



## (51) International Patent Classification:

F04F 13/00 (2009.01) E21B 41/00 (2006.01)

## (21) International Application Number:

PCT/US2017/060080

## (22) International Filing Date:

06 November 2017 (06.11.2017)

## (25) Filing Language:

English

## (26) Publication Language:

English

## (30) Priority Data:

62/417,542 04 November 2016 (04.11.2016) US

(71) Applicant (for US only): **SCHLUMBERGER TECHNOLOGY CORPORATION** [US/US]; 300 Schlumberger Drive, Sugar Land, Texas 77478 (US).

(71) Applicant (for CA only): **SCHLUMBERGER CANADA LIMITED** [CA/CA]; 125 - 9 Avenue SE, Calgary, Alberta T2G 0P6 (CA).

(71) Applicant (for FR only): **SERVICES PETROLIERS SCHLUMBERGER** [FR/FR]; 42 rue Saint Dominique, 75007 Paris (FR).

(71) Applicant (for all designated States except CA, FR, US): **SCHLUMBERGER TECHNOLOGY B.V.** [NL/NL]; Parkstraat 83, 2514 JG The Hague (NL).

(72) Inventor: **SHAMPINE, Rod William**; 703 E. 24th Street, Houston, Houston, Texas 77008 (US).

(74) Agent: **FLYNN, Michael L.** et al.; 10001 Richmond Avenue, IP Administration Center of Excellence, Room 4720, Houston, Texas 77042 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,

## (54) Title: PRESSURE EXCHANGER WITH PRESSURE RATIO

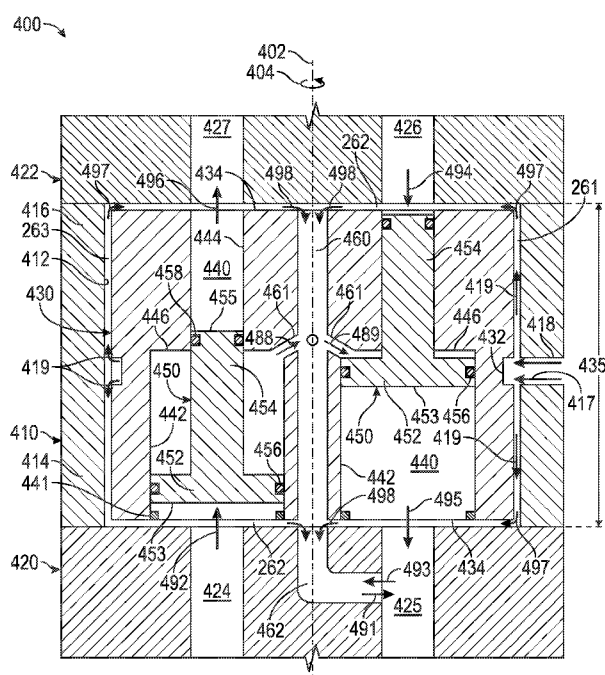


FIG. 17

(57) Abstract: Apparatus and methods for pressurizing well operations fluids via a pressure exchanger having a housing with a bore extending between first and second ends of the housing and a rotor rotatably disposed within the bore of the housing. A chamber extends through the rotor between first and second ends of the rotor. The chamber has a larger chamber diameter section and a smaller chamber diameter section. A piston assembly is slidably disposed within the chamber. The piston assembly has a larger piston diameter section slidably disposed within the larger chamber diameter section and a smaller piston diameter section slidably disposed within the smaller chamber diameter section.

EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,  
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,  
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,  
KM, ML, MR, NE, SN, TD, TG).

**Published:**

- *without international search report and to be republished  
upon receipt of that report (Rule 48.2(g))*

## **Pressure Exchanger with Pressure Ratio**

### **Cross-Reference to Related Applications**

**[0001]** This application claims the benefit of U.S. Provisional Patent Application No. 62/417,542, entitled "PRESSURE EXCHANGER WITH PRESSURE RATIO," filed November 4, 2016, the entire disclosure of which is hereby incorporated herein by reference.

### **Background of the Disclosure**

**[0002]** A variety of fluids are used in oil and gas operations. Fluids may be pumped into the subterranean formation through the use of one or more high-pressure pumps. Dirty fluids, such as solids-laden fluids containing insoluble abrasive solid particles, can reduce functional life and increase maintenance of the high-pressure pumps.

**[0003]** Pressure exchangers provide a way to exchange pressure energy between two fluid flows. An example pressure exchanger has a rotating rotor with multiple flow cavities, channels, or other chambers. The rotor rotates in a housing via a fluid-lubricated bearing. Disc valves at opposing ends of the pressure exchanger intermittently seal corresponding ends of the chambers between alternating passage of different ports of each disc valve. Fluid flow entering each chamber is directed along a small, off-axial vector, thus imparting rotation to the rotor.

**[0004]** As the rotor rotates, each chamber is in turn connected to a source of dirty fluid via a dirty fluid input port of one of the disc valves, such that the dirty fluid enters each chamber as the chamber passes the dirty fluid input port. As the rotor further rotates, each chamber is then connected to a source of high-pressure clean fluid via a clean fluid input port of one of the disc valves, such that the high-pressure clean fluid enters each chamber as the chamber passes the clean fluid input port, and an interface between the dirty fluid and the clean fluid is pushed away from the clean fluid input side, thus pressurizing and then ejecting the dirty fluid as further rotation causes the chamber to pass a dirty fluid discharge port of one of the disc valves. The now depressurized clean fluid may then be ejected as further rotation causes the chamber to pass a clean fluid discharge port of one of the disc valves. The cycle may be repeated continuously to form a continuous stream of pressurized dirty fluid.

**[0005]** The clean fluid received by the pressure exchangers is pressurized to a level that is about equal to or greater than the intended discharge pressure of the dirty fluid. Accordingly, high-pressure pumps are utilized to generate the high-pressure clean fluid, and high-pressure

fluid conduits transfer the pressurized clean fluid to the pressure exchangers. The disc valves also have leakage between the high-pressure clean side and the low-pressure dirty side, and leakage between the high-pressure dirty side and the low-pressure clean side. There is also a flow rate that is injected into the bearings that flows into both low-pressure sides. There may also be diffusion and mixing in each chamber that spreads the clean/dirty interface and leads to dirty returns on the “clean” side.

### **Summary of the Disclosure**

**[0006]** This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify indispensable features of the claimed subject matter, nor is it intended for use as an aid in limiting the scope of the claimed subject matter.

**[0007]** The present disclosure introduces an apparatus that includes a pressure exchanger, the pressure exchanger including a housing, a rotor, and a piston assembly. The housing has a bore extending between first and second ends of the housing. The rotor is rotatably disposed within the bore of the housing, and includes a chamber extending through the rotor between first and second ends of the rotor. The chamber includes a larger chamber diameter section and a smaller chamber diameter section. The piston assembly is slidably disposed within the chamber. The piston assembly includes a larger piston diameter section slidably disposed within the larger chamber diameter section, and a smaller piston diameter section slidably disposed within the smaller chamber diameter section.

**[0008]** The present disclosure also introduces an apparatus including a pressure exchanger having a housing, a first cap, a second cap, a rotor, and multiple piston assemblies. The housing has a bore extending between first and second ends of the housing. The first cap covers the bore at the first end of the housing. The first cap includes a first fluid inlet and a first fluid outlet. The second cap covers the bore at the second end of the housing. The second cap includes a second fluid inlet and a second fluid outlet. The rotor is rotatably disposed within the bore of the housing. The rotor includes multiple chambers distributed around a central axis of the rotor. Each chamber extends through the rotor between first and second ends of the rotor. Each chamber includes a larger chamber diameter section and a smaller chamber diameter section. Each piston assembly is slidably disposed within a corresponding one of the chambers. Each piston assembly includes a larger piston diameter section slidably disposed within a

corresponding one of the larger chamber diameter sections, and a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections.

**[0009]** The present disclosure also introduces a method including fluidly connecting a pressure exchanger with a source of a first fluid and a source of a second fluid. The pressure exchanger includes a rotor and multiple piston assemblies. The rotor includes multiple chambers extending through the rotor. Each chamber includes a larger chamber diameter section and a smaller chamber diameter section. Each piston assembly is slidably disposed within a corresponding one of the chambers. Each piston assembly includes a larger piston diameter section slidably disposed within a corresponding one of the larger chamber diameter sections, and a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections. The method also includes, while the rotor rotates, injecting the first fluid at a first pressure into the larger chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge a second fluid at a second pressure from corresponding ones of the smaller chamber diameter sections, and injecting the second fluid into the smaller chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge the first fluid from corresponding ones of the larger chamber diameter sections.

**[0010]** These and additional aspects of the present disclosure are set forth in the description that follows, and/or may be learned by a person having ordinary skill in the art by reading the materials herein and/or practicing the principles described herein. At least some aspects of the present disclosure may be achieved via means recited in the attached claims.

### **Brief Description of the Drawings**

**[0011]** The present disclosure is understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

**[0012]** FIG. 1 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

**[0013]** FIG. 2 is a schematic view of the apparatus shown in FIG. 1 in an operational stage according to one or more aspects of the present disclosure.

- [0014] FIG. 3 is a schematic view of the apparatus shown in FIG. 2 in another operational stage according to one or more aspects of the present disclosure.
- [0015] FIG. 4 is a schematic view of the apparatus shown in FIGS. 2 and 3 in another operational stage according to one or more aspects of the present disclosure.
- [0016] FIG. 5 is a partially exploded view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0017] FIG. 6 is a sectional view of an example implementation of the apparatus shown in FIG. 5 according to one or more aspects of the present disclosure.
- [0018] FIG. 7 is another view of the apparatus shown in FIG. 6 in a different stage of operation.
- [0019] FIG. 8 is an enlarged view of the apparatus shown in FIG. 7 according to one or more aspects of the present disclosure.
- [0020] FIG. 9 is an enlarged view of the apparatus shown in FIG. 6 according to one or more aspects of the present disclosure.
- [0021] FIG. 10 is a sectional view of another example implementation of the apparatus shown in FIG. 5 according to one or more aspects of the present disclosure.
- [0022] FIG. 11 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0023] FIG. 12 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0024] FIG. 13 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0025] FIG. 14 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0026] FIG. 15 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0027] FIG. 16 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
- [0028] FIG. 17 is a schematic sectional view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

**Detailed Description**

**[0029]** It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for simplicity and clarity, and does not in itself dictate a relationship between the various implementations described below. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. It should also be understood that the terms “first,” “second,” “third,” *etc.*, are arbitrarily assigned, are merely intended to differentiate between two or more parts, fluids, *etc.*, and do not indicate a particular orientation or sequence.

**[0030]** The present disclosure introduces one or more aspects related to utilizing one or more pressure exchangers to divert a corrosive, abrasive, and/or solids-laden fluid (referred to herein as “dirty fluid”) away from high-pressure pumps, instead of pumping such fluid with the high-pressure pumps. A non-corrosive, non-abrasive, and solids-free fluid (referred to herein as “clean fluid”) may be pressurized by the high-pressure pumps, while the pressure exchangers, located downstream from the high-pressure pumps, transfer the pressure from the pressurized clean fluid to low-pressure dirty fluid. Such use of pressure exchangers may facilitate improved fluid control during well treatment operations and/or increased functional life of the high-pressure pumps and other wellsite equipment fluidly coupled between the high-pressure pumps and the pressure exchangers.

**[0031]** As used herein, a “fluid” is a substance that can flow and conform to the outline of its container when the substance is tested at a temperature of 71 °F (22 °C) and a pressure of one atmosphere (atm) (0.1 megapascals (MPa)). A fluid may be liquid, gas, or both. A fluid may be water based or oil based. A fluid may have just one phase or more than one distinct phase. A fluid may be a heterogeneous fluid having more than one distinct phase. Example heterogeneous fluids within the scope of the present disclosure include a solids-laden fluid or slurry (such as may comprise a continuous liquid phase and undissolved solid particles as a dispersed phase), an emulsion (such as may comprise a continuous liquid phase and at least one dispersed phase of

immiscible liquid droplets), a foam (such as may comprise a continuous liquid phase and a dispersed gas phase), and a mist (such as may comprise a continuous gas phase and a dispersed liquid droplet phase), among other examples also within the scope of the present disclosure. A heterogeneous fluid may comprise more than one dispersed phase. Moreover, one or more of the phases of a heterogeneous fluid may be or comprise a mixture having multiple components, such as fluids containing dissolved materials and/or undissolved solids.

**[0032]** Plunger pumps may be employed in high-pressure oilfield pumping applications, such as for hydraulic fracturing (“frac”) applications. Plunger pumps are often referred to as positive displacement pumps, intermittent duty pumps, triplex pumps, quintuplex pumps, or frac pumps, among other examples also within the scope of the present disclosure. Multiple plunger pumps may be employed simultaneously in large-scale operations, such as where tens of thousands of gallons of fluid are pumped into a wellbore. These pumps may be linked to each other with a manifold, such as may be plumbed to collect the output of the multiple pumps and direct it to the wellbore.

**[0033]** As described above, some fluids (*e.g.*, fracturing fluid) may contain ingredients that are abrasive to the internal components of a pump. For example, a fracturing fluid generally contains proppant or other solid particulate material that is insoluble in a base fluid. To create fractures, the fracturing fluid may be pumped at high pressures ranging, for example, between about 5,000 and about 15,000 pounds force per square inch (psi) or more. The proppant may initiate the fractures and/or keep the fractures propped open. The propped fractures provide highly permeable flow paths for oil and gas to flow from the subterranean formation, thereby enhancing the production of a well formed in the formation. However, the abrasive fracturing fluid may accelerate wear of the internal components of the pumps. Consequently, the repair, replacement, and maintenance expenses of the pumps can be quite high, and life expectancy can be low.

**[0034]** Example implementations of apparatus described herein relate generally to a fluid system for forming and pressurizing a solids-laden fluid (*e.g.*, fracturing fluid) having predetermined concentrations of solid material for injection into a wellbore during well treatment operations. The fluid system may include a blending or mixing device for receiving and mixing a solids-free carrying fluid or gel and a solid material to form the solids-laden fluid. The fluid system may also include a fluid pressure exchanger for increasing the pressure of or otherwise energizing the solids-laden fluid formed by the mixing device before being injected into the

wellbore. The fluid pressure exchanger may be utilized to pressurize the solids-laden fluid by facilitating or permitting pressure from a pressurized solids-free fluid to be transferred to a low-pressure solids-laden fluid, among other uses. The fluid pressure exchanger may comprise one or more chambers into which the low-pressure, solids-laden fluid and the pressurized, solids-free fluid are conducted. The solids-free fluid may be conducted into the chamber at a higher pressure than the solids-laden fluid, and may thus be utilized to pressurize the solids-laden fluid. The pressurized, solids-laden fluid is then conducted from the chamber to a wellhead for injection into the wellbore. By pumping just the solids-free fluid with the pumps and utilizing the pressure exchanger to increase the pressure of the solids-laden fluid, the useful life of the pumps may be increased. Example implementations of methods described herein relate generally to utilizing the fluid system to form and pressure the solids-laden fluid for injection into the wellbore during well treatment operations.

**[0035]** FIG. 1 is a schematic view of an example implementation of a chamber 100 of a fluid pressure exchanger for pressurizing a dirty fluid with a clean fluid according to one or more aspects of the present disclosure. The chamber 100 includes a first end 101 and a second end 102. The chamber 100 may include a border or boundary 103 between the dirty and clean fluids defining a first volume 104 and a second volume 105 within the chamber 100. The boundary 103 may be a membrane that is impermeable or semi-permeable to a fluid, such as a gas. The membrane may be an impermeable membrane in implementations in which the dirty and clean fluids are incompatible fluids, or when mixing of the dirty and clean fluids is to be substantially prevented, such as to recycle the clean fluid absent contamination by the dirty fluid. The boundary 103 may be a semi-permeable membrane in implementations permitting some mixing of the clean fluid with the dirty fluid, such as to foam the dirty fluid when the clean fluid comprises a gas.

