second end 406 and ultimately to line 250 for waste or recycling. When the outlet valve piston 516 is in the open position it partially contributes to defining the pressure chamber 532 because the outlet fluid path is now open between the outlet valve piston 516 and the outlet valve seat 518 and the pressure chamber 532 is fluid communication with the second end 406. Therefore, when the outlet valve piston 516 is in the open position, an outlet fluid path between the central chamber 414 passes through the pressure chamber 532.

[0076] The outlet valve 502 includes an outlet valve actuator 520 that responds to instructions from the control unit 100. Instructions from the control unit 100 cause the outlet valve piston 516 to actuate between the open position and the closed position.

[0077] The outlet valve actuator 520 includes a solenoid 550 that responds to electrical signals from the control unit 100. Based upon the electrical signals received from the control unit 100, the solenoid 550 can activate thereby connecting an air compressor 552 to an air line 554. The air line 554 is connected to one end of an outlet pilot valve body 556. The solenoid 550 can also de-activate thereby connecting the air line 554 to a vent port (not shown) of the solenoid valve 550. The outlet pilot valve body 556 includes an outlet pilot valve piston 558, which has one piston face that faces the pressurized air line 554. The pilot

valve piston 558 also has an opposite piston face that is connected to a outlet pilot valve stem 560. The outlet pilot valve stem 560 extends away from the outlet pilot valve piston 558. The outlet pilot valve stem 560 extends away from the outlet pilot valve piston 558 through an outlet pilot valve chamber 562. The outlet pilot valve stem 560 can move within
5 the outlet pilot valve chamber 562 without creating any pressure or fluid seals therein.

[0078] Three separate channels branch off of the outlet pilot valve chamber 562: a first outlet pilot chamber 568; a second outlet pilot chamber 566; and a third outlet pilot chamber 564.

[0079] The first outlet pilot chamber 568 is connected between the pilot valve chamber 562 and the central chamber 414, providing fluid communication therebetween.
10 The second outlet pilot chamber 566 is connected between and the first surface 519 of the outlet valve piston 516. The second outlet pilot chamber 566 can extend through the manifold plate 527. The second outlet pilot chamber 566 establishes fluid communication between the first surface 519 of the outlet valve piston 516 and the outlet pilot valve chamber
15 562. The third outlet pilot chamber 564 is connected between the second end 406 and the outlet pilot valve chamber 562 to establish fluid communication therebetween.

[0080] The pilot valve chamber 562 also includes an outlet pilot ball valve 570, an inlet pilot ball valve seat 572 and an outlet ball valve seat 574. The outlet pilot ball valve 570 can be seated in the inlet pilot ball valve seat 572, referred to as the inlet position. The outlet
20 pilot ball valve 570 can also be seated in the outlet pilot ball valve seat 574, referred to as the outlet position.

[0081] When the outlet pilot ball valve 570 is in the inlet position, there is fluid communication between the central chamber 414 and the first surface 519 of the outlet valve piston 516. When the outlet pilot ball valve 570 is in the inlet position, there is no fluid
25 communication between the second pilot chamber 566 and the third outlet pilot chamber 564 and the outlet valve piston 516 is in the closed position.

[0082] When the outlet pilot ball valve 570 is in the outlet position, there is no fluid communication between the central chamber 414 and either of the second outlet pilot chamber 566 or the third outlet pilot chamber 564. When the outlet pilot ball valve 570 is in
30 the outlet position fluid communication is established between the second outlet pilot chamber 566 and the third outlet pilot chamber 564. When the outlet pilot ball valve 570 is in the outlet position, the outlet valve piston 516 is in the open position. When the outlet valve piston 516 is in the open position an outlet fluid passage is provided from the central

chamber 414 to the second end 406 through the discharge flow port 530 and the pressure chamber 532.

[0083] In an additional optional feature of the concentrate valve body 400, the pressure chamber 532 includes a pressure relief system 600. The pressure relief system 600 includes an outlet pressure relief valve 602 and an outlet pressure relief chamber 604. The outlet pressure relief valve 602 is positioned between the pressure chamber 532 and the outlet end 406, as shown in Figure 5. The outlet pressure relief chamber 604 provides fluid communication between the pressure chamber 532 and the outlet end 406. The outlet pressure relief valve 602 can be any type of known pressure relief valve that will actuate when the pressure within the pressure chamber 532 increases beyond a set point, for example 500 to 1000 p.s.i. Actuation of the outlet pressure relief valve 602 will allow fluid communication from the pressure chamber 532 to the outlet end 406.

[0084] In an additional optional feature, the pilot valve bodies 456, 556 includes a spring (not shown) that provides a biasing force to physically direct the pilot valve pistons 458, 558 away from the pilot ball valves 470, 570. The pilot valve stems 460, 560 will similarly move away from the pilot ball valves under this biasing force. The biasing force of this spring is lower than the air pressure delivered by the lines 454, 554, for example 100 p.s.i. so that this spring will only physically move the pilot valve pistons 458, 558 when there is no air pressure delivered to the piston face.

[0085] In an additional optional feature, each of the concentrate access ports 242, 244 is replaced with two ports, and each of these ports is connected to a separate inlet valve 402 or outlet valve 502 low pressure brine valve.

[0086] The control unit 100 is a multi-processor based computing system that has one or more processors or microprocessors, micro-computers and Field Programmable Gate Arrays that execute control code and programs to control and monitor the system 10. The control unit 100 controls and monitors the hydraulic output of the hydraulic pump 12. The control unit 100 also controls and monitors information regarding the position of the reciprocating assembly 300 from an inner feedback loop 108 and an outer feedback loop 120.

[0087] The control unit 100 executes various programs to control the hydraulic output of the hydraulic pump 12 and thereby regulates the velocity and position of the reciprocating assembly 300 in accordance with a timing protocol 130, also referred to as a velocity profile. The timing protocol 130 is a series of algorithms that are stored in the non-volatile memory of

the control unit 100. The control unit 100 sends output commands to the hydraulic pump 12 to alter the angle of the swash plate 70, which regulates the hydraulic output of the hydraulic pump 12, also based upon the timing protocol 130.

