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(54) **COMPRESSION/EXPANSION PROCESS THAT ALLOWS TEMPERATURE TO VARY INDEPENDENT OF PRESSURE**

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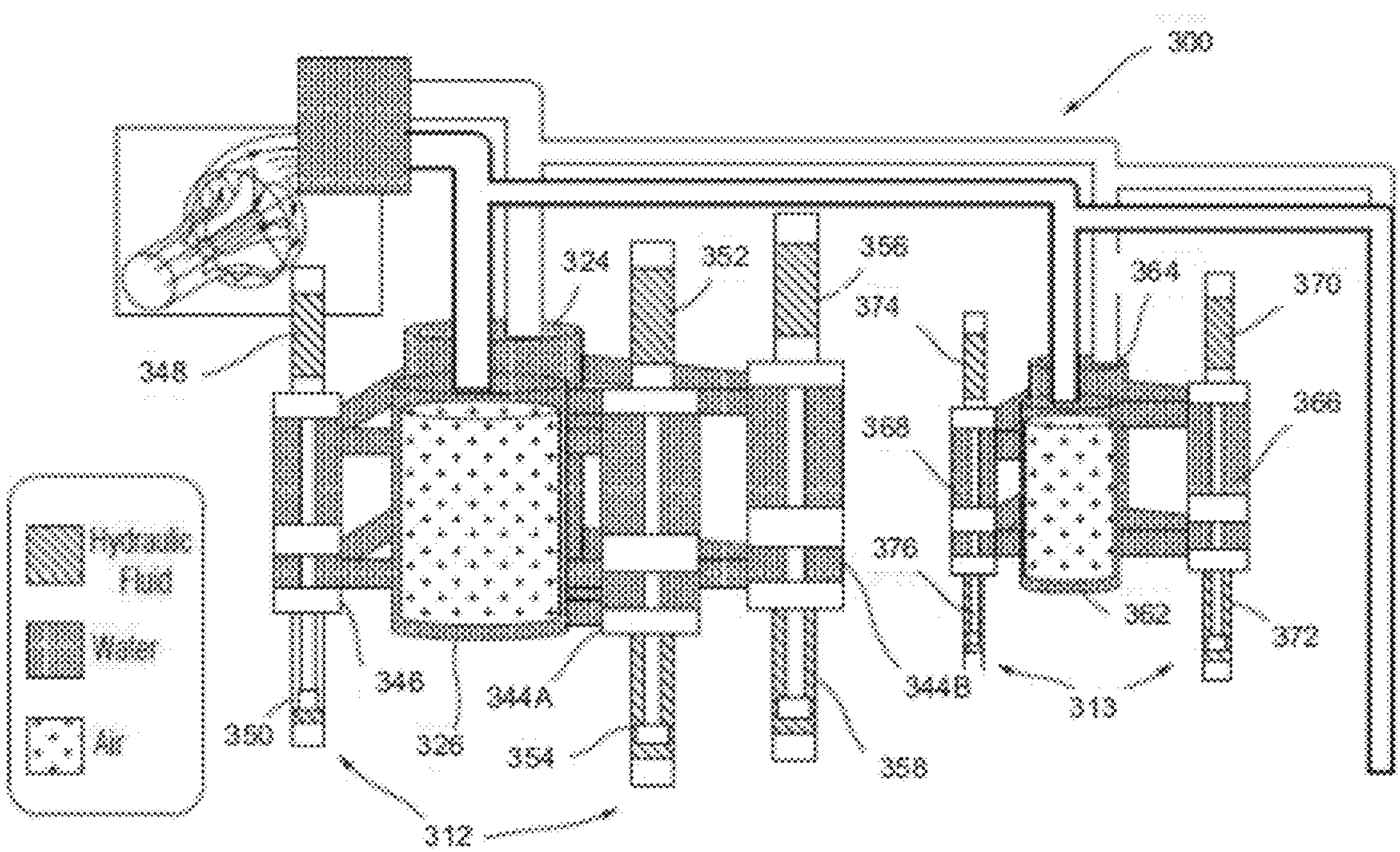
(57) **ABSTRACT**

Systems and methods are described herein to operate an air compression and/or expansion system in its most efficient regime, at a desired efficiency, and/or achieve a desired pressure ratio independent of discharge temperature, with little to no impact on thermal efficiency. For example, systems and methods are provided for controlling and operating hydraulic pumps/motors used within a hydraulically actuated device/system, such as, for example, a gas compression and/or expansion energy system, in its most efficient regime, continuously, substantially continuously, intermittently, or varied throughout an operating cycle or stroke of the system to achieve any desired pressure and temperature profile. Such systems and methods can achieve any desired pressure ratio independent of input or discharge temperature, and can also achieve any desired discharge temperature independent of pressure ratio, without altering any of the structural components of the device or system.



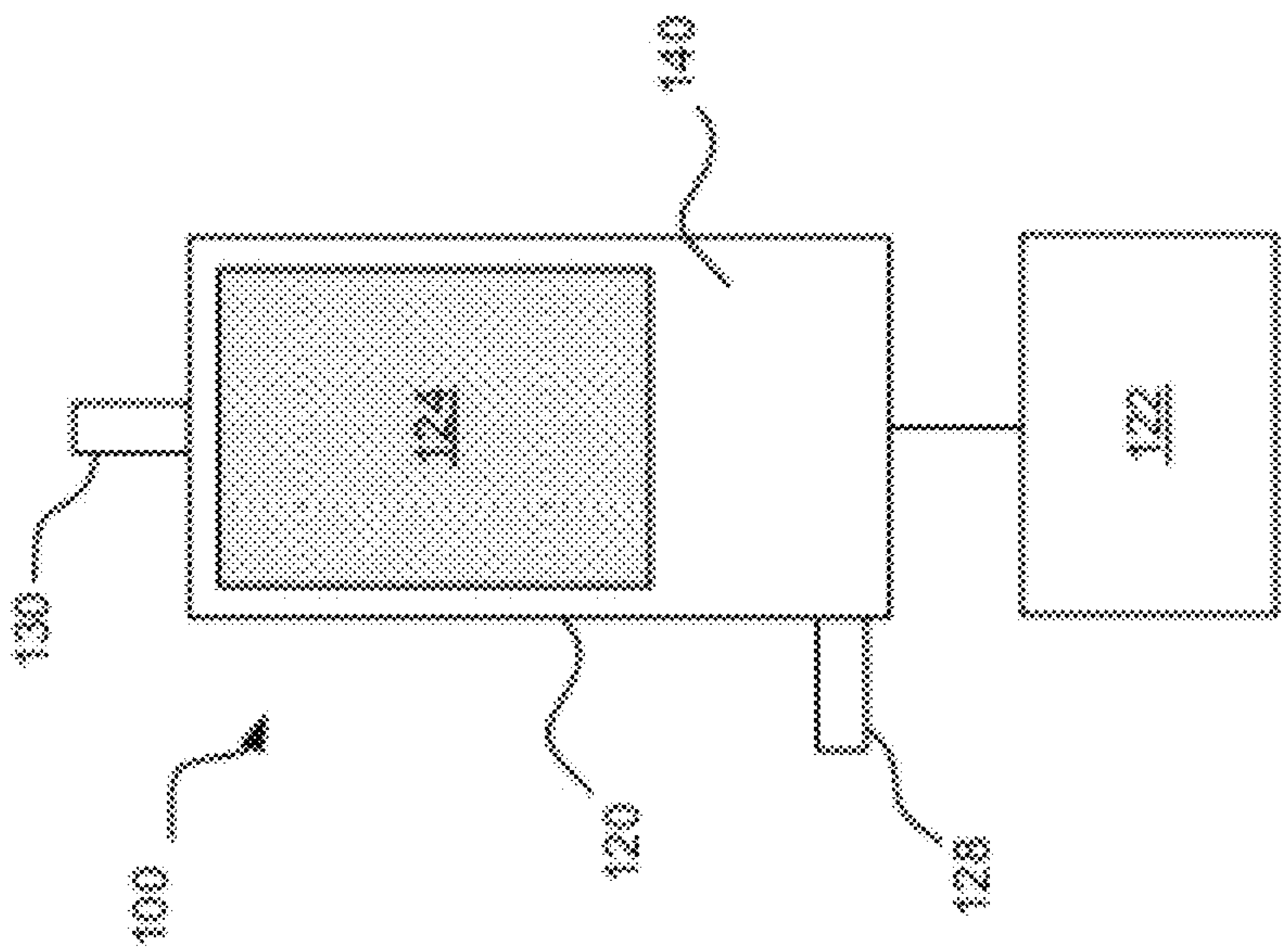


FIG. 1

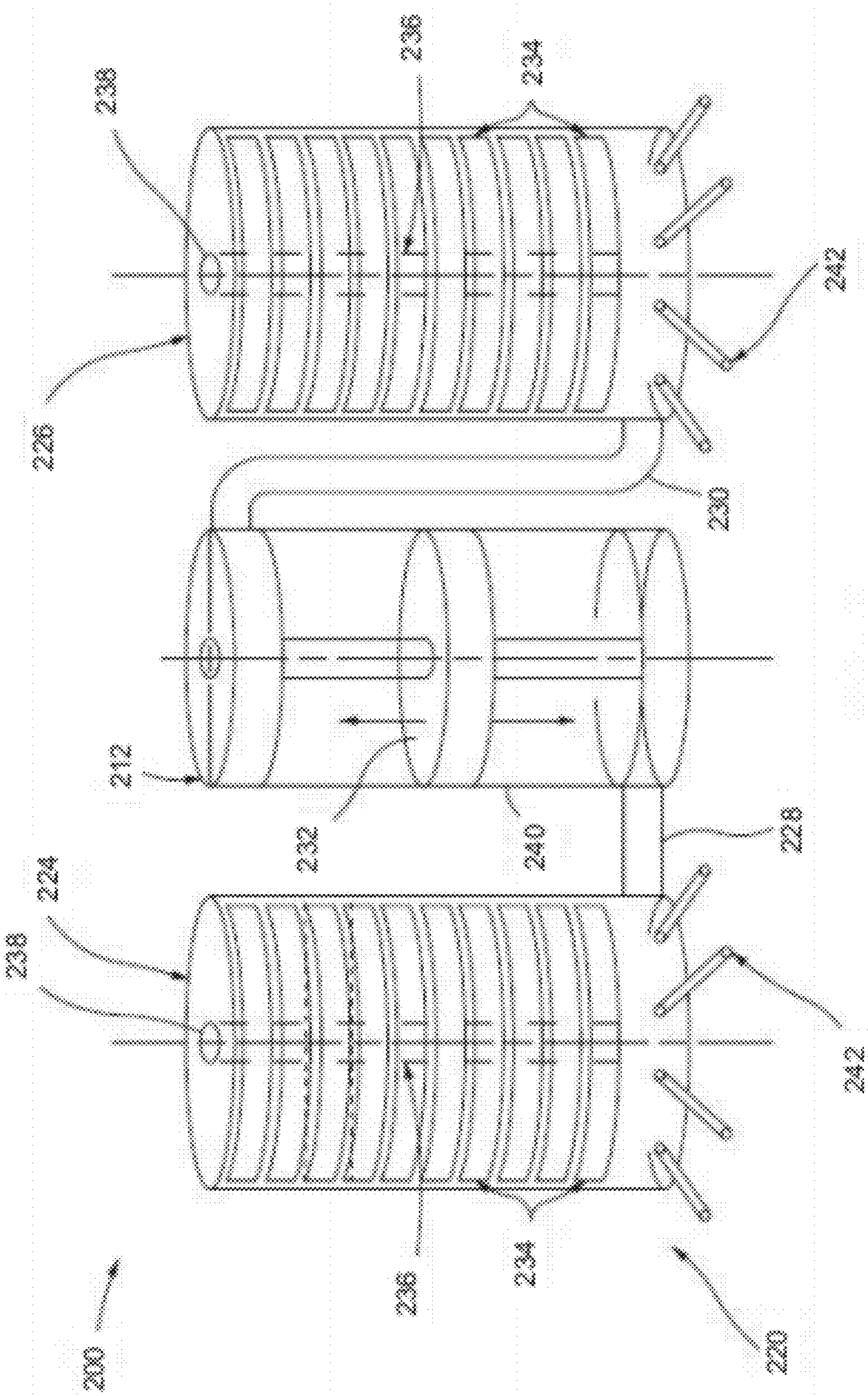

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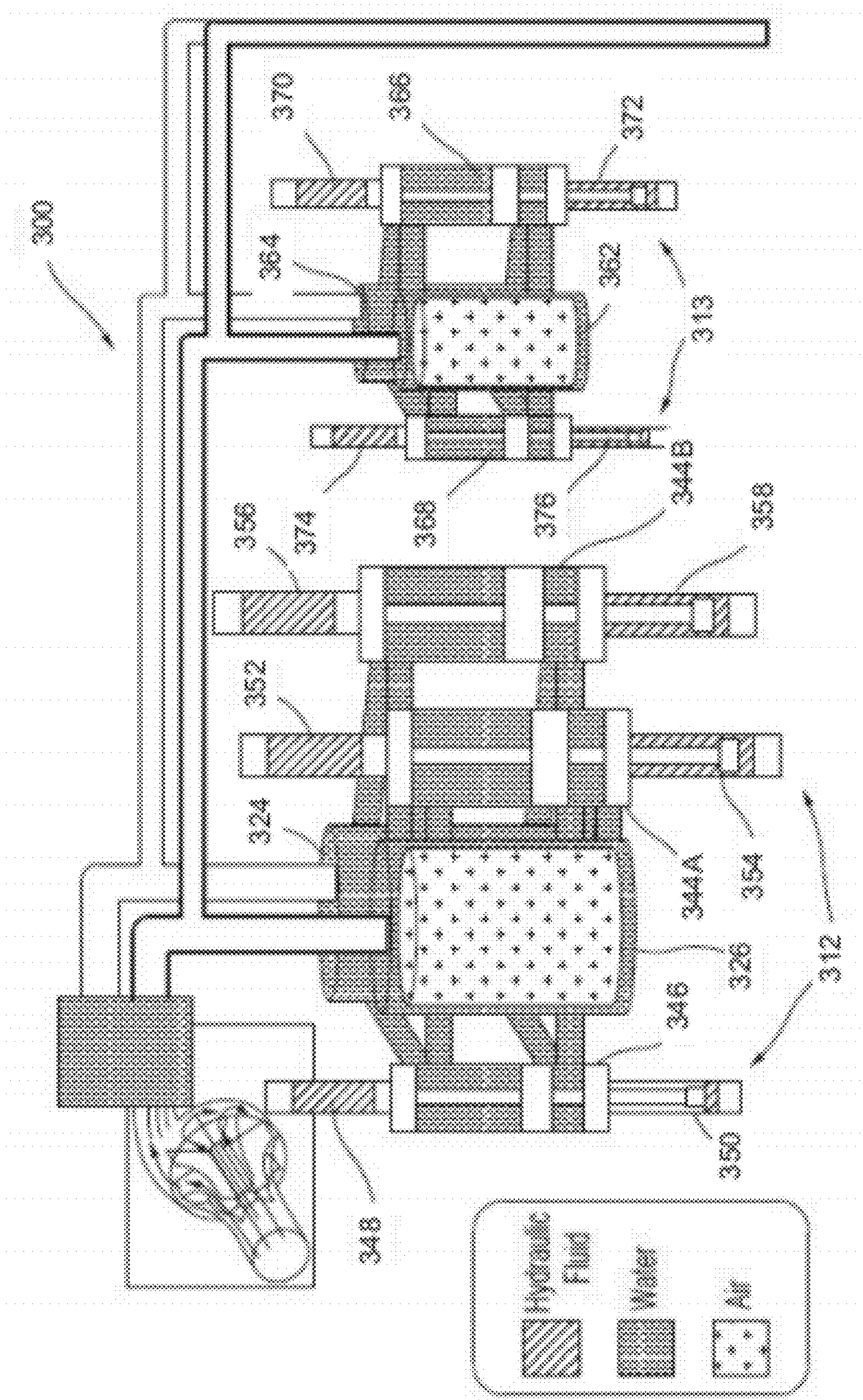
FIG. 2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366
372
364
362
313
374
368
376
344B
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358
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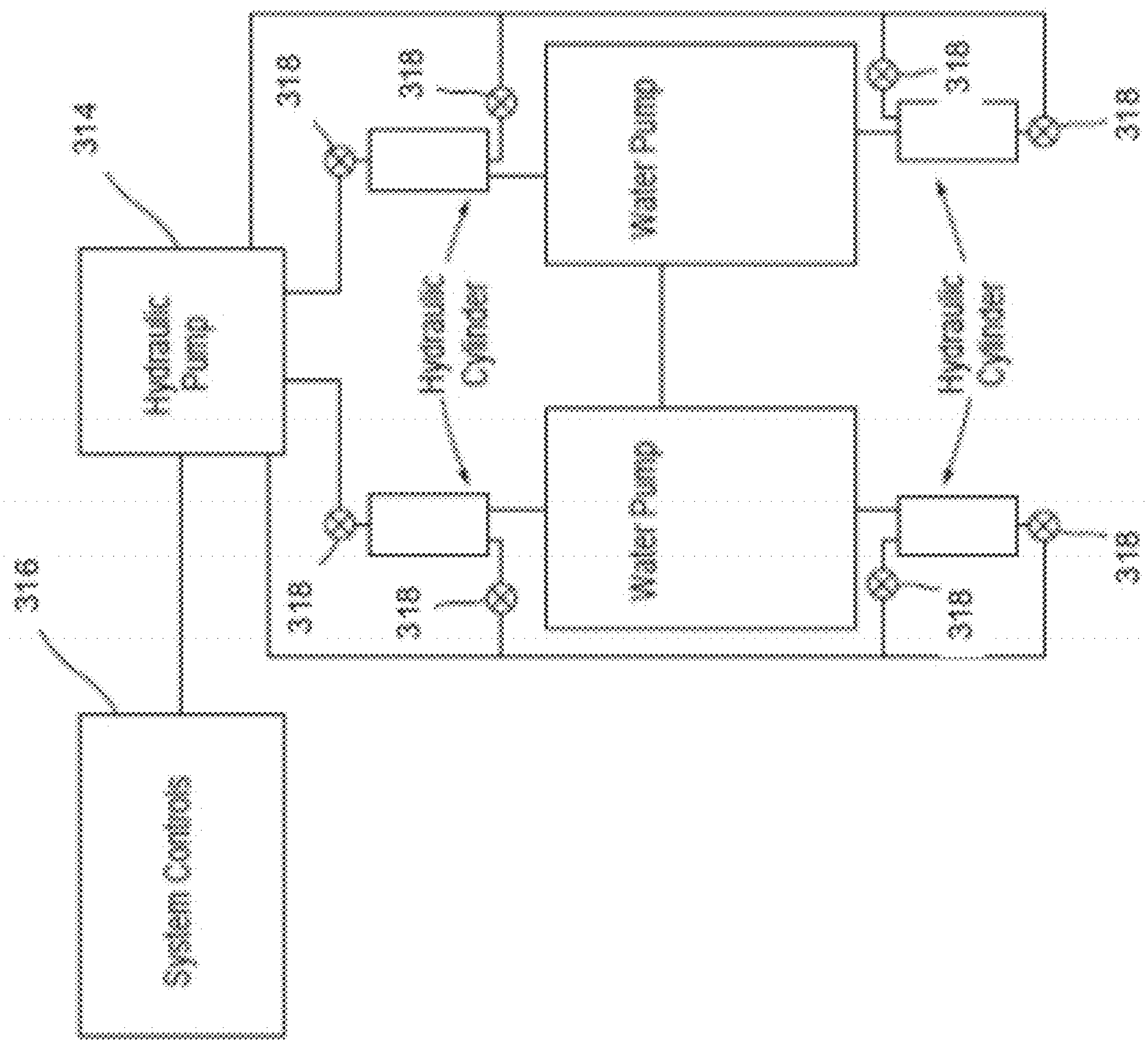
344A
354
312
326
346
350
348
Hydraulic Fluid
Water
Air