**[0036]** The boundary 103 may be a floating piston or separator slidably disposed along the chamber 100. The floating piston may physically isolate the dirty and clean fluids and be movable via pressure differential between the dirty and clean fluids. The floating piston may be retained within the chamber 100 by walls or other features of the chamber 100. The density of the floating piston may be set between that of the clean and dirty fluids, such as may cause gravity to locate the floating piston at an interface of the dirty and clean fluids when the chamber 100 is oriented vertically.

**[0037]** The boundary 103 may also be a diffusion or mixing zone in which the dirty and clean fluids mix or otherwise interact during pressurizing operations. The boundary 103 may also not exist, such that the first and second volumes 104 and 105 form a continuous volume within the chamber 100. A first inlet valve 106 is operable to conduct the dirty fluid into the first volume 104 of the chamber 100, and a second inlet valve 107 is operable to conduct the clean fluid into the second volume 105 of the chamber 100.

**[0038]** For example, FIG. 2 is a schematic view of the chamber 100 shown in FIG. 1 in an operational stage according to one or more aspects of the present disclosure, during which the dirty fluid 110 has been conducted into the chamber 100 through the first inlet valve 106 at the first end 101, such as via one or more fluid conduits 108. Consequently, the dirty fluid 110 may move the boundary 103 within the chamber 100 along a direction substantially parallel to the longitudinal axis 111 of the chamber 100, thereby increasing the first volume 104 and decreasing the second volume 105. The first inlet valve 106 may be closed after entry of the dirty fluid 110 into the chamber 100.

**[0039]** FIG. 3 is a schematic view of the chamber 100 shown in FIG. 2 in a subsequent operational stage according to one or more aspects of the present disclosure, during which a clean fluid 120 is being conducted into the chamber 100 through the second inlet valve 107 at the second end 102, such as via one or more fluid conduits 109. The clean fluid 120 may be conducted into the chamber 100 at a higher pressure compared to the pressure of the dirty fluid 110. Consequently, the higher-pressure clean fluid 120 may move the boundary 103 and the dirty fluid 110 within the chamber 100 back towards the first end 101, thereby reducing the volume of the first volume 104 and thereby pressurizing or otherwise energizing the dirty fluid 110. The clean fluid 120 may be a combustible or cryogenic gas that, upon combustion or heating, acts to pressurize the dirty fluid 110, whether instead of or in addition to the higher pressure of the clean fluid 120 acting to pressurize the dirty fluid 110. The boundary 103 and/or other components may include one or more burst discs to protect against overpressure from the clean fluid 120.

**[0040]** As shown in FIG. 4, the boundary 103 may continue to reduce the first volume 104 as the pressurized dirty fluid 110 is conducted from the chamber 100 to a wellhead (not shown) at a higher pressure than when the dirty fluid 110 entered the chamber 100, such as via a first outlet valve 112 and one or more conduits 113. The second inlet valve 107 may then be closed, such as

in response to pressure sensed by a pressure transducer within the chamber 100 and/or along one or more of the conduits and/or inlet valves.

**[0041]** After the pressurized dirty fluid 110 is discharged from the chamber 100, the clean fluid 120 may be drained via an outlet valve 114 at the second end 102 of the chamber 100 and one or more conduits 116. The discharged clean fluid 120 may be stored as waste fluid or reused during subsequent iterations of the fluid pressurizing process. For example, additional quantities of the dirty and clean fluids 110, 120 may then be introduced into the chamber 100 to repeat the pressurizing process to achieve a substantially continuous supply of pressurized dirty fluid 110.

**[0042]** A fluid pressure exchanger comprising the apparatus shown in FIGS. 1-4 and/or others within the scope of the present disclosure may also comprise more than one of the example chambers 100 described above. FIG. 5 is a schematic view of an example fluid pressure exchanger 200 comprising multiple chambers 100 shown in FIGS. 1-4 and designated in FIG. 5 by reference numeral 150. FIGS. 6 and 7 are sectional views of the pressure exchanger 200 shown in FIG. 5. The following description refers to FIGS. 5-7, collectively.

**[0043]** The pressure exchanger 200 may comprise a housing 210 having a bore 212 extending between opposing ends 208, 209 of the housing 210. An end cap 202 may cover the bore 212 at the end 208 of the housing 210, and another end cap 203 may cover the bore 212 at the opposing end 209 of the housing 210. The housing 210 and the end caps 202, 203 may be sealingly engaged and statically disposed with respect to each other. The housing 210 and the end caps 202, 203 may be distinct components or members, or the housing 210 and one or both of the end caps 202, 203 may be formed as a single, integral, or continuous component or member. A rotor 201 may be slidably disposed within the bore 212 of the housing 210 and between the opposing end caps 202, 203 in a manner permitting relative rotation of the rotor 201 with respect to the housing 210 and end caps 202, 203. The rotor 201 may have a plurality of bores or chambers 150 extending through the rotor 201 and circumferentially spaced around an axis of rotation 211 extending longitudinally through the rotor 201. The rotor 201 may be a discrete member, as depicted in FIGS. 5-7, or an assembly of discrete components, such as may permit replacing worn portions of the rotor 201 and/or utilizing different materials for different portions of the rotor 201 to account for expected or actual wear.

**[0044]** The rotation of the rotor 201 about the axis 211 is depicted in FIG. 5 by arrow 220. Rotation of the rotor 201 may be achieved by various means. For example, rotation may be induced by utilizing force of the fluids received by the pressure exchanger 200, such as in

implementations in which the fluids may be directed into the chambers 150 at a diagonal angle with respect to the axis of rotation 211, thereby imparting a rotational force to the rotor 201 to rotate the rotor 201. Rotation may also be achieved by a longitudinal geometry or configuring of at least a portion of the chambers 150 as they extend through the rotor 201. For example, an inlet portion of each chamber 150, or the entirety of each chamber 150, may extend in a helical manner with respect to the axis of rotation 211, such that the incoming stream of clean fluid imparts a rotational force to the rotor 201 to rotate the rotor 201.

**[0045]** Rotation may also be imparted via a motor 260 operably connected to the rotor 201. For example, the motor 260 may be an electrical or fluid powered motor connected with the rotor 201 via a shaft, a transmission, and/or other intermediate driving members, such as may extend through at least one of the end caps 202, 203 and/or the housing 210, to transfer torque to the rotor 201 to rotate the rotor 201. The motor 260 may also be connected with the rotor 201 via a magnetic shaft coupling, such as in implementations in which a driven magnet may be physically connected with the rotor 201, and a driving magnet may be located outside of the pressure exchanger 200 and magnetically connected with the driven magnet. Such implementations may permit the motor 260 to drive the rotor 201 without a shaft extending through the end caps 202, 203 and/or housing 210.

**[0046]** Rotation may also be imparted into the rotor 201 via an electrical motor (not shown) disposed about and connected with the rotor 201. For example, the electrical motor may comprise an electrical stator disposed about or included as part of the housing 210, and an electrical rotor connected about or included as part of the rotor 201. The electrical stator may comprise field coils or windings that generate a magnetic field when powered by electric current from a source of electric power. The electrical rotor may comprise windings or permanent magnets fixedly disposed about or included as part of the rotor 201. The electrical stator may surround the electrical rotor in a manner permitting rotation of the rotor 201/electrical rotor assembly within the housing 210/electrical stator assembly during operation of the electrical motor. The electrical motors utilized within the scope of the present disclosure may include, for example, synchronous and asynchronous electric motors.

**[0047]** The pressure exchanger 200 may also comprise means for sensing or otherwise determining the rotational speed of the rotor 201. For example, the rotor speed sensing means may comprise one or more sensors 214 associated the rotor 201 and operable to convert position or presence of a rotating or otherwise moving portion of the rotor 201, a feature of the rotor 201,

or a marker 215 disposed in association with the rotor 201, into an electrical signal or information related to or indicative of the position and/or speed of the rotor 201. Each sensor 214 may be disposed adjacent the rotor 201 or otherwise disposed in association with the rotor 201 in a manner permitting sensing of the rotor or the marker 215 during pressurizing operations.

**[0048]** Each sensor 214 may sense one or more magnets on the rotor 201, one or more features on the rotor 201 that can be optically detected, conductive portions or members on the rotor 201 that can be sensed with an electromagnetic sensor, and/or facets or features on the rotor 201 that can be detected with an ultrasonic sensor, among other examples. Each sensor 214 may be or comprise a linear encoder, a capacitive sensor, an inductive sensor, a magnetic sensor, a Hall effect sensor, and/or a reed switch, among other examples. The speed sensing means may also include an intentionally imbalanced rotor 201 whose vibrations may be detected with an accelerometer and utilized to determine the rotational speed of the rotor 201.

**[0049]** The sensors 214 may extend through the housing 210, the end caps 202, 203, or another pressure barrier fluidly isolating the internal portion of the pressure exchanger 201 in a manner permitting the detection of the presence of the rotor 201 or the marker 215 at a selected or predetermined position. The sensor 214 and/or an electrical conductor connected with the sensor 214 may be sealed against the pressure barrier, such as to prevent or minimize fluid leakage. However, a non-magnetic housing 210 and/or end caps 202, 203 may be utilized, such as may permit a magnetic field to pass therethrough and, thus, permit the sensors 214 to be disposed on the outside of the housing 210 and/or end caps 202, 203. The sensor 214 may also be an ultrasonic transducer operable to send a pressure wave through the housing 210 and into the rotor 201, such as in implementations in which the housing 210 is a steel housing and the rotor 201 is a ceramic stator. The pressure wave may be reflected from varying markers or portions of the rotor 201 and sensed by the ultrasonic transducer to determine the rotational speed of the rotor 201.

**[0050]** The end caps 202, 203 may functionally replace the valves 106, 107, 112, and 114 depicted in FIGS. 1-4. For example, the first end cap 202 may be substantially disc-shaped, or may comprise a substantially disc-shaped portion, through which an inlet 204 and an outlet 205 extend. The inlet 204 may act as the first inlet valve 106 shown in FIGS. 1-4, and the outlet 205 may act as the first outlet valve 112 shown in FIGS. 1-4. Similarly, the second end cap 203 may be substantially disc-shaped, or may comprise a substantially disc-shaped portion, through which an inlet 206 and an outlet 207 extend. The inlet 206 may act as the second inlet valve 107 shown

in FIGS. 1-4, and the outlet 207 may act as the second outlet valve 114 shown in FIGS. 1-4. The fluid inlets and outlets 204-207 may have a variety of dimensions and shapes. For example, as in the example implementation depicted in FIG. 5, the inlets and outlets 204-207 may have dimensions and shapes substantially corresponding to the cross-sectional dimensions and shapes of the openings of each chamber 150 at the opposing ends of the rotor 201. However, other implementations are also within the scope of the present disclosure, provided that the chambers 150 may each be sealed against the end caps 202, 203 in a manner preventing or minimizing fluid leaks. For example, the surfaces of the end caps 202, 203 that mate with the corresponding ends of the rotor 201 may comprise face seals and/or other sealing means.

**[0051]** In the example implementation depicted in FIG. 5, the rotor 201 comprises eight chambers 150. However, other implementations within the scope of the present disclosure may comprise as few as two chambers 150, or as many as several dozen. The rotational speed of the rotor 201 may also vary, and may be timed as per the velocity of the boundary 103 between the dirty and clean fluids and the length 221 of the chambers 150 so that the timing of the inlets and outlets 204-207 are adjusted in order to facilitate proper functioning as described herein. The rotational speed of the rotor 201 may be based on the intended flow rate of the pressurized dirty fluid exiting the chambers 150 collectively, the amount of pressure differential between the dirty and clean fluids, and/or the dimensions of the chambers 150. For example, larger dimensions of the chambers 150 and greater rotational speed of the rotor 201 relative to the end caps 202, 203 and housing 210 will increase the discharge volume of the pressurized dirty fluid.

**[0052]** The size and number of instances of the fluid pressure exchanger 200 utilized at a wellsite in oil and gas operations may depend on the location of the fluid pressure exchanger 200 within the process flow stream at the wellsite. For example, some oil and gas operations at a wellsite may utilize multiple pumps (such as the pumps 306 shown in FIG. 11) that each receive low-pressure dirty fluid from a common manifold (such as the manifold 308 shown in FIG. 11) and then pressurize the dirty fluid for return to the manifold. For such operations, an instance of the fluid pressure exchanger 200 may be utilized between each pump and the manifold, and/or one or more instances of the fluid pressure exchanger 200 may replace one or more of the pumps. In such implementations, the rotor 201 may have a length 221 ranging between about 25 centimeters (cm) and about 150 cm and a diameter 222 ranging between about 10 cm and about 30 cm, the cross-sectional area (flow area) of each chamber 150 may range between about 5 cm<sup>2</sup> and about 20 cm<sup>2</sup>, and/or the volume of each chamber 150 may range between about 75 cubic cm

(cc) and about 2500 cc. However, other dimensions are also within the scope of the present disclosure. Some oil and gas operations at a wellsite may utilize multiple pumps that each receive low-pressure dirty fluid directly from a corresponding mixer (such as the mixer 304 shown in FIG. 11) or another source of dirty fluid, and then pressurize the dirty fluid for injection directly into a well (such as the well 311 shown in FIG. 11). For such operations, an instance of the fluid pressure exchanger 200 may be utilized between each pump and the well, and/or one or more instances of the fluid pressure exchanger 200 may replace one or more of the pumps.

**[0053]** In some implementations, the pumps may each receive low-pressure clean fluid from the manifold (such as may be received at the manifold from a secondary fluid source) and then pressurize the clean fluid for return to the manifold. The pressurized clean fluid may then be conducted from the manifold to one or more instances of the fluid pressure exchanger 200 to be utilized to pressurize low-pressure dirty fluid received from a gel maker, proppant blender, and/or other low-pressure processing device, and the pressurized dirty fluid discharged from the fluid pressure exchanger(s) 200 may be conducted towards a well. Examples of such operations include those shown in FIGS. 12-18, among other examples within the scope of the present disclosure. In such implementations, the length 221 of the rotor 201, the diameter 222 of the rotor 201, the flow area of each chamber 150, the volume of each chamber 150, and/or the number of chambers 150 may be much larger than as described above.

**[0054]** FIG. 6 is a sectional view of the pressure exchanger 200 shown in FIG. 5 during an operational stage in which two of the chambers are substantially aligned with the inlet and outlet 204, 205 of the first end cap 202 but not with the inlet and outlet 206, 207 of the second end cap 203. Thus, the inlet 204 fluidly connects one of the depicted chambers 150, designated by reference number 250 in FIG. 6, with the one or more conduits 108 supplying the non-pressurized dirty fluid, such that the non-pressurized dirty fluid may be conducted into the chamber 250. At the same time, the outlet 205 fluidly connects another of the depicted chambers 150, designated by reference number 251 in FIG. 6, with the one or more conduits 113 conducting previously pressurized dirty fluid out of the chamber 251, such as for conduction into a wellbore (not shown). As the rotor 201 rotates relative to the end caps 202, 203, the chambers 250, 251 will rotate out of alignment with the inlet and outlet 204, 205, thus preventing fluid communication between the chambers 250, 251 and the respective conduits 108, 113.