[0088] The timing protocol 130 includes two features, the first feature defines the desired position of the reciprocating assembly 300 by an assembly sequence 132. The second feature of the timing protocol 130 coordinates the opening and closing of the concentrate valve bodies 400, 401 by a sequence defined by a valve sequence 134. The assembly sequence 132 and the valve sequence 134 are coordinated by the control unit 100 to ensure that the movement of each reciprocating assembly 300 is coordinated with the movement of the other reciprocating assemblies 300 to ensure that a nearly constant flow of high pressure feed water is delivered to the desalination process 316. Furthermore, the assembly sequence 132 and the valve sequence 134 are coordinated by the control unit 100 to ensure that the correct concentrate valve bodies 400, 401 are properly actuated to allow the flow of high pressure concentrate into and out of the concentrate working chambers 230 and 232 at the correct time to ensure the greatest efficiency of energy recovery in the movement of the reciprocating assembly 300.

[0089] Pursuant to the assembly sequence 132, the control unit 100 regulates the hydraulic output of the hydraulic pump 12 and thereby the position of the reciprocating assembly 300.

[0090] To aid in moving the reciprocating assembly 300 within the parameters of the assembly sequence 132, the control unit 100 receives information from an inner feedback loop 108 and an outer feedback loop 120, as shown in Figure 6. The inner feedback loop 108 includes a sensor 112, that indirectly senses the rate and direction of hydraulic output the hydraulic pump 12. Optionally, the sensor 112 can measure the angle of the swash plate 70 when using a hydraulic transmission that is operating at a constant rotational speed. In this option, the sensor 112 can be a rotational potentiometer that measures the angle between the swash plate 70 and the input shaft 60 of the hydraulic pump 12. The sensor 112 is realized using any suitable sensor, as is known in the art, to provide the detected angular information to the control unit 100 by way of an electronic signal, for example a change in voltage, current and the like.

[0091] Upon receipt of the angular information from the sensor 112, the control unit 100 determines the required hydraulic output of the hydraulic pump 12 to ensure that the reciprocating assembly 300 is moving according to the assembly sequence 132.

[0092] For example, the control unit 100 receives the angular information from the inner feedback loop to determine whether the swash plate 70 is in the correct angular position to provide the correct hydraulic output within a given timeframe by comparison to the assembly sequence 132 velocity profile algorithm. For example, if the hydraulic output of the hydraulic pump unit 12 is incorrect, by incorrect it is meant that the hydraulic output of the hydraulic pump 12 is providing either too much or too little hydraulic output to match the assembly sequence 132, the angle of the swash plate 70 may be changed, either inclined or declined, to correct the hydraulic output of the hydraulic pump 12. The relationship between the angle of the swash plate 70 and the hydraulic output of the hydraulic pump 12 is calibrated and saved in the memory of the control unit 100.

[0093] The control unit 100 also receives information from an outer feedback loop 120. The outer feedback loop 120 includes a second sensor schematically represented as sensor 122 in Figure 6, that senses, either directly or indirectly, the position of the piston rod 14 and thereby the position of the reciprocating assembly 300. For example, sensor 122 is a position sensor that provides positional information to the control unit 100 regarding the location of the piston rod 14. As depicted in Figure 6, the position sensor 122 may be positioned adjacent rod 30, which is connected to the piston rod 14 and extends from a back end of the hydraulic cylinder 18. However, this positioning is only exemplary, as such, the position sensor 122 could be positioned at any location along rods 14, the reciprocating assembly 300 or elsewhere. The position sensor may be realized using any suitable linear, position sensor as is known in the art, such as a linear variable differential transformer sensor to provide the actual linear position of the piston rod 14 to the control unit 100 by way of an electronic signal, for example a change in voltage, current and the like.

[0094] In operation, the control unit 100 co-ordinates the movement of the reciprocating assembly 300 with the actuation of the high and low pressure brine valves within the concentrate valve bodies 400, 401.

[0095] The positional information of the outer feedback loop 120, provided by the sensor 122 is directed to the control unit 100. The positional information is regularly provided, for example every 0.1 to 10 ms, more specifically every 1 to 2 ms, and the control unit 100 compares this actual positional information, referred to as the actual position value, with an ideal position value 152 of the reciprocating assembly 300, as determined by the assembly sequence 132. The control unit 100 uses a subtractor 156 to subtract the actual position value 150 from the ideal position value 152 to produce a first difference value 155.

A multiplier 157 multiplies the first difference value 155 by a gain factor Ka 154 to produce a first multiplied value 159. The gain factor Ka 154 is determined by an initial calibration and alignment procedure to insure proper functionality of the system without excessive overshoot or undershoot of the reciprocating assembly position. The current position value 150 is also stored by the electronic controller unit 100 and it is compared to the previous position value 158 of the reciprocating assembly 300 from the previous 1ms sample. Using a subtractor 160, the control unit 100 subtracts the current position 150 from the previous position 158 and the known 1ms sample window to control unit 100 calculates an actual velocity value 162. A subtractor 164 subtracts the current ideal position value 152 and the ideal position value 168 for the previous 1ms to calculate an ideal velocity value 170. A subtractor 172 subtracts the actual velocity value 162 from the ideal velocity value 170 to generate a second difference value 174. A multiplier 178 multiplies the difference value 174 by the gain factor Kv 176 to produce a second multiplied value 180. The gain factor Kv 176 is determined by an initial calibration and alignment procedure to insure proper functionality of the system without excessive overshoot or undershoot. The first multiplied value 159 and the second multiplied value 180, are summed, by an adder 182 to generate a sum value 184. The sum value 184 can be either positive or negative. If the sum value 182 is positive then the control unit 100 will send a swash plate command 186 to the hydraulic pump 12 to cause the angle of the swash plate 70 to change so that the hydraulic output of the hydraulic pump 12 causes the reciprocating assembly 300 to move in the first direction. If the sum value 184 is negative, then a subordinate controller 190 will send a swash plate command 186 that causes the angle of the swash plate 70 to change so that the hydraulic output of the hydraulic pump 12, which in turn causes the reciprocating assembly 300 to move in the second direction.