FIG. 3A

FIG. 3B



314
Hydraulic Pump
316
System Controls
318
Hydraulic Cylinder
Water Pump
Water Pump
Hydraulic Cylinder

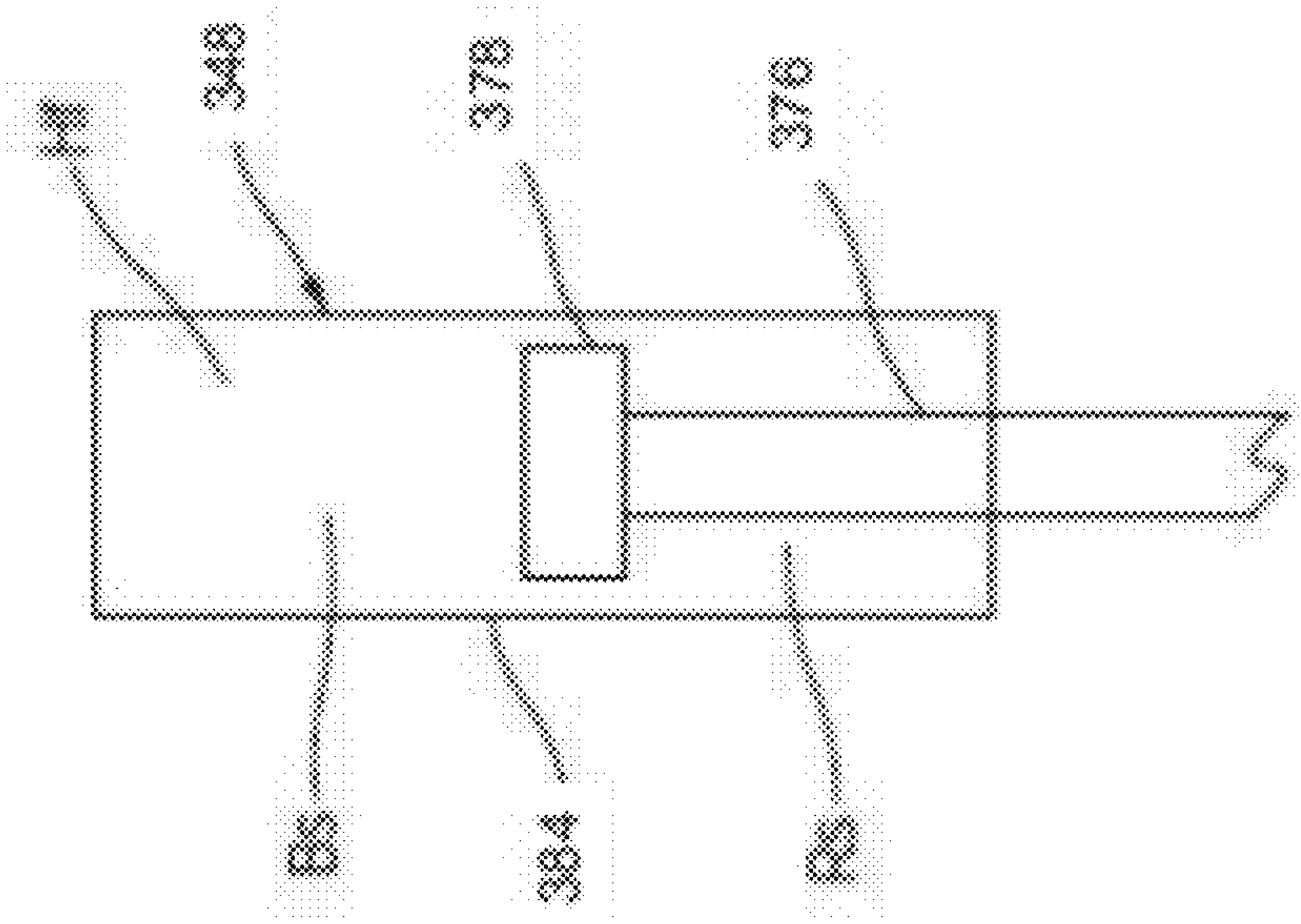


FIG. 4B

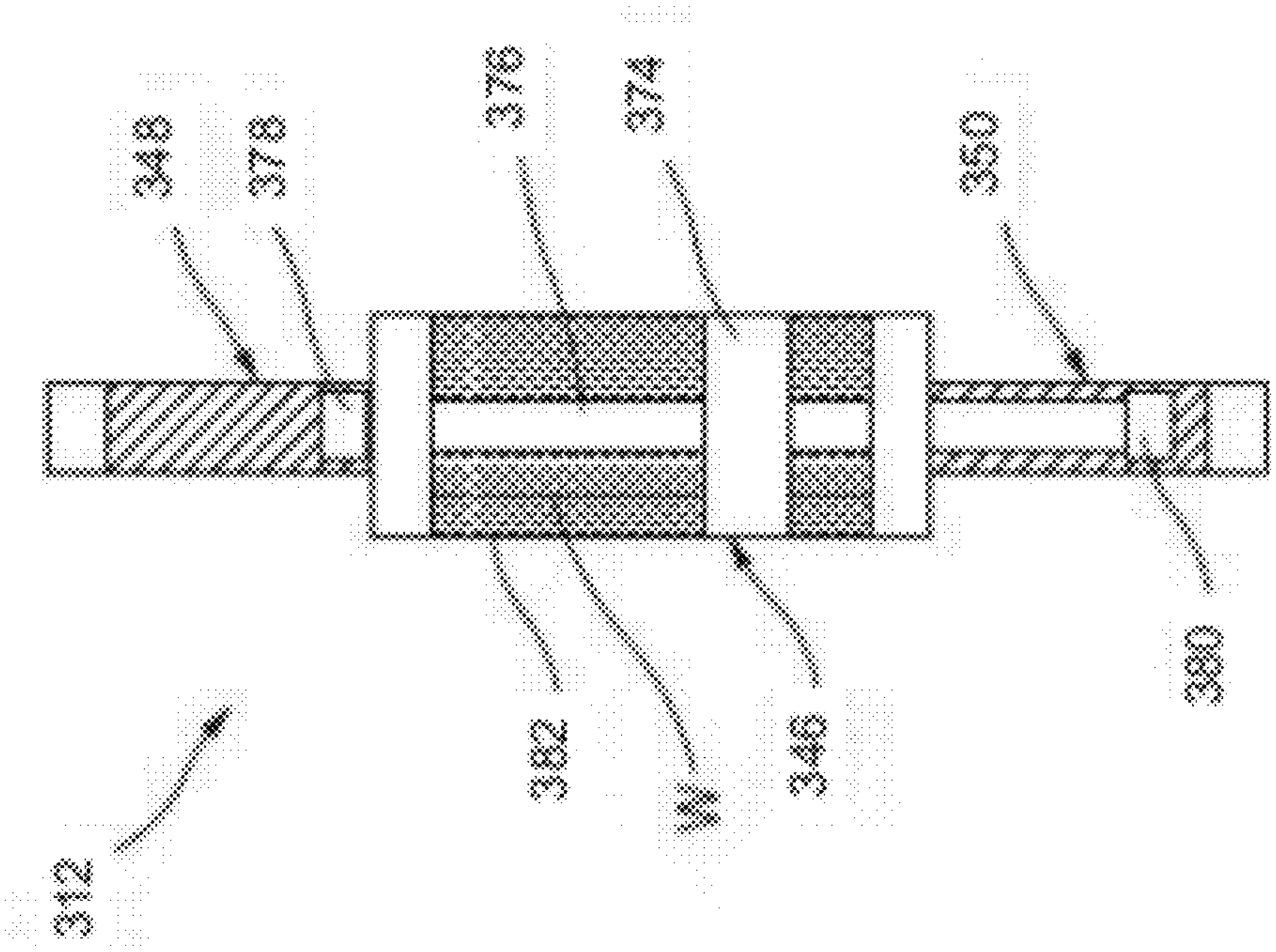


FIG. 4A

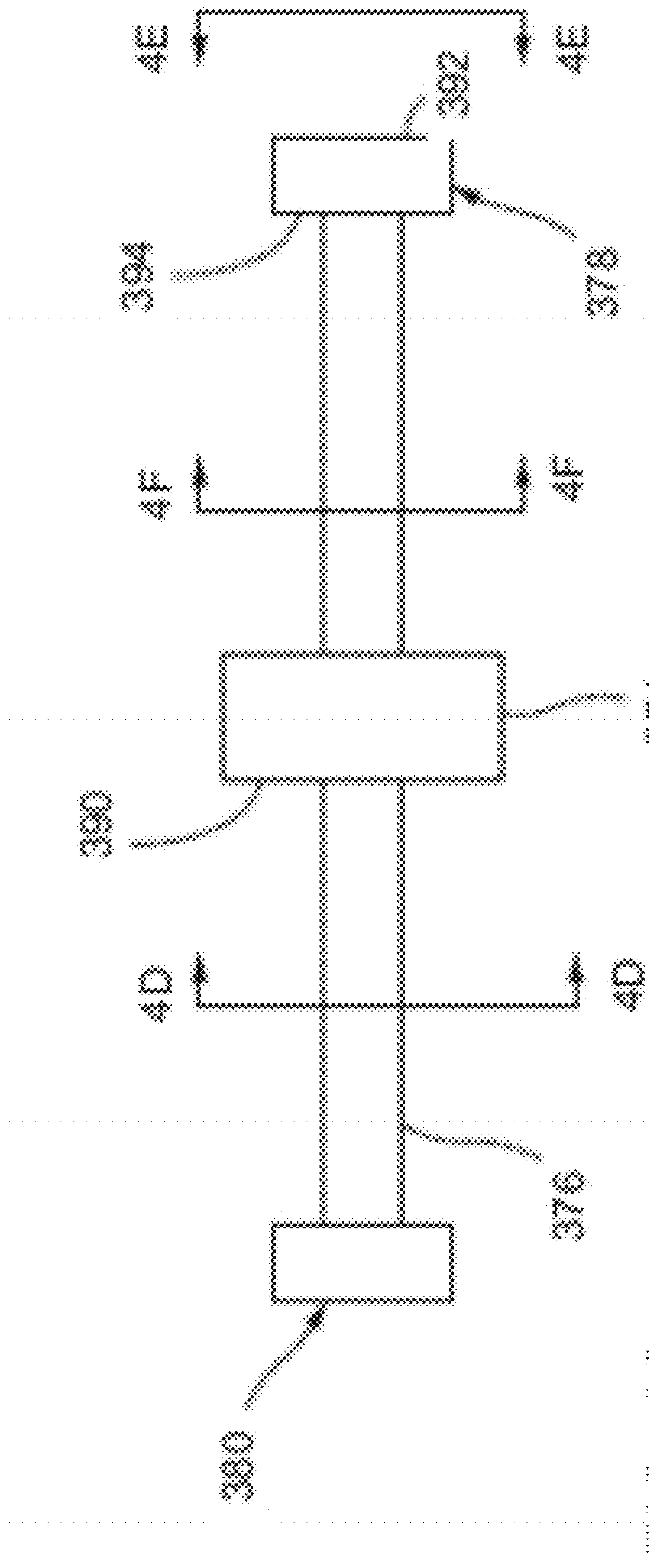


FIG. 4C

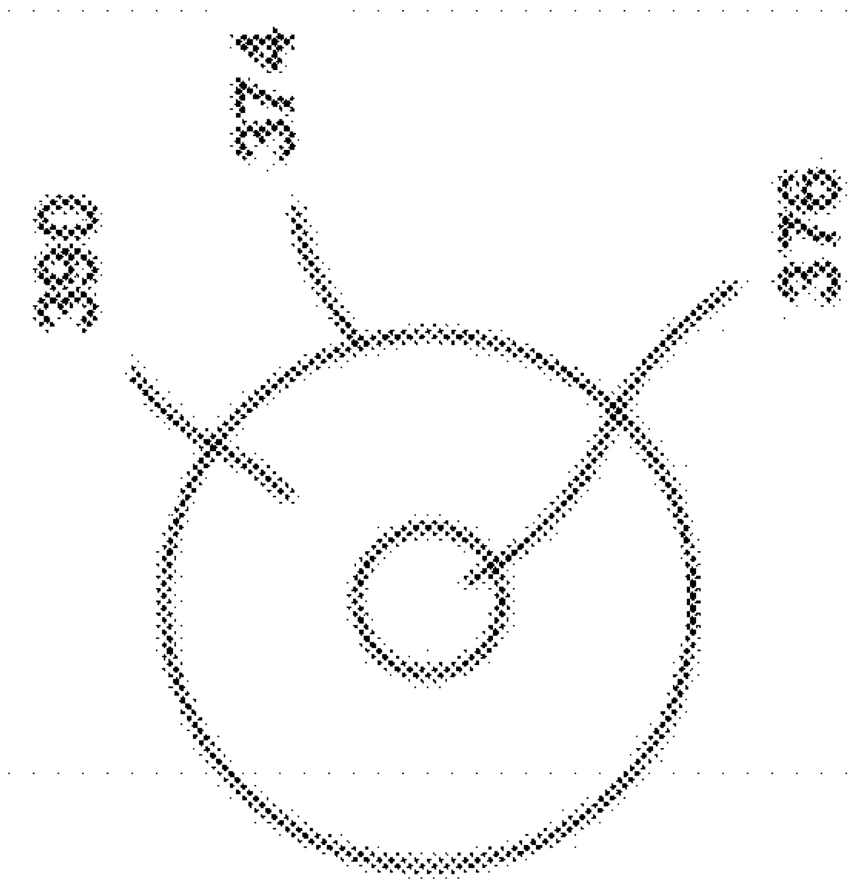


FIG. 4D

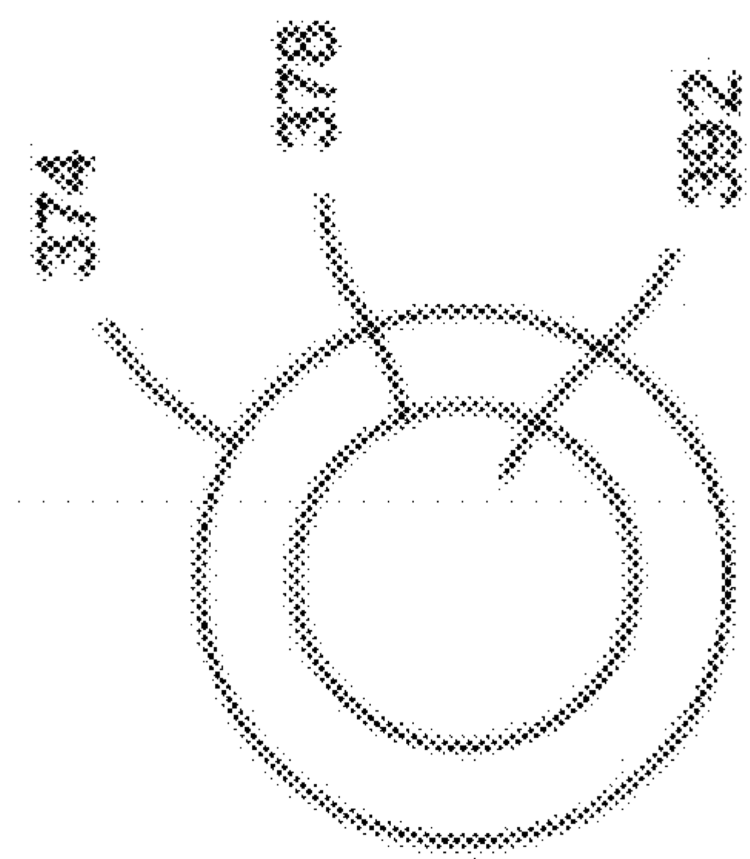


FIG. 4E

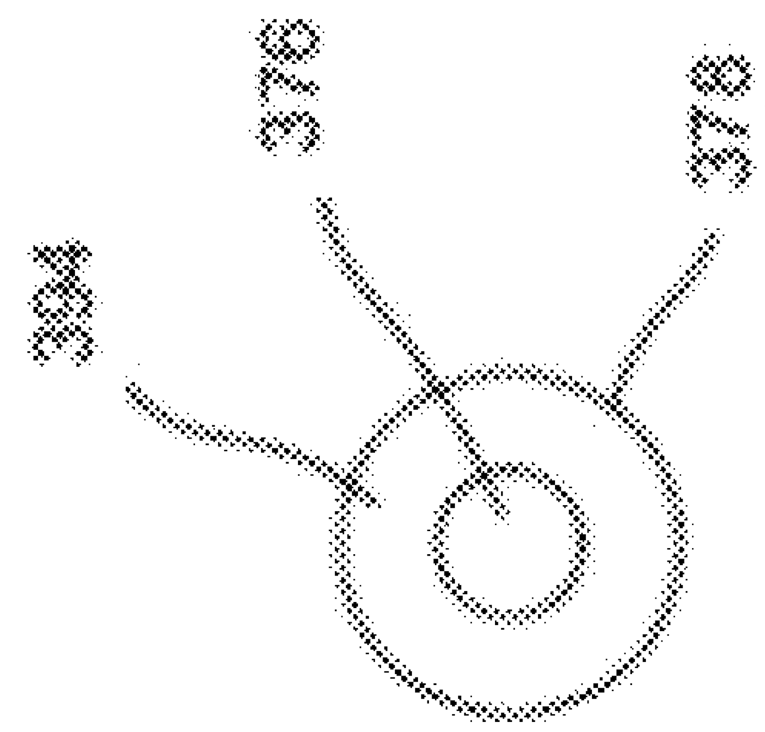
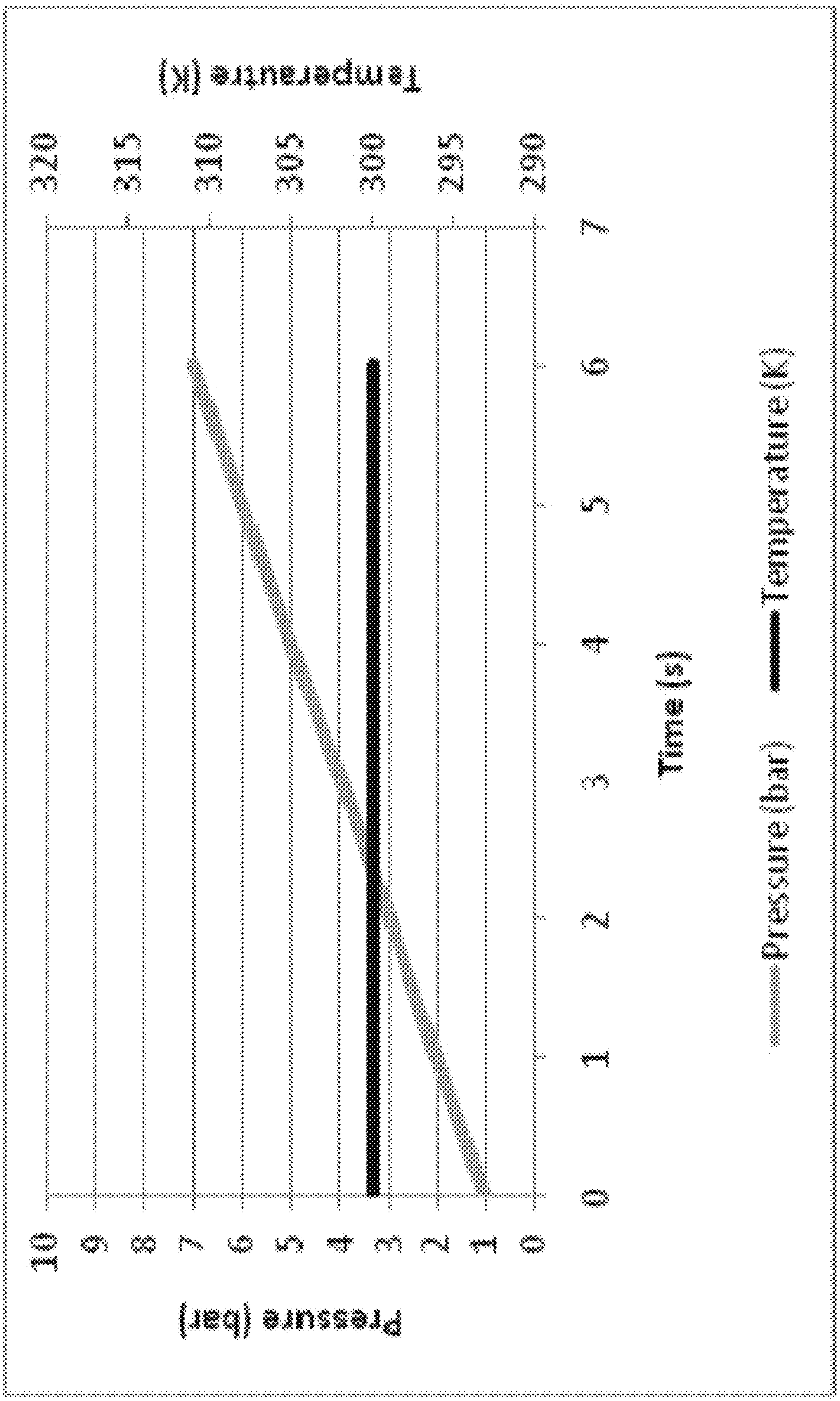


