

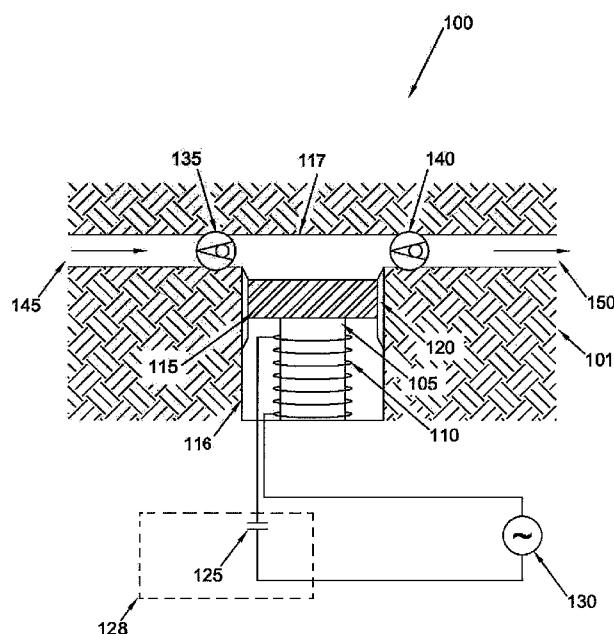


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[Continued on next page]

(54) Title: HYDRAULIC PUMP WITH SOLID-STATE ACTUATOR

FIG. 1



(57) Abstract: A hydraulic pump includes a port and a piston assembly fluidically coupled to the port. The piston assembly includes a piston and a solid-state actuator, where a shape change of the solid-state actuator is induced when a field is applied to the solid-state actuator, and where alternating shape changes of the solid-state actuator provide reciprocating movement to the piston.



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HYDRAULIC PUMP WITH SOLID-STATE ACTUATOR

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 61/451,302, which
5 was filed March 10, 2011 and is hereby incorporated by reference in its entirety.

BACKGROUND

The present disclosure relates to providing hydraulic power and, more particularly, to
providing hydraulic power with a solid-state hydraulic pump that utilizes a solid-state actuator to
drive a piston and thereby provide the force for volumetric displacement of fluid in a piston
10 chamber.

In general, conventional hydraulic pumps may include a piston, a cylinder, and a pump
chamber. The piston may reciprocate within the cylinder to compress or expand the volume of a
pump chamber. One or more valves may provide for opening an inlet and an outlet of the pump
chamber to allow fluid into the pump chamber in an expansion stroke of the piston and fluid out
15 of the chamber in the compression stroke of the piston. A sealing member may be provided
between the cylinder and the piston to prevent the fluid being pumped from leaking into the gap
between the piston and the cylinder.

Conventional pumps often rely on a source of mechanical power such as a motor or an
engine to provide the reciprocating movement to the piston. These conventional pumps have
20 numerous rotating parts and have inherent inefficiencies. These conventional pumps also have a
tendency to heat the fluids that they pump. These conventional pumps also need a large diameter
for the windings and tend to be an inductive electrical load.

It is desirable to provide a pump that has a reduced number of rotating parts, exhibits higher
efficiencies, and has a lower tendency to heat the fluids that it pumps.

25

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present embodiments and advantages thereof may be
acquired by referring to the following description taken in conjunction with the accompanying
drawings, in which like reference numbers indicate like features.

30 Figure 1 is an illustration of a hydraulic pump, in accordance with certain embodiments of
the present disclosure.

Figure 2 is an illustration of a hydraulic pump, in accordance with certain embodiments of the present disclosure.

Figure 3 is an illustration of a hydraulic pump system used to facilitate heat transfer, in accordance with certain embodiments of the present disclosure.

5 Figure 4 is an illustration of a heat pump system, in accordance with certain embodiments of the present disclosure.

Figures 5A, 5B, and 5C are partial illustrations of a completely sealed hydraulic pump, in accordance with certain embodiments of the present disclosure.

10 While embodiments of this disclosure have been depicted and described and are defined by reference to exemplary embodiments of the disclosure, such references do not imply a limitation on the disclosure, and no such limitation is to be inferred. The subject matter disclosed is capable of considerable modification, alteration, and equivalents in form and function, as will occur to those skilled in the pertinent art and having the benefit of this disclosure. The depicted and described embodiments of this disclosure are examples only and are not exhaustive of the
15 scope of the disclosure.

DETAILED DESCRIPTION

20 The present disclosure relates to providing hydraulic power and, more particularly, to providing hydraulic power with a solid-state hydraulic pump that utilizes a solid-state actuator to drive a piston and thereby provide the force for volumetric displacement of fluid in a piston chamber.

25 Illustrative embodiments of the present disclosure are described in detail herein. In the interest of clarity, not all features of an actual implementation may be described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the specific implementation goals, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of the present disclosure.