[0096] The swash plate angular information from the sensor 112 provides information regarding the hydraulic output of the hydraulic pump 12 to the subordinate controller 190 of the control unit 100. The control unit 100 uses this angular information to expedite the movement of the swash plate 70 to the position as determined by the control unit 100 output commands 186. This inner control loop 108 provides greater acceleration of the movement of the swash plate 70 to increase the responsiveness of the hydraulic pump 12 to commands from the control unit 100.

[0097] Each reciprocating assembly 300 operates in a closed loop manner with the hydraulic pump 12. Therefore the movement, i.e., acceleration, constant velocity, and

deceleration, of the reciprocating assembly 300 can be controlled, by precise control of the hydraulic output of the hydraulic pump 12, to reproduce the assembly sequence 132.

[0098] An example assembly sequence 132 is depicted in Figure 7 where a 60 second cycle of one reciprocating assembly 300 is shown. Line 700 represents the velocity over time of a reciprocating assembly 300. Line 702 represents the displacement over time of the reciprocating assembly 300. The boxes labelled "State" indicate the time at which brine valves are moved to the position shown in each box. A reciprocating assembly 300 may work at a higher frequency, for example between 5 and 12 cycles per minute, and through a stroke longer than what is shown in Figure 7. In the system 10 of Figure 1, each of the three reciprocating assemblies moves through a cycle as shown in Figure 7, but with the cycles being out of phase from each other by 120 degrees.

[0099] Following line 700, at time 0, the reciprocating assembly 300 is slightly ahead of a fully retracted position (on the left side in Figure 3). The reciprocating assembly 300 moves in a forward direction (to the right in Figure 3) by linearly accelerating from rest (zero velocity) up to a selected constant velocity. This velocity is maintained for a period of time (a constant velocity period) as the reciprocating assembly 300 continues its stroke in the forward direction. As the reciprocating assembly 300 approaches a fully advanced position (on the right side of Figure 3) at the end of its stroke in the forward direction, a deceleration period begins, during which the reciprocating assembly 300 decelerates from the selected constant velocity to zero velocity. Once the reciprocating assembly 300 is stopped, it remains stopped for a short dwell time, then moves through a short displacement in the opposite direction (alternatively called a "bump"), then stops for a further short dwell time. After the second dwell period, the reciprocating assembly 300 continues a stroke in the reverse direction (towards the left in Figure 3). The reciprocating assembly 300 is linearly accelerated in the reverse direction to the selected constant velocity. The constant velocity is maintained for a period of time as the reciprocating assembly 300 continues its backward stroke. As the reciprocating assembly 300 approaches the fully retracted position at the end of this stroke, a deceleration period begins during which the reciprocating assembly 300 decelerates from the constant velocity to zero velocity. Once the reciprocating assembly 300 is stopped, it remains stopped for a second short dwell time, is bumped in the forward direction, and then stops for another short dwell period before repeating the cycle. The displacements of the reciprocating assembly 300 produced by these accelerations and decelerations are shown by line 702.

[00100] As the reciprocating assembly 300 moves through a cycle, the feed water working chambers 228, 234 increase or decrease in volume. The feed water valve assemblies 258, 260 operate automatically to pressurize and expel feed water when a working chamber 228, 234 decreases in volume. Similarly, the feed water valve assemblies 258, 260 operate automatically to draw in low pressure feed water when a working chamber 228, 234 increases in volume.

[00101] The inlet valve 402 and outlet valve 502 of each energy recovery valve (concentrate valve body) 400, 401 is opened and closed by controller 100. A schedule of the opened and closed states of these valves is included in Figure 7. Each state begins at the time indicated by the vertical line extending downward from the corresponding box with a heading "State". Each state ends with the beginning of the next state. In Figure 7, ERV1 denotes the inlet valve 402 of energy recovery valve 401. ERV2 denotes the outlet valve 502 of energy recovery valve 401. ERV3 denotes the inlet valve 402 of energy recovery valve 400. ERV4 denotes the outlet valve 502 of energy recovery valve 400. Optionally, concentrate access port 244 could be replaced with two ports, one connected to ERV1 and the other connected to ERV2. Similarly, concentrate access port 242 could be replaced with two ports, one connected to ERV3 and the other connected to ERV4. Collectively, these four valves may be referred to as the brine valves. Further, the two inlet valves 402 may be referred to as low pressure brine valves and the two outlet valves 502 may be referred to as high pressure brine valves.

[00102] As shown in Figure 7, the brine valves are preferably operated during dwell periods, preferably beginning at or near the start of a dwell period. The dwell period provides time for the brine valves to move while the reciprocating assembly 300 is stopped. When the reciprocating assembly 300 changes directions, there is a sequence of action including steps of a) closing all of the brine valves, b) moving, or "bumping", the reciprocating assembly 300 in the direction of the next stroke, and then c) opening two of the brine valves. In particular, a low pressure brine valve is opened in communication with a piston 224, 226 that is about to move towards that low pressure brine valve and a high pressure brine valve is opened in communication with a piston 224, 226 that is about to move away from that high pressure brine valve. The intervening movement, or bump, of the reciprocating assembly 300 reduces the pressure in a concentrate chamber 230, 323 that is about to be put in communication with low pressure brine. The bump also increases the pressure in a concentrate chamber 230, 232 that is about to be put in communication with high pressure

brine. These pressure transitions occur before any brine valves are opened so that pressures are more nearly equal on opposite sides of the brine valves when they are opened. The pressure transition caused by bumping the reciprocating assembly 300 seems to occur somewhat gradually over the duration of the bump which can be actively controlled.