FIG. 4F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315
310
305
300
295
290
Pressure (bar)
10
9
8
7
6
5
4
3
2
1
0
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6
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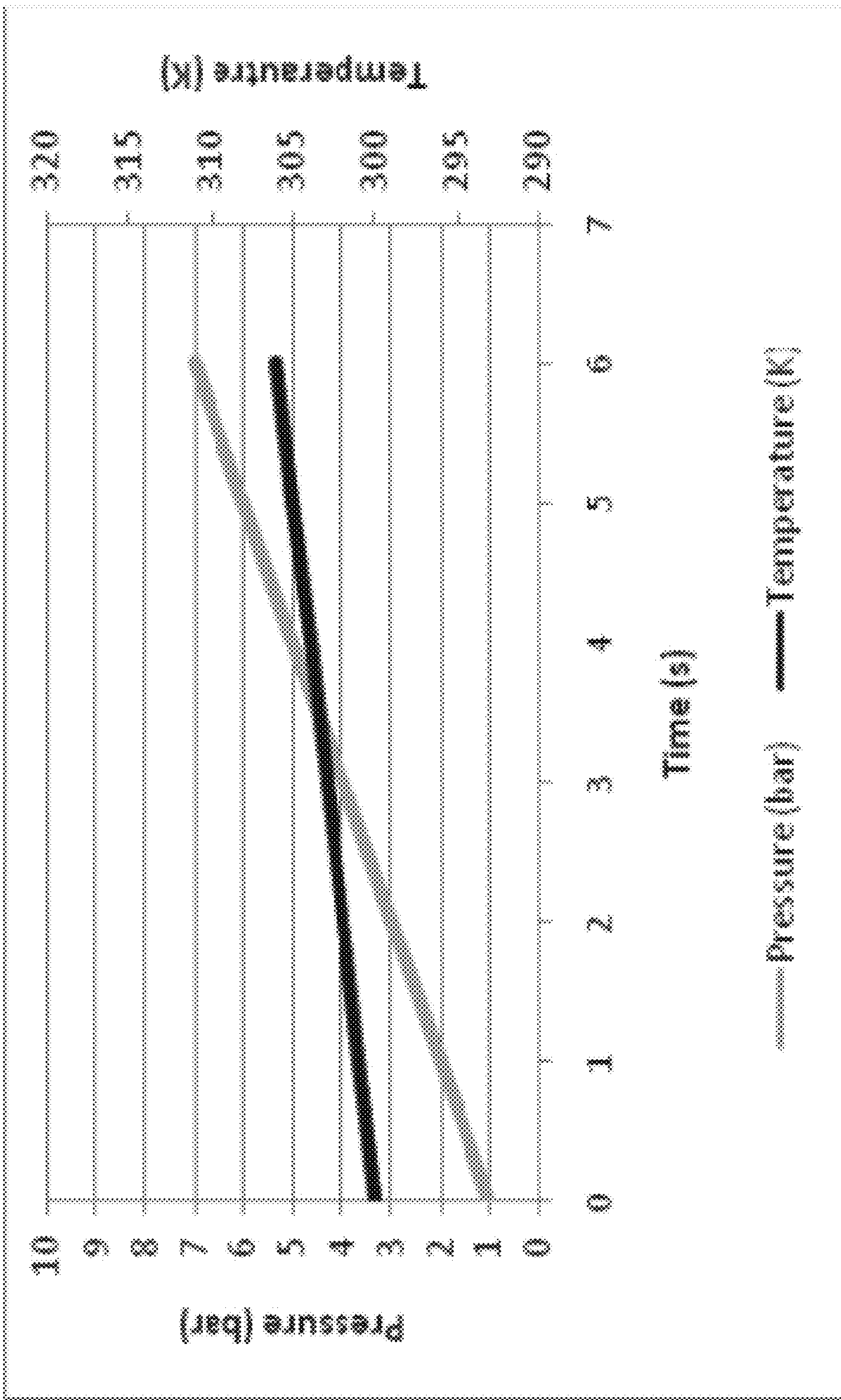
Time (s)
Pressure (bar)
Temperature (K)

FIG. 5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Pressure (bar)
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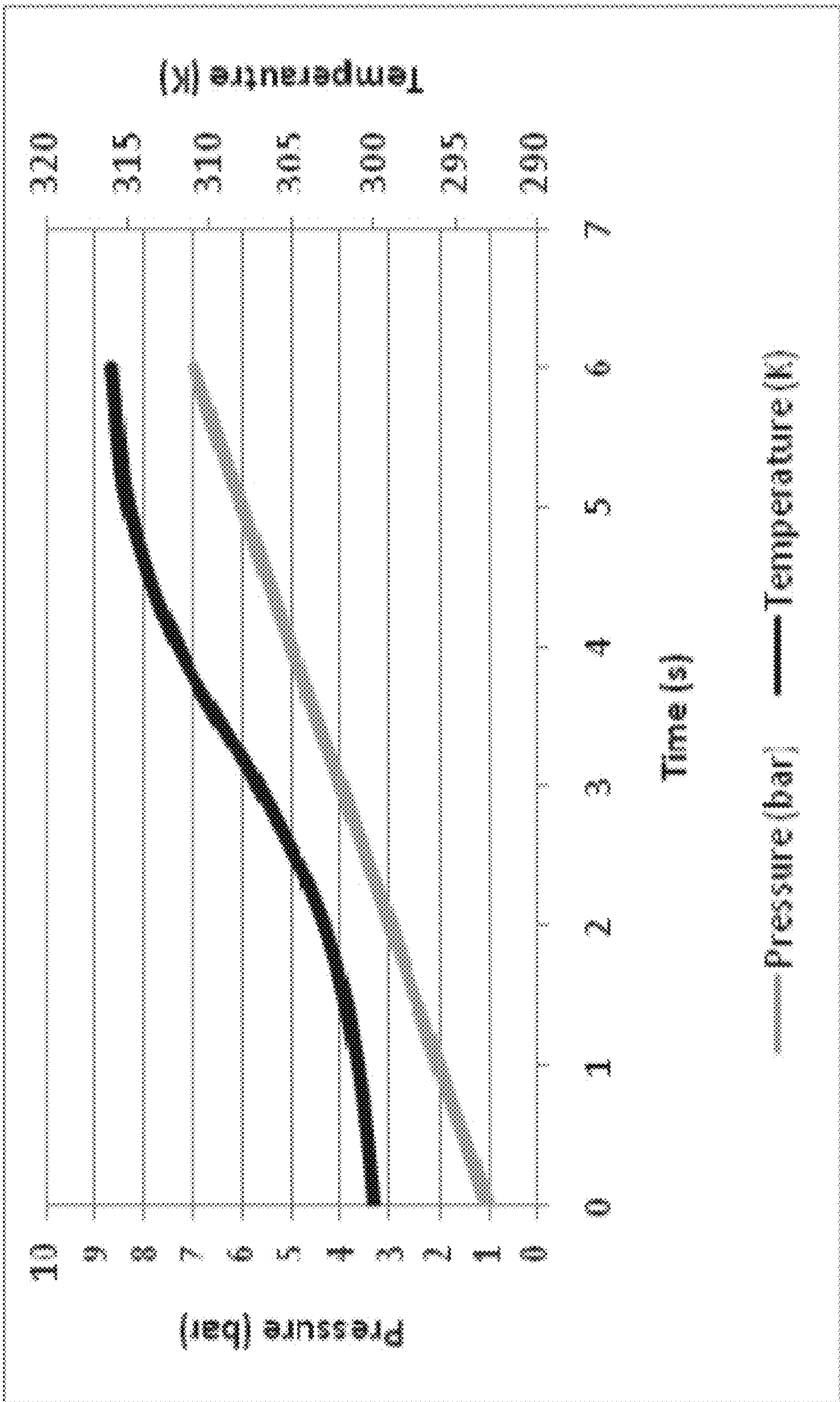
Time (s)
Pressure (bar)
Temperature (K)

FIG. 6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Pressure (bar)
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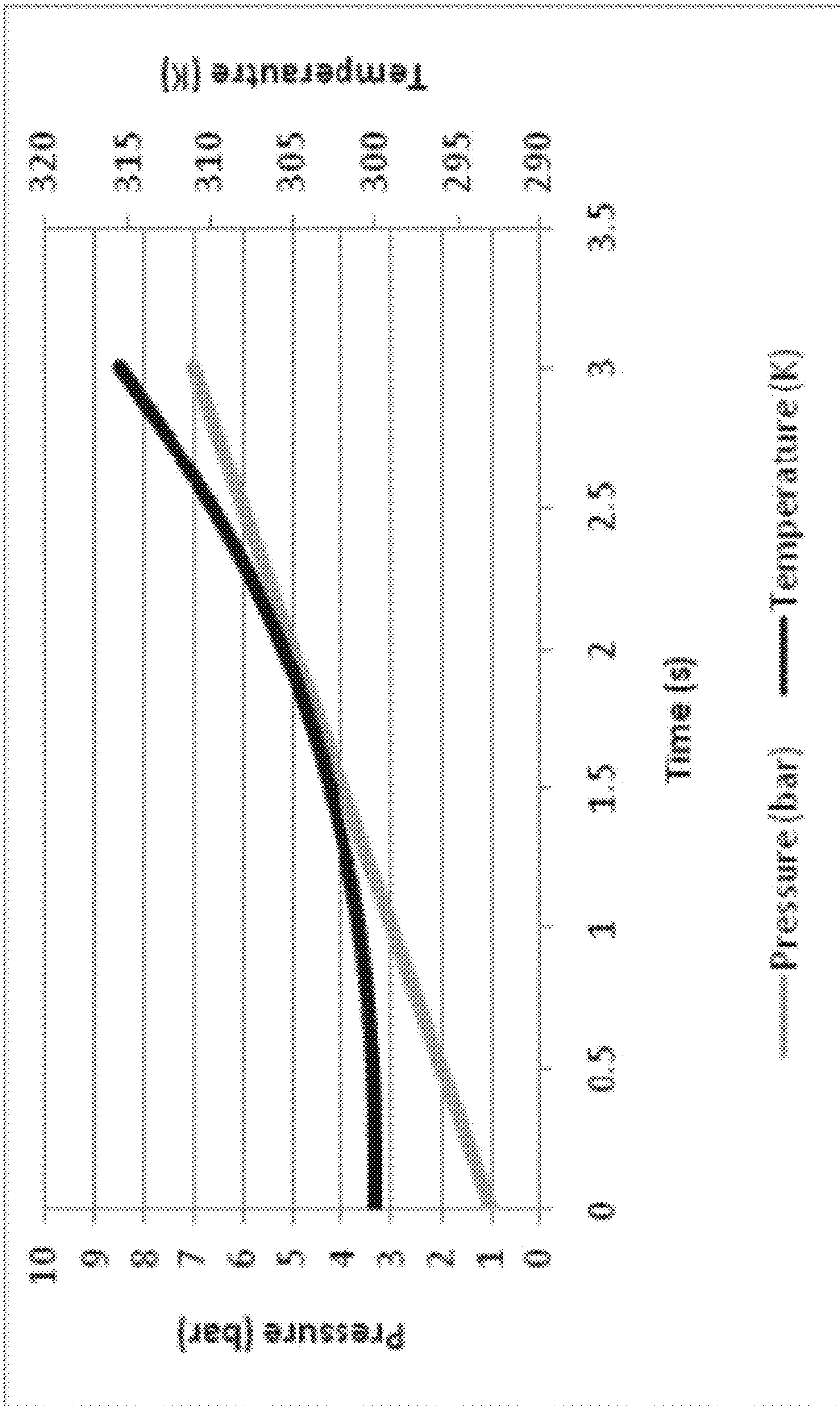
Time (s)
Pressure (bar)
Temperature (K)

FIG. 7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290
Pressure (bar)
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7
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3.5
Time (s)
Pressure (bar)
Temperature (K)

FIG. 8

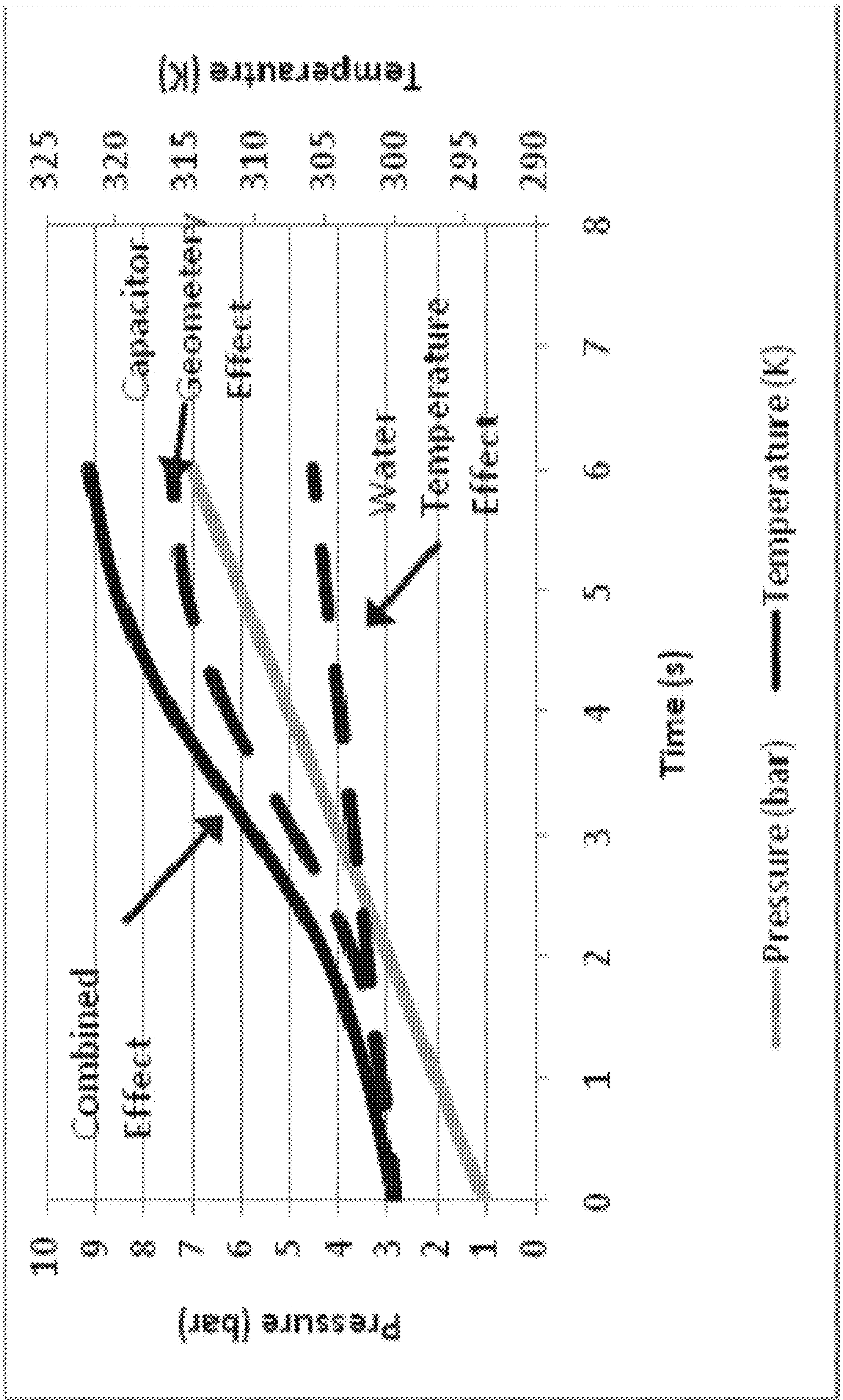
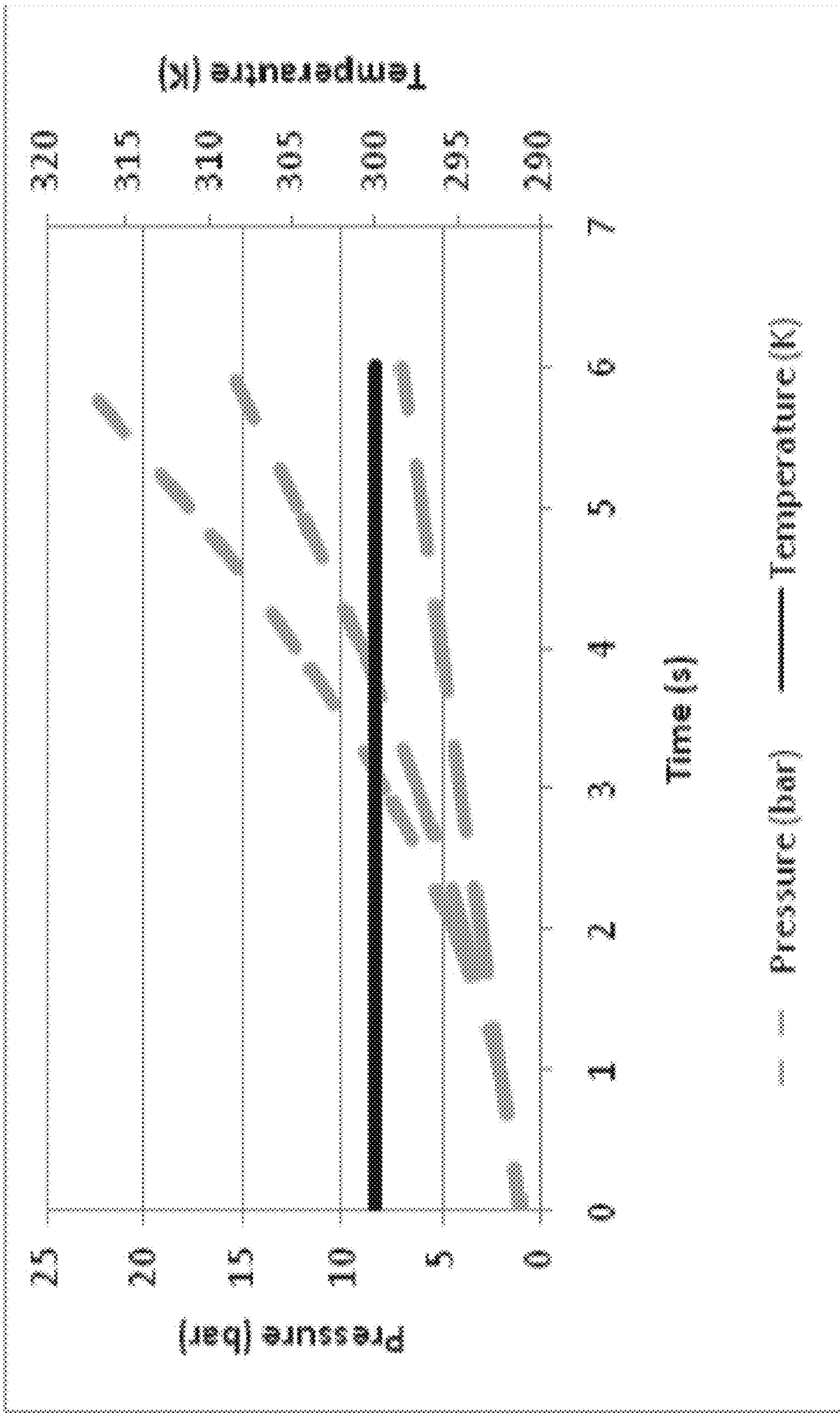