**[0055]** FIG. 7 is another view of the apparatus shown in FIG. 6 during another operational stage in which the chambers 250, 251 are substantially aligned with the inlet and outlet 206, 207 of the second end cap 203 but not with the inlet and outlet 204, 205 of the first end cap 202. Thus, the inlet 206 fluidly connects the chamber 250 with the one or more conduits 109 supplying the pressurizing or energizing clean fluid, such that the clean fluid may be conducted into the chamber 250. At the same time, the outlet 207 fluidly connects the other chamber 251 with the one or more conduits 116 conducting previously used, pressurizing, clean fluid out of the chamber 251, such as for recirculation to the clean fluid source (not shown). As the rotor 201 further rotates relative to the end caps 202, 203 and the housing 210, the chambers 250, 251 will rotate out of alignment with the inlet and outlet 206, 207, thus preventing fluid communication between the chambers 250, 251 and the respective conduits 109, 116.

**[0056]** The pressurizing process described above with respect to FIGS. 1-4 is achieved within each chamber 150, 250, 251 with each full rotation of the rotor 201 relative to the end caps 202, 203. For example, as the rotor 201 rotates relative to the end caps 202, 203 and the housing 210, the non-pressurized dirty fluid is conducted into the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with inlet 204 of the first end cap 202, as indicated in FIG. 6 by arrow 231. The rotation is continuous, such that the flow rate of non-pressurized dirty fluid into the chamber 250 increases as the chamber 250 comes into alignment with the inlet 204, and then decreases as the chamber 250 rotates out of alignment with the inlet 204. Further rotation of the rotor 201 relative to the end caps 202, 203 permits the pressurizing clean fluid to be conducted into the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the inlet 206 of the second end cap 203, as indicated in FIG. 7 by arrow 232. The influx of the pressurizing clean fluid into the chamber 250 pressurizes the dirty fluid, such as due to the pressure differential between the dirty and clean fluids described above with respect to FIGS. 1-4.

**[0057]** Further rotation of the rotor 201 relative to the end caps 202, 203 and the housing 210 permits the pressurized dirty fluid to be conducted out of the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the outlet 205 of the first end cap 202, as indicated in FIG. 6 by arrow 233. The discharged fluid may substantially comprise just the (pressurized) dirty fluid or a mixture of the dirty and clean fluids (also pressurized), depending on the timing of the rotor 201 and perhaps whether the chambers include the boundary 103 shown in FIGS. 1-4. Further rotation of the rotor 201 relative to the end caps

202, 203 permits the reduced-pressure clean fluid to be conducted out of the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the outlet 207 of the second end cap 203, as indicated in FIG. 7 by arrow 234. The pressurizing process then repeats as the rotor 201 further rotates and the chamber 250 again comes into alignment with the inlet 204 of the first end cap 202.

**[0058]** Depending on the number and size of the chambers 150, the non-pressurized dirty fluid inlet 204 and the pressurizing clean fluid inlet 206 may be wholly or partially misaligned with each other about the central axis 211, such that the dirty fluid may be conducted into the chamber 150 to entirely or mostly fill the chamber 150 before the clean fluid is conducted into that chamber 150. The non-pressurized dirty fluid inlet 204 is completely closed to fluid flow from the conduit 108 before the pressurizing clean fluid inlet 206 begins opening. The pressurized dirty fluid outlet 205 and the reduced-pressure clean fluid outlet 207, however, may be partially open when the pressurizing clean fluid inlet 206 is permitting the clean fluid into the chamber 150. Similarly, the non-pressurized dirty fluid inlet 204 may be partially open when the pressurized dirty fluid outlet 205 and/or the reduced-pressure clean fluid outlet 207 is at least partially open.

**[0059]** The pressurized dirty fluid outlet 205 and the reduced-pressure clean fluid outlet 207 may be wholly or partially misaligned with each other about the central axis 211. For example, the pressurized dirty fluid (and perhaps a pressurized mixture of the dirty and clean fluids) may be substantially discharged from a chamber 150 via the pressurized dirty fluid outlet 205 before the remaining reduced-pressure clean fluid is permitted to exit through the reduced-pressure clean fluid outlet 207. As the rotor 201 continues to rotate relative to the end caps 202, 203 and the housing 210, the pressurized dirty fluid outlet 205 becomes closed to fluid flow, and the reduced-pressure clean fluid outlet 207 becomes open to discharge the remaining reduced-pressure clean fluid. Thus, the reduced-pressure clean fluid outlet 207 may be completely closed to fluid flow while the pressurized dirty fluid (or mixture of the dirty and clean fluids) is discharged from the chamber 150 to the wellhead. Complete closure of the reduced-pressure clean fluid outlet 207 may permit the pressurized fluid to maintain a higher-pressure flow to the wellhead.

**[0060]** The inlets and outlets 204-207 may also be configured to permit fluid flow into and out of more than one chamber 150 at a time. For example, the non-pressurized dirty fluid inlet 204 may be sized to simultaneously fill more than one chamber 150, the inlet and outlets 204-

207 may be configured to permit non-pressurized dirty fluid to be conducted into a chamber 150 while the reduced-pressure clean fluid is simultaneously being discharged from that chamber 150. Depending on the size of the rotor 201 and the chambers 150, the fluid properties of the dirty and clean fluids, and the rotational speed of the rotor 201 relative to the end caps 202, 203, the pressurizing process within each chamber 150 may also be achieved in less than one rotation of the rotor 201 relative to the end caps 202, 203 and the housing 210, such as in implementations in which two, three, or more iterations of the pressurizing process is achieved within each chamber 150 during a single rotation of the rotor 201.

**[0061]** The flow of dirty fluid out of the pressure exchanger 200 via the fluid conduit 116 may be prevented or otherwise minimized by controlling the timing of the opening and closing of the fluid inlets 204, 206 and outlets 205, 207 of the pressure exchanger 200. For example, during the pressurizing operations, as the chambers 150 rotate, each chamber 150 is in turn aligned and, thus, fluidly connected with the low-pressure inlet 204 to receive the dirty fluid and the low-pressure outlet 207 to discharge the clean fluid. As the dirty fluid fills the chamber 150, the boundary 103 moves toward the low-pressure outlet 207 as the clean fluid is pushed out of the chamber 150. However, the rotation of the rotor 201 seals off the outlet 207 of the chamber 150 when or just before the boundary 103 reaches the outlet 207 to prevent or minimize the dirty fluid from entering into the fluid conduit 116. The chamber 150 then becomes aligned with the high-pressure inlet 206 and the high-pressure outlet 205 to permit the high-pressure clean fluid to enter the chamber 150 via the inlet 206 to push the dirty fluid from the chamber 150 via the outlet 205 at an increased pressure. As the clean fluid fills the chamber 150, the boundary 103 moves toward the high-pressure outlet 205 as the dirty fluid is pushed out of the chamber 150. However, the rotation of the rotor 201 seals off the outlet 205 of the chamber 150 when or just before the boundary 103 reaches the outlet 205 to prevent or minimize the clean fluid from entering into the fluid conduit 113. The clean fluid left in the chamber 150 may be pushed out through the fluid conduit 116 by the dirty fluid when the chamber 150 again becomes aligned with the low-pressure inlet 204 to receive the dirty fluid and the low-pressure outlet 207 to discharge the clean fluid. Such cycle may be continuously repeated to continuously receive and pressurize the stream of dirty fluid to form a substantially continuous or uninterrupted stream of dirty fluid.

**[0062]** FIGS. 8 and 9 are enlarged views of portions of the pressure exchanger 200 shown in FIGS. 7 and 6, respectively, according to one or more aspects of the present disclosure. The following description refers to FIGS. 6-9, collectively.

**[0063]** Small gaps or spaces 261, 262, 263 may be maintained between the rotor 201 and the housing 210, and between the rotor 201 and the end caps 202, 203, to permit rotation of the rotor 201 within the housing 210 and the end caps 202, 203. For clarity, the housing 210 and the end caps 202, 203 may be collectively referred to hereinafter as a “housing assembly.” The spaces 261, 262, 263 may permit fluid flow between the rotor 201 and the housing assembly. For example, dirty fluid within the pressure exchanger 200 may flow through the space 261 along the end cap 202 from the high-pressure outlet 205 to the low-pressure fluid inlet 204, and through the spaces 261, 262, 263 along the housing 210 and the end caps 202, 203 from the high-pressure outlet 205 to the clean fluid low-pressure outlet 207. Clean fluid within the pressure exchanger 200 may flow through the space 263 along the end cap 203 from the high-pressure inlet 206 to the low-pressure outlet 207, as indicated by arrow 265, and through the spaces 261, 262, 263 along the housing 210 and the end caps 202, 203 from the high-pressure inlet 206 to the dirty fluid inlet and outlet 204, 205, as indicated by arrows 265, 266, 267.

**[0064]** The fluid flow through the spaces 261, 262, 263 within the pressure exchanger 200 may form a fluid film or layer operating as a hydraulic bearing and/or otherwise providing lubrication between the rotating rotor 201 and the static housing assembly, such as may prevent or reduce contact or friction between the rotor 201 and the housing assembly during pressurizing operations. The flow of fluids through the spaces 261, 262, 263 may be biased such that substantially just the clean fluid, and not the dirty fluid, flows through the spaces 261, 262, 263 during pressurizing operations, as indicated by arrows 265, 266, 267. Biasing the flow of clean fluid through the spaces 261, 262, 263 may also cause the clean/dirty fluid boundary 103 (shown in FIGS. 1-4) to maintain a net velocity directed toward the dirty fluid outlet 205. Accordingly, biasing the flow of clean fluid may result in substantially just the clean fluid being communicated through the spaces 261, 262, 263, such as to prevent or minimize friction or wear caused by the dirty fluid between the rotor 201 and the housing assembly. Biasing the flow of the clean fluid may also result in substantially just the clean fluid being discharged via the clean fluid outlet 207, such as to prevent or minimize contamination of the clean fluid discharged from the pressure exchanger 200. The apparatus and method implemented to bias the flow of clean fluid through the spaces 261, 262, 263 is further described below.

**[0065]** FIG. 10 is a sectional view of another example implementation of the pressure exchanger 200 shown in FIG. 5 according to one or more aspects of the present disclosure and designated in FIG. 10 by reference numeral 270. The pressure exchanger 270 is substantially similar in structure and operation to the pressure exchanger 200, including where indicated by like reference numbers, except as described below.

**[0066]** The pressure exchanger 270 may include a rotor 272 slidably disposed within the bore of the housing 210 and between the opposing end caps 202, 203 in a manner permitting relative rotation of the rotor 272 with respect to the housing 210 and the end caps 202, 203. The rotor 272 may have multiple bores or chambers 274 extending through the rotor 272 between the opposing ends 208, 209 of the housing 210 and circumferentially spaced around an axis of rotation 276 extending longitudinally along the rotor 272. For the sake of clarity, cross-hatching of the rotor 272 is removed from FIG. 10, and just four chambers 274 are depicted, it being understood that other chambers 274 may also exist.

**[0067]** The chambers 274 extend through the rotor 272 in a helical manner about or otherwise with respect to the axis of rotation 276. As described above, such helical chamber implementations may be utilized to impart rotation to the rotor 272 instead of with a separate motor 260 or other rotary driving means. Such helical chamber implementations may also permit the length 278 of the chambers 274 to be greater than the axial length 280 of the rotor 272, which may permit the axial length 280 of the rotor 272 to be reduced. The increased length 278 of the chambers 274 may also permit the rotor 272 to be rotated at slower speeds than a rotor having chambers that extend substantially parallel with respect to the axis of rotation.

**[0068]** The pressure exchangers 200, 270 shown in FIGS. 5-10 and/or otherwise within the scope of the present disclosure may utilize various forms of the dirty and clean fluids described above. For example, the dirty fluid may be a high-density and/or high-viscosity, solids-laden fluid comprising insoluble solid particulate material and/or other ingredients that may compromise the life or maintenance of pumps disposed downstream of the fluid pressure exchangers 200, 270, especially when such pumps are operated at higher pressures. Examples of the dirty fluid utilized in oil and gas operations may include treatment fluid, drilling fluid, spacer fluid, workover fluid, a cement composition, fracturing fluid, acidizing fluid, stimulation fluid, and/or combinations thereof, among other examples also within the scope of the present disclosure. The dirty fluid may be a foam, a slurry, an emulsion, or a compressible gas. The viscosity of the dirty fluid may be sufficient to permit transport of solid additives or other solid

particulate material (collectively referred to hereinafter as “solids”) without appreciable settling or segregation. Chemicals, such as biopolymers (*e.g.* polysaccharides), synthetic polymers (*e.g.* polyacrylamide and its derivatives), crosslinkers, viscoelastic surfactants, oil gelling agents, low molecular weight organogelators, and phosphate esters, may also be included in the dirty fluid, such as to control viscosity of the dirty fluid.

**[0069]** The composition of the clean fluid may permit the clean fluid to be pumped at higher pressures with reduced adverse effects on the downstream and/or other pumps. For example, the clean fluid may be a solids-free fluid that does not include insoluble solid particulate material or other abrasive ingredients, or a fluid that includes low concentrations of insoluble solid particulate material or other abrasive ingredients. The clean fluid may be a liquid, such as water (including freshwater, brackish water, or brine), a gas (including a cryogenic gas), or combinations thereof. The clean fluid may also include substances, such as tracers, that can be transferred to the dirty fluid upon mixing within the chambers 150, 250, 274, or upon transmission through a semi-permeable implementation of the boundary 103. The viscosity of the clean fluid may also be increased, such as to minimize or reduce viscosity contrast between the dirty and clean fluids. Viscosity contrast may result in channeling of the lower viscosity fluid through the higher viscosity fluid. The clean fluid may be viscosified utilizing the same chemicals and/or techniques described above with respect to the dirty fluid.

**[0070]** The clean and/or dirty fluid may be chemically modified, such as via one or more fluid additives temporarily (or regularly) injected into the clean and/or dirty fluids to produce a reaction at the clean/dirty boundary 103 that acts to stabilize the boundary 103 (*e.g.*, a membrane, mixing zone). For example, viscosity modification may be utilized to help form a substantially flat flow profile within the chambers 150, 250, 274. Also, one or repeated pulses of a crosslinker applied to the clean fluid may be utilized to form crosslinked gel pills in the chambers 150, 250, 274 to act as boundary stabilizers. Such stabilizers may be safely pumped into the well and replaced over time.

**[0071]** Furthermore, the clean and dirty fluids may be selected or formulated such that a reaction between the clean and dirty fluids creates a physical change at the clean/dirty boundary 103 that stabilizes the boundary 103. For example, the clean and dirty fluids may crosslink when interacting at the boundary 103 to produce a floating, viscous plug. The clean and dirty fluids may be formulated such that the plug or another product of such reaction may not damage

downstream components when trimmed off and injected into the well by the action of the outlet 205 or another discharge valve.

**[0072]** The following are additional examples of the dirty and clean fluids that may be utilized during oil and gas operations. However, the following are merely examples, and are not considered to be limiting to the dirty and clean fluids and that may also be utilized within the scope of the present disclosure.