5 For example, the bump can have a duration of about 200 to 1000 ms, which is longer than a pressure variation caused by opening a brine valve. In a prior system without holes 225 and bumping step, water hammer, pressure spikes or other undesirable pressure effects were noticed under certain operating conditions which would cause the water cylinders 200 to shake and produce unstable flows. These undesirable conditions appear to have been
10 eliminated in a modified system having holes 225 and a bumping step. The modified system is also produces less audible noise.

[00103] This written description uses examples to disclose the invention, including the best mode, to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The
15 patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art.

CLAIMS:

We claim:

- 5 1. An apparatus comprising,
a) a cylinder; and,
b) a piston inside of the cylinder,
wherein,
the cylinder is closed at both ends but for one or more ports on either side of the piston,
10 the piston has a higher active surface area on one of its faces relative to its other face, and
the pump has an opening providing a fluid passageway from one face of the piston to the
other face of the piston at least near a fully extended or fully retracted position of the piston.
- 15 2. The apparatus of claim 1 wherein the opening is a hole from one face of the piston to
the other face of the piston.
3. The apparatus of claim 1 or 2 wherein the opening has an area of 0.02% or more of
the area of higher active surface area of the piston.
- 20 4. The apparatus of any one of claims 1 to 3 comprising an actuating assembly for
moving the piston while any port or ports in communication with the piston face with lower
active surface area are closed.
- 25 5. The apparatus of claim 4 wherein the actuating assembly comprises a hydraulic
piston connected to the piston inside the cylinder, a hydraulic pump connected to provide
controllable hydraulic pressure to opposed sides of the hydraulic piston and a control unit for
controlling the hydraulic pump.
- 30 6. A process for altering pressures inside a pump comprising a cylinder and a piston
inside of the cylinder, wherein, the cylinder is closed at both ends but for one or more ports
on either side of the piston, the piston has a higher active surface area on one of its faces
relative to its other face, and the pump has an opening providing a fluid passageway from
one face of the piston to the other face of the piston at least near a fully extended or fully

retracted position of the piston, the process comprising moving the piston while any port or ports in communication with the piston face with lower active surface area are closed.

7. The process of claim 6 wherein the piston is moved through 2 to 5% of its stroke while the one or more ports in communication with the piston face with lower active surface area are closed.

8. The process of claim 6 or 7 wherein the one or more ports in communication with the piston face with larger active surface area are in communication while the piston is moved with one way check valves configured to permit flow of feed water from an inlet source to the cylinder and to an output line.

9. The process of any one of claims 6 to 8 wherein the step of moving the piston occurs after the piston has moved to a fully extended or retracted position.

10. A system comprising,

a) a pump comprising an apparatus according to any one of claims 1 to 5; and,

b) an RO unit,

wherein,

the higher active surface area face of the piston is in communication with a feed side of the RO unit, and

the lower active surface area face of the piston is in communication with a retentate side of the RO unit.

11. A process of operating a system according to claim 10 comprising,

a) completing a process according to any one of claims 6 to 9; and,

b) opening a brine inlet or outlet valve after step a).