30 To facilitate a better understanding of the present disclosure, the following examples of certain embodiments are given. In no way should the following examples be read to limit, or define, the scope of the disclosure. Embodiments of the present disclosure may be applicable to horizontal, vertical, deviated, or otherwise nonlinear wellbores in any type of subterranean

formation. Embodiments may be applicable to injection wells as well as production wells, including hydrocarbon wells.

In certain embodiments according to the present disclosure, a solid-state material, such as a magnetostrictive material, may be used to provide movement to a piston that is fluidically coupled to a port. The port may include an inlet and/or an outlet. In certain embodiments, the solid-state material, piston, and port may be within a hydraulic pump. Magnetostrictive materials have the property that, when a magnetic field is applied to the material, a strain is induced in the material, causing a change in the linear dimensions. This strain and change in the linear dimensions of the material may cause movement to a piston within a hydraulic pump. A suitable material for the magnetostrictive material may be Terfenol-D, available from Etrema Products, Inc. Various materials, *e.g.*, iron and iron alloys such as Terfenol, may provide suitable magnetostrictive and giant magnetostrictive responses. A magnetic field may be applied to these materials, *e.g.*, by applying an electric current to a coil surrounding the material or to a loop anywhere else in the magnetic circuit.

Figure 1 is an illustration of one example hydraulic pump comprising a solid-state material to actuate the hydraulic pump, in accordance with certain embodiments of the present disclosure. As shown in Figure 1, a hydraulic pump 100 may include body 101, a solid-state actuator 105, a coil 110, a pump piston 115 in a cylinder 116 to compress or expand the volume of a pump chamber 117, a seal 120, phase balancing electronics 125, a power source 130, an inlet check valve 135, an outlet check valve 140, and ports which may include a low-pressure inlet 145 and a high-pressure outlet 150.

The solid-state actuator 105 may comprise a piezoelectric or magnetostrictive material. The solid-state actuator 105 may be any suitable piezoelectric or magnetostrictive materials include any piezoceramic, piezoelectric, electrostrictive, ferroelectric, relaxor ferroelectric, or magnetostrictive material that that can be driven by an electrical or magnetic input and that provides a mechanical output in the form of a force or motion. When an electric or magnetic field is applied to such materials, the materials change shape in response to the applied field. These materials also usually respond to mechanical force or motion by generating an electric field which produces a voltage across its electrical connections, *e.g.*, across electrodes, or a magnetic field which in turn may produce voltage across a conductor coiled around the materials.

For purposes of the present disclosure, each solid-state actuator 105 is considered to have one or more electrical or magnetic connections and one or more mechanical connections. Each

connection may be considered to be an input or an output or both, depending on whether the actuator is being used at the time to convert electrical energy into force or motion or to convert force or motion into electrical energy. As a result, the solid-state actuator 105 comprising such materials may be used as an actuator and as a sensor. The solid-state actuator 105 may comprise the piezoelectric or magnetostrictive material in the form of a stack, a series of thin plates stacked and wired electrically in parallel. The piezoelectric or magnetostrictive material may also possess a polycrystalline, single crystal, or amorphous structure.

As shown in Figure 1, the coil 110 may be coiled around the solid-state actuator 105. The coil 110 may include a insulated conductor and may be in electrical connection with the power source 130. In certain embodiments, as shown in Figure 1, the balancing electronics 125 may also be in electrical connection with the power source 130 and the coil 110. In certain embodiments, the balancing electronics 125 may include a capacitor. In other embodiments, the balancing electronics 125 may include an inductor. In certain embodiments, the balancing electronics 125 may be used to balance the capacitance of the solid-state actuator 105. In certain embodiments, the balancing electronics 125 may be used to create an electrical resonance. In certain embodiments, the electrical resonance is near the mechanical resonance of the system.

In certain embodiments, a shape change in the solid-state actuator 105 may be induced by applying and/or varying a voltage across the coil 110. The shape change of the piezoelectric or magnetostrictive materials may be controlled by the application of electric or magnetic fields. It should be appreciated that the shape may be controlled in various ways in various embodiments, for example, by using alternative means to vary a magnetic field, such as with a permanent magnet or electromagnet.

In one non-limiting example, a shape change or strain of 0.5% may occur along the long axis of the stack. It should be understood that the shape change or strain may be greater or less than 0.5% with various embodiments. In some embodiments, a small strain such as 0.5% may displace the cross-sectional area of the stack resulting in a net volume change when measured along the primary stack axis. Such shape change may be used to pressurize and pump a fluid in certain embodiments.

In certain embodiments, the hydraulic pump 100 may use the solid-state actuator 105 to provide hydraulic pressure. As shown in Figure 1, the hydraulic pump 100 may comprise the piston 115. The shape changed induced in the solid-state actuator 105 may move the piston up and down, forcing fluid flow from the low-pressure inlet 145 to the high-pressure outlet 150.