**[0073]** For fracturing operations, the dirty fluid may be a slurry, with a continuous phase comprising water, and a dispersed phase comprising proppant (including foamed slurries), including implementations in which the dispersed proppant includes two or more different size ranges and/or shapes, such as may optimize the amount of packing volume within the fractures. The dirty fluid may also be a cement composition (including foamed cements), or a compressible gas. For such fracturing implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

**[0074]** For cementing operations, including squeeze cementing, the dirty fluid may be a cement composition comprising water as a continuous phase and cement as a dispersed phase, or a foamed cement composition. For such cementing implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

**[0075]** For drilling, workover, acidizing, and other wellbore operations, the dirty fluid may be a homogenous solution comprising water, soluble salts, and other soluble additives, a slurry with a continuous phase comprising water and a dispersed phase comprising additives that are insoluble in the continuous phase, an emulsion or invert emulsion comprising water and a hydrocarbon liquid, or a foam of one or more of these examples. In such implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

**[0076]** In the above example implementations, and/or others within the scope of the present disclosure, the dirty fluid 110 may include proppant; swellable or non-swellable fibers; a curable resin; a tackifying agent; a lost-circulation material; a suspending agent; a viscosifier; a filtration control agent; a shale stabilizer; a weighting agent; a pH buffer; an emulsifier; an emulsifier activator; a dispersion aid; a corrosion inhibitor; an emulsion thinner; an emulsion thickener; a gelling agent; a surfactant; a foaming agent; a gas; a breaker; a biocide; a chelating agent; a scale inhibitor; a gas hydrate inhibitor; a mutual solvent; an oxidizer; a reducer; a friction reducer; a clay stabilizing agent; an oxygen scavenger; cement; a strength retrogression inhibitor; a fluid

loss additive; a cement set retarder; a cement set accelerator; a light-weight additive; a de-foaming agent; an elastomer; a mechanical property enhancing additive; a gas migration control additive; a thixotropic additive; and/or combinations thereof.

**[0077]** FIG. 11 is a schematic view of an example wellsite system 370 that may be utilized for pumping a fluid from a wellsite surface 310 to a well 311 during a well treatment operation. Water from one or more water tanks 301 may be substantially continuously pumped to a gel maker 302, which mixes the water with a gelling agent to form a carrying fluid or gel, which may be a clean fluid. The gel may be substantially continuously pumped into a blending/mixing device, hereinafter referred to as a mixer 304. Solids, such as proppant and/or other solid additives stored in one or more solids containers 303, may be intermittently or substantially continuously pumped into the mixer 304 to be mixed with the gel to form a substantially continuous stream or supply of treatment fluid, which may be a dirty fluid. The treatment fluid may be pumped from the mixer 304 to a plurality of plunger, frac, and/or other pumps 306 through a system of conduits 305 and a manifold 308. Each pump 306 pressurizes the treatment fluid, which is then returned to the manifold 308 through another system of conduits 307. The stream of treatment fluid is then directed to the well 311 via a wellhead 313 through a system of conduits 309. A control unit 312 may be operable to control various portions of such processing via wired and/or wireless communications (not shown).

**[0078]** FIG. 12 is a schematic view of an example implementation of another wellsite system 371 according to one or more aspects of the present disclosure. The wellsite system 371 comprises one or more similar features of the wellsite system 370 shown in FIG. 11, including where indicated by like reference numbers, except as described below.

**[0079]** The wellsite system 371 includes a fluid pressure exchanger 320, which may be utilized to eliminate or reduce pumping of dirty fluid through the pumps 306. The dirty fluid may be conducted from the mixer 304 to one or more chambers 100/150/250/251/274 of the fluid pressure exchanger 320 via the conduit system 305. The fluid pressure exchanger 320 may be, comprise, and/or otherwise have one or more aspects in common with the apparatus shown in one or more of FIGS. 1-10. Thus, as similarly described above with respect to FIGS. 1-10, the fluid pressure exchanger 320 comprises a non-pressurized dirty fluid inlet 331, a pressurized clean fluid inlet 332, a pressurized fluid discharge or outlet 333, and a reduced-pressure fluid discharge or outlet 334. Consequently, the pumps 306 may conduct the clean fluid to and from the manifold 308 and then to the pressurized clean fluid inlet 332 of the fluid pressure exchanger

320, where the pressurized clean fluid may be utilized to pressurize the dirty fluid received at the non-pressurized dirty fluid inlet 331 from the mixer 304.

**[0080]** A centrifugal or other type of pump 314 may supply the clean fluid to the manifold 308 from one or more holding or frac tanks 322 through a conduit system 315. An additional source of fluid to be pressurized by the manifold 308 may be flowback fluid from the well 311. The pressurized clean fluid is conducted from the manifold 308 to one or more chambers of the fluid pressure exchanger 320 via a conduit system 316. The pressurized fluid discharged from the fluid pressure exchanger 320 is then conducted to the wellhead 313 of the well 311 via a conduit system 309. The reduced-pressure clean fluid remaining in the fluid pressure exchanger 320 (or chamber 100/150 thereof) may then be conducted to one or more settling tanks/pits 318 via a conduit system 317, where the fluid may be recycled back into the high-pressure stream via a centrifugal or other type of pump 321 and a conduit system 319, such as to the tank(s) 322.

**[0081]** The wellsite system 371 may further comprise pressure sensors 350 operable to generate electric signals and/or other information indicative of the pressure of the clean fluid upstream of the pressure exchanger 320 and/or the pressure of the dirty fluid discharged from the pressure exchanger 320. For example, the pressure sensors 350 may be fluidly connected along the fluid conduits 309, 316. Additional pressure sensors may also be fluidly connected along the fluid conduits 305, 317, such as may be utilized to monitor pressure of the low-pressure clean and dirty fluids.

**[0082]** Some of the components, such as conduits, valves, and the manifold 308, may be configured to provide dampening to accommodate pressure pulsations. For example, liners that expand and contract may be employed to prevent problems associated with pumping against a closed valve due to intermittent pumping of the high-pressure fluid stream.

**[0083]** FIG. 13 is a schematic view of an example implementation of another wellsite system 372 according to one or more aspects of the present disclosure. The wellsite system 372 is substantially similar in structure and operation to the wellsite system 371, including where indicated by like reference numbers, except as described below.

**[0084]** In the wellsite system 372, the clean fluid may be conducted to the manifold 308 via a conduit system 330, the pump 314, and the conduit system 315. That is, the fluid stream leaving the gel maker 302 may be split into a low-pressure side, for utilization by the mixer 304, and a high-pressure side, for pressurization by the manifold 308. Similarly, although not depicted in FIG. 13, the fluid stream entering the gel maker 302 may be split into the low-pressure side, for

utilization by the gel maker 302, and the high-pressure side, for pressurization by the manifold 308. Thus, the clean fluid stream and the dirty fluid stream may have the same source, instead of utilizing the tank 322 or other separate clean fluid source.

**[0085]** FIG. 13 also depicts the option for the reduced-pressure fluid discharged from the fluid pressure exchanger 320 to be recycled back into the low-pressure clean fluid stream between the gel maker 302 and the mixer 304 via a conduit system 343. In such implementations, the flow rate of the proppant and/or other ingredients from the solids container 303 into the mixer 304 may be regulated based on the concentration of the proppant and/or other ingredients entering the low-pressure stream from the conduit system 343. The flow rate from the solids container 303 may be adjusted to decrease the concentration of proppant and/or other ingredients based on the concentrations in the fluid being recycled into the low-pressure stream. Similarly, although not depicted in FIG. 13, the reduced-pressure fluid discharged from the fluid pressure exchanger 320 may be recycled back into the low-pressure flow stream before the gel maker 302, or perhaps into the low-pressure flow stream between the mixer 304 and the fluid pressure exchanger 320.

**[0086]** FIG. 14 is a schematic view of an example implementation of another wellsite system 373 according to one or more aspects of the present disclosure. The wellsite system 373 is substantially similar in structure and operation to the wellsite system 372, including where indicated by like reference numbers, except as described below.

**[0087]** In the wellsite system 373, the source of the clean fluid is the tank 322, and the reduced-pressure fluid discharged from the fluid pressure exchanger 320 is not recycled back into the high-pressure stream, but is instead directed to a tank 340 via a conduit system 341. However, in similar implementations, the reduced-pressure fluid discharged from the fluid pressure exchanger 320 may not be recycled back into the high-pressure stream, as depicted in FIG. 13. In either case, utilizing the tank 322 or other source of the clean fluid separate from the discharge of the gel maker 302 and the fluid pressure exchanger 320 may permit a single-pass clean fluid system with very low probability of proppant entering the pumps 306.

**[0088]** FIG. 15 is a schematic view of an example implementation of another wellsite system 374 according to one or more aspects of the present disclosure. The wellsite system 374 is substantially similar in structure and operation to the wellsite system 373, including where indicated by like reference numbers, except as described below.

**[0089]** Unlike the wellsite system 373, the wellsite system 374 utilizes multiple instances of the fluid pressure exchanger 320. The low-pressure discharge from the mixer 304 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a conduit system 351. Similarly, the high-pressure discharge from the manifold 308 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a conduit system 352. The pressurized fluid discharged from the fluid pressure exchangers 320 may be combined and conducted towards the well 311 via a conduit system 353, and the reduced-pressure discharge from the fluid pressure exchangers 320 may be combined or separately conducted to the tank 340 via a conduit system 354.

**[0090]** FIG. 16 is a schematic view of an example implementation of another wellsite system 375 according to one or more aspects of the present disclosure. The wellsite system 375 is substantially similar in structure and operation to the wellsite system 373, including where indicated by like reference numbers, except as described below.

**[0091]** Unlike the wellsite system 373, the wellsite system 375 includes multiple instances of the fluid pressure exchanger 320 between the manifold 308 and a corresponding one of the pumps 306. The low-pressure discharge from the mixer 304 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a corresponding conduit of a conduit system 361. The high-pressure discharge from each of the pumps 306 may be conducted to a corresponding one of the fluid pressure exchangers 320 via corresponding conduits 307. The pressurized fluid discharged from each fluid pressure exchanger 320 is returned to the manifold 308 for combination, via a conduit system 362, and then conducted towards the well 311 via a conduit system 363. The reduced-pressure discharge from the fluid pressure exchangers 320 may be combined or separately conducted to one or more tanks 340 via a conduit system 364.

**[0092]** One or more of the pressure exchangers 320 may be integrated or otherwise combined with the manifold 308 as a single unit or piece of wellsite equipment. For example, one or more of the pressure exchangers 320 and the manifold 308 may be combined to form a manifold 390 comprising fluid pathways and connections of the manifold 308 and one or more of the pressure exchangers 320 hard-piped or otherwise integrated with or along such fluid pathways and connections. Accordingly, the mixer 304 and each pump 306 may be fluidly connected with corresponding inlet ports of the manifold 390 instead of with individual inlet ports 331, 332 of the pressure exchangers 320. For example, the manifold 390 may comprise a

plurality of clean fluid inlet ports each fluidly connected with a corresponding fluid conduit 307 to receive the clean fluid from the pumps 306. Each clean fluid inlet port may in turn be fluidly connected with the clean fluid inlet 332 of a corresponding pressure exchanger 320. The manifold 390 may further comprise a plurality of dirty fluid inlet ports, each fluidly connected with a corresponding fluid conduit of the conduit system 361 and operable to receive the dirty fluid from the mixer 304. Each dirty fluid inlet port may in turn be fluidly connected with the dirty fluid inlet 331 of a corresponding pressure exchanger 320. The manifold 390 may also comprise a plurality of clean fluid outlet ports, each fluidly connected with a corresponding fluid conduit of the conduit system 364 and operable to discharge the clean fluid from the manifold 390. Each clean fluid outlet port may in turn be fluidly connected with the clean fluid outlet 334 of a corresponding pressure exchanger 320. The manifold 390 may also comprise a dirty fluid outlet port fluidly connected with the conduit system 363 and operable to discharge the dirty fluid from the manifold 390. The dirty fluid outlet port may in turn be fluidly connected with the dirty fluid outlets 333 of the pressure exchangers 320.

**[0093]** Combinations of various aspects of the example implementations depicted in FIGS. 12-16 are also within the scope of the present disclosure. For example, the high-pressure side may comprise a dual-stage pumping scheme that pumps a clean fluid from the pumps 306 at a medium pressure and pumps flowback fluid into the clean fluid stream to increase the pressure of the pressurized fluid entering the fluid pressure exchanger 320.

**[0094]** A wellsite system within the scope of the present disclosure may be utilized to form a substantially continuous stream or supply of dirty fluid having a predetermined solids concentration before being pressurized by one or more pressure exchangers and injected into a well during a well treatment operation. For example, the solids concentration of the dirty fluid stream being formed and injected into the well may be held substantially constant during the well treatment operation. However, the solids concentration of the dirty fluid may be dynamically varied during the well treatment operation.

**[0095]** The present disclosure also introduces implementations of a rotating pressure exchanger that permits separation of the pumping operations and separation of the pumped fluids. Such implementations, among others within the scope of the present disclosure, may also permit the formation of an intended pressure ratio between the pressurized clean fluid received by the pressure exchanger and the pressurized dirty fluid discharged from the pressure exchanger.

**[0096]** FIG. 17 is a schematic sectional view of an example implementation of a pressure exchanger 400 according to one or more aspects of the present disclosure. The pressure exchanger 400 is substantially similar in structure and operation to the pressure exchangers 200, 270, 320 described above, except as described below. The pressure exchanger 400 may be interchangeable with the pressure exchangers 200, 270, 320, such that one or more of the pressure exchangers 400 may be utilized as part of the wellsite systems 371-375 shown in FIGS. 12-16, respectively, instead of or in conjunction with one or more of the pressure exchangers 200, 270, 320. One or more aspects of the following description may also refer to one or more of FIGS. 1-16.

**[0097]** The pressure exchanger 400 may comprise a housing 410 having a bore 412 extending between opposing ends 414, 416 of the housing 410. An end cap 420 may cover the bore 412 at the end 414 of the housing 410, and another end cap 422 may cover the bore 412 at the opposing end 416 of the housing 410. The housing 410 and the end caps 420, 422 may be sealingly engaged and statically disposed with respect to each other. The housing 410 and the end caps 420, 422 may be distinct components or members, or the housing 410 and one or both of the end caps 420, 422 may be formed as a single, integral, or continuous component or member. A rotor 430 may be slidably disposed within the bore 412 of the housing 410 and between the opposing end caps 420, 422 in a manner permitting relative rotation of the rotor 430 with respect to the housing 410 and end caps 420, 422 along an axis of rotation 402, as indicated by arrow 404. The rotor 430 may have a plurality of bores or chambers 440 extending through the rotor 430 between opposing faces 434 (*i.e.*, ends) of the rotor 430. The chambers 440 may be circumferentially spaced or otherwise distributed around the axis of rotation 402. The rotor 430 may be a discrete member, as depicted in FIG. 17, or an assembly of discrete components, such as may permit replacing worn portions of the rotor 430 and/or utilizing different materials for different portions of the rotor 430 to account for expected or actual wear. The rotor 430 may have a length 435, which may be two or more times as long as the length 221 of the rotor 201 of the pressure exchanger 200 shown in FIG. 5 or another pressure exchanger that does not comprise piston assemblies disposed within corresponding chambers.

**[0098]** Each chamber 440 may comprise a larger diameter section 442 and a smaller diameter section 444 separated by a radially extending transition surface or shoulder 446. Each chamber 440 may contain a stepped piston assembly 450 slidably disposed therein. Each piston assembly 450 may comprise a larger diameter section 452 slidably and sealingly engaging a side

surface of the larger diameter section 442 of a corresponding chamber 440 (*i.e.*, an inner surface of the rotor 430 defining the larger diameter section 442). Each piston assembly 450 may further comprise a smaller diameter section 454 slidably and sealingly engaging a side surface of the smaller diameter section 444 of a corresponding chamber 440 (*i.e.*, an inner surface of the rotor 430 defining the smaller diameter section 444). Each larger diameter section 452 may terminate with or otherwise comprise a larger diameter face 453, and each smaller diameter section 454 may terminate with or otherwise comprise a smaller diameter face 455. Each larger diameter section 442 may contain an end stop or a shoulder 441 extending radially therein, such as may be operable to limit the movement of the piston assemblies 450 to prevent the piston assemblies 450 from making contact with the end cap 420. The end stop or shoulder 441 may be located at an entrance of each larger diameter section 442 adjacent the end cap 420.