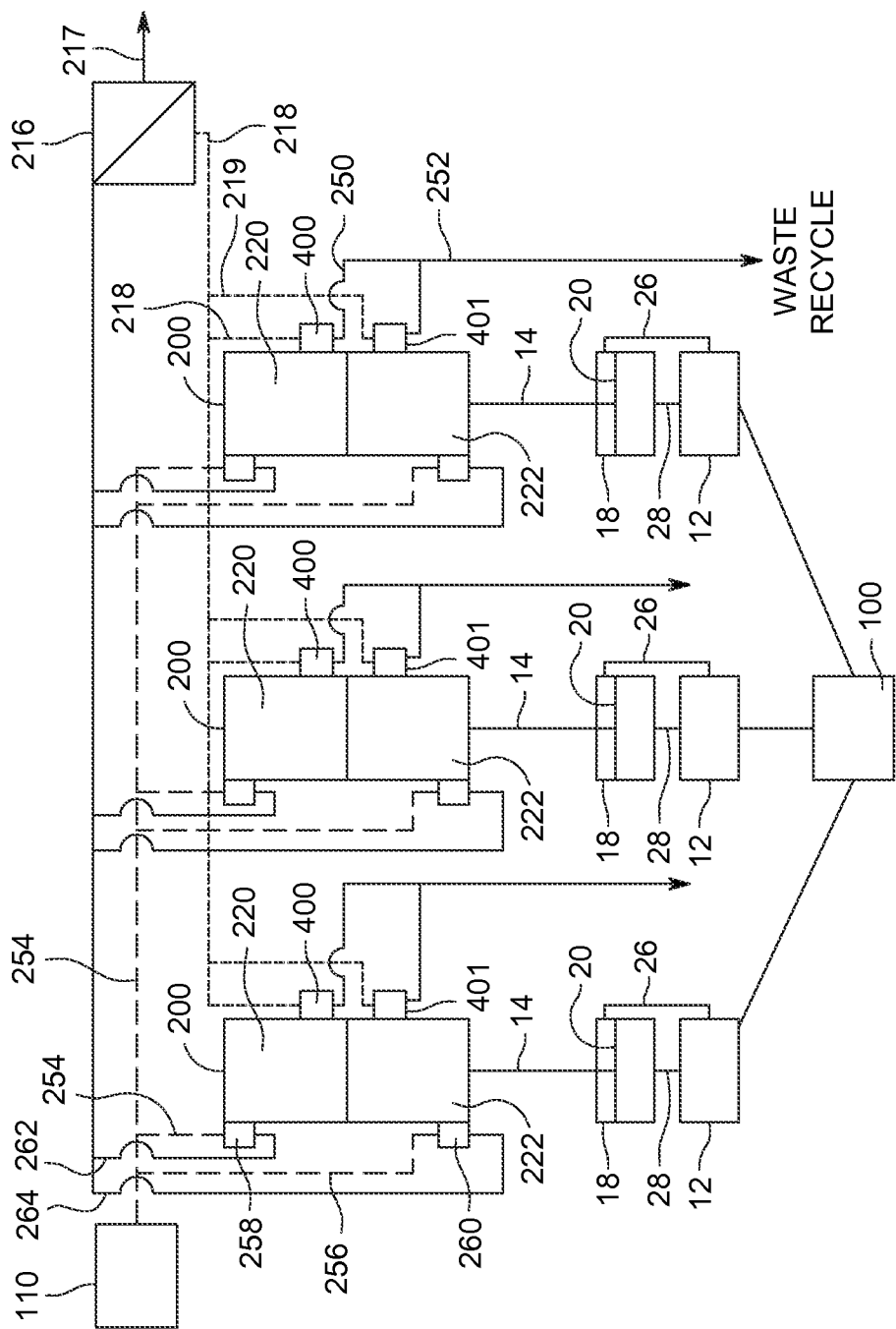


FIG. 1

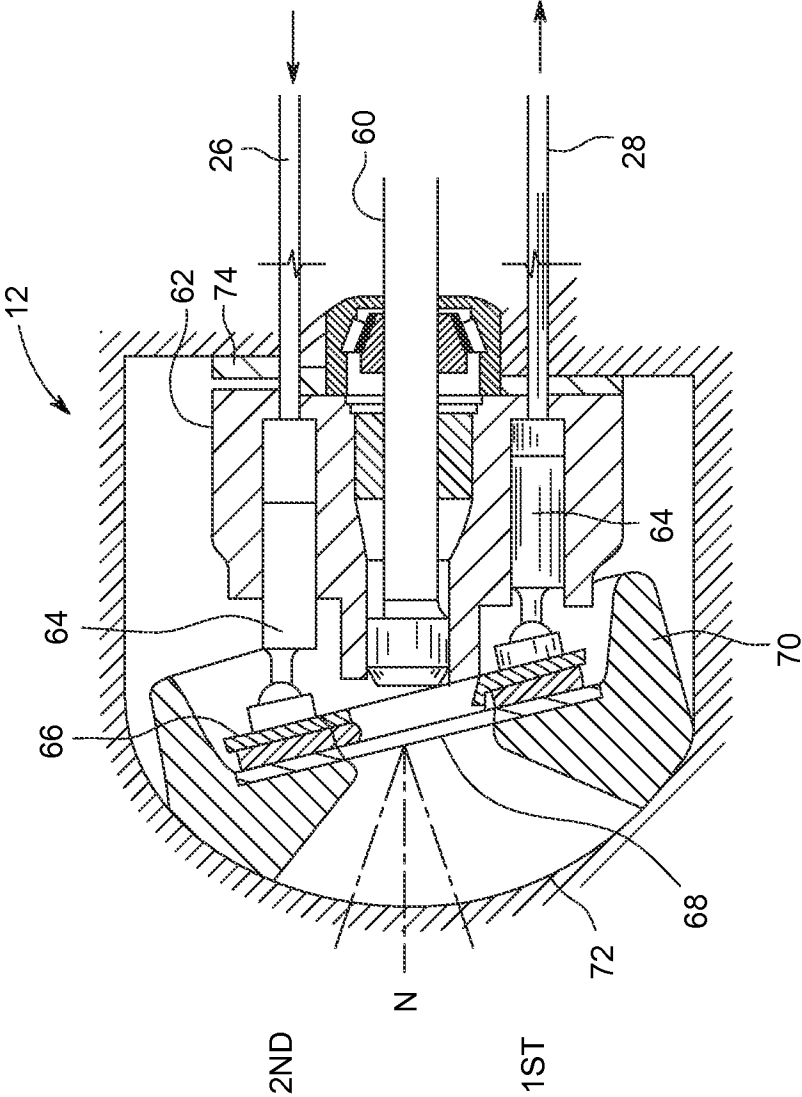


FIG. 2