The hydraulic pump 100 may further include the inlet check valve 135 and the outlet check valve 140. In some embodiments, the inlet check valve 135 and the outlet check valve 140 may rectify the flow and create a steady flow passage from the low-pressure inlet 145 to the high-pressure outlet 150. In certain embodiments, the inlet check valve 135 and the outlet check valve 140 may comprise reed valves. In other embodiments, a compact system of valves may be needed to rectify the high frequency reciprocating pump output. In some embodiments, simple and compact valves may be used for this purpose. In other embodiments, separate sets of valves may act as check valves. In other embodiments, the valves may be powered by their own solid-state actuators.

The hydraulic pump 100 may further comprise the seal 120. The seal 120 may comprise a seal or a flexure. In some embodiments, the seal 120 may form a seal around the piston 115 to ensure that no fluids come into contact with the solid-state actuator 105. In some embodiments, the seal 120 may be a ring. In some embodiments, the seal 120 may be a baffle. In some embodiments, the seal 120 may comprise an elastomer, a plastic, a metal, a ceramic, or glass.

In some embodiments, each cycle of the pump 100 displaces an amount of fluid proportional to the strain induced in the solid-state actuator 105. In certain cases, the total fluid flow is proportional to the fluid displaced in each cycle and frequency of reciprocation. In some embodiments, frequency synchronization with the hydraulic pumps of the present disclosure may be guaranteed, although the phasing may not be adjustable. While valves have been employed successfully at lower frequencies, their frequency response limited to several thousand Hertz.

In certain embodiments, the hydraulic pumps of the present disclosure may be capable of high-pressure operation with low flow rates. In some embodiments, effective generation of fluid power requires that the hydraulic pumps of the present disclosure operate at a substantial bias pressure. In some embodiments, for pump applications where occasional access is possible, the bias pressure can be set once and then it can be monitored and even adjusted if needed. In other embodiments, such as remote installations, adjustment may be done by different means. In particular, in some embodiments, an accumulator and charge system may function well, but a bootstrapping bias pressurization may be an appropriate secondary method. Bootstrapping may involve additional valves and can be demonstrated to reliably elevate system pressure, but the additional valves require volume and increase the number of components.

Figure 2 is an illustration of a hydraulic pump comprising an arrangement of piston assemblies, in accordance with certain embodiments of the present disclosure. In certain embodiments, a hydraulic pump 200 may comprise a pump body 101 (as shown in Figure 1), one

or more solid-state actuators 105, one or more pistons 115 in one or more cylinders 116 to compress or expand the volume of a pump chamber 117, one or more seals 120, an inlet check valve 135, an outlet check valve 140, a low-pressure inlet 145, and a high-pressure outlet 150. In certain embodiments, the arrangement of piston assemblies may be connected in parallel in the fluid circuit. In certain embodiments, the arrangement of piston assemblies may be electrically driven together in either parallel or series circuit. In some embodiments, an arrangement of piston assemblies provides for more fluid movement per cycle. An increase in fluid movement per cycle may help to overcome the leakiness and the fluidic backlash in the check valves. The arrangement of piston assemblies may have a combination of solid-state actuators that have different electrical loads. A solid-state actuator with a capacitive load (*i.e.*, piezoelectric) may be combined with a solid-state actuator with an inductive load (*i.e.*, magnetostrictor) to create a balanced electric load. A check valve may be located between the plurality of piston assemblies in case the different piston assemblies are not being driven in phase. Other parts may be in between the piston assemblies, such as a thermal radiator or a hydraulic accumulator.

Figure 3 is an illustration of a hydraulic pump system that may be used to facilitate heat transfer, in accordance with certain embodiments of the present disclosure. As shown in Figure 3, a hydraulic pump 300 may pass fluid through one or more radiators 310, over a circuit board 320, and through one or more radiators 310. Elements in the system may be fluidically coupled with a conduit assembly, which may include any suitable connections, piping, tubing, hose, *etc.* As depicted, the hydraulic pump system may be a closed-loop system. The fluid passed over the circuit board 320 may absorb heat generated from the circuit board 320 and radiate the heat to the environment through the one or more radiators 310. A radiator 310 may be any suitable heat exchanger to receive the fluid and transfer heat from the fluid passing therethrough to an exterior area adjacent to the radiator. In some embodiments, the hydraulic pump 300 may comprise each of the same components included in the hydraulic pump 100 discussed above with respect to Figure 1. In certain embodiments, the hydraulic pump 300 may need less pressure but operates at increased flow rates than conventional pumps. In other embodiments, the hydraulic pump 300 operates with a higher efficiency than conventional pumps. In other embodiments, the hydraulic pump 300 may pass fluid through conduits created on the surface of the circuit board 320 or on the interior of the circuit board 320.