Pressure (bar)
Temperaute (K)
Time (s)
Combined Effect
Capacitor Geometery Effect
Water Temperature Effect
Pressure (bar)
Temperature (K)
0 1 2 3 4 5 6 7 8 9 10
290 295 300 305 310 315 320 325
0 1 2 3 4 5 6 7 8

FIG. 9


Pressure (bar)
25
20
15
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Time (s)
320
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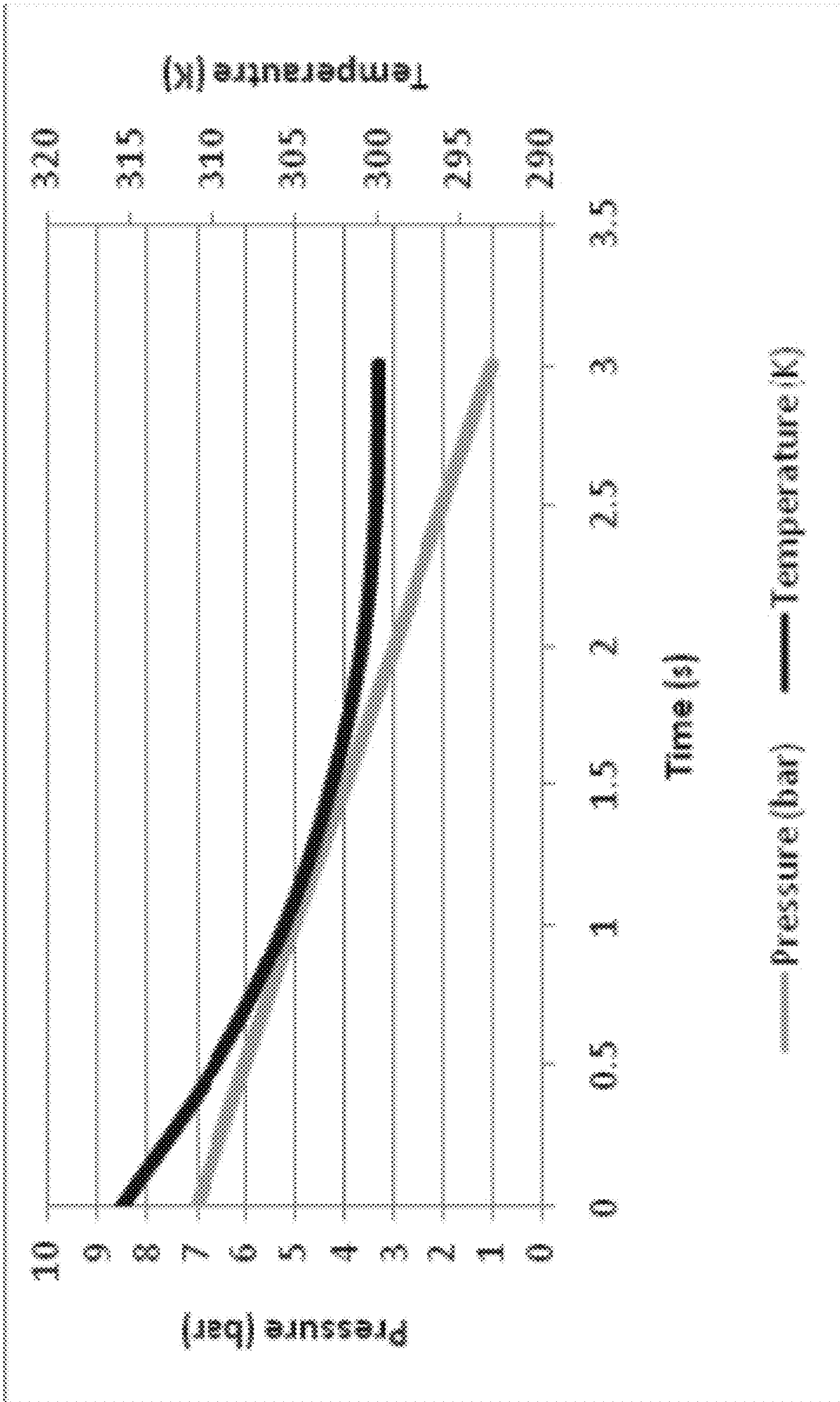
295
290
Pressure (bar)
Temperature (K)

FIG. 10


Temperature (K)
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Pressure (bar)
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Time (s)
Pressure (bar)
Temperature (K)

FIG. 11

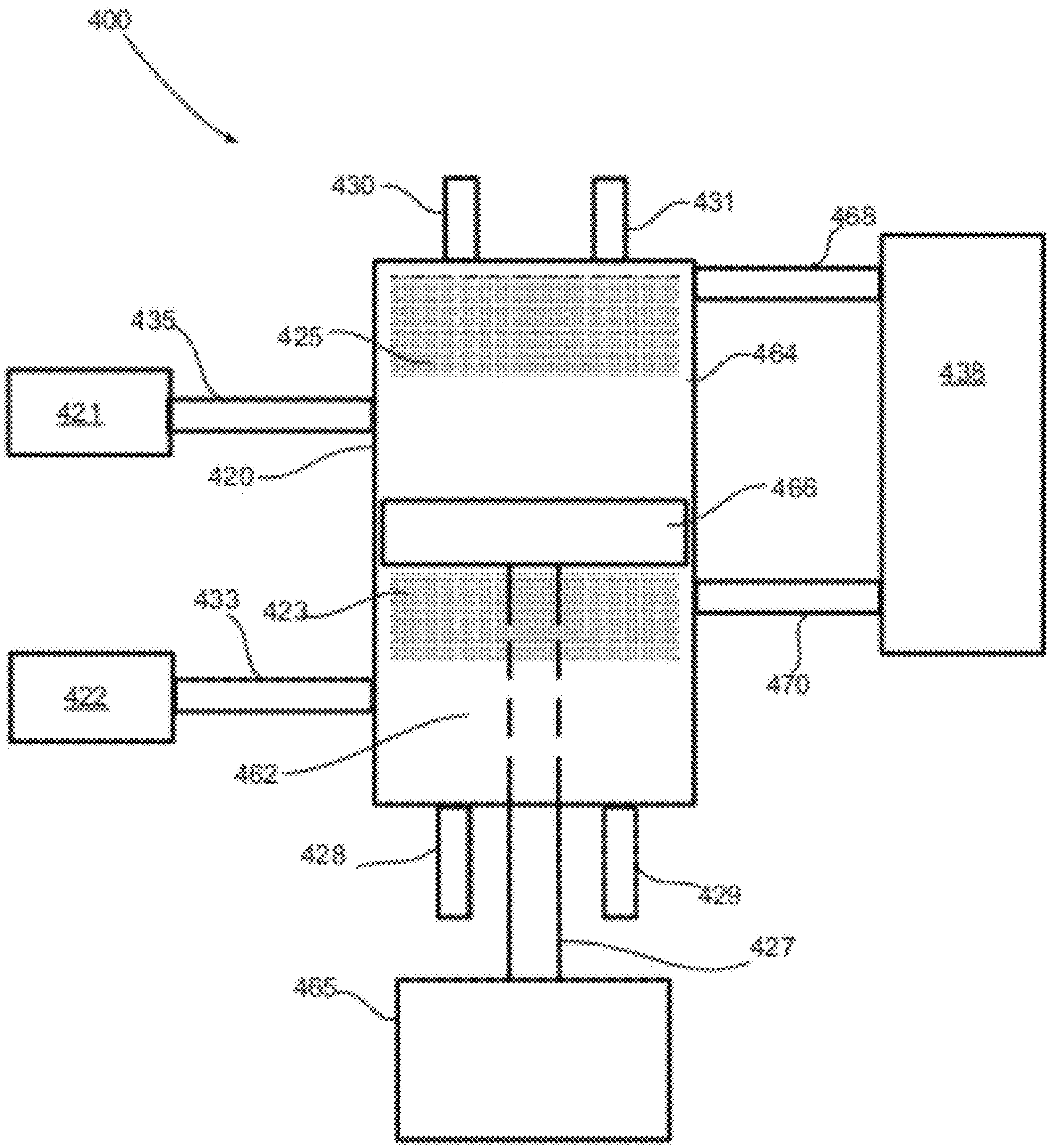
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FIG. 12

COMPRESSION/EXPANSION PROCESS THAT ALLOWS TEMPERATURE TO VARY INDEPENDENT OF PRESSURE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/432,945, entitled "Compression/Expansion Process That Allows Temperature to Vary Independent of Pressure," filed Jan. 14, 2011, the disclosure of which is hereby incorporated by reference herein in its entirety.

BACKGROUND

[0002] The invention relates generally to devices, systems and methods for the compression and/or expansion of a gas, such as air, and particularly to such a device that allows the temperature of the gas to be varied independently of its pressure during compression and/or expansion.

[0003] Devices and systems used to compress and/or expand a gas, such as air, and/or to pressurize and/or pump a liquid, such as water, can generate heat during, for example, a compression process. Adiabatic compression assumes that no energy (heat) is transferred to or from the gas during the compression, and all supplied work is added to the internal energy of the gas, resulting in increases of temperature and pressure. The increase in temperature means compression does not follow a simple pressure to volume ratio. Although adiabatic compression is less efficient, it is a very fast process for compressing a gas. An air compressor can achieve near adiabatic compression and expansion when the compressor has good insulation, a large gas volume, and/or a relatively fast compression stroke. In practice, there will always be a certain amount of heat flow out of the compressed gas to the compressor itself Thus, making a perfect adiabatic compressor would require perfect heat insulation of all parts of the machine.

[0004] In contrast to adiabatic compression, isothermal compression assumes that the compressed gas remains at a constant temperature throughout the compression or expansion process. During the compression cycle, energy is removed from the system at the same rate as heat is added by the mechanical work of compression. An air compressor can achieve near isothermal compression when the compressor has a large heat exchanging surface, a small gas volume, and/or a relatively slow compression stroke. In practice, there will always be a certain amount of heat flow into the compressed gas, resulting in an increased temperature of the gas.

[0005] Since perfect isothermal compression is generally not attainable with conventional compression technologies, known compressor systems have a multi-stage compressor that may include intercoolers that cool air between stages of compression and/or after-coolers that cool air after compression. In such a system, however, the air may still achieve substantial temperatures during each stage of compression, prior to being cooled, which will introduce inefficiencies in the system. For example, unless an infinite number of compression stages with corresponding intercoolers are used, perfect isothermal compression cannot be achieved.

[0006] Since perfect adiabatic and isothermal compression are not practical, a polytropic model is used to measure real-world results. This model takes into account both a rise in temperature in the gas as well as some loss of energy (heat) to the compressor's components. This assumes that heat may enter or leave the system, and that input shaft work can appear as both increased pressure (usually useful work) and increased temperature above adiabatic (usually losses due to cycle efficiency). Compression efficiency is then the ratio of the actual temperature rise (polytropic) vs. theoretical 100 percent (adiabatic).

[0007] For a given gas volume reduction (i.e., ratio of final volume to initial volume), an adiabatic compression process results in the highest final gas pressure, the highest final gas temperature, and the highest work consumption. In contrast, for the same volume reduction, an isothermal compression process results in the lowest final pressure, lowest final gas temperature (i.e. the same as the starting temperature), and lowest work consumption. Processes that involve levels of heat flow intermediate to those in adiabatic (zero heat flow) and isothermal (maximum heat flow), result in intermediate values of gas pressure, gas temperature, and work consumption. Those skilled in the art will recognize that a perfectly isothermal air compression process is a theoretical extreme that can only be achieved in reality by involving a relatively cold heat sink; regardless it is a useful metric for air compression/expansion discussion and analysis. While it is possible to provide cooling or heating to have a discharge temperature lower than the inlet during a compression process (or vice versa for an expansion process), the theoretical extremes discussed here assume no heat removal or addition using a separate cycle (such as a Rankine or heat engine cycle) is employed to increase heat transfer to or from the process.

[0008] Compression and/or expansion systems and related thermodynamic processes are usually designed to have a target temperature and pressure at the input or output of the system, whether that process involves expansion or compression. Generally, a design output pressure is achieved using a compressor/expander device and the desired temperature is adjusted with an after treatment such as, for example, a cooler or a heater. Processes that use a series of compressor/expander devices (stages) with intercoolers between each stage that cool the gas between stages of compression and/or after coolers that cool the gas after the final compression stage come closest to achieving isothermal compression. These multi-stage systems are really no different than a single compression/expansion device except that several are placed in series to achieve a higher output pressure or accept a higher input pressure (depending on the desired function of the system) at a different discharge temperature than would have been achieved with a single stage. The temperature achieved after the compression or expansion process is a function solely of the pressure ratio and isentropic/polytropic efficiency for adiabatic compression, and cannot be optimized independently from the pressure ratio.

[0009] Other processes, such as oil flooded screw compressors, can achieve a lower discharge temperature by cooling during the compression process, however this result is secondary to the primary function of the oil as a lubricant for the rotors. Such devices cannot independently tailor the discharge temperature and pressure, and are specified primarily based upon delivery pressure. After treatments such as, for example, a cooler or a heater, are still required to deliver the process fluid at the required temperature.

[0010] Having to deal separately with temperature and pressure requirements of a process fluid is a product of the fact that, for a given pressure ratio, temperature is a function purely of the isentropic efficiency of the device. No heat transfer is built into the process as a specific function of the device (in contrast to devices such as screw compressors described above, where the reduced discharge temperature is a byproduct of the sealing the oil provides). Popular design methodology suggests reducing the discharge temperature (for compression or expansion) is a desired goal insofar as it indicates an increase in isentropic efficiency. The reason for this design methodology is that conventional compression systems and processes are not capable of decoupling temperature from pressure.

[0011] A compression/expansion process that can achieve a desired pressure ratio independent of discharge temperature, with little to no impact on thermal efficiency would be very valuable to modern industry and represents a novel and unparalleled approach to compression and expansion.

SUMMARY OF THE INVENTION

[0012] Systems and methods are described herein to operate an air compression and/or expansion system in its most efficient regime, at a desired efficiency, and/or achieve a desired pressure ratio independent of discharge temperature, with little to no impact on thermal efficiency. For example, systems and methods are provided for controlling and operating hydraulic pumps/motors used within a hydraulically actuated device/system, such as, for example, a gas compression and/or expansion energy system, in its most efficient regime, continuously, substantially continuously, intermittently, or varied throughout an operating cycle or stroke of the system to achieve any desired pressure and temperature profile. In such a system, a variety of different operating regimes can be used depending on the desired output gas pressure and the desired stored pressure of the compressed gas. Hydraulic cylinders used to drive working pistons within the system can be selectively actuated and/or can be actuated to achieve varying force outputs to incrementally increase the gas pressure, within the system for a given cycle. Such systems and methods can achieve any desired pressure ratio independent of input or discharge temperature, and can also achieve any desired discharge temperature independent of pressure ratio, without altering any of the structural components of the device or system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a schematic illustration of a compression and/or expansion device according to an embodiment.

[0014] FIG. **2** shows a single stage of one embodiment of an air compression and expansion system.

[0015] FIG. **3**A is a schematic illustration of a portion of another embodiment of an air compression and expansion system.

[0016] FIG. **3**B is a schematic illustration of a portion of the air compression and expansion system of FIG. **3**A illustrating a system controller and hydraulic pump.

[0017] FIGS. **4**A and **4**B are each a schematic illustration of a portion of an actuator of the air compression and expansion system of FIG. **3**.

[0018] FIG. **4**C is a side view of a portion of an actuator of the system of FIG. **3**.

[0019] FIG. **4**D is a cross sectional view taken along line **4**D-**4**D in FIG. **4**C.

[0020] FIG. **4**E is an end view taken along line **4**E-**4**E in FIG. **4**C.

[0021] FIG. **4**F is a cross sectional view taken along line **4**F-**4**F in FIG. **4**C.

[0022] FIGS. **5-11** are each an example graph illustrating the operation of a compression and/or expansion device according to an embodiment.

[0023] FIG. **12** is a schematic illustration of a compression and/or expansion device, according to another embodiment.

DETAILED DESCRIPTION

[0024] Systems, methods and devices used to compress and/or expand a gas, such as air, and/or to pressurize and/or pump a liquid, such as water, are described herein. Such devices and systems can be used, for example, within a compressed air energy storage (CAES) system. In some compression and/or expansion devices and systems, a hydraulic actuator can be used to move or compress a gas within a pressure vessel. For example, an actuator can move a liquid within a pressure vessel such that the liquid compresses the gas in the pressure vessel. Such compression devices and systems are described in U.S. patent application Ser. No. 12/785,086; U.S. patent application Ser. No. 12/785,093; and U.S. patent application Ser. No. 12/785,100, each titled “Compressor and/or Expander Device” (collectively referred to as “the Compressor and/or Expander Device applications”), incorporated herein by reference in their entirety. The Compressor and/or Expander Device applications describe a CAES system that can include multiple stages of compression and/or expansion. Other examples of devices and systems for expanding and/or compressing as gas are described in U.S. Provisional patent application Ser. No. 12/977,724, to Ingersoll et. al. (“the Ingersoll I application”), entitled “System and Methods for Optimizing efficiency of a Hydraulically Actuated System,” the disclosure of which is incorporated herein by reference in its entirety.