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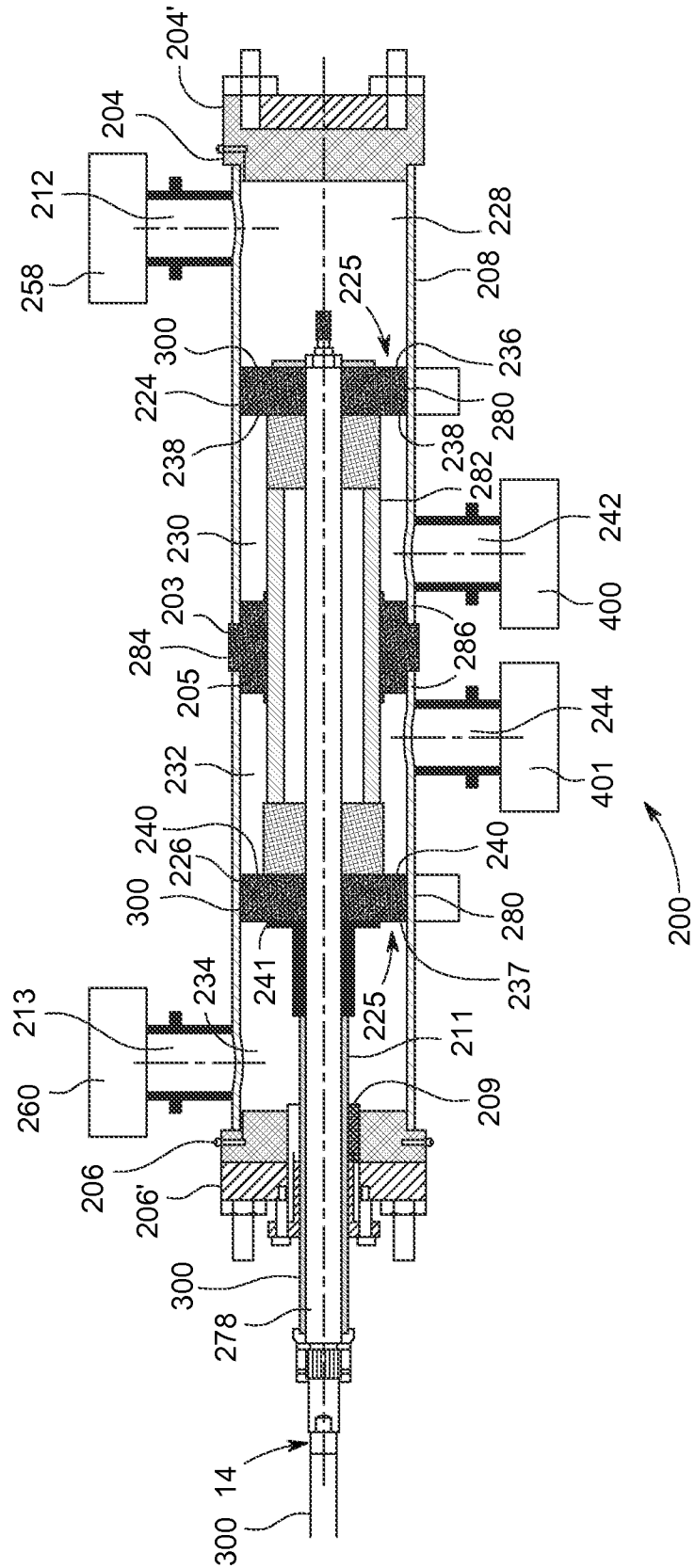