Figure 4 is an illustration of a heat pump system, in accordance with certain embodiments of the present disclosure. As shown in Figure 4, a hydraulic pump 400 may pass fluid through one or more radiators 410, through one or more expansion valves 420, and over one or more

electronics 430. Elements in the system may be fluidically coupled with a conduit assembly, and the hydraulic pump system may be a closed-loop system, similar to the system of Figure 3. In some embodiments, the hydraulic pump 400 may comprise each of the same components included in the hydraulic pump 100 discussed above with respect to Figure 1.

5 In certain embodiments, the hydraulic pump 400 may heat the fluid when it compresses the fluid. In certain embodiments, the fluid may then be cooled when it passes through the radiator 410. Additionally, in certain embodiments, the one or more expansion valves 420 may allow the fluid to expand and further cool. The fluid may then pass over the one or more electronics 420 and absorb heat.

10 In certain embodiments, a hydraulic pump according to the present disclosure may be employed to charge a hydraulic accumulator. The stored hydraulic energy in the accumulator may be used for any suitable downhole purpose. For example, the energy stored in the hydraulic accumulator may be used to move a downstream valve, piston, sliding side door, *etc.* Using the example of Figure 4, the hydraulic pump 400 may be coupled to a hydraulic accumulator in lieu
15 of the radiator 410 shown. And, instead of the downstream components 420, 430 depicted in Figure 4, any suitable downstream components may be coupled in fluidic communication with upstream accumulator.

Referring again to the example of Figure 1, the hydraulic pump 100 may be provided with control electronics 128. The control electronics 128 may include phase balancing electronics
20 125 or may be provided separately. Though not shown, control electronic 128 also may be provided with any of the embodiments illustrated in Figures 2-4. In certain embodiments, control electronics 128 (which may include, *e.g.*, a microprocessor) may be configured to drive the pump to provide flow control and/or provide pressure control. By way of non-limiting
25 example, the flow control may be provided by controlling a frequency of excitation; the pressure control may be provided by controlling drive amplitude and/or by controlling excitation. In certain embodiments, generic digital control may be provided from memory and/or an outside controller to provide programmable arbitrary flow control and/or pressure control. In certain
embodiments, digital control may be tied to temperature, pressure, flow, and/or another hydraulic pump used in a sense mode. Certain embodiments may be configured to have the
30 capability to duplicate pressure and/or flow of coupled hydraulic and may thereby act as a hydraulic amplifier.

Control electronic 128 also may be provided to two or more pumps. In certain embodiments, a plurality of pumps may be coupled and configured to operate generally

synchronously. The plurality of pumps may operate mutually out of phase to reduce ripple. A plurality of pumps or sets of pumps may be controlled to operate one set to provide a gross setting (possibly using a physically larger, optimized pump) and other sets to trim/fine tune.

5 Certain embodiments may include a plurality of pumps (or sets of pumps). In certain embodiments, one pump or set of pumps may provide a gross setting, with another providing constructive flow/pressure, and with a third that is reversed to provide destructive flow/pressure to provide for greater gross setting and additional trimming/fine tuning. An accumulator also may be provided to further decrease ripple. For an optional ability to control the solid-state actuator, electronics (with one or more controller(s), memory, drive circuitry, electronic
10 communication interface) can be used with a variety of sensors (including this invention) to measure pressure, flow, displacement, *etc.*, in and/or out).

Figures 5A, 5B, and 5C are partial illustrations of a completely sealed hydraulic pump 500, in accordance with certain embodiments of the present disclosure. The hydraulic pump 500 may include certain elements previously disclosed herein, such as a pump body 101, a solid-state
15 actuator 105, a coil 110, a pump piston 115, and a port that may include a high-pressure outlet 150. However, the hydraulic pump 500 eliminates seals in operation to eliminate the potential for system leaks in conventional pumps, which may leak either in control elements (check valves, solenoids, *etc.*) and/or between the oil volume and the exterior. Thus, the hydraulic pump 500 may be useful in a variety of applications including but not limited to uses as a jacking
20 device, manipulating the control surfaces in aircraft, boats, *etc.* Using any suitable method, the hydraulic section may be closed off so that the assembly would be virtually free of moving parts, wear and contaminant creation, contaminant ingress and, properly designed immune to pressure. In various embodiments, suitable methods may include but not be limited to metal-to-metal-seals, weldments, compression fittings, possibly welded closed, *etc.* As depicted in Figure 5A, the
25 hydraulic pump 500 may include a bellows 510 coupled to the piston 115 on the outlet side for the production of output pressure in conjunction with actuation of the piston 115. In certain embodiments, a spring 505 disposed between the piston 115 and the pump body 101 may provide resiliency for the piston cycle.

Figures 5B and 5C illustrate alternative embodiments of the hydraulic pump 500. Instead
30 of including the piston 115, bellows 510, and spring 505 configuration, the solid-state actuator 105 may be configured to directly actuate a compliant element 520 (Figure 5B) or a diaphragm 525 (Figure 5C). The compliant element 520 may be any suitable compliant body with a shape and resilient material in the non-limiting example depicted, the solid-state actuator 105 is

configured to directly contact a convex side of the compliant element 520. Likewise, the diaphragm 525 may be any suitable bellows-type element with a shape and resilient material to provide an output pressure to the outlet 150 upon actuation of the solid-state actuator 105 and a return force upon relaxation of the solid-state actuator 105.