[0025] In some compression and/or expansion devices and systems, one or more hydraulic pumps/motors can be used to move (or be moved by) gas and liquid within the system, and systems and methods are described herein to operate the hydraulic pump/motor in its most efficient regime, continuously, substantially continuously, intermittently, or varied throughout an operating cycle or stroke of the system to achieve any desired pressure and temperature profile. Compression and/or expansion devices and systems can have efficient or optimal operating ranges that can vary as a function of, for example, mass flow rate, pressure, temperature, overall system efficiency, among other parameters. Systems and methods are provided that allow the hydraulic pumps/motors to be operated as a function of any given parameter (e.g. gas inlet temperature, gas outlet temperature, inlet pressure, outlet pressure, pressure ratio, system efficiency, etc.) throughout the stroke or cycle of the gas compression and/or expansion system to achieve any desired pressure and temperature profile.

[0026] As described herein, devices and systems used to compress and/or expand a gas, such as air, and/or to pressurize and/or pump a liquid, such as water, can release and/or absorb heat during, for example, a compression or expansion process, using one or more heat transfer mechanisms. Such systems and methods as described herein, can be used to operate a gas compression and/or expansion system in its most efficient regime, at a desired efficiency, and/or to achieve a desired pressure ratio independent of discharge temperature, with little to no impact on thermal efficiency.

[0027] In some embodiments, the devices and systems described herein can be configured for use only as a compressor. For example, in some embodiments, a compressor device described herein can be used as a compressor in a natural gas pipeline, a natural gas storage compressor, or any other industrial application that requires compression of a gas. In another example, a compressor device described herein can be used for compressing carbon dioxide. For example, carbon dioxide can be compressed in a process for use in enhanced oil recovery or for use in carbon sequestration.

[0028] In some embodiments, the devices and systems described herein can be configured for use only as an expansion device. For example, an expansion device as described herein can be used to generate electricity. In some embodiments, an expansion device as described herein can be used in a natural gas transmission and distribution system. For example, at the intersection of a high pressure (e.g., 500 psi) transmission system and a low pressure (e.g., 50 psi) distribution system, energy can be released where the pressure is stepped down from the high pressure to a low pressure. An expansion device as described herein can use the pressure drop to generate electricity. In other embodiments, an expansion device as described herein can be used in other gas systems to harness the energy from high to low pressure regulation.

[0029] In some embodiments, a compression and/or expansion device as described herein can be used in an air separation unit. In one example application, in an air separator, a compression and/or expansion device can be used in a process to liquefy a gas. For example, air can be compressed until it liquefies and the various constituents of the air can be separated based on their differing boiling points. In another example application, a compression and/or expansion device can be used in an air separator co-located with in a steel mill where oxygen separated from the other components of air is added to a blast furnace to increase the burn temperature.

[0030] In some embodiments, a compression and/or expansion device as described herein can be used in a chemical reaction process. In one example application, the compressor and/or expansion device can be the reaction vessel in a chemical reaction process. Some chemical reactions only take place at a certain temperature, pressure, range of temperatures, or range of temperatures. For example, gas and/or liquid reactants in the compression and/or expansion device can be maintained at a certain temperature or with in a certain temperature range by changing the pressure in the compression and/or expansion device. The temperature of the gas and/or liquid reactants can be changed over time by changing the pressure in the compression and/or expansion device as the reaction proceeds. In another example application, the rate of a reaction can also be a function of temperature and/or pressure. Thus, the reaction rate can be maximized, minimized, or optimized for other factors (e.g., selectivity or efficiency) by changing the temperature and/or pressure in the compression and/or expansion device.

[0031] A compression and/or expansion system as described herein can include one or multiple stages of compression and/or expansion. For example, a system can include a single stage compression/expansion device, two stages, three stages, etc. Each stage of compression/expansion can have a variety of different configurations and can include one or more actuators that are used to compress/expand a gas (e.g. air) within a compression/expansion device. In some embodiments, an actuator can include one or more pump/motor systems, such as for example, one or more hydraulic pumps/motors and/or one or more pneumatic pumps/motors that can be use to move, or be moved by, one or more fluids within the system between various water pumps/motors and pressure vessels. As used herein, "fluid" can mean a liquid, gas, vapor, suspension, aerosol, or any combination thereof. The Compressor and/or Expander Device applications incorporated by reference above describe various compression and expansion systems in which the systems and methods described herein can be employed.

[0032] As described herein, in some embodiments of a gas compression and/or expansion system, hydraulic pumps/motors can be used to drive (or be driven by) one or more hydraulic actuators, which in turn can drive (or be driven by) a working piston. The working piston can act on (or be acted on by) a gas contained in a working chamber to compress or expand the gas, directly, or indirectly through a liquid disposed between the working piston and the gas in the working chamber. As used herein the term "piston" is not limited to pistons of circular cross-section, but can include pistons with a cross-section of a triangular, rectangular, or other multi-sided shape.

[0033] In some embodiments, a hydraulic actuator as described herein can be used to drive, or be driven by, a working piston within, for example, a water pump/motor, to move water (or other liquid) in and out of the working chamber of a pressure vessel used to compress and/or expand a gas, such as air, contained in the working chamber. Although particular embodiments of an actuator are described herein to drive, or be driven by, a water pump/motor and/or a compression and/or expansion device, it should be understood that the various embodiments and configurations of an actuator can be used to drive, or be driven by, a working piston within a water pump, a compression and expansion device, a compression device, an expansion device, any other device in which a working piston is used to move a fluid, and/or any device to which motive force can be applied or from which motive force can be received.

[0034] The loads applied to the working piston(s) can be varied during a given cycle of the system. For example, selectively establishing fluid communication between the hydraulic pump/motor(s) and different hydraulic pistons, and/or different surfaces of the hydraulic piston(s), in the hydraulic actuator(s), the ratio of the net working surface area of the hydraulic actuator(s) to the working surface area of the working piston acting on the gas in the working chamber can be varied. Thus, the ratio of the pressure of the hydraulic fluid provided by (or received by) the hydraulic pump/motor to the pressure of the gas in the working chamber can be varied during a given cycle or stroke of the system. A state in which a hydraulic actuator has a particular piston area ratio (e.g., the ratio of the net working surface area of the hydraulic actuator to the working surface area of the working piston acting on, or being acted on by, the gas in a working chamber) at a given time period can be referred to herein as a "gear," and a change in from one state to another state can be referred to herein as a "gear change." In addition, the number of working pistons/working chambers and hydraulic actuators can be varied as well as the number of piston area ratio changes within a given cycle.

[0035] As described herein, heat energy can be removed from a gas during a compression process (or can be added to a gas during an expansion process) via a liquid that is present in one or more pressure vessels of a compressor/expander device to control the gas temperature throughout the process. The heat energy can be transferred between the gas and the liquid, the compressor/expander device, and/or a heat transfer element disposed within the working chamber. This allows an operator to modify the amount of energy that is added or removed throughout the process (depending on whether the process is compressing or expanding), thereby achieving a desired pressure ratio independent of temperature. This can be done in a manner that has very little impact on thermal efficiency, in order to make the temperature control capability of the process transparent to the performance and cost of the device.

[0036] In some embodiments, a heat transfer element can be positioned within the interior of a working chamber of a compressor/expander device that can provide sufficient gas/liquid interface and/or sufficient thermal capacity to efficiently intermediate in, and enhance, the transfer of heat between the gas and the liquid. The heat transfer element can provide for an increased heat transfer area both with gas that is being compressed and with gas that is being expanded (either through an gas/liquid interface area or gas/heat transfer element interface), while allowing the exterior structure and overall shape and size of a working chamber/pressure vessel to be optimized for other considerations, such as pressure limits and/or shipping size limitations. The heat transfer element can be a variety of different configurations, shapes, sizes, structures, etc. to provide a relatively high surface area per unit volume or mass with the gas as it is being compressed/expanded and/or at an end of the stroke of a compression/expansion cycle. The heat transfer element can be formed from one or more of a variety of different materials that provide a relatively high volumetric specific heat as compared to the gas. The combined effects of density, volume and specific heat, and how these parameters behave per unit volume, can contribute to the absorption performance of a particular heat transfer element. For example, both water and various metals provide a relatively high volumetric specific heat as compared to air, particularly at atmospheric air density. Thus, when the metal or water absorbs the heat from the air as it is begin compressed, the air and/or water temperature increases only moderately. Such heat transfer elements are described in U.S. patent application Ser. No. 12/977,679; titled "Methods and Devices for Optimizing Heat Transfer within a Compression and/or Expansion Device," ("the Ingersoll II application"), the disclosure of which is incorporated herein by reference in its entirety.

[0037] The use of a liquid (such as water) as a medium through which heat passes during compression and/or expansion may allow for a continuous cooling process during compression and may provide a mechanism by which heat may be moved in and/or out of the compression vessel. It can provide the reverse during expansion. A liquid can have a relatively high thermal capacity as compared to a gas (such as air) such that a transfer of an amount of heat energy from the gas to the liquid produces a significant decrease in the temperature of the gas but only a modest increase in the temperature of the liquid. This allows buffering of the system from substantial temperature changes.

[0038] Heat that is transferred between the gas and liquid or components of the compressor/expander device itself may be moved from or to the working chamber through one or more heat exchangers that are in contact with the liquid or components of the compressor/expander device. That is, during compression the liquid may receive heat from gas that is being compressed, and pass this heat to the external environment continuously, both while gas is being compressed and while gas is being received by the working chamber for later compression. Similarly, heat addition may occur when a compressor/expander device is operating in an expansion mode both during expansion and as expanded gas is passed from a pressure vessel. Thus, the liquid within a working chamber can be used to transfer heat from gas that is compressed (or to gas that is expanded) and can also act in combination with a heat exchanger to transfer heat to an external environment (or from an external environment).

[0039] As described herein, a gas compression and/or expansion system can have a heat removal process that can be varied independent of process conditions. For example, different pressure ratios (i.e., ratio of initial pressure to final pressure in a compression cycle) will result in different heat energy fluxes within the device. Therefore, the device can include a heat transfer system or methods that allow heat to be transferred out of the process fluid regardless of the heat energy flux and fluid pressure. One type of heat exchanger that can be used to accomplish this is a heat pipe as described in the Compressor and/or Expander Device applications and the Ingersoll I application incorporated by reference above.

[0040] In some embodiments, as a liquid (such as water) is moved into a working chamber to compress a gas (such as air), if there is relatively little vertical mixing of the liquid, a temperature gradient can be established in the liquid, with the highest (during compression, or lowest, during expansion, of the gas) temperature at the gas/liquid interface. Thus, the layer of liquid at the top of the liquid column (closest to the gas/liquid interface) will contain a higher proportion of the heat energy received from the gas during compression (or has given up a higher proportion of the heat energy to the gas during expansion) than the remainder of the liquid. A portion of this top layer of liquid can be removed from the working chamber after the compression or expansion cycle has been completed, and transferred to another stage of the system and/or out of the system entirely.

[0041] In some embodiments, a gas compression/expansion system can have variable displacement capability. As a liquid (such as water) is moved into a pressure vessel, a gas (such as air) is compressed at a rate proportional to the displacement of the liquid. The flow of liquid into the pressure vessel can be stopped at any time during the compression stroke once a predetermined pressure is achieved. In this manner, the pressure ratio can be modified quickly and easily, while the discharge temperature can be maintained at a desired value by changing the heat transfer characteristics within the system. During subsequent compression cycles, the flow of liquid into the pressure vessel can be stopped at the same time to achieve the same displacement or can be changed to increase or decrease the displacement depending on any of a number of variables such as, for example, pressure vessel parameters including pressure, temperature and thermal efficiency, system parameters including pressures upstream or downstream of the pressure vessel (i.e., earlier or later compression stages of the system), overall system efficiency and electricity generation, and power grid parameters including electricity price, electricity supply/demand and grid stability. Thus, in addition to the compression and expansion system being capably of varying temperature independent of pressure, the reverse is also true and the system is capable of varying pressure independent of temperature. When such systems are paired in series to achieve higher pressures (called a staged process), the pressure ratio within each system can be changed by varying the stroke and amount of water displaced to not only change the discharge pressure, but also change the distribution of work and heat transfer in each. In this manner, not only is the pressure and temperature of the whole process independently variable, but the pressure and temperature within each stage can be varied as well.

[0042] FIG. **1** schematically illustrates a portion of a compression and/or expansion device (also referred to herein as "compression/expansion device") according to an embodiment. A compression/expansion device **100** can include one or more pressure vessels **120** (also referred to herein as "cylinder") having a working chamber **140**, an actuator **122** by which the volume of working chamber **140**, and/or the portion of the volume of the working chamber **140** that can be occupied by gas, can be changed (decreased to compress the gas, increased to expand the gas), and one or more heat transfer elements **124** disposed within the working chamber **140**. The compression/expansion device **100** can be used, for example, to compress or expand a gas, such as air, within the working chamber **140**. The device provides the flexibility of being able to vary temperature independent of pressure and pressure independent of temperature without introducing significant penalties to efficiency and performance. The device **100** integrates thermal management with pressure ratio management such that separate devices are not required to vary either parameter.

[0043] The pressure vessel **120** can include one or more gas inlet/outlet conduits **130** in fluid communication with the working chamber **140**. Optionally, the pressure vessel **120** can include one or more liquid inlet/outlet conduits **128** in fluid communication with the working chamber **140**. The working chamber **140** can contain at various time periods during a compression and/or expansion cycle, a quantity of gas (e.g., air) that can be communicated to and from working chamber **140** via the inlet/outlet conduits **130**, and optionally can also contain a quantity of liquid (e.g., water) that can be communicated to and from working chamber **140** via the inlet/outlet conduits **128**. The compression/expansion device **100** can also include multiple valves (not shown in FIG. **1**) coupled to the inlet/outlet conduits **128**, **130** and/or to the pressure vessel **120**. The valves can be configured to operatively open and close the fluid communication to and from the working chamber **140**. Examples of use of such valves are described in more detail in the Compressor and/or Expander Device applications incorporated by reference above.

[0044] The actuator **122** can be any suitable mechanism for selectively changing the volume of the working chamber **140** and/or the portion of the volume of the working chamber that can be occupied by gas. For example, the working chamber **140** can be defined by a cylinder and the face of a piston (not shown in FIG. **1**) disposed for reciprocal movement within the cylinder. Movement of the piston in one direction would reduce the volume of the working chamber **140**, thus compressing gas contained in the working chamber **140**, while movement of the piston in the other direction would increase the volume of the working chamber **140**, thus expanding gas contained in the working chamber **140**. The actuator can thus be the piston and a suitable device for moving the piston within the cylinder, such as a pneumatic or hydraulic actuator such as, for example, the hydraulic actuators described in the Ingersoll I application incorporated by reference above.

[0045] In some embodiments, the working chamber can have a fixed volume, i.e. a volume defined by a chamber with fixed boundaries, and the portion of the volume of the working chamber **140** that can be occupied by gas can be changed by introducing a liquid into, or removing a liquid from, the working chamber **140**. Thus, the working chamber **140** has a volume with a first portion containing a volume of liquid, and a second portion that can contain gas, which volume is the total volume of the working chamber **140** less the volume of the first portion (the volume of the liquid). In such embodiments, the actuator **122** can be any suitable device for introducing liquid into, or removing liquid from, the working chamber, such as a hydraulic actuator that can move a liquid in and out of the working chamber **140** via liquid inlet/outlet conduit **128**. In such an embodiment, the actuator **122** can include a water pump (not shown) that drives a hydraulically driven piston (not shown) disposed within a housing (not shown) and can be driven with one or more hydraulic pumps (not shown) to move a volume of liquid in and out of the working chamber **140**. An example of such a hydraulic actuator is described in the Compressor and/or Expander Device applications incorporated by reference above.

[0046] In some embodiments, the working chamber can be configured to combine the techniques described above, i.e. the working chamber can have a variable volume, e.g. using a cylinder and piston as described above, and the portion of the variable volume that can be occupied by gas can be changed by introducing liquid into, or removing a liquid from, the working chamber. In another embodiment, a constant volume of liquid can be maintained in the variable volume working chamber throughout all, or a portion, of the compression cycle. As described above, in some embodiments, the working chamber **140** can contain a liquid, and/or the actuator **122** can be used to change the portion of the working chamber **140** that is available to contain gas, by moving a liquid (such as water) into and out of the working chamber, such that gas (such as air) within the working chamber **140** is compressed by the liquid. In such embodiments, depending on the rate at which the working chamber **140** is filled with liquid, and the heat transfer properties of the heat transfer element **124**, the gas and the heat transfer element **124** will be relatively closer or farther from thermal equilibrium, and thus, during some or all of the compression cycle, the liquid in the working chamber **140** can be caused to contact the heat transfer element **124** to receive from the heat transfer element **124** heat energy it received from the compressed gas. Optionally, the volume may be decreased by a mechanical piston directly such as in a reciprocating compressor with a reduced volume of water disposed within the chamber for the purpose of effecting heat transfer. Optionally, at the end of the compression cycle, any pressurized gas remaining in the working chamber **140** can be released from the working chamber **140**, and transferred to the next step or stage in the compression process or to a storage facility. Liquid can then be moved into the working chamber **140**, to substantially fill the volume occupied by gas that was released from the working chamber **140** after compression (which volume is now filled with gas at a lower pressure) by introducing more liquid and/or by reducing the volume of the working chamber (e.g. by moving a piston). The heat energy stored in the heat transfer element **124** can then be transferred (again, by conductive and/or convective transfer) to the water in the working chamber **140**.

[0047] In some embodiments, the working chamber **140** can be partially filled with a liquid (e.g. water) that can be communicated to and from the working chamber **140** via the inlet conduit **128** and the outlet conduit **130**, respectively, or via other conduits (not shown). During the compression cycle, heat energy generated during the compression process can be transferred from the gas, to the heat transfer element **124**, and then to the liquid. A volume of the heated liquid can then be discharged from the pressure vessel **120** via the outlet conduit **130** or via a separate liquid discharge conduit (not shown). As described above with respect to the heat transfer element **124**, the volume of liquid that occupies a portion of working chamber **140** reduces the remaining volume of the working chamber **140** available for a mass of gas to be compressed. In other words, although the liquid in the working chamber **140** provides a mechanism by which the heat energy generated by the compression of the gas can be removed from the pressure vessel **120** (i.e. by first quenching the heat transfer element **124** to transfer the heat energy to the liquid, and then discharging the heated liquid out of the pressure vessel **120**), both the liquid and the heat transfer element occupy a portion of the working chamber **140**, thereby reducing the mass of gas that can be compressed. In some embodiments, the heat transfer element and the volume of liquid in the working chamber **140** can be designed to remove a sufficient amount of heat energy generated during the compression process, while maximizing the amount of gas in the working chamber **140** to be compressed. For example, having multiple heat transfer elements **124** that are movable with respect to each other such that the density of the heat transfer element **124** disposed in the portion of the working chamber containing gas can be varied throughout a compression cycle can reduce the volume of liquid for quenching the heat transfer element **124**.

[0048] Heat energy transferred from the gas to the heat transfer element **124** can in turn be transferred out of the pressure vessel **120** by any suitable means, include a heat pipe, circulating fluid, etc., to a location where it can be dissipated, used in other processes, and/or stored for future use in the compression/expansion device (e.g. in an expansion cycle). In addition, or alternatively, heat energy transferred from the gas to the heat transfer element **124** can be transferred from the heat transfer element **124** to fluid contained in the working chamber **140**. The heat energy can then be transferred from the fluid out of the pressure vessel. Similar techniques can be used to transfer heat energy from outside the pressure vessel to the heat transfer element **124** and thence to the gas in the working chamber, e.g. during an expansion cycle.