**[0099]** Each piston assembly 450 may comprise fluid seals 456, 458 adjacent opposing faces 453, 455 of the piston assembly 450, such as may permit each larger and smaller diameter section 452, 454 to sealingly engage the side surface of each corresponding larger and smaller diameter section 442, 444 of each chamber 440. The piston assemblies 450 fluidly isolate the dirty fluid within the smaller diameter section 444 of the chamber 440 from the clean fluid within the larger diameter section 442 of the chamber 440, thus decoupling the pressure of clean fluid from the pressure of the dirty fluid.

**[00100]** The end cap 420 may comprise a high-pressure inlet port 424 fluidly connected with a source of pressurized clean fluid, such as the pumps 306. The end cap 420 may further comprise a low-pressure outlet port 425 fluidly connected with a destination of depressurized clean fluid, such as the settling tank/pit 318, 340 or the suction port of the mixer 304. The end cap 422 may comprise a low-pressure inlet port 426 fluidly connected with a source of low-pressure dirty fluid, such as the discharge port of the mixer 304. The end cap 422 may further comprise a high-pressure outlet port 427 fluidly connected with a destination of the pressurized dirty fluid, such as the well 311.

**[00101]** During fluid pressurizing operations, as the rotor 430 rotates with respect to the housing 410 and the end caps 420, 422, the piston assemblies 450 are alternately pushed in opposing directions along the corresponding chambers 440 as the clean and dirty fluids are injected and discharged via the ports 424-427. When one or more of the chambers 440 and the corresponding piston assemblies 450 are aligned with the inlet port 426, the low-pressure dirty fluid enters the smaller diameter sections 444 of the one or more chambers 440, as indicated by

arrow 494, pushing against the faces 455 of the smaller diameter sections 454 to move the piston assemblies 450 and force the clean fluid out of the larger diameter sections 442 of the chambers 440, as indicated by arrow 495. When one or more chambers 440 and corresponding piston assemblies 450 are then aligned with the inlet port 424, the pressurized clean fluid enters the larger diameter sections 442 of the one or more chambers 440, as indicated by arrow 492, pushing against the faces 453 of the larger diameter sections 452 to move the piston assemblies 450 and force the dirty fluid out of the smaller diameter sections 442 of the chambers 440, as indicated by arrow 496, thus pressurizing the dirty fluid.

**[00102]** As the piston assemblies 450 are cycled in opposing directions, fluid (*e.g.*, the clean fluid, the dirty fluid, a lubricating fluid, or a combination thereof) may be alternately received into and discharged from a portion or volume of each chamber 440 fluidly isolated between the opposing seals 456, 458. Accordingly, the rotor 430 may further comprise a plurality of fluid passages 461 extending through the rotor 430 fluidly connecting the chambers 440 with each other. The fluid passages 461 may permit the fluid within the chambers 440 between the seals 456, 458 to be alternately transferred between (*i.e.*, into and out of) the chambers during pressurizing operations, as indicated by arrows 488, 489. Each of the fluid passages 461 may connect with a corresponding one of the chambers 440 adjacent to or along the transition shoulder 446.

**[00103]** The rotor 430 may further comprise a fluid passage 460 (*i.e.*, a bore) extending longitudinally through the rotor 430 between the opposing faces 434 of the rotor 430 and a fluid groove or channel 432 extending circumferentially around the rotor 430. The fluid passage 460 may be an axial fluid passage, substantially coinciding with the axis of rotation 402, and may be fluidly connected with each of the plurality of fluid passages 461. The end cap 420 may also comprise a fluid passage 462 extending therethrough between an inner face of the end cap 420 and the low-pressure fluid outlet 425. An end (*i.e.*, opening) of the fluid passage 462 at the inner face of the end cap 420 may be aligned with an end (*i.e.*, opening) of the fluid passage 460 across a corresponding space 262 to fluidly connect the fluid passage 460 with the low-pressure fluid outlet 425. The housing 410 may further comprise one or more fluid passages 418 (*i.e.*, ports) extending through the wall of the housing 410 into the bore 412. The fluid passage 418 may be aligned with the channel 432.

**[00104]** During fluid pressurizing operations, the fluid passages 460, 461, 462 permit the fluid sealed within the chamber 440 between the seals 456, 458 to be evacuated or vented to the outlet

port 425, as indicated by arrows 488, 491, for example, when the piston assembly 450 is moved by the pressurized clean fluid received from the inlet 424, as indicated by arrow 492. The fluid passages 460, 462 may further permit low-pressure fluid to enter the portion or volume of each chamber 440 isolated between the seals 456, 458 from the outlet port 425, as indicated by arrows 489, 493, when the piston assembly 450 is moved by the low-pressure dirty fluid received via the inlet 426, as indicated by arrow 494. However, if an equal number of piston assemblies 450 are moving in opposing directions at substantially the same speed, the fluid being discharged from the isolated chamber portions of one or more chambers 440 may flow directly into the isolated chamber portions of the remaining chambers 440, such that little or no fluid is discharged into or received from the outlet port 425.

**[00105]** Due to small gaps or spaces 261, 263 between the rotor 430 and the housing 410, and small gaps and spaces 262 between the faces 434 of the rotor 430 and faces of the end caps 420, 422, during the pressurizing operations, some of the clean fluid being passed out of the port 424 may leak into or otherwise enter the spaces 261, 262, 263 and flow toward or into the ports 425, 426, 427. Similarly, some of the dirty fluid being passed from the chambers 440 into the port 427, and from the port 426 into the chambers 440, may also leak into or otherwise enter the spaces 261, 262, 263 and flow toward or into the ports 425, 426, respectively, causing friction or wear to the housing 410, the end caps 420, 422, and the rotor 430.

**[00106]** During fluid pressurizing operations, the fluid passages 460, 462 are open to a relatively low pressure of the outlet port 425, resulting in areas or zones of relatively low pressure adjacent the fluid passages 460, 462 along the spaces 262 between the rotor 430 and the end caps 420, 422. The dirty fluid that may have entered the spaces 262 may then travel inwardly toward the low-pressure area surrounding the fluid passages 460, 462 and into the fluid passages 460, 462, as indicated by arrows 498. The dirty fluid that entered the fluid passages 460, 462 may then pass into the outlet port 425 and be discharged out of the pressure exchanger 400. Accordingly, the fluid passages 460, 462 may prevent or reduce friction or wear to the housing 410, the end caps 420, 422, and the rotor 430 by causing the dirty fluid that leaked into the spaces 261, 262, 263 to flow in a radially inward direction with respect to the axis 402 to be captured by and removed via the passages 460, 462. The fluid passages 460, 462 may prevent or reduce the amount of dirty fluid travelling in a radially outward direction from the ports 426, 427 along the spaces 262 between the end caps 420, 422 and the rotor 430 and into the spaces 261, 263 (*i.e.*, circumferential spaces) between the housing 410 and the rotor 430.

**[00107]** Additional fluid (*e.g.*, the clean fluid, a lubricating fluid, a cooling fluid) may be injected into the spaces 261, 263 between the housing 410 and the rotor 430 via the passage 418, as indicated by arrows 417. The fluid may be passed around the rotor 430 via the channel 432 and flow out of the channel 432 in opposing directions along the spaces 261, 262, as indicated by arrows 419. The fluid may flow 419 along the spaces 261, 263 between the rotor 430 and the housing 410, providing lubrication and/or cooling. The fluid may also enter the spaces 262 between the rotor 430 and the end caps 420, 422, as indicated by arrows 497, and flow toward the fluid passages 460, 462. As the fluid passes through the spaces 261, 262, 263, the additional fluid may sweep the dirty fluid in the spaces 261, 262, 263 toward and into the fluid passages 460, 462, which may also prevent or minimize friction or wear to the housing 410, the end caps 420, 422, and the rotor 430. The flow rate of the additional fluid between the fluid passage 418 and the fluid passages 460, 462 through the spaces 261, 262, 263 may depend on the size (*i.e.*, clearance) of the spaces 261, 262, 263.

**[00108]** The stepped piston assemblies 450 facilitate intensification or increase in pressure on opposing sides of the piston assembly 450, because the face area 453 of the piston assembly 450 exposed to the pressure at the inlet port 424 is substantially larger than the face area 455 of the piston assembly 450 exposed to the pressure at the outlet port 427. The increase in pressure may depend on the differences in the surface areas of the opposing faces 453, 455, wherein the pressure increase ratio may be directly proportional to a face surface area ratio. As corresponding volumes of the larger and smaller diameter sections 442, 444 are substantially different, the volumetric flow of the dirty fluid discharged from the smaller diameter section 444 via the outlet port 427 is substantially smaller than the volumetric flow of the clean fluid received into the larger diameter section 442 via the inlet port 424. The decrease in volumetric flow may also depend on the differences in the surface areas of the opposing faces 453, 455.

**[00109]** For example, a 2:1 face surface area ratio may produce a 2:1 increase in pressure. The ratio of the face area 453 to the face area 455 within the scope of the present disclosure may range, for example, between about 1.1:1.0 and about 10:1. It is to be understood that the face area ratio within the scope of the present disclosure may also be reversed, resulting in a pressure output decrease and a volumetric flow output increase. For example, the area of the face 453 may be substantially smaller than the area of the face 455, such that the input pressure at the inlet port 424 is reduced at the outlet port 427, but the volumetric flow rate produced at the outlet port 427 is proportionately increased compared to the volumetric flow rate at the inlet port 424. The

face area ratio within the scope of the present disclosure may also be 1:1, wherein the inlet pressure and volumetric flow rate at the inlet port 424 is substantially similar to the outlet pressure and volumetric flow rate at the outlet port 427.

**[00110]** In view of the entirety of the present disclosure, including the figures and the claims, a person having ordinary skill in the art will readily recognize that the present disclosure introduces an apparatus comprising a pressure exchanger comprising: (A) a housing having a bore extending between first and second ends of the housing; (B) a rotor rotatably disposed within the bore of the housing, wherein the rotor comprises a chamber extending through the rotor between first and second ends of the rotor, and wherein the chamber comprises: (1) a larger chamber diameter section; and (2) a smaller chamber diameter section; and (C) a piston assembly slidably disposed within the chamber, wherein the piston assembly comprises: (1) a larger piston diameter section slidably disposed within the larger chamber diameter section; and (2) a smaller piston diameter section slidably disposed within the smaller chamber diameter section.

**[00111]** The chamber may be one of a plurality of chambers distributed around a central axis of the rotor, and the piston assembly may be one of a plurality of piston assemblies each disposed within a corresponding one of the chambers.

**[00112]** As the rotor is rotating with respect to the housing, the pressure exchanger may be operable to: receive a first fluid at a first pressure into the larger chamber diameter section, thereby moving the piston assembly within the chamber to discharge a second fluid at a second pressure from the smaller chamber diameter section; and receive the second fluid into the smaller chamber diameter section, thereby moving the piston assembly within the chamber to discharge the first fluid from the larger chamber diameter section. The pressure exchanger may comprise: a first cap covering the bore at the first end of the housing, wherein the first cap comprises a first fluid inlet and a first fluid outlet; and a second cap covering the bore at the second end of the housing, wherein the second cap comprises a second fluid inlet and a second fluid outlet. The second pressure may be substantially greater than the first pressure. The first fluid may be a clean fluid and the second fluid may be a dirty fluid.

**[00113]** The larger piston diameter section may sealingly engage a side surface of the larger chamber diameter section, and the smaller piston diameter section may sealingly engage a side surface of the smaller chamber diameter section.

**[00114]** The chamber may be one of a plurality of chambers distributed around a central axis of the rotor, the piston assembly may be one of a plurality of piston assemblies each disposed

within a corresponding one of the chambers, the rotor may comprise a plurality of fluid passages extending through the rotor and fluidly connecting the chambers, and the fluid passages may be configured to transfer a fluid between the chambers during pressure exchanger operations. Each chamber may comprise a transition area between the larger chamber diameter section and the smaller chamber diameter section, and each fluid passage may connect with a corresponding one of the chambers adjacent to or along the transition area.

**[00115]** The chamber may be one of a plurality of chambers distributed around a central axis of the rotor, the piston assembly may be one of a plurality of piston assemblies each disposed within a corresponding one of the chambers, and the rotor may comprise: a first fluid passage extending through the rotor between the first and second ends of the rotor; and a plurality of second fluid passages extending through the rotor, wherein each of the second fluid passages may extend between a corresponding one of the chambers and the first fluid passage. The pressure exchanger may comprise: a first cap covering the bore at the first end of the housing, wherein the first cap may comprise a first fluid inlet and a first fluid outlet, and wherein the first cap may comprise a third fluid passage fluidly connecting the first fluid passage and the first fluid outlet; and a second cap covering the bore at the second end of the housing, wherein the second cap may comprise a second fluid inlet and a second fluid outlet.

**[00116]** The present disclosure also introduces an apparatus comprising a pressure exchanger comprising: (A) a housing having a bore extending between first and second ends of the housing; (B) a first cap covering the bore at the first end of the housing, wherein the first cap comprises a first fluid inlet and a first fluid outlet; (C) a second cap covering the bore at the second end of the housing, wherein the second cap comprises a second fluid inlet and a second fluid outlet; (D) a rotor rotatably disposed within the bore of the housing, wherein the rotor comprises a plurality of chambers distributed around a central axis of the rotor, wherein each of the chambers extends through the rotor between first and second ends of the rotor, and wherein each of the chambers comprises: (1) a larger chamber diameter section; and (2) a smaller chamber diameter section; and (E) a plurality of piston assemblies each slidably disposed within a corresponding one of the chambers, wherein each of the piston assemblies comprises: (1) a larger piston diameter section slidably disposed within a corresponding one of the larger chamber diameter sections; and (2) a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections.

**[00117]** As the rotor rotates within the housing, the pressure exchanger may be operable to: receive a first fluid at a first pressure into the larger chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge a second fluid at a second pressure from corresponding ones of the smaller chamber diameter sections; and receive the second fluid into the smaller chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge the first fluid from corresponding ones of the larger chamber diameter sections. The second pressure may be substantially greater than the first pressure. The first fluid may be a clean fluid and the second fluid may be a dirty fluid.

**[00118]** Each larger piston diameter section may sealingly engage a side surface of a corresponding one of the larger chamber diameter sections, and each smaller piston diameter section may sealingly engage a side surface of a corresponding one of the smaller chamber diameter sections.

**[00119]** The rotor may comprise a plurality of fluid passages extending through the rotor and fluidly connecting the chambers, and the fluid passages may be configured to transfer a fluid between the chambers during pressure exchanger operations. Each of the chambers may comprise a transition area between the larger chamber diameter section and the smaller chamber diameter section, and each of the fluid passages may connect with a corresponding one of the chambers adjacent to or along the transition area.

**[00120]** The rotor may comprise: a first fluid passage extending through the rotor between the first and second ends of the rotor; and a plurality of second fluid passages extending through the rotor, wherein each of the second fluid passages may extend between a corresponding one of the chambers and the first fluid passage. The first cap may comprise a third fluid passage fluidly connecting the first fluid passage and the first fluid outlet.

**[00121]** The present disclosure also introduces a method comprising: (A) fluidly connecting a pressure exchanger with a source of a first fluid and a source of a second fluid, wherein the pressure exchanger comprises: (1) a rotor comprising a plurality of chambers extending through the rotor, wherein each of the chambers comprises: (a) a larger chamber diameter section; and (b) a smaller chamber diameter section; and (2) a plurality of piston assemblies each slidably disposed within a corresponding one of the chambers, wherein each of the piston assemblies comprises: (a) a larger piston diameter section slidably disposed within a corresponding one of the larger chamber diameter sections; and (b) a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections; and (B) while the rotor

rotates: (1) injecting the first fluid at a first pressure into the larger chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge a second fluid at a second pressure from corresponding ones of the smaller chamber diameter sections; and (2) injecting the second fluid into the smaller chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge the first fluid from corresponding ones of the larger chamber diameter sections.