5 While the hydraulic pump 500 is depicted by way of examples without limitation in Figures 5A-5C as each including a single assembly for the solid-state actuator 105, certain embodiments may include a plurality of the solid-state actuators 105. Any number of the solid-state actuators 105 of may work on the pump piston 115, the compliant element 520, or other suitable surface to provide added power, force, and displacement. As a non-limiting example, a plurality of the
10 solid-state actuators 105 on the order of thousands, tens of thousands, or more, may work in conjunction on one or more suitable surfaces, and, for example, may be on a nanometric scale. Additionally, certain embodiments may be implemented in medical applications, with, for example, the solid-state actuators 105 configured to mimic the peristaltic motion of the esophagus, the motion of the diaphragm, bowels, heart, etc.

15 Therefore, the present disclosure is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed above are illustrative only, as the present disclosure may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein
20 shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the present disclosure. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. The indefinite articles “a” or “an,” as used in the claims, are defined herein to mean
25 one or more than one of the element that that a particular article introduces; and subsequent use of the definite article “the” is not intended to negate that meaning.

WHAT IS CLAIMED IS:

1. A hydraulic pump comprising:
a port;
a piston assembly fluidically coupled to the port, wherein the piston assembly comprises:
5 a piston; and
2. a solid-state actuator, wherein a shape change of the solid-state actuator is induced when a field is applied to the solid-state actuator, and wherein alternating shape changes of the solid-state actuator provide reciprocating movement to the piston. The hydraulic pump of claim 1, wherein the field is a magnetic field.
- 10 3. The hydraulic pump of claim 1, wherein the field is an electric field.
4. The hydraulic pump of claim 1, wherein the port comprises an inlet or an outlet.
5. The hydraulic pump of claim 1, wherein the solid-state actuator comprises one or both of a magnetostrictive material and a piezoelectric material.
6. The hydraulic pump of claim 1, wherein the piston assembly further comprises:
15 a coil disposed about the solid-state actuator to apply the field to the solid-state actuator.
7. The hydraulic pump of claim 1, further comprising an inlet valve and an outlet valve to rectify fluid flow through the port.
8. The hydraulic pump of claim 1, further comprising an inlet valve and an outlet valve fluidically coupled to the piston to facilitate a steady flow passage.
- 20 9. The hydraulic pump of claim 1, wherein the solid-state actuator comprises a stack of plates connected in parallel, wherein the plates comprise piezoelectric material or magnetostrictive material.
10. The hydraulic pump of claim 1, wherein the piston assembly is part of an arrangement of piston assemblies to be driven together.
- 25 11. The hydraulic pump of claim 10, wherein the arrangement of piston assemblies is to be driven in parallel.
12. The hydraulic pump of claim 10, wherein the arrangement of piston assemblies is to be driven in series.
13. The hydraulic pump of claim 1, wherein the piston assembly further comprises a seal
30 disposed between the piston and a cylinder to allow the piston to sealingly reciprocate within the cylinder.

14. A method of pumping fluid with a hydraulic pump comprising a solid-state actuator, the method comprising:

providing a hydraulic pump comprising:

a port; and

5 a piston assembly fluidically coupled to the port, wherein the piston assembly comprises:

a piston; and

a solid-state actuator, wherein a shape change of the solid-state actuator is induced when a field is applied to the solid-state actuator, and wherein alternating shape changes
10 of the solid-state actuator provide reciprocating movement to the piston;

applying a varying field to the solid-state actuator to induce the series of shape changes of the solid-state actuator and provide the reciprocating movement to the piston; and

displacing at least a portion of a fluid through the port.

15. The method of claim 14, further comprising:

15 fluidically coupling the hydraulic pump to a radiator to receive pumped fluid from the hydraulic pump, wherein the radiator transfers heat from the pumped fluid to an exterior area adjacent to the radiator.

16. The method of claim 15, further comprising:

20 fluidically coupling the hydraulic pump to a closed-loop conduit assembly, wherein at least a portion of the closed-loop conduit assembly is proximate to a heat source.