[0049] The heat transfer element **124** can be a variety of different configurations, shapes, sizes, structures, etc. to provide a relatively high surface area per unit volume or mass that can be in contact with the gas (e.g., air) as it is being compressed or expanded within the working chamber **140**. In some embodiments, it may be desirable to include a heat transfer element **124** that can be formed with a material that can provide high thermal conductivity in a transverse and a longitudinal direction within the working chamber **140**. The heat transfer element **124** can be formed from one or more of a variety of different materials. For example, the heat transfer element **124** can be formed with metals (e.g. stainless steel), metal wires, hybrid wires, carbon fiber, nano-materials, and composite materials (e.g. carbon polymer compounds) which have anti-corrosion properties, are lighter weight, and are less expensive than some metallic materials.

[0050] The heat transfer element **124** can be disposed at various locations within the working chamber **140** so as to optimize the heat transfer within the pressure vessel **120**. For example, in some embodiments, the heat transfer element **124** can be disposed within the working chamber **140** near an end portion of the working chamber **140** in a portion occupied by the gas (e.g., air) near the end of a compression cycle. As the gas is compressed during the compression cycle, the work done on the gas adds heat energy to the gas. The heat energy is continuously transferred (primarily by conductive and/or convective, rather than radiant, heat transfer) to the heat transfer element **124**. This transfer maintains the gas temperature at a lower value than would be the case without the heat transfer element **124**, and moderately increases the temperature of the heat transfer element **124**. Other examples of heat transfer elements and systems that can be used to optimize heat transfer are described in the Ingersoll II application incorporated by reference above.

[0051] FIG. **2** illustrates a portion of a compressed gas storage system **200** that includes a compressor/expander device **220** and an actuator **212**. The compressor/expander device **220** illustrates a single stage of a compressed gas storage system. The compressor/expander device **220** includes a first pressure vessel **224** and a second pressure vessel **226**. The first and second pressure vessels **224**, **226** are each coupled fluidly to the actuator **212** by a conduit or housing **228** and **230**, respectively. The actuator **212** can include a water pump that includes a hydraulically driven piston **232**. The piston **232** is disposed within a housing or reservoir **240** and can be driven with one or more hydraulic pumps (not shown in FIG. **2**) to move toward and away from the conduit **228** of first pressure vessel **224** to alternately reduce and then increase the portion of the internal volume of the first pressure vessel **224** available to contain gas (with an equivalent, but opposite increase and reduction of the portion of the volume of the second pressure vessel **226** available to contain gas). Each of the first and second pressure vessels **224**, **226** are at least partially filled with a liquid, such as water, that is moved by the actuator **212** to alternately compress and drive gas from the volume of each of the first and second pressure vessels **224**, **226**, when operated in a compression mode, or to be moved by compressed gas received in either of the first and second pressure vessels **224**, **226** when operated in an expansion mode.

[0052] Each pressure vessel **224**, **226** can be considered to define a working chamber for compressing and/or expanding a gas. The working chamber has a volume that is defined by the volume of the pressure vessel. The working chamber has a portion of this volume that can contain gas and a portion that contains liquid—the portion of the volume that contains gas is equal to the total volume of the working chamber less the volume of the portion containing liquid. Operation of the water pump to urge liquid from the pump cylinder into the pressure vessel reduces the volume of the portion of the working chamber that can contain gas, thus compressing the gas contained in that portion (e.g. during a compression cycle). Similarly, operation of the water pump to allow liquid to be transferred from the pressure vessel to the water pump increases the volume of the portion of the working chamber that can contain gas, allowing the gas to expand. Alternatively, a working chamber can be considered to be defined by the pressure vessel and the portion of the water pump in fluidic communication with the pressure vessel (i.e. on one side of the working piston), and any conduit or other volume connecting the pressure vessel and the water pump. So defined, the working chamber has a variable volume, which volume can be changed by movement of the working piston.

A portion of the variable volume can be occupied by liquid (e.g. water), while the remaining portion can be occupied by gas (e.g. air). The pressure of the gas contained in the working chamber is essentially equal to the pressure of any liquid contained in the working chamber, and to the pressure acting on the corresponding side or face of the working piston.

[0053] The compressor/expander device **220** may also include fins, dividers and/or trays **234** that can be positioned within the interior of the first and second pressure vessels **224**, **226**. The dividers **234** can increase the overall area within a pressure vessel that is in direct or indirect contact with gas, which can improve heat transfer. The dividers **234** can provide for an increased heat transfer area with both gas that is being compressed and gas that is being expanded (either through an gas/liquid interface area or gas/divider interface), while allowing the exterior structure and overall shape and size of a pressure vessel to be optimized for other considerations, such as pressure limits and/or shipping size limitations.

[0054] In this embodiment, the dividers **234** are arranged in a stack configuration within the first and second pressure vessels **224** and **226**. Each divider **234** can be configured to retain a pocket of gas. In one illustrative embodiment, each of the dividers **234** can include an upper wall, a downwardly extending side wall that may conform in shape and substantially in size to the inner wall of the pressure vessel, and an open bottom. The open bottom of each of the dividers **234** face in a common, substantially downward direction when the pressure vessel is oriented for operation. It is to be appreciated that although the figures show dividers that conform in size and shape to the interior of the pressure vessels **224**, **226**, and are generally shaped similarly to one another, other configurations are also possible and contemplated, including embodiments that include dividers that are substantially smaller in width than the interior of a pressure vessel and/or that are shaped and sized differently than one another, among other configurations. Various other shapes and configurations of dividers can be used, such as, for example, the dividers that are shown and described in U.S. Provisional App. No. 61/216,942 and the Compressor and/or Expander Device applications incorporated by reference above.

[0055] As shown in FIG. **2**, a manifold **236** can extend centrally through the stack of dividers **234** and fluidly couple each of the dividers **234** to an inlet/outlet port **238** of the pressure vessels **224**, **226**. In other embodiments, the manifold may include multiple tubes and/or may be located peripherally about the stack of dividers or in other positions. Gas may enter and/or exit the pressure vessels **224**, **226** through the ports **238**, and can provide a conduit for fluid communication between pockets of gas associated with each divider **234**. In other embodiments, such as those in which dividers do not retain a pocket of gas, the manifold may not be included.

[0056] As discussed above, heat can be transferred from and/or to gas that is compressed and/or expanded by liquid (e.g., water) within a pressure vessel. A gas/liquid or gas/divider interface (e.g., provided in part by dividers discussed above) may move and/or change shape during a compression and/or expansion process in a pressure vessel. This movement and/or shape change may provide a compressor/expander device with a heat transfer surface that can accommodate the changing shape of the internal areas of a pressure vessel through which heat is transferred during compression and/or expansion. In some embodiments, the liquid may allow the volume of gas remaining in a pressure vessel after compression to be nearly eliminated or completely eliminated (i.e., zero clearance volume).

[0057] A liquid (such as water) can have a relatively high thermal capacity as compared to a gas (such as air) such that a transfer of heat energy from the gas to the liquid significantly decreases the temperature rise of the gas but incurs only a modest increase in the temperature of the liquid. This allows buffering of the system from substantial temperature changes. Heat that is transferred between the gas and liquid or components of the vessel itself may be moved from or to the pressure vessel through one or more heat exchangers that are in contact with the liquid or components of the vessel. One type of heat exchanger that can be used to accomplish this is a heat pipe, as discussed in greater detail below.

[0058] Thus, the liquid within a pressure vessel can be used to transfer heat from air that is compressed (or to air that is expanded) and can also act in combination with a heat exchanger to transfer heat to an external environment (or from an external environment). By way of example, as shown in FIG. **2**, a heat exchanger that includes a circular array of heat pipes **242** that extend through a wall of the pressure vessels **224** and **226** and can contact both the liquid within the vessels and the external environment. The heat pipes **242** are just one example embodiment of a type of heat exchanger that can be used to transfer heat to or from liquid of a pressure vessel. It should be understood that other types of heat exchangers and other heat pipe configurations can alternatively be used. For example, other heat management devices can be used (alternatively or in addition to) such as, for example, fins, pins, convection-inducing shapes, and/or swirl-inducing shapes, etc.

[0059] The embodiment of FIG. **2** is one example of an arrangement of pressure vessels and an actuator that can be used within a gas compression and storage system. It should be understood, that other arrangements are also possible and contemplated. By way of example, although the actuator is shown as including a single, double acting piston that is oriented vertically, other embodiments may include housings with actuators that include horizontally oriented pistons and/or multiple hydraulic pistons that operate in parallel to move fluid within working chambers. According to some embodiments, actuators may lack pistons altogether and instead comprise pumps that move fluid into and out of the pressure vessels. Multiple pumps and/or pistons can additionally, or alternatively, be used in parallel to move fluid into and out of the pressure vessels, according to some embodiments. Still, according to other embodiments, an actuator, such as a hydraulic piston, may have a direct mechanical connection to the motor/generator of the system, as embodiments of the system are not limited to that shown in the figures. Another embodiment can combine the water pump **212** with the pressure vessel **220** such that the mechanical piston moves within the pressure vessel.

[0060] FIGS. **3**A-**3**B illustrate schematically an example of a two-stage gas energy compression and expansion system **300**. FIG. **3**A is a schematic illustration of a portion of the system **300**. Stage one includes a pair of pressure vessels **324**, **326** connected in fluid communication to an actuator **312**. For example, various types of conduit or housing (as shown in FIG. **3**A) can be used to fluidically couple various components of the actuator **312** to the pressure vessels. The pressure vessels **324**, **326** can each include dividers or tray (not shown in FIG. **3**A) as described above for previous embodiments.

The actuator **312** includes liquid pumps driven by hydraulic actuators or cylinders as described below. As shown in FIG. **3**A, the actuator **312** includes liquid pumps **344**A, **344**B and **346**. In this embodiment, liquid pumps **344**A and **344**B are constructed in two portions to reduce the height of the pumping equipment, and in this embodiment liquid pumps **344**A and **344**B act in concert as a single pump. Each of the liquid pumps **344**A, **344**B and **346** include a liquid piston, or working piston, that is hydraulically driven with a pair of hydraulic cylinders. Liquid pump **344**A is coupled to and driven by hydraulic cylinders **352** and **354**; liquid pump **344**B is coupled to and driven by hydraulic cylinders **356** and **358**; and liquid pump **346** is coupled to and driven by hydraulic cylinders **348** and **350**. A common drive rod couples the liquid pistons to their respective hydraulic cylinders. The hydraulic cylinders for stage one can all be controlled by a first high efficiency hydraulic pump **314** as shown in FIG. **3**B. A hydraulic pump/motor, such as, for example, an Artemis Digital Displacement hydraulic pump manufactured by Artemis Intelligent Power Ltd. can be used. Other examples of hydraulic pumps that can be used are described in U.S. Pat. No. 7,001,158, entitled "Digital Fluid Pump," and in U.S. Pat. No. 5,259,738, entitled "Fluid-Working Machine," the entire disclosures of which are hereby incorporated by reference.

[0061] As shown in FIG. **3**B, a system controller or hydraulic controller **316** can be used to operate and control the hydraulic pump/motor **314**. The hydraulic pump/motor **314** can be connected to each end of the hydraulic cylinders associated with the various liquid pumps (or working actuators) of the system. A valve is coupled between each end (i.e. each hydraulic chamber) of the hydraulic cylinders and the hydraulic pump, which can be selectively opened and closed, e.g. under control of the hydraulic controller **316**, to fluidically couple or fluidically isolate, respectively, the output of the hydraulic pump **314** and each hydraulic chamber of each hydraulic cylinder to selectively actuate a specific hydraulic cylinder and, more particularly, a particular side (e.g., blind side and/or rod side, as described in more detail below) of the hydraulic piston in the specific hydraulic cylinder. Each valve is designated by **318** in FIG. **3**B.

[0062] As shown in FIG. **3**A, stage two of the system **300** includes a pair of pressure vessels **362** and **364** connected in fluid communication to an actuator **313** that includes liquid pumps **366** and **368**. As with the stage one configuration, each of the pressure vessels **362** and **364** can include dividers and each of the liquid pumps **366** and **368** include a liquid piston that is hydraulically driven by (or, in expansion mode, drives) a pair of hydraulic cylinders, also shown in FIG. **3**A. Liquid pump **366** is coupled to and driven by hydraulic cylinders **370** and **372** and liquid pump **368** is coupled to and driven by hydraulic cylinders **374** and **376**. The hydraulic cylinders for stage two can all be driven by, or drive a second high efficiency hydraulic pump/motor (not shown) in a similar fashion as stage one, using the same hydraulic controller **316**, or a second hydraulic controller (not shown). It is to be appreciated that the stage two hydraulic cylinders can be driven by, or drive various configurations of hydraulic pump/motor, and that the system **300** can have, for example, one, two, three, four, or more hydraulic pump/motors.

[0063] Each of the first and second pressure vessels **324** and **326** of the first stage are fluidly coupled to the pressure vessels **362** and **364** of the second stage by a conduit that may include one or more valves (not shown in FIG. **3**A) to selectively open and close fluid communication between the volumes of the corresponding pressure vessels. The first and second pressure vessels **324** and **326** of stage one can also each include a valve (not shown) that opens to allow the receipt of air from the environment (e.g., at atmospheric pressure) or air that has been optionally pre-compressed from atmospheric pressure to a desired pressure, for example, 1-3 bar. Additional valves can be used between the pressure vessels of stage two and a storage structure or cavern (not shown) in which the compressed air from the system may be stored. Valves can be coupled to and disposed at locations along the conduit connecting the various components or directly to the components.

[0064] FIGS. **4**A-**4**F illustrate an example of a portion of an actuator of a gas compression and expansion system **300**. FIG. **4**A schematically illustrates the various components of a portion of actuator **312** including the liquid pump **346**, and its corresponding hydraulic cylinders **348** and **350**; and FIG. **4**B schematically illustrates the various components of the hydraulic cylinder **348**. It should be understood, however, that each of the liquid pumps and hydraulic cylinders in both the first stage and the second stage of the system **300** can be similarly constructed and function in the same manner as liquid pump **346** and hydraulic cylinder **348**. As shown in FIG. **4**A, the liquid pump **346** includes a cylindrical liquid reservoir or housing **382** that can contain liquid, such as, for example, water W (though other working liquids could be used), a liquid piston, or working piston, **374** and a drive rod **376** coupled to the piston **374**. The drive rod **376** is also coupled to hydraulic drive pistons **378** and **380** of the hydraulic cylinders **348** and **350**, respectively. Thus, the hydraulic cylinders **348** and **350** can be used to operate or drive the piston **374** back and forth within the housing **382**, pressurizing and moving the liquid W contained therein. The liquid housing **382** is divided into two portions, one on each side of piston **374**. Each portion is in fluid communication with a pressure vessel, such as the pressure vessels described above (not shown in FIG. **4**A). As described above, each side of working piston **374** bears the same pressure as that of the gas contained in the pressure vessel with which that side of working piston **374** bounds a working chamber containing the air.

[0065] FIG. **4**B schematically illustrates the hydraulic cylinder **348**. As shown in FIG. **4**B, the hydraulic cylinder **348** includes a cylindrical housing **384** in which a hydraulic drive piston **378** is movably disposed. As stated above, the drive piston **378** is coupled to the drive rod **376**. Within the housing **384** of the hydraulic cylinder **348**, hydraulic fluid Hf can be pumped in and out, as will be described in more detail below.

[0066] The housing **384** of the hydraulic cylinder **348** defines an interior volume that is divided into two portions at any given time during a stroke of the hydraulic cylinder by the drive piston or hydraulic piston **378**. As shown in FIG. **4**B, the portion of the interior volume within the housing **384** above the drive piston **378** (or on the opposite side of the piston **378** from the rod **376**) is referred to herein as the "blind side" or "bore side" Bs, and the portion of the interior volume within the housing **384** shown below the drive piston **378** (or on the same side as the rod **376**) is referred to herein as the rod side Rs. To drive the hydraulic cylinders, hydraulic fluid Hf can be pumped into each hydraulic cylinder on either (or both) sides of the drive piston to achieve varying pressures and flow rates within the system. For example, at various steps in the process of compressing air for energy storage, the pressurized hydraulic fluid Hf can be pumped into the housing **384** only on the blind side Bs, only on the rod side Rs, or on both sides, depending on the desired output pressure, flow rate and/or direction of force desired at the various steps of a compression or expansion cycle.

[0067] For example, referring to the liquid pump **346** and its associated hydraulic cylinders **348** and **350**, to move the working piston **374** within the housing **382** to change the volume of the working chamber bounded in part by the working piston, one or both of the hydraulic cylinders **348** and **350** can be actuated at a given time period to provide the desired force to move the piston. For example, to move the piston **374** upward, hydraulic fluid can be pumped into the blind side, or both the blind side and the rod side of the hydraulic cylinder **350**, or hydraulic fluid can be pumped into the rod side of the hydraulic cylinder **348**, or a combination thereof To move the piston **374** downward, hydraulic fluid can be pumped into the blind side of hydraulic cylinder **348**, both the blind side and the rod side of the hydraulic cylinder **348**, or the rod side of the hydraulic cylinder **350**, or a combination thereof Each of these modes has a different total area of hydraulic piston bearing the pressure of the hydraulic fluid, and thus will exert a different force on the working piston **374**. It is to be appreciated that varying the pressure of the hydraulic fluid can act in concert with the varying combinations of reservoir pressurization to provide a wide range of force to move the piston.

[0068] The system **300** can be configured to operate within a desired energy efficiency range of the hydraulic pump(s). The operating pressure range of the hydraulic pump(s) and the ratio of surface areas of the liquid pistons to the hydraulic drive pistons (also referred to herein as "piston ratio") can be used to determine an optimal operating sequence for the compression process. In addition, by varying which hydraulic pump(s) is actuated to move a liquid piston at a particular point in the cycle, the pressure in the system can be further varied. The pump has a preferred range of pressure and flow, within which it can be continuously operated as the air piston strokes.

[0069] As shown, for example, in FIGS. **4**C-**4**F, the liquid piston **374** has an operating surface **390** that has a surface area SA_w that is the same on both sides of the liquid piston (i.e. the annular area bounded by the outer perimeter of the liquid piston **374** and the outer perimeter of the rod **376**), and the hydraulic drive piston **378** has an operating surface **392** on the blind side with surface area SA_b (i.e. the circular surface area bounded only by the outer perimeter of the hydraulic drive piston) and an operating surface **394** on the rod side with a surface area SA_r (i.e. the annular area bounded by the outer perimeter of the hydraulic drive piston and the outer perimeter of the rod). The operating surface area of a piston is the surface area of the piston on which force is exerted by hydraulic fluid pressure. Thus, when a hydraulic cylinder is actuated by communicating pressurized hydraulic fluid to the blind side, the effective surface area of the hydraulic piston is greater than when the same pressure is communicated to the rod side (i.e., $SA_b > SA_r$). Thus, for a given hydraulic fluid pressure, more force is applied to the rod **376** (albeit in different directions) when the hydraulic fluid pressure is applied to the blind side than when it is applied to the rod side. It is also possible to generate yet a different amount of force for a given hydraulic pressure by applying the hydraulic fluid pressure to both sides of a piston. In this mode of operation, referred to as a regenerative mode, the net piston area is equal to the difference between the blind side area SA_b and the rod side area SA_r. This net area corresponds to the cross-sectional area of the rod, and is referred to as $SA_{(b-r)}$.