**[00122]** The second pressure may be substantially greater than the first pressure.

**[00123]** The first fluid may be a clean fluid and the second fluid may be a dirty fluid.

**[00124]** Each larger piston diameter section may sealingly engage a side surface of a corresponding one of the larger chamber diameter sections, and each smaller piston diameter section may sealingly engage a side surface of a corresponding one of the smaller chamber diameter sections.

**[00125]** The rotor may comprise a plurality of fluid passages extending through the rotor and fluidly connecting the chambers, and the method may comprises, while the rotor rotates, transferring one or more of the first fluid, the second fluid, and a third fluid between the chambers via the fluid passages. The plurality of fluid passages may be a plurality of first fluid passages, the rotor may comprise a second fluid passage extending through the rotor, and the pressure exchanger may comprise: a first cap at a first end of the housing and comprising a first fluid inlet, a first fluid outlet, and a third fluid passage fluidly connecting the second fluid passage and the first fluid outlet; and a second cap at a second end of the housing and comprising a second fluid inlet and a second fluid outlet. The method may comprise, while the rotor rotates, transferring one or more of the first fluid, the second fluid, and the third fluid via the second and third fluid passages.

**[00126]** The foregoing outlines features of several implementations so that a person having ordinary skill in the art may better understand the aspects of the present disclosure. A person having ordinary skill in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same functions and/or achieving the same benefits of the implementations introduced herein. A person having ordinary skill in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

**[00127]** The Abstract at the end of this disclosure is provided to permit the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

**WHAT IS CLAIMED IS:**

1. An apparatus comprising:

a pressure exchanger comprising:

a housing having a bore extending between first and second ends of the housing;

a rotor rotatably disposed within the bore of the housing, wherein the rotor comprises a chamber extending through the rotor between first and second ends of the rotor, and wherein the chamber comprises:

a larger chamber diameter section; and

a smaller chamber diameter section; and

a piston assembly slidably disposed within the chamber, wherein the piston assembly comprises:

a larger piston diameter section slidably disposed within the larger chamber diameter section; and

a smaller piston diameter section slidably disposed within the smaller chamber diameter section.

2. The apparatus of claim 1 wherein the chamber is one of a plurality of chambers distributed around a central axis of the rotor, and wherein the piston assembly is one of a plurality of piston assemblies each disposed within a corresponding one of the chambers.

3. The apparatus of claim 1 wherein, as the rotor is rotating with respect to the housing, the pressure exchanger is operable to:

receive a first fluid at a first pressure into the larger chamber diameter section, thereby moving the piston assembly within the chamber to discharge a second fluid at a second pressure from the smaller chamber diameter section; and

receive the second fluid into the smaller chamber diameter section, thereby moving the piston assembly within the chamber to discharge the first fluid from the larger chamber diameter section.

4. The apparatus of claim 3 wherein the pressure exchanger further comprises:  
a first cap covering the bore at the first end of the housing, wherein the first cap comprises a first fluid inlet and a first fluid outlet; and  
a second cap covering the bore at the second end of the housing, wherein the second cap comprises a second fluid inlet and a second fluid outlet.
5. The apparatus of claim 3 wherein the second pressure is substantially greater than the first pressure.
6. The apparatus of claim 3 wherein the first fluid is a clean fluid and the second fluid is a dirty fluid.
7. The apparatus of claim 1 wherein the larger piston diameter section sealingly engages a side surface of the larger chamber diameter section, and wherein the smaller piston diameter section sealingly engages a side surface of the smaller chamber diameter section.
8. The apparatus of claim 1 wherein:  
the chamber is one of a plurality of chambers distributed around a central axis of the rotor;  
the piston assembly is one of a plurality of piston assemblies each disposed within a corresponding one of the chambers;  
the rotor further comprises a plurality of fluid passages extending through the rotor and fluidly connecting the chambers; and  
the fluid passages are configured to transfer a fluid between the chambers during pressure exchanger operations.
9. The apparatus of claim 8 wherein each chamber comprises a transition area between the larger chamber diameter section and the smaller chamber diameter section, and wherein each fluid passage connects with a corresponding one of the chambers adjacent to or along the transition area.

10. The apparatus of claim 1 wherein the chamber is one of a plurality of chambers distributed around a central axis of the rotor, wherein the piston assembly is one of a plurality of piston assemblies each disposed within a corresponding one of the chambers, and wherein the rotor further comprises:

a first fluid passage extending through the rotor between the first and second ends of the rotor;  
and

a plurality of second fluid passages extending through the rotor, wherein each of the second fluid passages extends between a corresponding one of the chambers and the first fluid passage.

11. The apparatus of claim 10 wherein the pressure exchanger further comprises:

a first cap covering the bore at the first end of the housing, wherein the first cap comprises a first fluid inlet and a first fluid outlet, and wherein the first cap further comprises a third fluid passage fluidly connecting the first fluid passage and the first fluid outlet; and

a second cap covering the bore at the second end of the housing, wherein the second cap comprises a second fluid inlet and a second fluid outlet.

12. An apparatus comprising:

a pressure exchanger comprising:

a housing having a bore extending between first and second ends of the housing;

a first cap covering the bore at the first end of the housing, wherein the first cap comprises a first fluid inlet and a first fluid outlet;

a second cap covering the bore at the second end of the housing, wherein the second cap comprises a second fluid inlet and a second fluid outlet;

a rotor rotatably disposed within the bore of the housing, wherein the rotor comprises a plurality of chambers distributed around a central axis of the rotor, wherein each of the chambers extends through the rotor between first and second ends of the rotor, and wherein each of the chambers comprises:

a larger chamber diameter section; and

a smaller chamber diameter section; and

a plurality of piston assemblies each slidably disposed within a corresponding one of the chambers, wherein each of the piston assemblies comprises:

a larger piston diameter section slidably disposed within a corresponding one of the larger chamber diameter sections; and

a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections.

13. The apparatus of claim 12 wherein, as the rotor rotates within the housing, the pressure exchanger is operable to:

receive a first fluid at a first pressure into the larger chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge a second fluid at a second pressure from corresponding ones of the smaller chamber diameter sections; and receive the second fluid into the smaller chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge the first fluid from corresponding ones of the larger chamber diameter sections.

14. The apparatus of claim 13 wherein the second pressure is substantially greater than the first pressure.

15. The apparatus of claim 13 wherein the first fluid is a clean fluid and the second fluid is a dirty fluid.
16. The apparatus of claim 12 wherein each larger piston diameter section sealingly engages a side surface of a corresponding one of the larger chamber diameter sections, and wherein each smaller piston diameter section sealingly engages a side surface of a corresponding one of the smaller chamber diameter sections.
17. The apparatus of claim 12 wherein the rotor further comprises a plurality of fluid passages extending through the rotor and fluidly connecting the chambers, and wherein the fluid passages are configured to transfer a fluid between the chambers during pressure exchanger operations.
18. The apparatus of claim 17 wherein each of the chambers comprises a transition area between the larger chamber diameter section and the smaller chamber diameter section, and wherein each of the fluid passages connects with a corresponding one of the chambers adjacent to or along the transition area.
19. The apparatus of claim 12 wherein the rotor further comprises:  
a first fluid passage extending through the rotor between the first and second ends of the rotor;  
and  
a plurality of second fluid passages extending through the rotor, wherein each of the second fluid passages extends between a corresponding one of the chambers and the first fluid passage.
20. The apparatus of claim 19 wherein the first cap further comprises a third fluid passage fluidly connecting the first fluid passage and the first fluid outlet.

21. A method comprising:

fluidly connecting a pressure exchanger with a source of a first fluid and a source of a second fluid, wherein the pressure exchanger comprises:

a rotor comprising a plurality of chambers extending through the rotor, wherein each of the chambers comprises:

a larger chamber diameter section; and

a smaller chamber diameter section; and

a plurality of piston assemblies each slidably disposed within a corresponding one of the chambers, wherein each of the piston assemblies comprises:

a larger piston diameter section slidably disposed within a corresponding one of the larger chamber diameter sections; and

a smaller piston diameter section slidably disposed within a corresponding one of the smaller chamber diameter sections; and

while the rotor rotates:

injecting the first fluid at a first pressure into the larger chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge a second fluid at a second pressure from corresponding ones of the smaller chamber diameter sections; and

injecting the second fluid into the smaller chamber diameter sections, thereby moving corresponding ones of the piston assemblies within the chambers to discharge the first fluid from corresponding ones of the larger chamber diameter sections.

22. The method of claim 21 wherein the second pressure is substantially greater than the first pressure.

23. The method of claim 21 wherein the first fluid is a clean fluid and the second fluid is a dirty fluid.

24. The method of claim 21 wherein each larger piston diameter section sealingly engages a side surface of a corresponding one of the larger chamber diameter sections, and wherein each smaller piston diameter section sealingly engages a side surface of a corresponding one of the smaller chamber diameter sections.

25. The method of claim 21 wherein the rotor further comprises a plurality of fluid passages extending through the rotor and fluidly connecting the chambers, and wherein the method further comprises, while the rotor rotates, transferring one or more of the first fluid, the second fluid, and a third fluid between the chambers via the fluid passages.

26. The method of claim 25 wherein:

the plurality of fluid passages is a plurality of first fluid passages;

the rotor further comprises a second fluid passage extending through the rotor;

the pressure exchanger further comprises:

a first cap at a first end of the housing and comprising a first fluid inlet, a first fluid outlet, and a third fluid passage fluidly connecting the second fluid passage and the first fluid outlet; and

a second cap at a second end of the housing and comprising a second fluid inlet and a second fluid outlet; and

the method further comprises, while the rotor rotates, transferring one or more of the first fluid, the second fluid, and the third fluid via the second and third fluid passages.