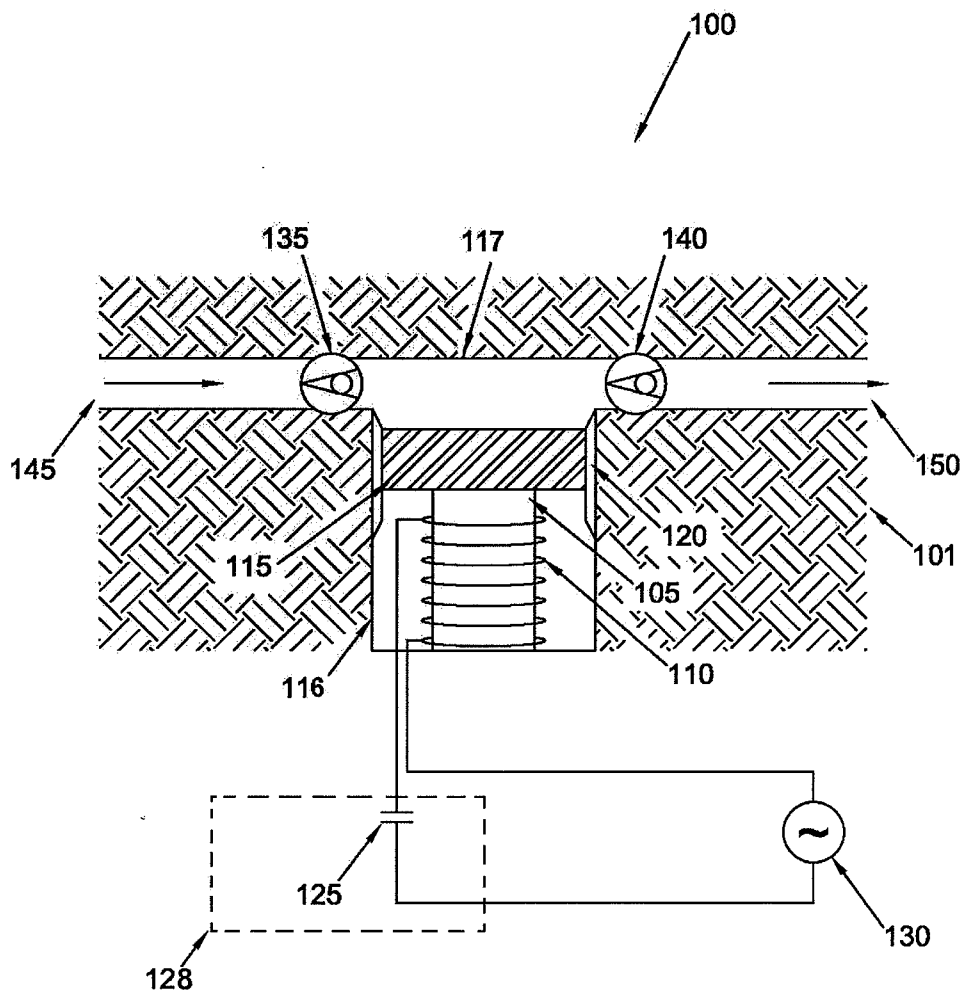
17. The method of claim 14, wherein the field is a magnetic field.

18. The method of claim 14, wherein the field is an electric field.

19. The method of claim 14, wherein the solid-state actuator comprises a magnetostrictive material.

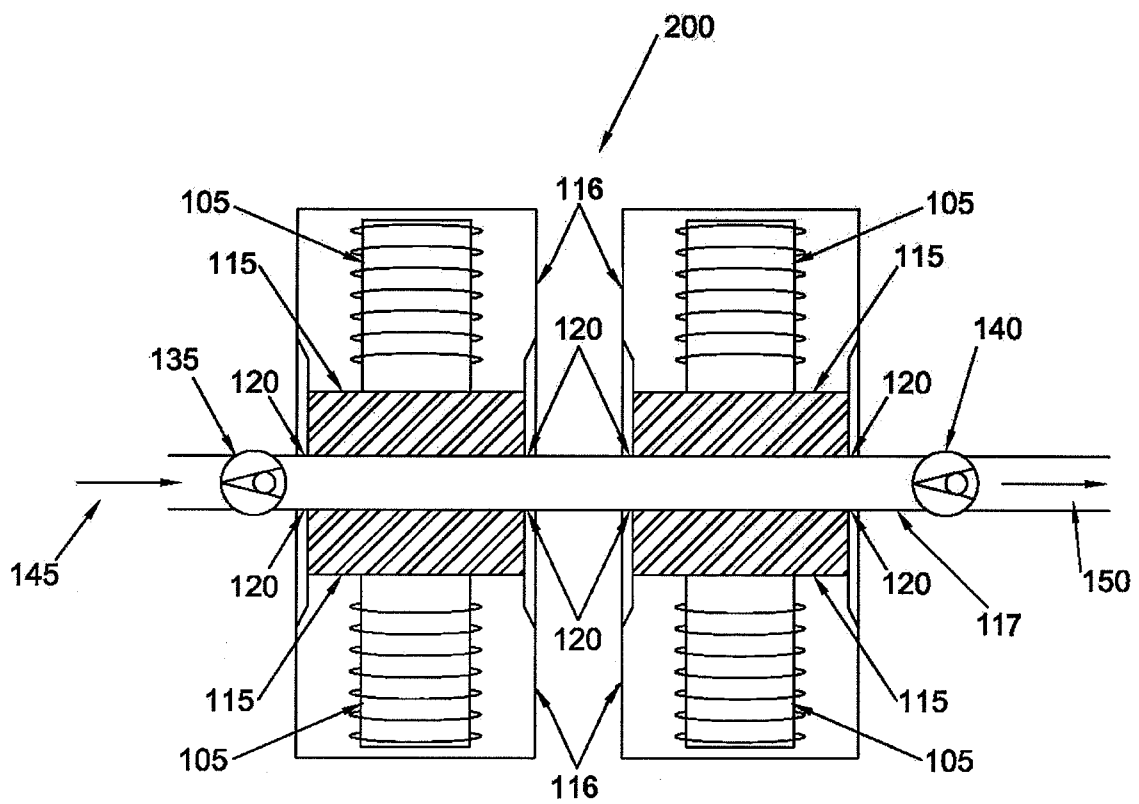
25 20. The method of claim 14, wherein the solid-state actuator comprises a piezoelectric material.