[0070] In some embodiments, a combination of surface areas associated with hydraulic drive piston **378** and hydraulic drive piston **380** are pressurized to achieve a desired output force on rod **376**, which may correspond to a second pressure of liquid W. The effective or net operating surface area A_{net} being pressurized for a given gear is then equal to the sum of the surface areas associated with the various portions of the hydraulic cylinders **348** and **350** being pressurized with hydraulic fluid. The sum of the surface areas can also be referred to as the surface area of the hydraulic piston(s) SA_h. It is to be appreciated that other embodiments include those in which the hydraulic fluid pressure communicated to the various surface areas in actuator **312** may be different from each other.

[0071] The ratio of the surface area of the working piston or liquid piston SA_w to the surface area of the hydraulic piston(s) SA_h dictates the hydraulic pressure needed to achieve a desired liquid pressure, and thus gas pressure, at a given point in the cycle. By varying the surface area ratio for a given liquid pump/hydraulic cylinder set, varying levels of liquid pressure can be achieved at different points within the compression cycle for the same levels of hydraulic pressure. The pressure of the hydraulic fluid needed to achieve a particular liquid pressure (and/or gas pressure) can be calculated as follows.

$$F_h \text{ (force of hydraulic fluid)} = P_h \text{ (hydraulic pressure)} \times SA_h \text{ (}SA_r \text{ or } SA_b \text{ or } SA_{(b-r)}\text{)}$$

$$F_w \text{ (force applied to liquid)} = P_w \text{ (liquid pressure)} \times SA_w$$

$$F_h = F_w$$

$$P_w \times SA_w = P_h \times SA_h$$

$$P_w = P_h \times (SA_h/SA_w) \text{ and } P_h = P_w \times (SA_w/SA_h)$$

[0072] A maximum and minimum operating pressure for each hydraulic pump can be established, e.g. as the limits of a range of operating pressure within which the hydraulic pump operates at or above a desired energy efficiency. This pressure range can be used to determine the piston ratio (e.g., (SA_h/SA_w)) needed at various points during a compression cycle to operate the system so as to approach or achieve operation within the maximum efficiency range of the hydraulic pump. For example, for a hydraulic pump having a maximum efficient operating pressure of 300 bar and a desired maximum output pressure of the air (and therefore the liquid) is 30 bar, the piston ratio (i.e., (SA_w/SA_h)) required at the end of the pressurization cycle, when the liquid and gas pressure reaches 30 bar, is 10:1. Correspondingly, if the hydraulic pump has a minimum efficient operating pressure of 120 bar, and the air enters the system at 3 bar, then the piston ratio (i.e., (SA_w/SA_h)) required at the start of the pressurization cycle, when the liquid and gas pressure is 3 bar, is 40:1. The number of liquid pumps and hydraulic pumps needed, and the piston ratios (and corresponding size of the hydraulic cylinders and liquid pumps) for the various liquid pump/hydraulic sets can then be determined such that the system can operate within the desired efficiency range for the entire compression cycle (i.e., compressing the gas from 3 bar to 30 bar). There are a variety of different operating sequences that can be used to incrementally increase the pressure in the system and to achieve this output. It is understood that the approach can be applied using hydraulic pumps with maximum operating pressures higher or lower than 300 bar, and minimum operating pressures higher or lower than 120 bar.

[0073] At a given time during a compression or expansion cycle, the actuator **312** can be referred to as being in a particular "state" or gear that is associated with the piston area ratios being pressurized within the actuator at that time. As described above, when the system makes a change in the ratio of the pressure of the hydraulic fluid in the hydraulic actuator to the pressure of the liquid in the liquid pump(s) actuated by the hydraulic actuator (i.e., the ratio of the pressurized surface area of the liquid piston to the net operating pressurized surface area(s) of the hydraulic piston(s) actuating the liquid piston) this is referred to as a "gear shift" or "gear change." There is a variety of different combinations or sequences of gear changes (changes in piston area ratios) that can be incorporated into a particular operating sequence of the system.

[0074] In the example of system **300**, where each liquid pump has two identical associated hydraulic cylinders to actuate the liquid pump, there are sixteen possible states for the two actuators, i.e. every combination of each chamber being pressurized or not pressurized (two states for four chambers gives 2^4 combinations). For identical hydraulic cylinders (i.e. in which the blind side area of each cylinder is the same and the rod side area of each cylinder is the same), there are four different possible gears (with associated piston area ratios) that can be used to actuate each working or liquid piston in each direction. For example, to move a liquid piston upward in one liquid pump, hydraulic fluid can be pumped into (1) the rod side of the upper hydraulic cylinder (or the rod side of the upper hydraulic cylinder and the blind side of both cylinders, which cancel each other out), (2) the blind side of the lower hydraulic cylinder (or the blind side of the lower cylinder and the rod side of both cylinders, which cancel each other out), (3) both the blind side and the rod side of the lower hydraulic cylinder, or (4) both the rod side of the upper hydraulic cylinder and the blind side of the lower hydraulic cylinder. The state in which none of the chambers is pressurized does not produce any force on the working piston, nor (for identical cylinders) does the state in which all chambers are pressurized. In the embodiment depicted in FIG. **3**A, each stage is configured with two liquid pumps that actuate one after the other, and because each liquid pump in this embodiment has four possible gears, the compression process has eight possible gears. It is to be appreciated that other embodiments include those in which the hydraulic fluid pressure communicated to the various surface areas in actuator **312** may be different from each other and may create more than four possible gears in each liquid pump. It is appreciated that given an actuator that can achieve four possible gears, it may be preferable to use fewer gears than four gears, for example three gears. The reasons for such a preference may involve the dynamic response of the fluid and/or mechanical components to the gear shift events. Correspondingly, an embodiment configured with two liquid pumps may be operated using five, six, or seven of the possible eight gears. Moreover, the compression process may also vary according to the current pressure of the compressed air storage vessel, e.g. when the storage vessel is at relatively low pressure, the preferred compression process may use one, two, three, four, five, six, or seven of the possible eight gears.

[0075] In other embodiments, an actuator can be configured to have a different number of possible different gears and gear changes based on, for example, the number of hydraulic cylinders, the size (e.g., diameter) of the housing of a hydraulic cylinder in which a hydraulic piston is movably disposed, the size (e.g., diameter) of the hydraulic pistons disposed within the housing of the hydraulic cylinders, the number and size of drive rods coupled to the hydraulic pistons, and/or the size of the working piston to be actuated. Other examples of actuators are described in the Ingersoll I application incorporated by reference above.

[0076] Thus, the hydraulic pressure time profile can be varied as needed to achieve a particular output gas pressure. The efficiency range of the hydraulic pump system can determine the number of gears and gear shifts that may be needed for a desired gas pressure range (difference between input or start pressure and output or end pressure). For example, if the hydraulic pump's efficiency range is narrower, then more gears may be needed for a given gas pressure range. The size and number of gears can also depend on the particular operating speed (RPM) of the system.

[0077] As discussed above, heat can be transferred from air (or other gas) that is compressed in the working chamber to reduce the work consumed by the compression process. Heat can be transferred from gas to a liquid, and/or gas to dividers within the working chamber, and/or from the liquid out of the working chamber. In some embodiments, to increase the total amount of heat energy transferred during each cycle, the system can be operated at a relatively slow speed. For example, in some embodiments, a complete compression or expansion cycle may be slow enough to provide sufficient time for enough heat energy to be transferred between the gas and the liquid to approximate an isothermal compression and/or expansion process, achieving work reduction or extraction and the efficiencies associated therewith. Additionally or alternatively, faster speeds may allow larger power levels to be achieved during expansion, isothermally or with temperature changes, which may be desirable at particular times during the system operation.

[0078] The use of a liquid (e.g. water) as a medium through which heat passes during compression and/or expansion may allow for a continuous temperature moderation process and may provide a mechanism by which heat energy may be moved in and/or out of the working chamber. That is, during compression the liquid may receive heat energy from gas that is being compressed, and pass this heat energy to the external environment continuously, or in batches, both while gas is being compressed and while gas is being received by the working chamber for later compression. Similarly, heat energy addition may occur when a compressor/expander device is operating in an expansion mode both during expansion and as expanded gas is passed from a pressure vessel.

[0079] As discussed above, the liquid within a pressure vessel can be in contact with the gas at one or more gas/liquid interfaces and gas/divider interfaces, across which heat energy is transferred from gas that is compressed and/or to gas that is expanded. The pressure vessel/working chamber can also include a heat exchanger, such as one or more heat pipes as discussed above, that transfers heat energy between the liquid and an environment that is external to the device. Heat energy may be moved from gas that is compressed and/or to gas that is expanded to achieve isothermal or near isothermal compression and/or expansion processes.

[0080] As described above, adiabatic compression assumes that no energy (heat) is transferred to or from the gas during the compression process, and all applied work is added to the internal energy of the gas, resulting in increases of both temperature and pressure. In contrast, isothermal compression assumes that the compressed gas remains at a constant temperature throughout the compression process, and energy is removed from the system at the same rate as heat is added by the mechanical work of compression. For a given gas volume reduction (i.e., ratio of final volume to initial volume), an adiabatic compression process results in the highest final gas pressure, the highest final gas temperature, and the highest work consumption. For the same volume reduction, an isothermal compression process results in the lowest final pressure and consumes half of the work as the adiabatic compression process. The difference in the amount of mechanical work required is reflected in the heat energy that is retained in the compressed gas. This due to the fact that if there is no temperature difference throughout the process, the internal energy (U) remains invariant. The equation below is a simplified version of the conservation of energy or the first law of thermodynamics. If dU is zero, then the amount of heat transferred (dQ) equals the work input (dW).

$$dU=dQ-dW$$

for $dU=0$, $dQ=dW$

[0081] The use of adiabatic compression (or near adiabatic compression) may be desirable in some applications since approximately twice as much energy is stored at the end of the compression process. However, since approximately half of this stored energy is heat energy, and perfect insulation is not practical, the heat energy will flow out of the compressed gas over time. In applications where the compressed gas is going to be stored for a period of time, isothermal compression (or near isothermal compression) may be desirable to prevent work from being lost in the form of heat energy flow out of the compressed gas over time. For example, in compressed gas energy storage, where a compressed gas is moved out of a compression device to a storage structure for potentially longer term storage, minimizing the work lost due to heat flow out of the compressed gas/system may be desirable.

[0082] In the gas compression/expansion devices and systems described herein, the heat transfer characteristics can be varied to approximate near adiabatic compression and/or expansion or near isothermal compression and/or expansion, and anywhere in between those two theoretical limits. For example, as described above, heat energy can be removed from a gas during a compression process (or can be added to a gas during an expansion process) via a liquid that is present in one or more pressure vessels of a compressor/expander device to control the gas temperature throughout the process. In other examples, a heat transfer element can be positioned within the interior of a working chamber of a compressor/expander device to provide sufficient gas/liquid interface and/or sufficient thermal capacity to efficiently intermediate in, and enhance, the transfer of heat between the gas and the liquid.

[0083] As described above, the rate at which heat energy is added to the gas as it is being compressed (or released from the gas during an expansion process) can also be varied to approximate near adiabatic compression and/or expansion or near isothermal compression and/or expansion, and anywhere in between those to theoretical limits, by changing the rate at which mechanical work is being done on the gas (i.e., changing the speed of the compression/expansion stroke, or the rate of change of volume of the working chamber).

[0084] The following discussion compares the operation of a compression/expansion device as described herein. In each case, it is assumed that the same quantity of gas is compressed (or expanded) over the same pressure ratio, the initial temperature of the gas is the same for compression cycles, but the temperature of the gas is allowed to vary over the course of the compression cycle. Since the pressure ratio is held constant and only the temperature is allowed to vary, the ratio of the mechanical work done on the gas to the heat flow out of the system is relatively constant in these examples. Typically the pressure will vary when the temperature is caused to change through the stroke, however these graphs keep pressure fixed to best illustrate the flexibility such a system can have by isolating a single variable for discussion purposes. That being said, it is possible to change the discharge temperature while maintaining the same pressure profile by changing the volumetric compression/expansion ratio. This is possible with the system described above by changing stroke length, and/or changing the volume of water in the system. As will be apparent from the discussion below, one or more of the system variables can be changed to achieve any desired temperature and pressure profile.

[0085] Each of FIGS. **5-11** is an example graph illustrating the operation of a compression and/or expansion device as described herein. The values shown in FIGS. **5-11** are exemplary and for comparisons purposes only and the systems and methods described herein are not limited to the data disclosed in these figures. FIG. **5** illustrates one example of a compressor/expander device designed and operated to achieve essentially isothermal compression. The pressure of a quantity of gas is raised from an initial pressure of 1 bar to a final pressure of 7 bar (i.e., 7:1 pressure ratio) over a six second compression stroke. In this example, during the compression stroke, energy is continuously being transferred to a heat transfer element positioned within the interior of a working chamber of a compressor/expander device. The energy is then transferred from the heat transfer element to a liquid (such as water) present in the compressor/expander device. A portion of the liquid is then removed from the working chamber after the compression cycle has been completed, and transferred to another stage of the system and/or out of the system entirely. Heat energy is removed from the system at the same rate as heat energy is added by the mechanical work of compression, so the temperature of the gas remains constant throughout the compression stroke.

[0086] FIG. **6** illustrates another example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is raised from an initial pressure of 1 bar to a final pressure of 7 bar (i.e., 7:1 pressure ratio) over a six second compression stroke. In this example, less liquid is removed from the working chamber after the compression cycle has been completed, thus the heat transfer element is not "reset" to the initial temperature of the incoming gas. The heat transfer rate is a function of the temperature differential between the gas being compressed and the heat transfer element, therefore the heat transfer rate will be lower in this example than in the isothermal example shown in FIG. **5**. Since the heat transfer rate is lower, and less heat energy is being removed from the system (i.e., less heated liquid) than is being added by the mechanical work of compression, the temperature of the gas rises, in this example at a relatively linear rate throughout the compression stroke. The rate at which the temperature of the gas rises related to the volume of liquid removed from the working chamber after the compression cycle has been completed.

[0087] FIG. **7** illustrates another example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is raised from an initial pressure of 1 bar to a final pressure of 7 bar (i.e., 7:1 pressure ratio) over a six second compression stroke. As described above, the configuration (size, shape, structure, etc.) of the heat transfer element can be changed to vary the surface area per unit volume or mass within the gas as it is being compressed/expanded during a compression/expansion cycle. In this example, the heat transfer element has multiple components that are movable with respect to each other such that the volumetric density of the heat transfer element can be varied as a function of stroke throughout the compression cycle. The varying density at different times during the compression cycle changes the heat transfer rates throughout the compression cycle. As shown, the temperature profile resembles a polynomial function, which may be desirable for processes where the temperature profile is of interest (e.g., a chemical reaction process), and not just the initial and final temperature.

[0088] FIG. **8** illustrates another example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is raised from an initial pressure of 1 bar to a final pressure of 7 bar (i.e., 7:1 pressure ratio). In this example, the liquid removal rate and the heat transfer element configuration are the same as the example shown in FIG. **5**, however the compression stroke has been shortened to 3 seconds. As described above, the rate at which heat energy is added to the gas as it is being compressed (or released from the gas during an expansion process) can be varied by changing the rate at which mechanical work is being done on the gas (i.e., changing the speed of the compression/expansion stroke). By doubling the speed of the compression stroke, approximately the same amount of work is being done on the gas in half the time, thus increasing the rate at which heat energy is added to the gas as it is being compressed. Since the heat transfer element geometry and materials have not changed, the maximum rate at which heat is transferred to or from the gas has not changed. Therefore the increased rate of heat transfer necessary with a shorter stroke is not adequately met by the same geometry as was used in FIG. **5**. This results in the rise in temperature seen in FIG.**8** that was not seen in FIG. **5**.

[0089] FIG. **9** illustrates another example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is raised from an initial pressure of 1 bar to a final pressure of 7 bar (i.e., 7:1 pressure ratio) over a six second compression stroke. In this example, the effects of decreasing the amount of liquid (FIG. **6**) that is removed from the working chamber after the compression cycle and of changing the configuration of the heat transfer element (FIG. **7**) can be combined or superimposed, allowing a different temperature profile to be achieved than can be achieved with either effect separately. In reality the effects are not a simple summation of two separate effects, however it is a good first approximation and serves to illustrate the phenomenon.

[0090] FIG. **10** illustrates an example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is raised from an initial pressure of 1 bar to several final pressures isothermally at 300 K. It is possible to size a heat transfer element such that several different pressure profiles all result in a near-isothermal process as shown in FIG. **10**. Such a change can be effected in process without modification to the geometry and without shutting down the system. It can be appreciated that the temperature profile can be simultaneously altered in the manners shown in FIG. **5-9** at the same time the pressure profile is customized as shown in FIG. **10**.

[0091] FIG. **11** illustrates another example of the operation of a compression and/or expansion device where the pressure of a quantity of gas is lowered from an initial pressure of 7 bars to a final pressure of 1 bar (i.e., 7:1 pressure ratio) over a three second compression stroke. In this example, the liquid removal rate and the heat transfer element configuration are the same as the example shown in FIG. **8**, however the compressor/expander device is operating in an expansion cycle. It is to be appreciated that although FIGS. **5-10** illustrate the operation of a compression and/or expansion device during a compression cycle, the changes to the system variables illustrated in those examples are equally applicable to an expansion cycle.

[0092] FIG. **12** schematically illustrates a portion of a compressor/expander device according to another embodiment. A compressor/expander device **400** can include one or more pressure vessels (cylinders) **420** having a first working chamber **462** and a second working chamber **464**, an actuator **421** connected to a piston **466** via a piston rod **427**, and first heat transfer element **423** and a second heat transfer element **425** disposed within the pressure vessel **420**. The compression/expansion device **400** can be used in the same or similar manner as described above for previous embodiments, to compress and/or expand a gas (e.g., air). In this embodiment, the piston **466** is used to move a liquid within the pressure vessel **420** to compress and/or expand a gas within the pressure vessel **420**.

[0093] More specifically, the first heat transfer element **423** is disposed within the first working chamber **462** and the second heat transfer element **425** is disposed within the second working chamber **464**. The compressor/expander device **400** can be used, for example, to compress and/or expand a gas, such as air, within the first working chamber **462** or the second working chamber **464**. The compressor/expander device **400** can be used, for example, in a CAES system. The pressure vessel **420** can include an inlet conduit **428** and an outlet conduit **429** in fluid communication with the first working chamber **462** and an inlet conduit **430** and an outlet conduit **431** in fluid communication with the second working chamber **464**. The first working chamber **462** and the second working chamber **464** can contain, at various time periods during a compression and/or expansion cycle, a quantity of the gas (e.g., air) and a quantity of the liquid (e.g., water) that can be communicated to and from the working chambers via the inlet/outlet conduits. Optionally, the pressure vessel **420** can include one or more additional conduits in fluid communication with the first working chamber **462** or the second working chamber **464** specifically dedicated to communicating gas or liquid to or from the first and second working chambers **462**, **464**. The compressor/expander device **400** can also include multiple valves (not shown in FIG. **12**) coupled to the inlet/outlet conduits **428**, **429**, **430**, and **431** and/or to the pressure vessel **420**. The valves can be configured to operatively open and close the fluid communication to and from the working chambers **462** and **464**. Examples of use of such valves are described in more detail in the Compressor and/or Expander Device applications incorporated by reference above.

