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(54) **MAGNETIC REFRIGERATION SYSTEM WITH IMPROVED COAXIAL VALVE**

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(60) Provisional application No. 62/091,849, filed on Dec. 15, 2014, provisional application No. 61/917,025, filed on Dec. 17, 2013.

Publication Classification

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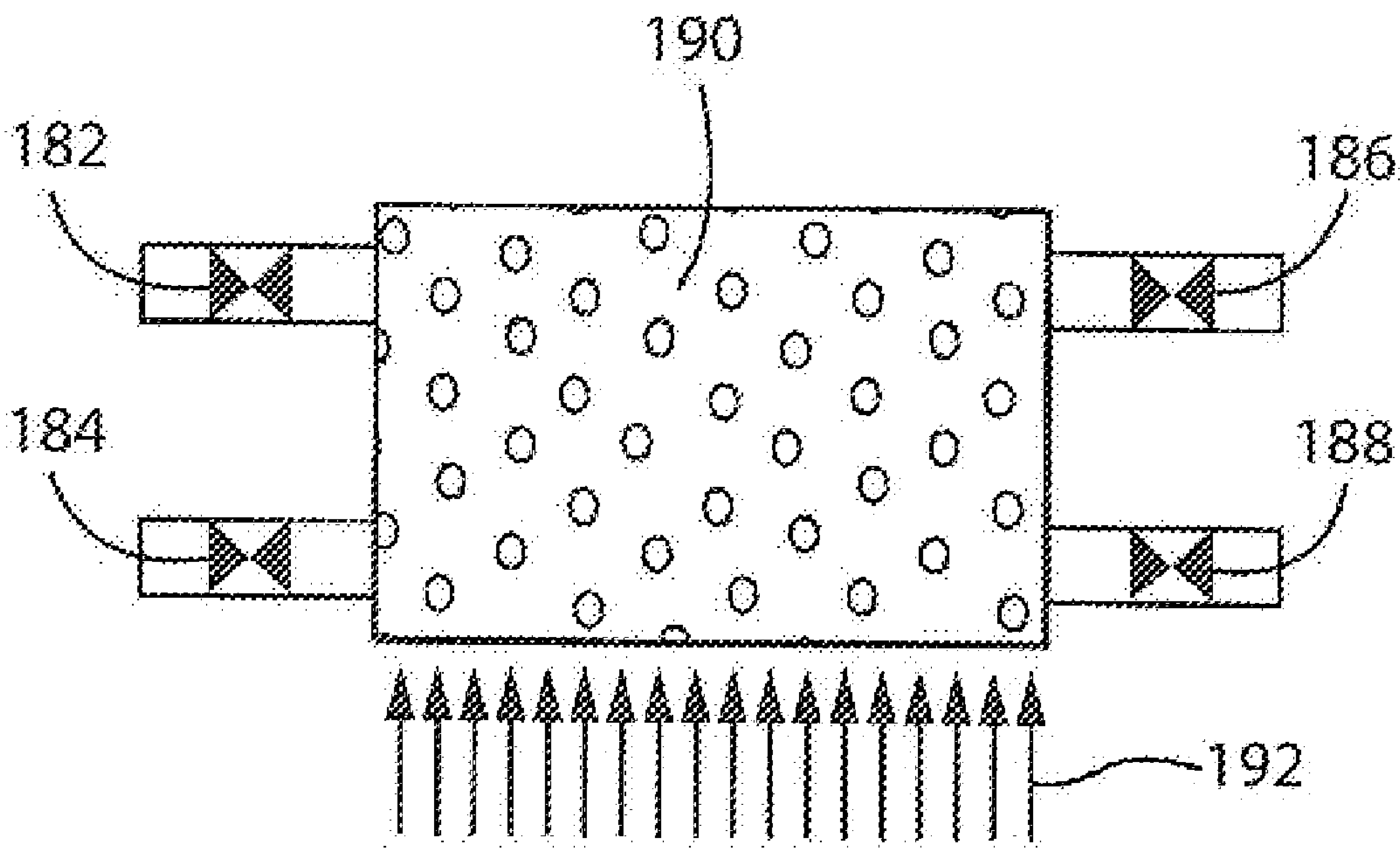
CPC *F25B 21/00* (2013.01)

(57) **ABSTRACT**

A magnetic refrigeration system provides a rotary valve design that balances the forces needed to seal valve surfaces, reduces influence of wear on leakage, makes assembly and adjustment of the valve easier, reduces potential for bypass flows, reduces stress on and corrosion of the drive shaft, and provides a more compact system.