FIG. 3

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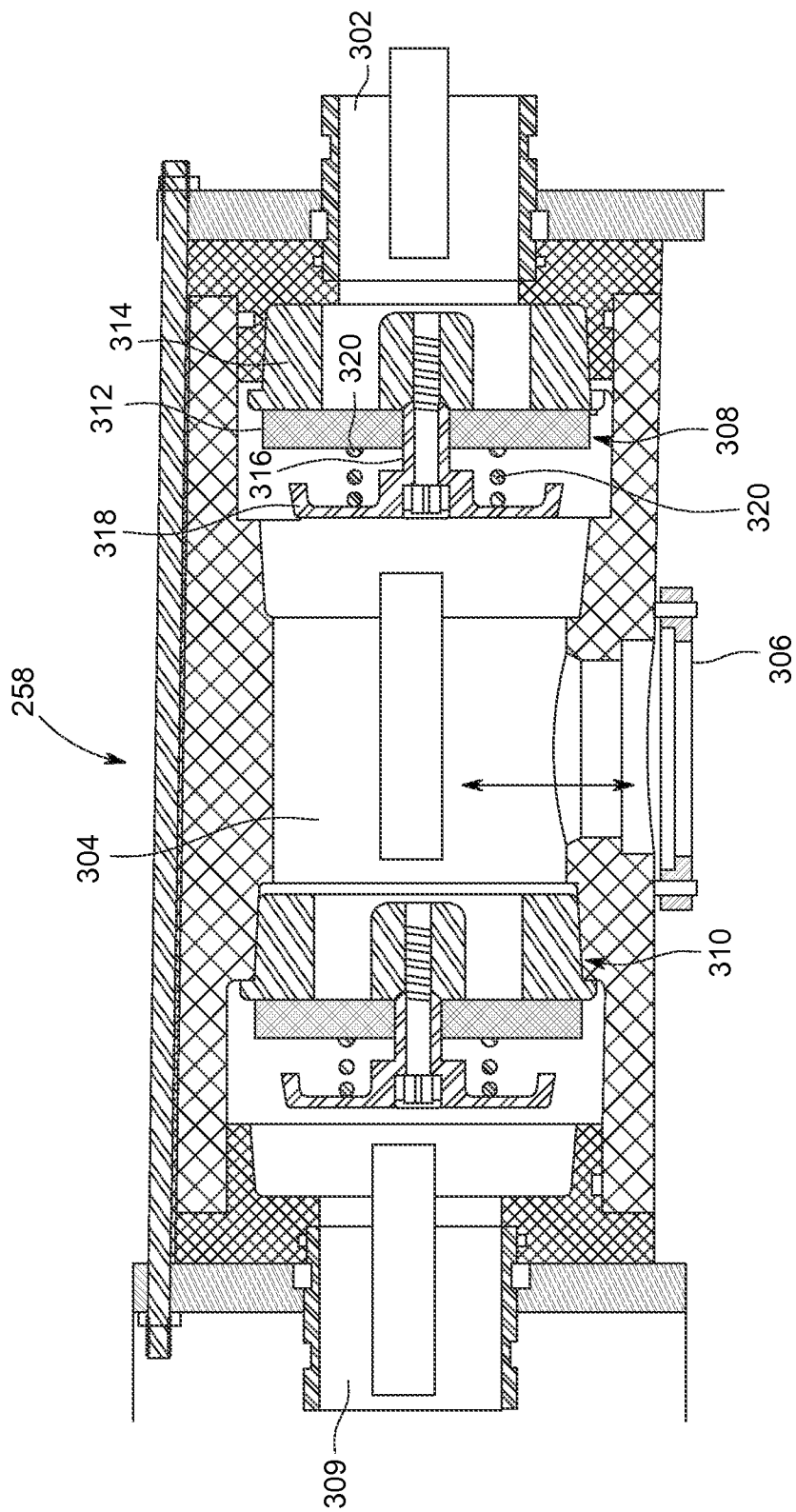
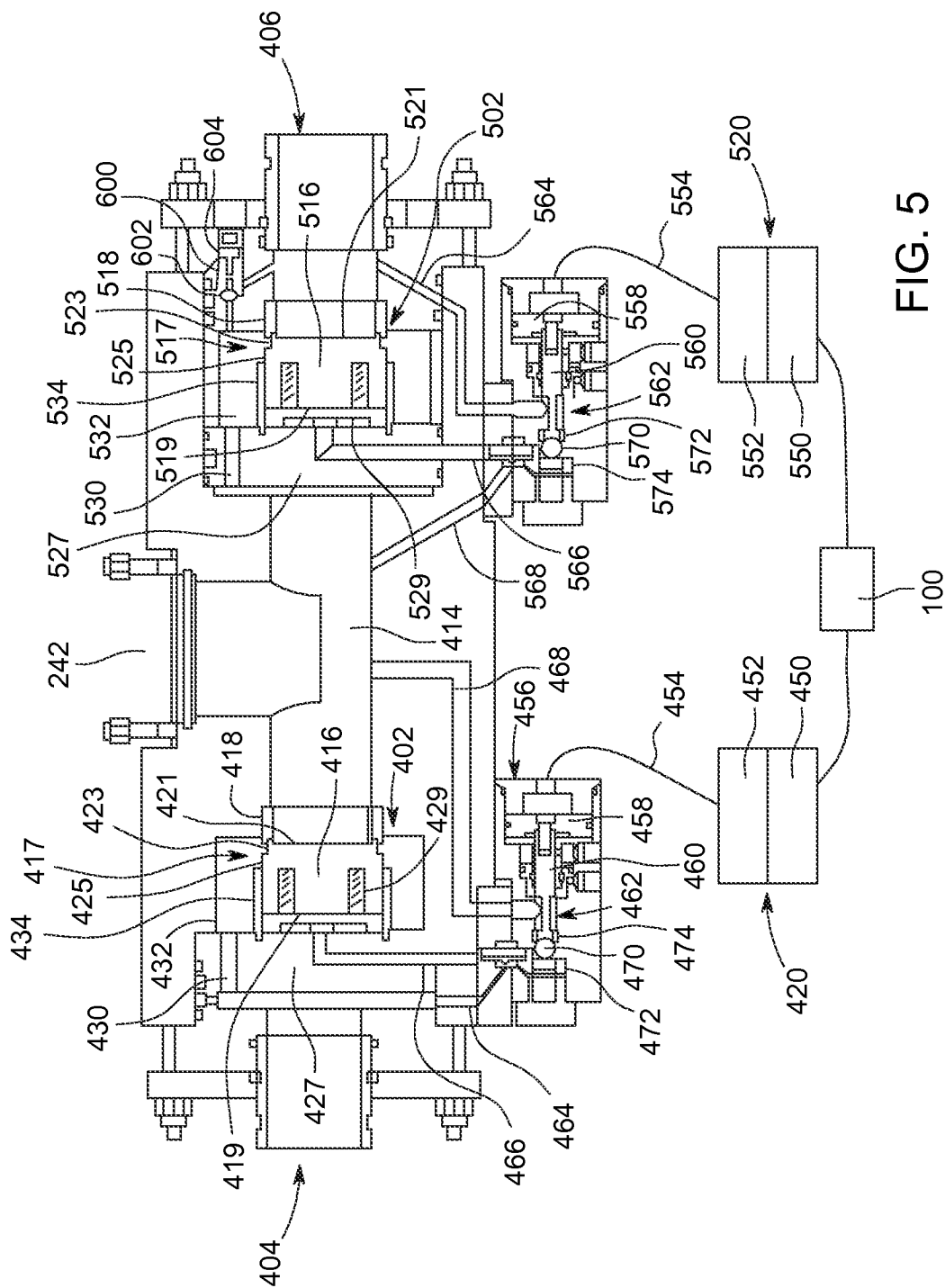