1/7

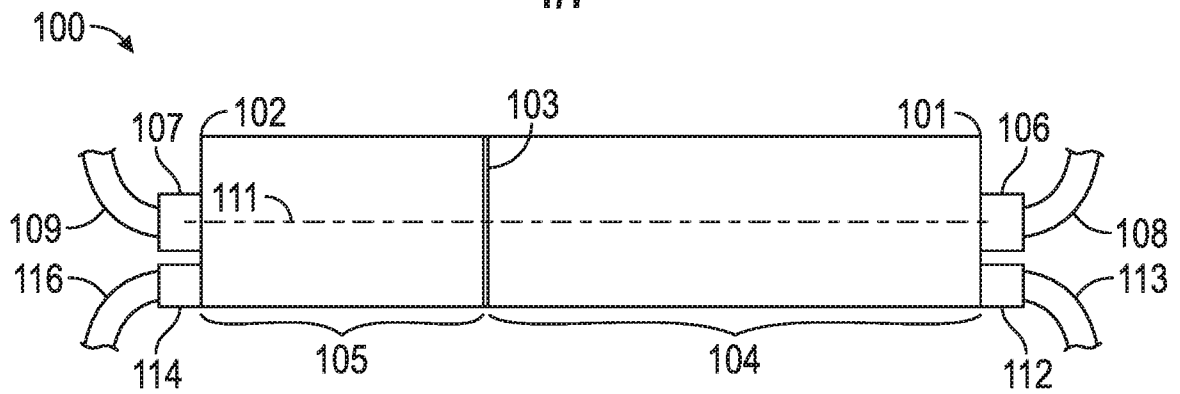


FIG. 1

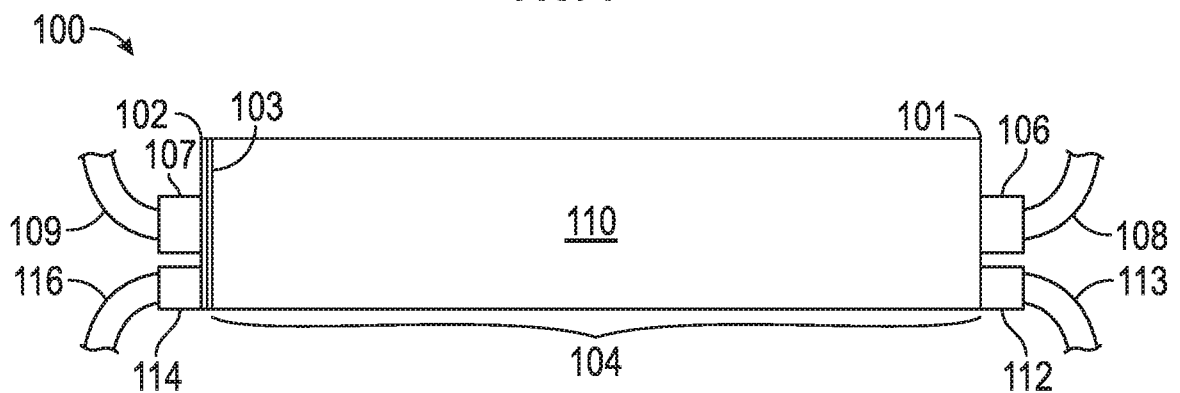


FIG. 2

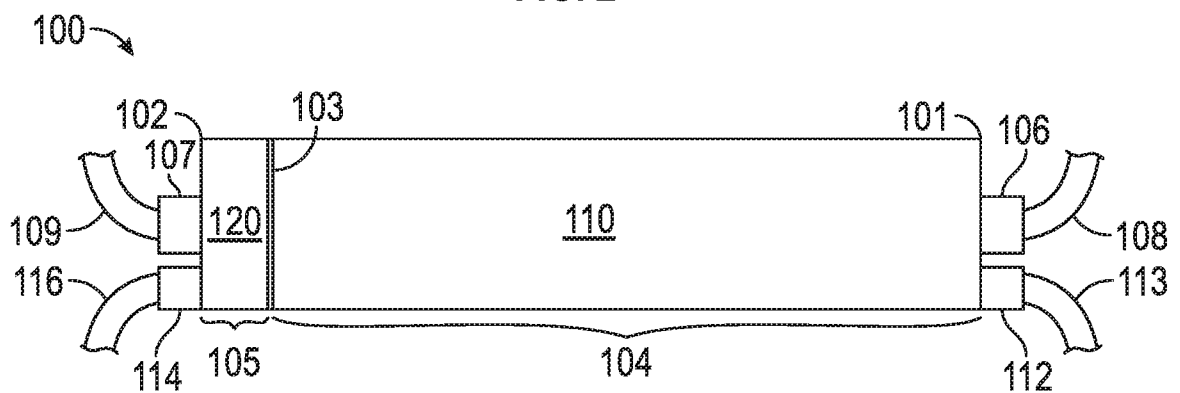


FIG. 3

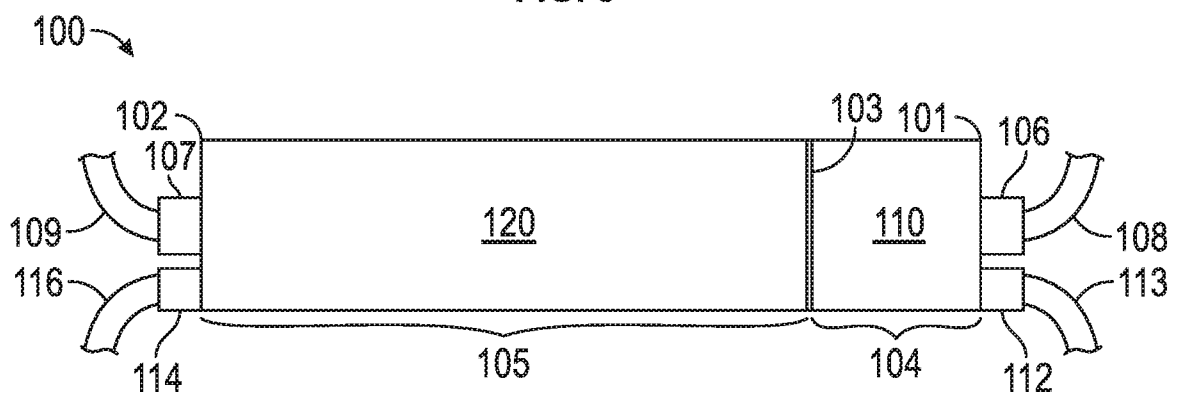


FIG. 4

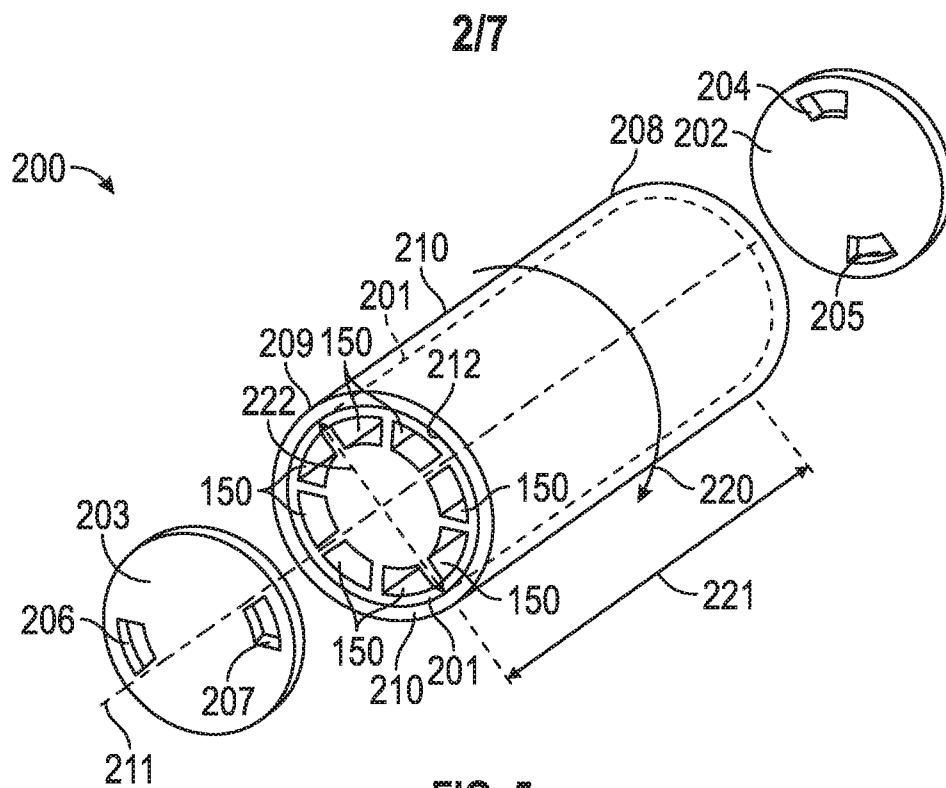


**FIG. 5**

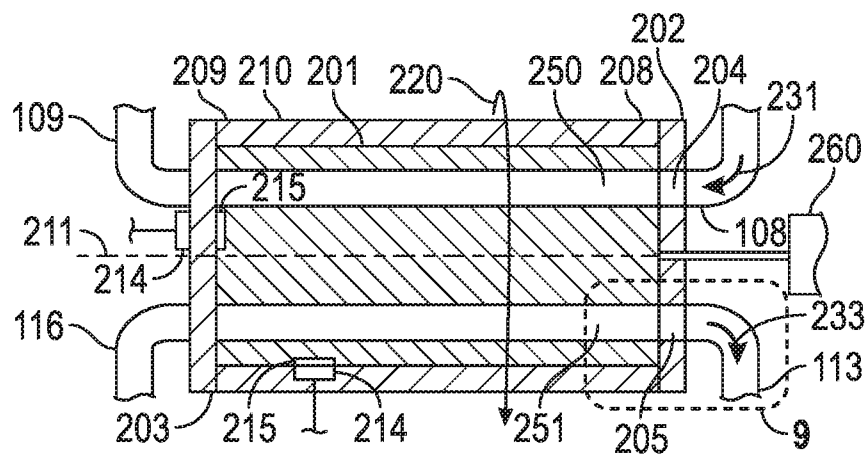


**FIG. 6**

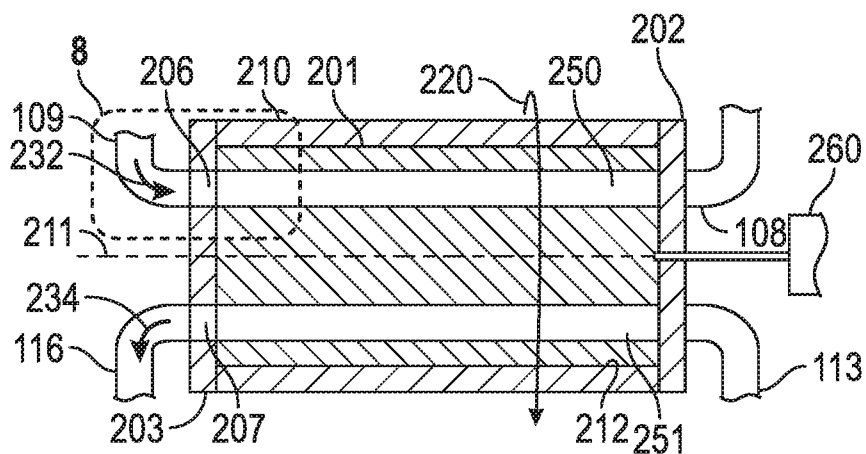


**FIG. 7**

3/7

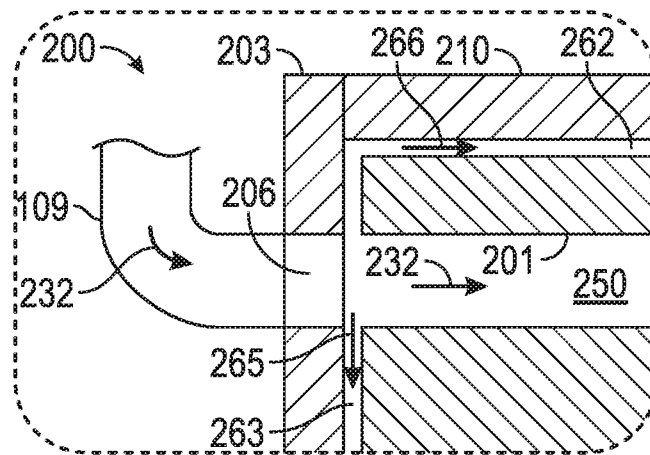


FIG. 8

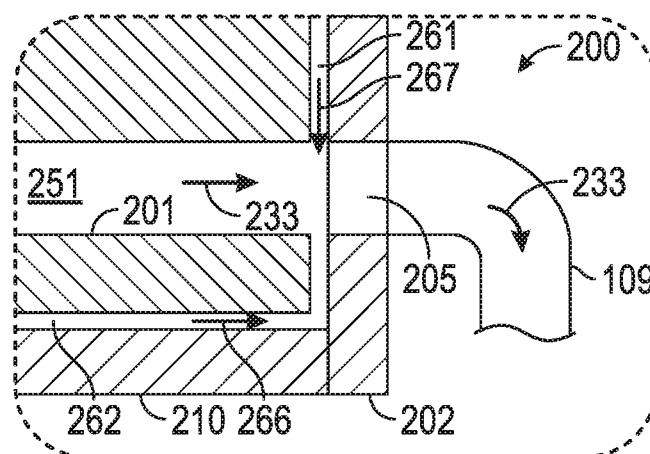


FIG. 9

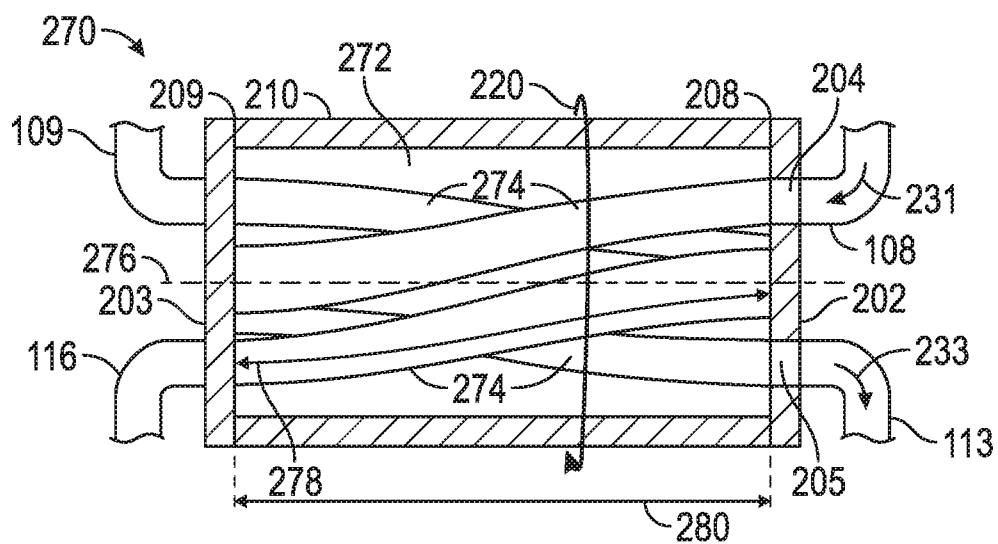
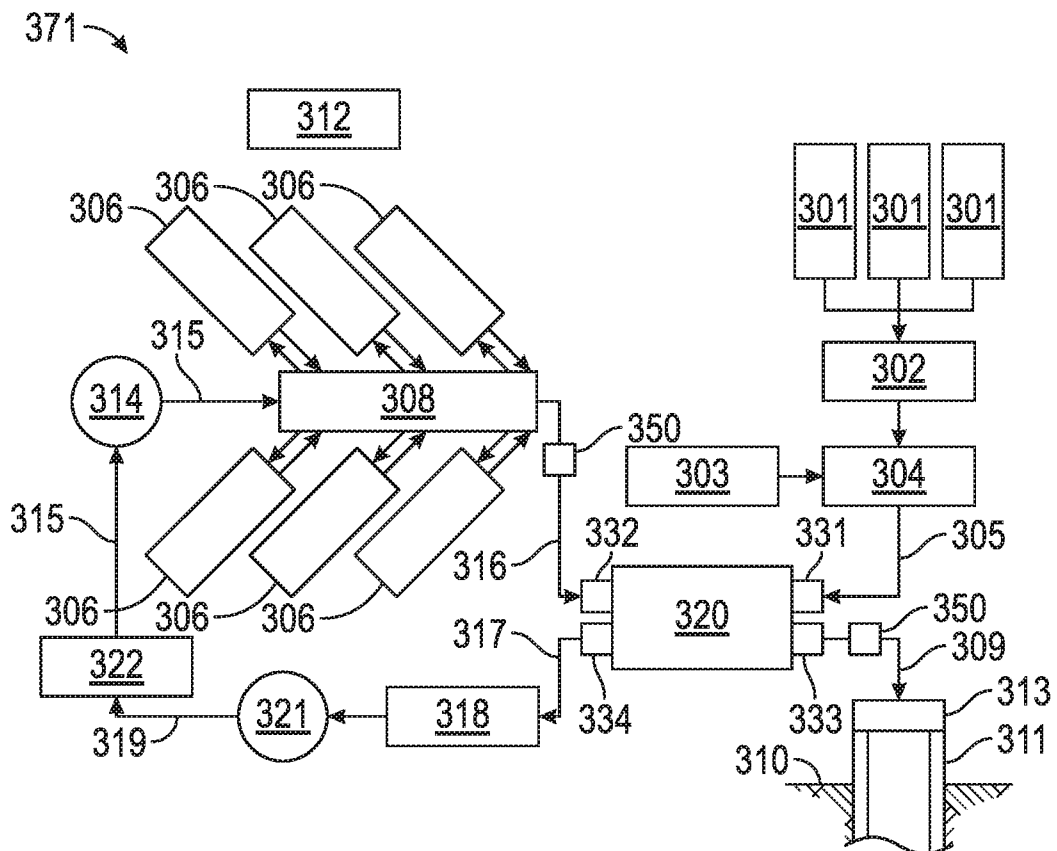
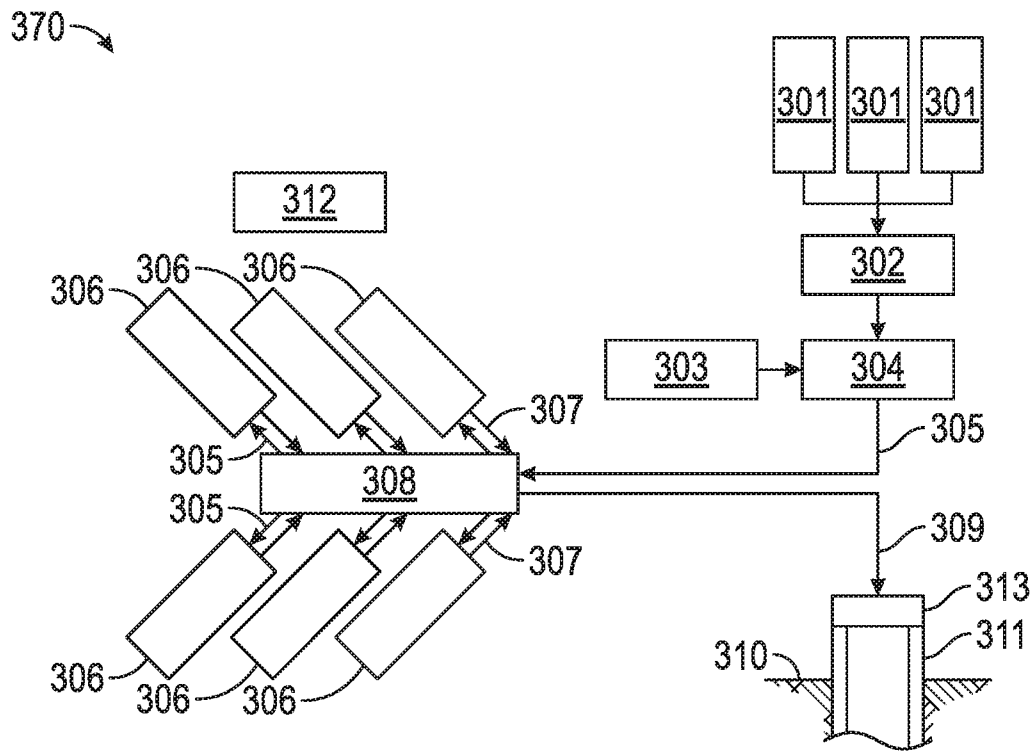
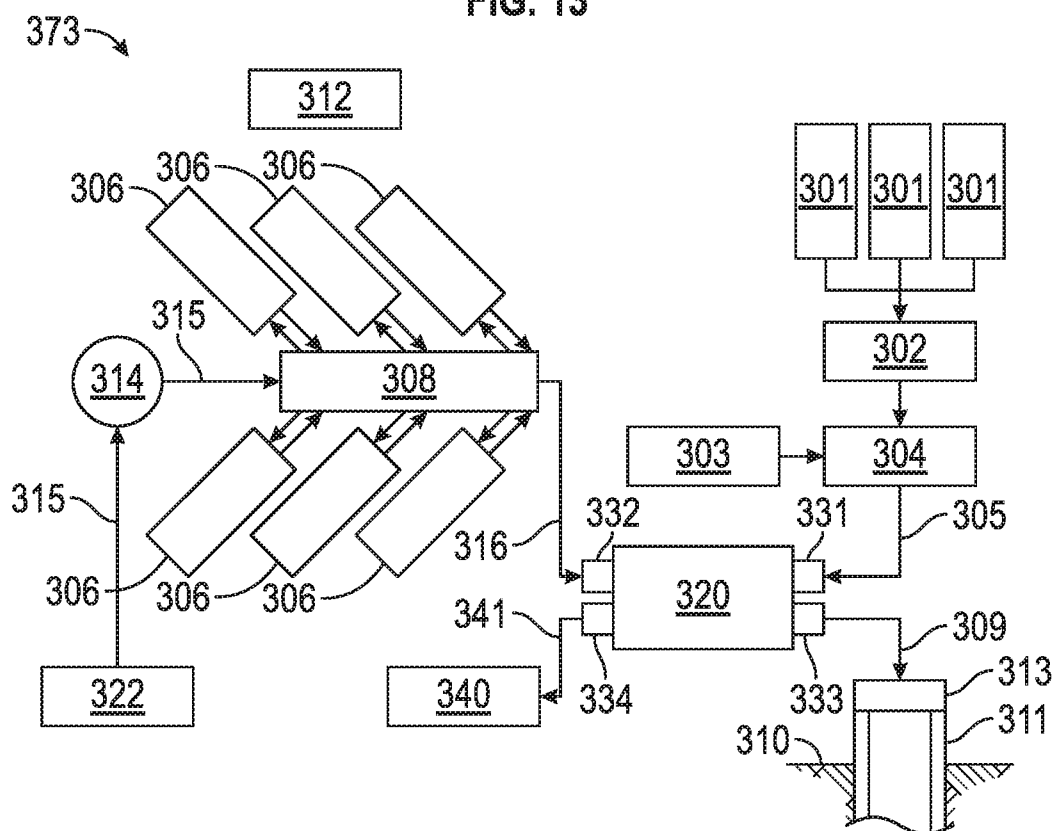
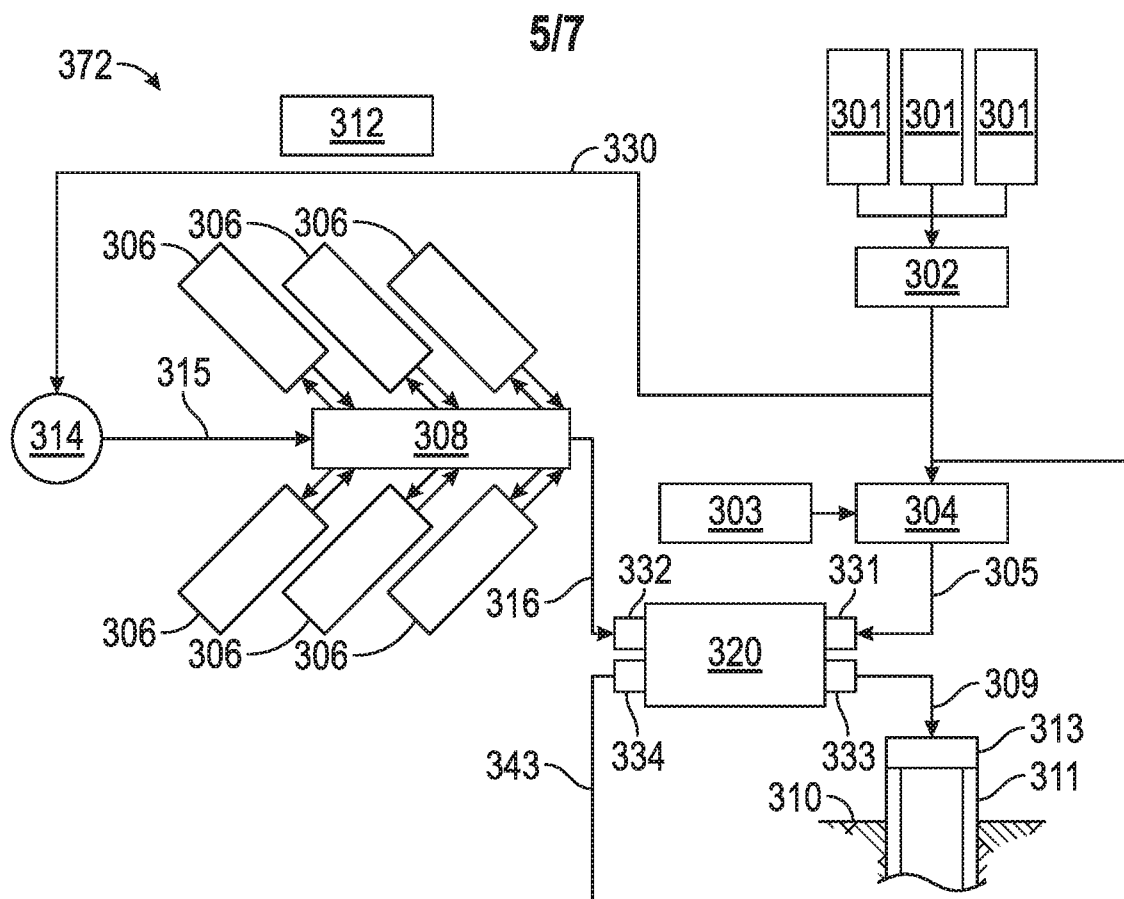