[0094] The actuator **465** can be any suitable mechanism for causing reciprocal movement of the piston **466** within the pressure vessel **420**. As the piston **466** is moved back and forth within the pressure vessel **420**, the volume of the first working chamber **462** and the second working chamber **464** and/or the portion of the volume of the first working chamber **462** and the second working chamber **464** that can be occupied by gas can be selectively changed. The actuator **465** can be for example, an electric motor or a hydraulically driven actuator such as, for example, the hydraulic actuators described in the Ingersoll I application incorporated herein by reference above. The actuator **465** can be coupled to the piston **466** via the piston rod **427** and used to move the piston **466** back and forth within the interior region of the pressure vessel **420**. For example, the working chamber **462** can be defined by the cylinder **420** and the bottom face of piston **466**. Similarly, the working chamber **464** can be defined by the cylinder **420** and the top face of the piston **466**. In this manner, the piston **466** is movably disposed within the interior region of the cylinder **420** and can divide the interior region between a first interior region (working chamber **462**) and a second interior region (working chamber **464**).

[0095] As the piston **466** moves back and forth within the interior region of the cylinder **420**, a volume of the first working chamber **462** and a volume of the second working chamber **464** will each change. For example, the piston **466** can be moved between a first position (e.g., top dead center) in which the first working chamber **462** includes a volume of fluid greater than a volume of fluid in the second working chamber **464**, and a second position (e.g., bottom dead center) in which the second working chamber **464** includes a volume of fluid greater than a volume of fluid in the first working chamber **462**. As used herein, "fluid" means a liquid, gas, vapor, suspension, aerosol, or any combination of thereof. At least one seal member (not shown), such as, for example, a rolling seal member can be disposed within the first working chamber **462** and the second working chamber **464** of the cylinder **420** and can be attached to the piston **466**. The arrangement of the rolling seal member(s) can fluidically seal the first working chamber **462** and the second working chamber **464** as the piston **466** moves between the first position (i.e., top dead center) and the second position (i.e., bottom dead center). Examples and use of a rolling seal member are described in more detail U.S. patent application Ser. No. 13/312,467 to Ingersoll et al. ("the Ingersoll III application"), entitled "Compressor and/or Expander Device with Rolling Piston Seal," the disclosure of which is incorporated herein by reference in its entirety

[0096] In some embodiments, the piston **466** is moved within the pressure vessel **420** to compress a gas, such as air, within the pressure vessel **420**. In some embodiments, the piston **466** can be configured to be single-acting (e.g., actuated in a single direction to compress and/or expand gas). As shown in FIG. **12**, the compressor/expander device **400** is configured to be double-acting in that the piston **466** can be actuated in two directions. In other words, the piston **466** can be actuated to compress and/or expand gas (e.g., air) in two directions. For example, in some embodiments, as the piston **466** is moved in a first direction, a first volume of a fluid (e.g., water, air, and/or any combination thereof) having a first pressure can enter the first working chamber **462** of the cylinder **420** on the bottom side of the piston **466**. In addition, a second volume of the fluid having a second pressure can be compressed by the top side of the piston **466** in the second working chamber **464**. The gas portion of the second volume of fluid can then exit the second working chamber **464**. When the piston **466** is moved in a second direction opposite the first direction, the gas portion of the first volume of fluid within the first working chamber **462** can be compressed by the piston **466**. The gas portion of the first volume of fluid can then exit the first working chamber **462** having a third pressure greater than the first pressure, and simultaneously a third volume of fluid can enter the second working chamber **464**.

[0097] The heat transfer element **423** disposed within the first working chamber **462** and the heat transfer element **425** disposed within the second working chamber **464** can be a variety of different configurations, shapes, sizes, structures, etc. to provide a relatively high surface area per unit volume or mass that can be in contact with the gas (e.g., air) as it is being compressed or expanded. In this embodiment, as shown in FIG. **8**, the heat transfer element **423** is disposed near the bottom surface of the piston **466** and the heat transfer element **425** is disposed at a top portion of the second working chamber **464**. In some embodiments, the heat transfer element **423** disposed within the first working chamber **462** can be attached to the bottom face of the piston **466**. Similarly, in some embodiments, the heat transfer element **425** disposed within the second working chamber **464** can be attached to the top face of the piston **466**, as described in further detail herein. In such embodiments, the heat transfer elements **423**, **425** can move with the piston **466** as it is actuated.

[0098] In some embodiments, it may be desirable to form the heat transfer elements **424** with a material that can provide high thermal conductivity. For example, the heat transfer elements **424** (i.e., the heat transfer element **423** and the heat transfer element **424**) can be formed with metals (e.g. stainless steel) in the form of, for example, sheet or wire, carbon fiber, nano-materials, and hybrid or composite materials (e.g. carbon polymer compounds) which have anti-corrosion properties, are lighter weight, and are less expensive than some metallic materials.

[0099] The compressor/expander device **400** also includes an actuator **421** and an actuator **422** that can each be configured the same as, or similar to, actuator **122** a described above. The actuators **421** and **422** can each include a piston (not shown) disposed within a housing (not shown). The actuator **422** can be actuated to move liquid between the housing and the first working chamber **462** via a liquid inlet/outlet **433**, and the actuator **421** can be actuated to move liquid between the housing and the second working chamber **464** via a liquid inlet/outlet **435**. The pistons of the actuators **421** and **422** can each be coupled to, for example, an electric motor or hydraulic actuator configured to actuate the pistons.

[0100] The compression/expansion device **400** can also include a first liquid outlet **468** coupled to, and in fluid communication with, a liquid purge system **438** and the first working chamber **462**, and a second liquid outlet **470** coupled to, and in fluid communication with, the liquid purge system **438** and the second working chamber **464**. The liquid purge system **438** can be configured the same as or similar to, and function the same as or similar to, the liquid purge systems **238** and **338** described above. The first liquid outlet **468** can be opened to evacuate a volume of the liquid from the first working chamber **462**, and the second liquid outlet **470** can be opened to evacuate a volume of the liquid from the second working chamber **464**, as described above for previous embodiments.

[0101] The liquid purge system **438** can include a first pump (not shown) coupled to, and in fluid communication with, the first liquid outlet **468**, and a first conduit (not shown) coupled to, and in fluid communication with, a thermal management facility (not shown). The liquid purge system **438** can also include a second pump (not shown) coupled to, and in fluid communication with, the second liquid outlet **470**, and a second conduit (not shown) coupled to, and in fluid communication with, the thermal management facility. The pumps can each be actuated to move liquid from the first working chamber **462** and the second working chamber **464** to the thermal management facility. The thermal management facility can include a pump (not shown) configured to pump cooled liquid to the actuator **421** and **422**. In some embodiments, the liquid purge system **438** and actuators **421** and **422** can be subsystems of a liquid management system that includes a thermal management facility.

[0102] In use, when the piston **466** is actuated to compress a gas within the pressure vessel **420**, the actuator **465** can be controlled to maintain a relatively constant pressure change profile throughout the stroke of the piston **466**. For example, when the piston **466** is actuated to compress a quantity of gas within the second working chamber **464**, the piston **466** can be actuated over a first distance at a first stroke speed and over a second distance at a second stroke speed. The first distance and the second distance can be the same or different and the first stroke speed and the second stroke speed can be the same or different depending on any of a variety of factors including, for example, the presence or absence of a liquid in the second working chamber **464**, the presence or absence of a heat transfer element **425** in the second working chamber **464**, the interaction between a volume of liquid and a heat transfer element **425** in the second working chamber, or the change in density of the heat transfer element **425** over the vertical distance of the pressure vessel. Said another way, as the piston **466** is actuated at the beginning of a compression stroke, a volume of liquid contained in the second working chamber **464** may not be in contact with the heat transfer element **425** and the piston can be actuated over the first distance at the first stroke speed to maintain a relatively constant compression rate of the quantity of the because the surface are of the liquid acting on the gas is substantially equal to the surface area of the piston **466**. As the liquid in the second working chamber **464** contacts and moves into the heat transfer element **425**, the surface area of the liquid acting on the gas is reduced because the heat transfer element **425** occupies a portion of the cross-sectional area of the pressure vessel. Thus, in order to maintain a relatively constant compression rate of the quantity of gas, the piston **466** can be actuated at a second stroke speed slower than the first stroke speed. As the compression stroke progresses, the stroke speed can be modified to maintain a relatively constant compression rate depending on the structure (e.g., density) of the heat transfer element **425** or to change the rate of compression. Similarly, the stroke speed can be modified to maintain a relatively constant heat transfer rate out of the quantity of gas as it is being compressed or to manage the temperature of the gas throughout the compression stroke to any desired profile as described herein.

[0103] While various embodiments of the invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Where methods and steps described above indicate certain events occurring in certain order, those of ordinary skill in the art having the benefit of this disclosure would recognize that the ordering of certain steps may be modified and that such modifications are in accordance with the variations of the invention. Additionally, certain of the steps may be performed concurrently in a parallel process when possible, as well as performed sequentially as described above. The embodiments have been particularly shown and described, but it will be understood that various changes in form and details may be made.

[0104] For example, although various embodiments have been described as having particular features and/or combinations of components, other embodiments are possible having any combination or sub-combination of any features and/or components from any of the embodiments described herein. For example, although certain embodiments of a heat transfer element were shown and described with respect to a particular embodiment of a compression/expansion device, it should be understood that the various embodiments of a heat transfer element including, for example, rods, tubes, fins, fibers, filaments, coils, plates, mesh, etc. can be used in any of he various embodiments of a compression and/or expansion device described herein and in other embodiments of a compress and/or expansion device not described herein. Additionally, the specific configurations of the various components of a compression and/or expansion device can also be varied. For example, the size and specific shape of the various components can be different than the embodiments shown, while still providing the functions as described herein.

[0105] Although the liquid in the compressor/expander devices was described above as including water, other liquids can be used, additionally or alternatively. As is to be appreciated, water may naturally condense out of air that is being compressed by the system, and in this respect, may combine with the liquid without adverse impact. Additionally, when used in embodiments of the expander/compressor devices, water may evaporate into air during expansion without having an adverse impact. Other types of liquids, however, may be used in addition to or in place of water. Some examples of such liquids may include additives or entire liquids formulated to prevent freezing, such as glycol, liquids that prevent evaporation, such as glycerin, and/or liquids to prevent foaming. Similarly, although the gas in the compressor/expander device was described above as being air (which is a convenient choice, so that ambient air can be used), other gases can be used, additionally or alternatively.

[0106] In addition, although the system **300** was described as having two stages each with two liquid pumps, and the liquid pumps are each actuated by two hydraulic actuators (an upper and a lower hydraulic actuator), in alternative embodiments, more hydraulic actuators can be coupled to the top and bottom of a liquid pump, which can provide additional possible gear modes. In addition, in other embodiments, a system can be configured with a different number of liquid pumps and/or a different number of stages, which can provide additional possible gear modes. In addition, the systems and methods described herein can be controlled using known computer systems and control system used for such purposes.

[0107] The system controller (e.g., **316**) can include, for example, a processor-readable medium storing code representing instructions to cause a processor to perform a process. The processor can be, for example, a commercially available personal computer, or other computing or processing device that is dedicated to performing one or more specific tasks. For example, the processor can be a terminal dedicated to providing an interactive graphical user interface (GUI). The processor, according to one or more embodiments, can be a commercially available microprocessor. Alternatively, the processor can be an application-specific integrated circuit (ASIC) or a combination of ASICs, which are designed to achieve one or more specific functions, or enable one or more specific devices or applications. In yet another embodiment, the processor can be an analog or digital circuit, or a combination of multiple circuits.

[0108] The processor can include a memory component. The memory component can include one or more types of memory. For example, the memory component can include a read only memory (ROM) component and a random access memory (RAM) component. The memory component can also include other types of memory that are suitable for storing data in a form retrievable by the processor. For example, electronically programmable read only memory (EPROM), erasable electronically programmable read only memory (EEPROM), flash memory, magnetic disk memory, as well as other suitable forms of memory can be included within the memory component. It is recognized than any and all of these memory components can be accessed by means of any form of communication network. The processor can also include a variety of other components, such as for example, co-processors, graphic processors, etc., depending upon the desired functionality of the code.

[0109] The processor can be in communication with the memory component, and can store data in the memory component or retrieve data previously stored in the memory component. The components of the processor can be configured to communicate with devices external to the processor by way of an input/output (I/O) component. According to one or more embodiments, the I/O component can include a variety of suitable communication interfaces. For example, the I/O component can include, for example, wired connections, such as standard serial ports, parallel ports, universal serial bus (USB) ports, S-video ports, local area network (LAN) ports, small computer system interface (SCCI) ports, analog to digital interface input devices, digital to analog interface output devices, and so forth. Additionally, the I/O component can include, for example, wireless connections, such as infrared ports, optical ports, Bluetooth® wireless ports, wireless LAN ports, or the like. The processor can also be connected to a network, which may be any form of interconnecting network including an intranet, such as a local or wide area network, or an extranet, such as the World Wide Web or the Internet. The network can be physically implemented on a wireless or wired network, on leased or dedicated lines, including a virtual private network (VPN).

What is claimed is:

1. An apparatus, comprising:

a hydraulic pump operable to deliver hydraulic fluid over at least a hydraulic pressure range that includes a predetermined lower pressure and a predetermined upper pressure, greater than said lower pressure;

a hydraulic actuator arrangement including a first hydraulic piston and a second hydraulic piston, each of said hydraulic pistons having a first side and a second side; and

a working actuator operably coupled to said hydraulic actuator arrangement, said working actuator having a working cylinder and a working piston disposed for reciprocating movement in the working cylinder, the working piston defining at least in part between a first side thereof and the working cylinder a working chamber configured to contain a quantity of gas,

said hydraulic actuator arrangement being operably coupled to said hydraulic pump to enable selective delivery of pressurized hydraulic fluid from said hydraulic pump to one or both of said first side and said second side of each of said first and second hydraulic pistons to yield an output force in a first force range corresponding to a first combination, and to yield an output force in a second force range, different than said first force range, corresponding to a second combination;

a hydraulic controller operable to cause the hydraulic actuator arrangement to move the working piston: a) at a first average speed over a first distance, and b) at a second average speed over a second distance different than the first average speed,

wherein the hydraulic controller is operable to compress the quantity of gas contained therein at an approximately constant rate as the working piston is moved over the first distance at the first stroke speed and the second distance at the second stroke speed.

2. The apparatus of claim **1**, further comprising:

a heat transfer element disposed within the working chamber, the heat transfer element configured to receive heat energy from the gas being compressed to reduce the temperature of the compressed gas.

3. The apparatus of claim **2**, wherein the heat transfer element is configured to transfer heat energy received from the compressed gas to the exterior of the working chamber.

4. The apparatus of claim **2**, wherein the heat transfer element is configured to transfer heat energy received from the compressed gas to a volume of liquid contained in the working chamber.

5. The apparatus of claim **4**, wherein the volume of liquid is not in contact with the heat transfer element during movement of the working piston over the first distance.

6. The apparatus of claim **5**, wherein at least a portion of the volume of liquid is in contact with at least a portion of the heat transfer element during movement of the working piston over the second distance.

7. The apparatus of claim **1**, wherein the first stroke speed corresponds to the first force range and the second stroke speed corresponds to the second force range.

8. An apparatus, comprising:

a hydraulic pump operable to deliver hydraulic fluid over at least a hydraulic pressure range that includes a predetermined lower pressure and a predetermined upper pressure, greater than said lower pressure;

a hydraulic actuator arrangement including a first hydraulic piston and a second hydraulic piston, each of said hydraulic pistons having a first side and a second side; and

a working actuator operably coupled to said hydraulic actuator arrangement, said working actuator having a working cylinder and a working piston disposed for reciprocating movement in the working cylinder, the working piston defining at least in part between a first side thereof and the working cylinder a working chamber configured to contain a quantity of gas,

said hydraulic actuator arrangement being operably coupled to said hydraulic pump to enable selective delivery of pressurized hydraulic fluid from said hydraulic pump to one or both of said first side and said second side of each of said first and second hydraulic pistons to yield an output force in a first force range corresponding to a first combination, and to yield an output force in a second force range, different than said first force range, corresponding to a second combination;

a hydraulic controller operable to cause the hydraulic actuator arrangement to move the working piston: a) at a first average speed over a first distance, and b) at a second average speed over a second distance different than the first average speed,

wherein the hydraulic controller is operable to compress the quantity of gas contained therein such that heat energy produced by compression of the quantity of gas is transferred from the quantity of gas to the exterior of the working chamber at a substantially constant rate as the working piston is moved over the first distance at the first stroke speed and the second distance at the second stroke speed.

9. The apparatus of claim **8**, further comprising:

a heat transfer element disposed within the working chamber, the heat transfer element configured to receive heat energy from the gas being compressed to reduce the temperature of the compressed gas.

10. The apparatus of claim **9**, wherein the heat transfer element is configured to transfer heat energy received from the compressed gas to the exterior of the working chamber.

11. The apparatus of claim **9**, wherein the heat transfer element is configured to transfer heat energy received from the compressed gas to a volume of liquid contained in the working chamber.

12. The apparatus of claim **8**, wherein the heat energy produced by compression of the quantity of gas is transferred from the quantity of gas to the exterior of the working chamber to maintain a substantially constant temperature during compression of the quantity of gas.

13. A method of compressing gas in a pressure vessel, the pressure vessel having a working piston disposed therein for reciprocating movement in the pressure vessel, the working piston defining at least in part between a first side thereof and the pressure vessel a working chamber configured to contain at least one of a liquid or a gas, the method comprising:

moving the working piston at a predetermined velocity profile to compress a quantity of gas contained therein so that the time rate of change of pressure is approximately constant over substantially the entire stroke.

14. The method of claim **13**, wherein the working chamber includes a heat transfer element disposed therein, and wherein the predetermined velocity profile is determined by taking into account the portion of the cross-sectional area occupied by the heat transfer element.

15. The method of claim **13**, further comprising:

moving a volume of liquid into the working chamber during at least a portion of a compression stroke,

wherein the predetermined velocity profile is determined by taking into account the volume of liquid being received in the working chamber.

16. The method of claim **13**, wherein the working chamber includes a heat transfer element disposed therein, the method further comprising:

moving a volume of liquid into the working chamber during at least a portion of a compression stroke,

wherein the predetermined velocity profile is determined by taking into account the portion of the cross-sectional area occupied by the heat transfer element and the volume of liquid being received in the working chamber.

17. The method of claim **13**, further comprising:

causing heat energy produced by the compression of the quantity of gas to be transferred from the quantity of gas to the exterior of the working chamber so that a predetermined temperature profile during compression of the quantity of gas is maintained.

18. The method of claim **17**, wherein the rate of temperature change is approximately constant over substantially the entire stroke.

19. The method of claim **13**, wherein the working chamber includes a heat transfer element disposed therein, the method further comprising:

causing the temperature of the quantity of gas to increase to a temperature above a temperature of the heat transfer element, and

causing heat energy produced by the compression of the quantity of gas to be transferred from the quantity of gas to the heat transfer element.

20. The method of claim **19**, wherein the predetermined velocity profile is determined by taking into account a rate at which heat energy produced by compression of the quantity of gas is transferred from the quantity of gas to the heat transfer element so that a predetermined temperature profile of the gas is maintained.

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