FIG. 4



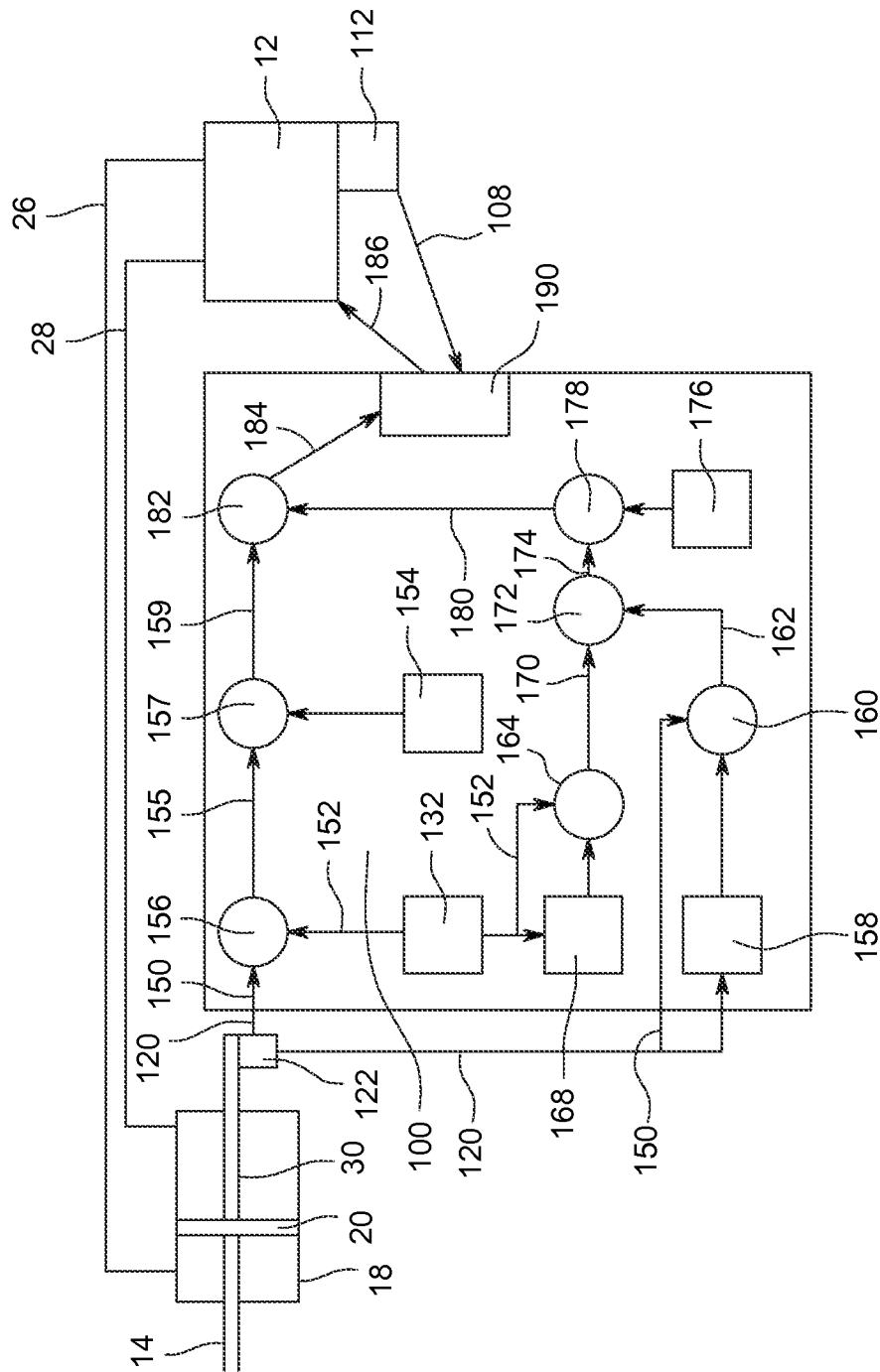


FIG. 6

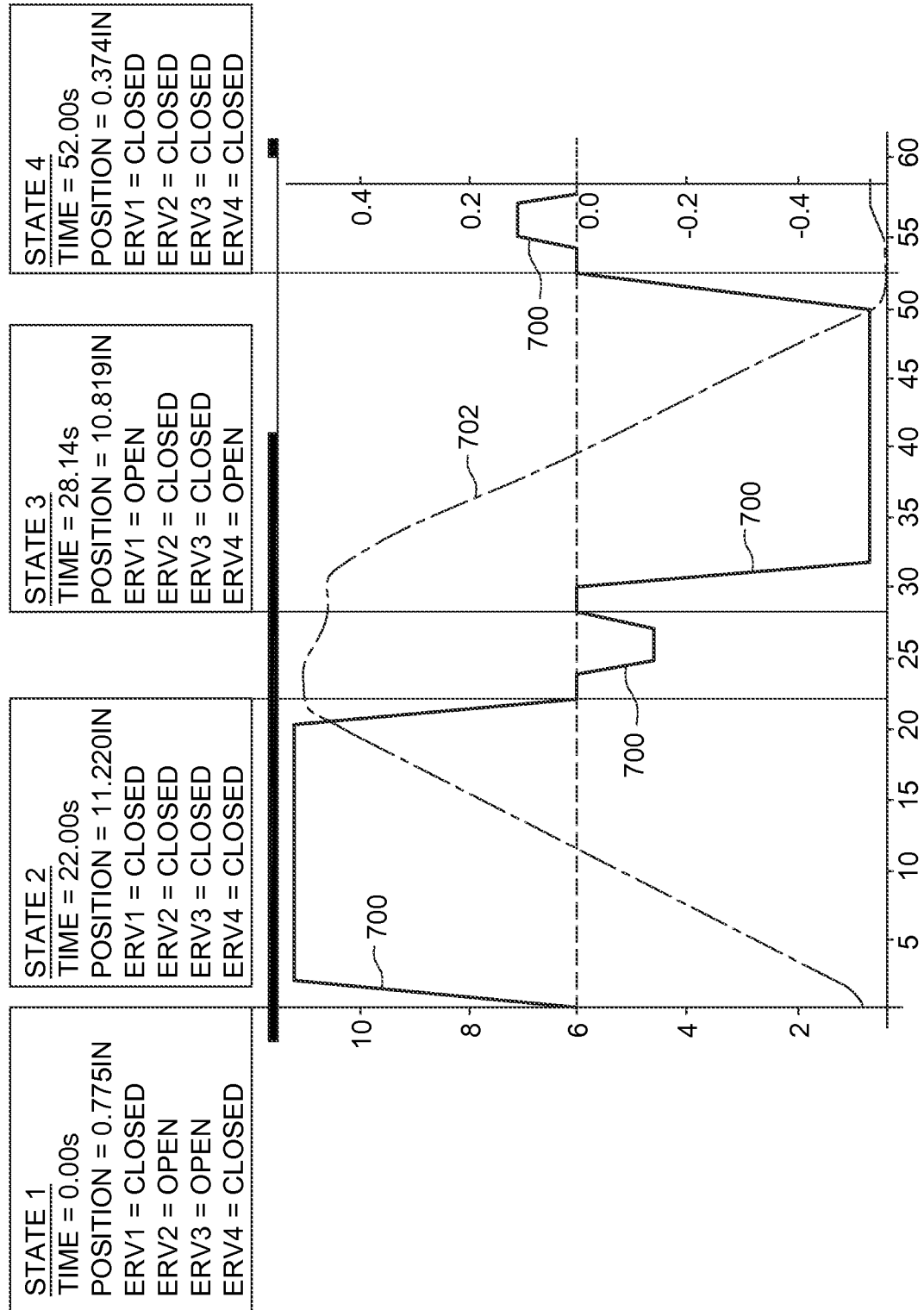


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/025854

A. CLASSIFICATION OF SUBJECT MATTER INV. F04B5/00 B01D61/08 F04B9/105 F04B53/12 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) F04B B01D		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 143 969 A (OWEN EAMES JAMES ET AL) 11 August 1964 (1964-08-11)	1-9
Y	column 1, line 9 - column 7, line 68; figures 1-3	10,11

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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents :		
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Date of the actual completion of the international search 16 July 2015	Date of mailing of the international search report 24/07/2015	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Jurado Orenes, A	

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2015/025854

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