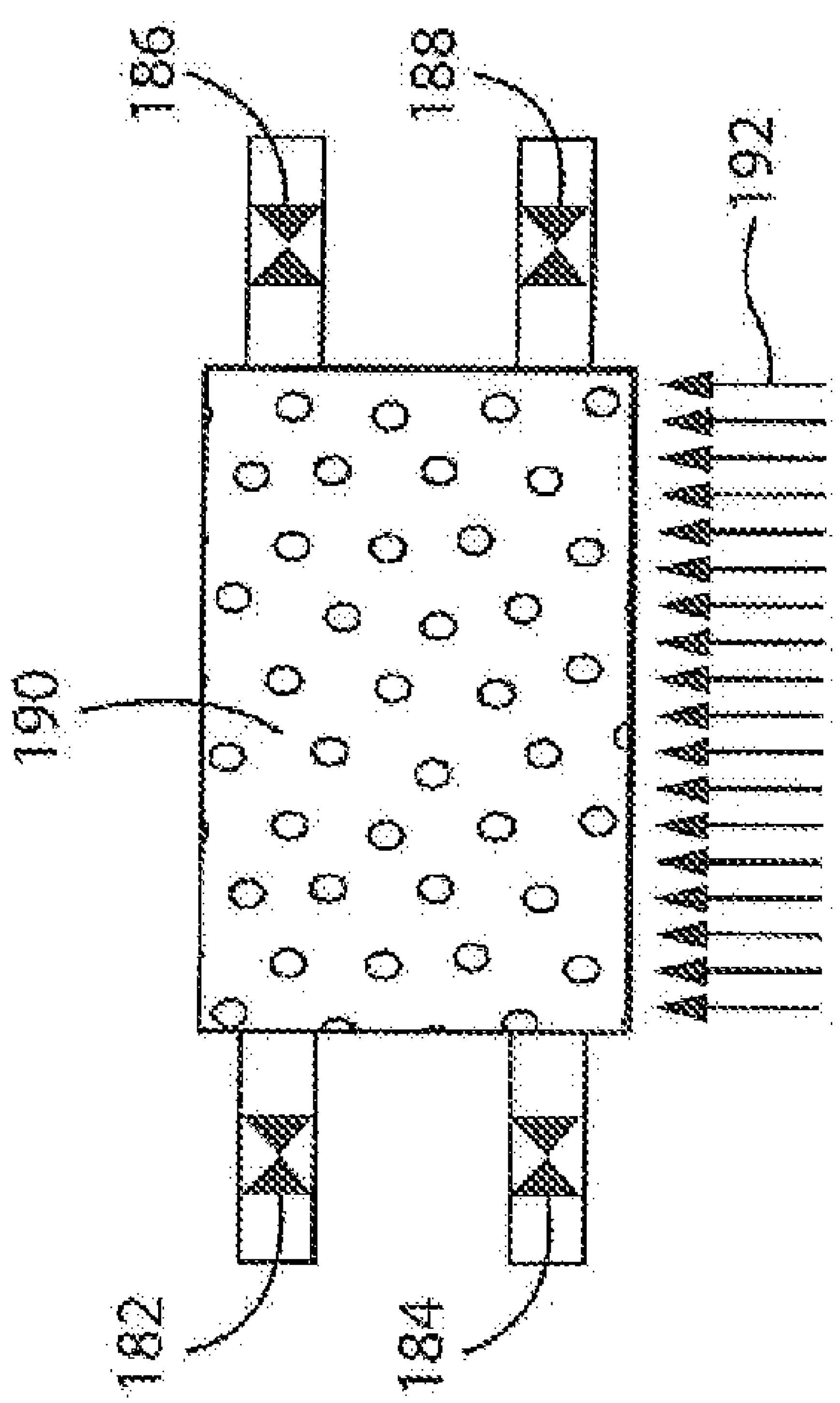


FIG. 1A