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FIG. 1



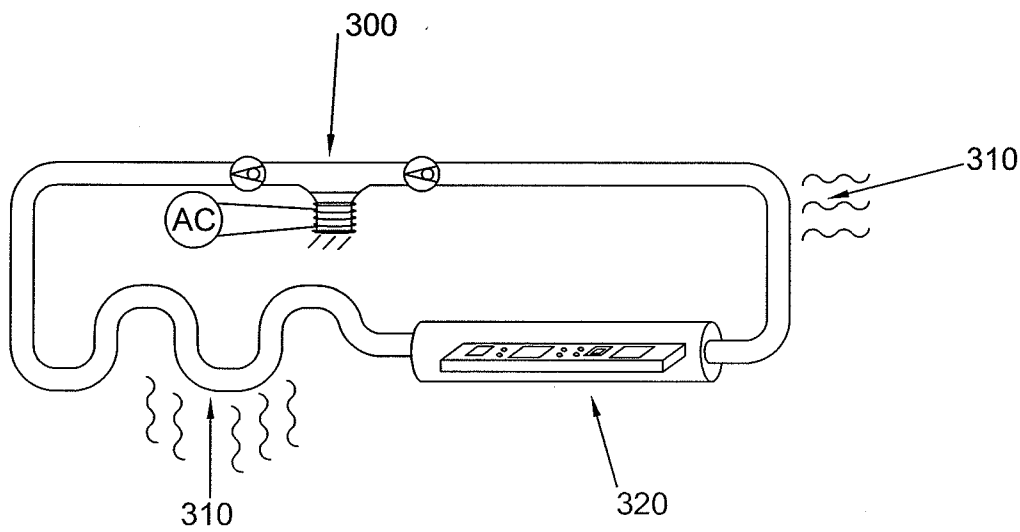
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FIG. 2



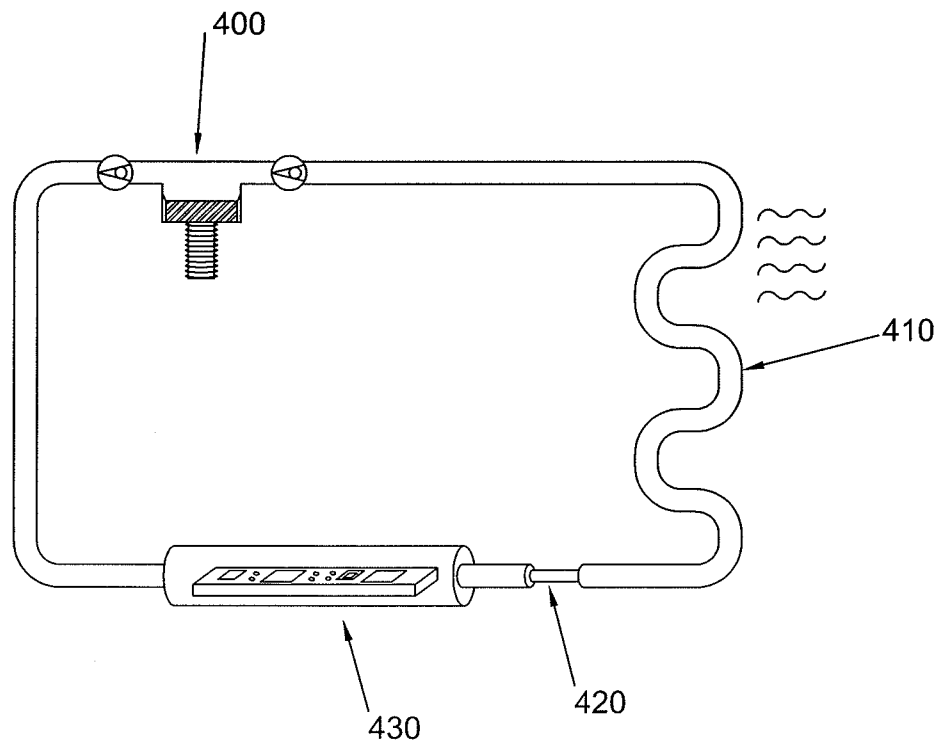
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FIG. 3