FIG. 10

4/7





6/7

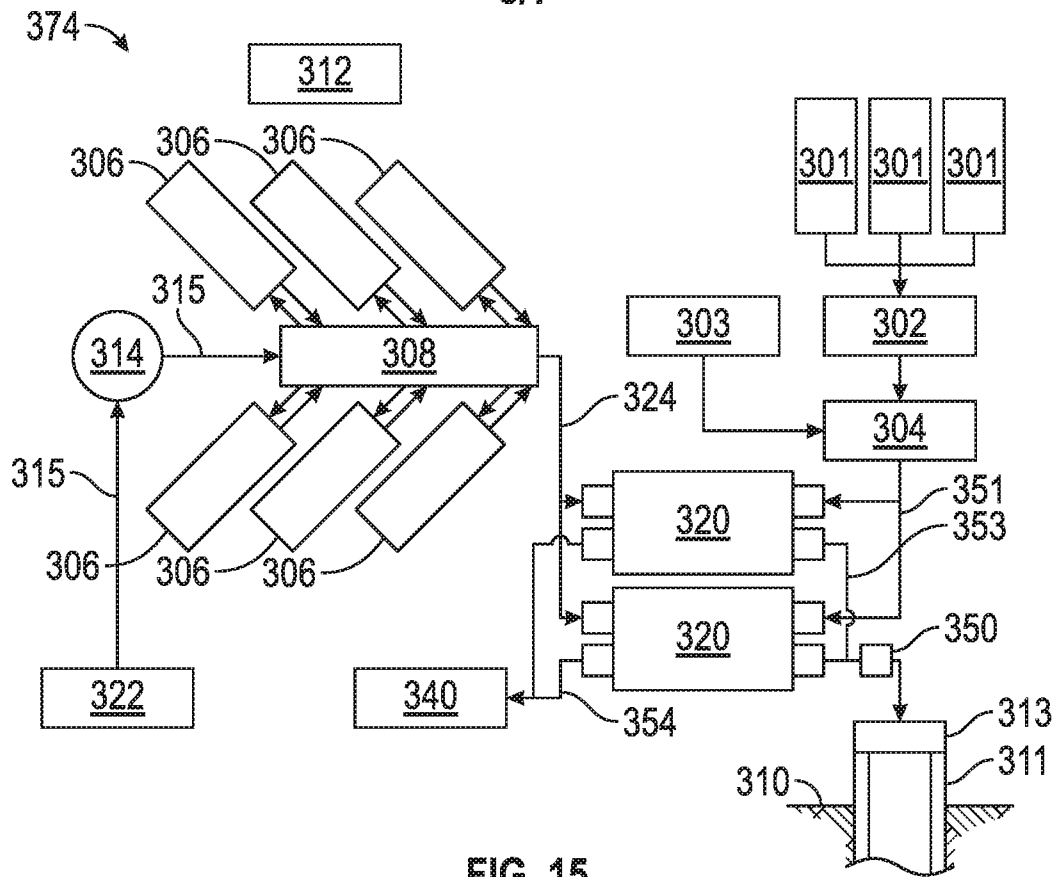


FIG. 15

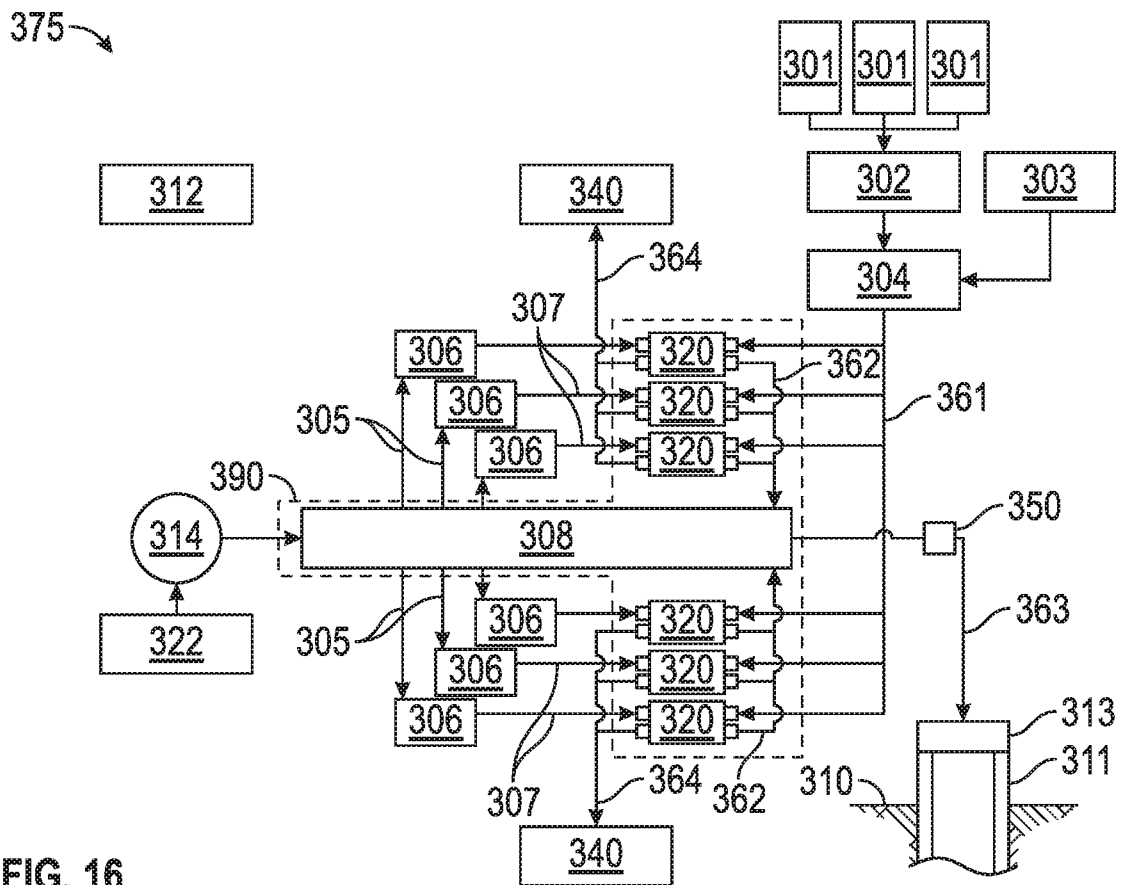


FIG. 16

717

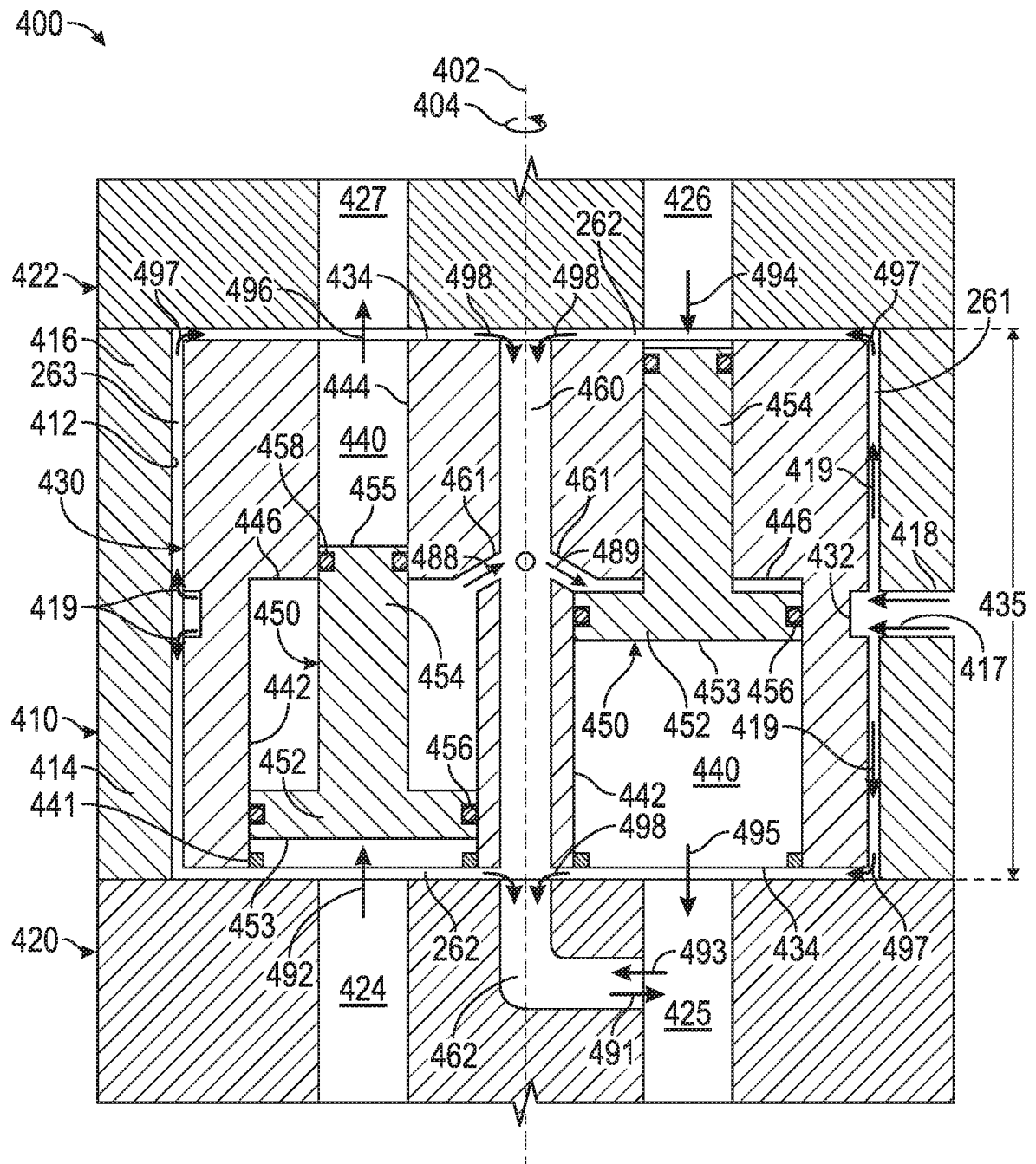


FIG. 17