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FIG. 4



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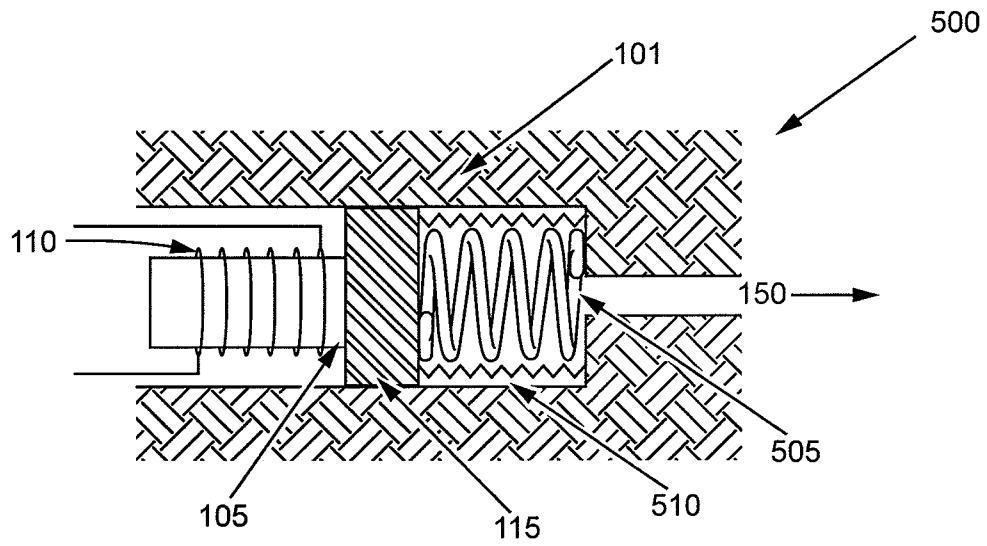


FIG. 5A

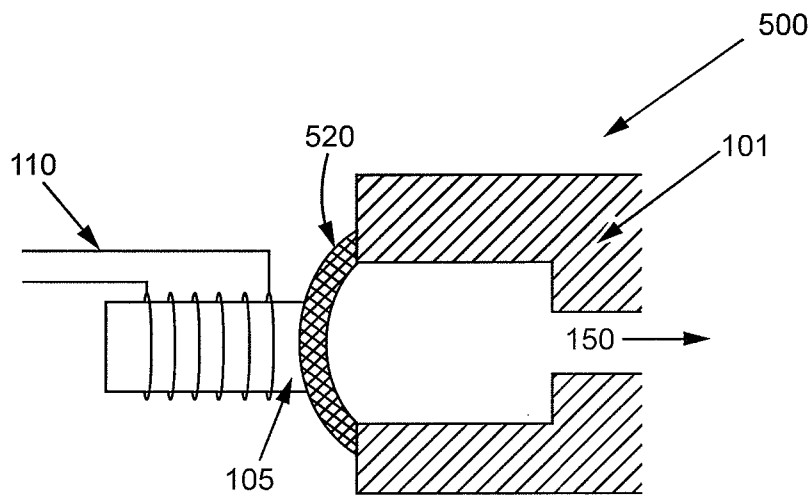


FIG. 5B

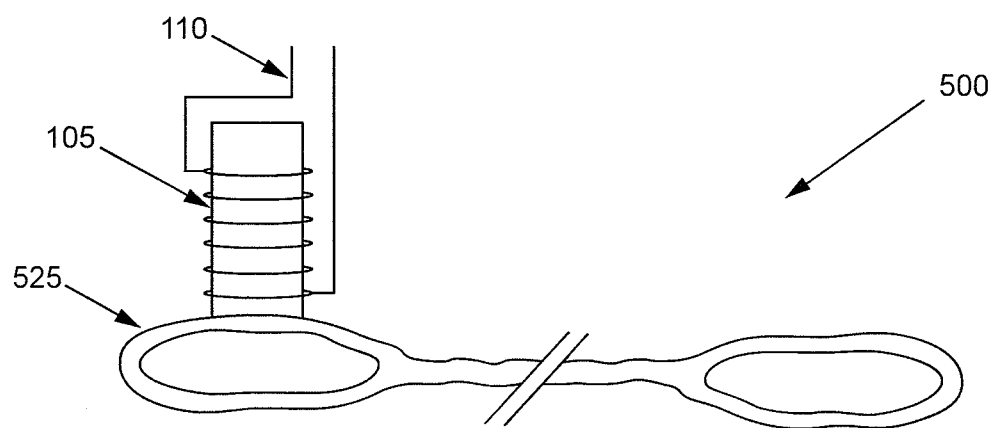


FIG. 5C