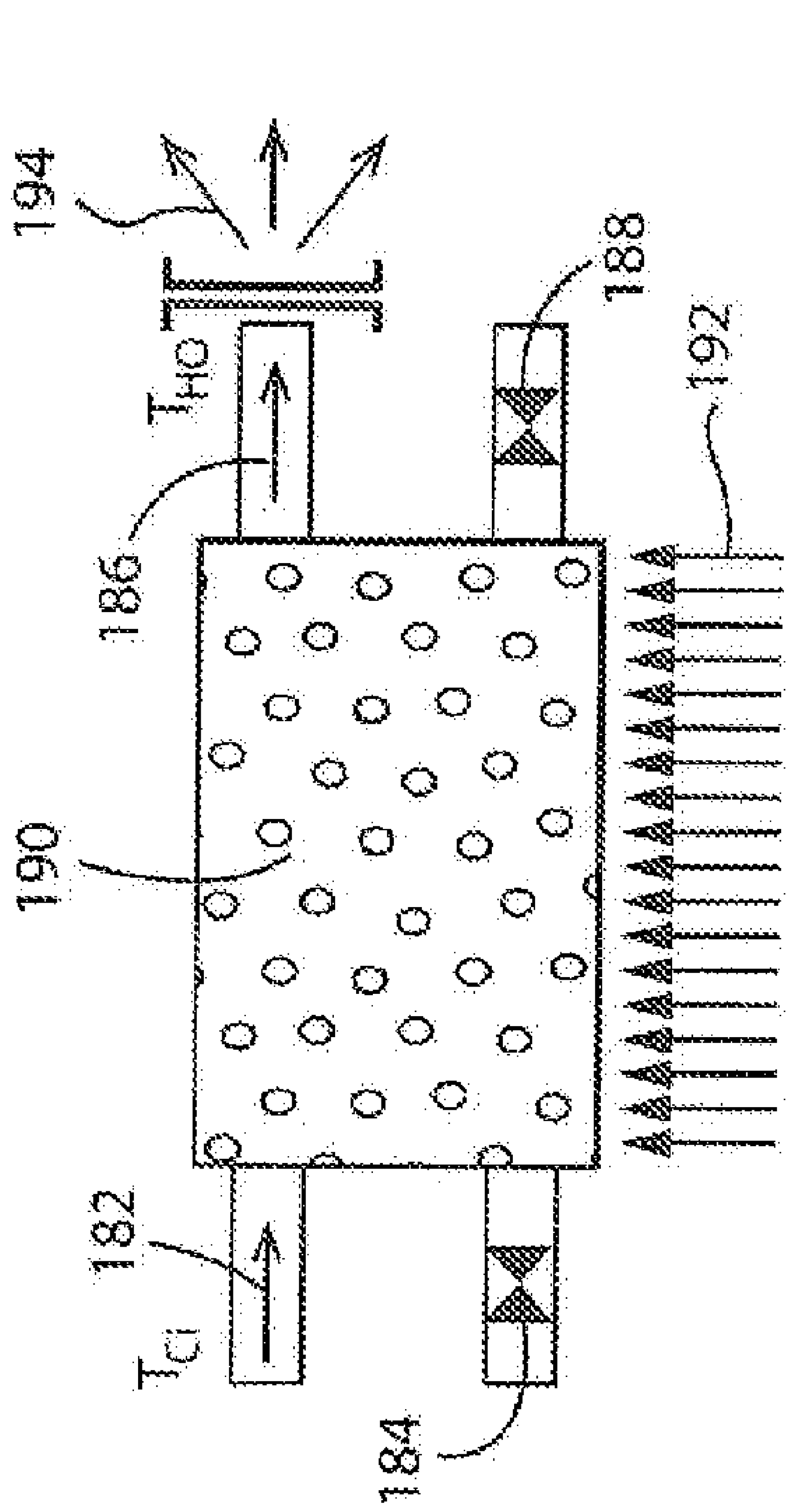


FIG. 1B

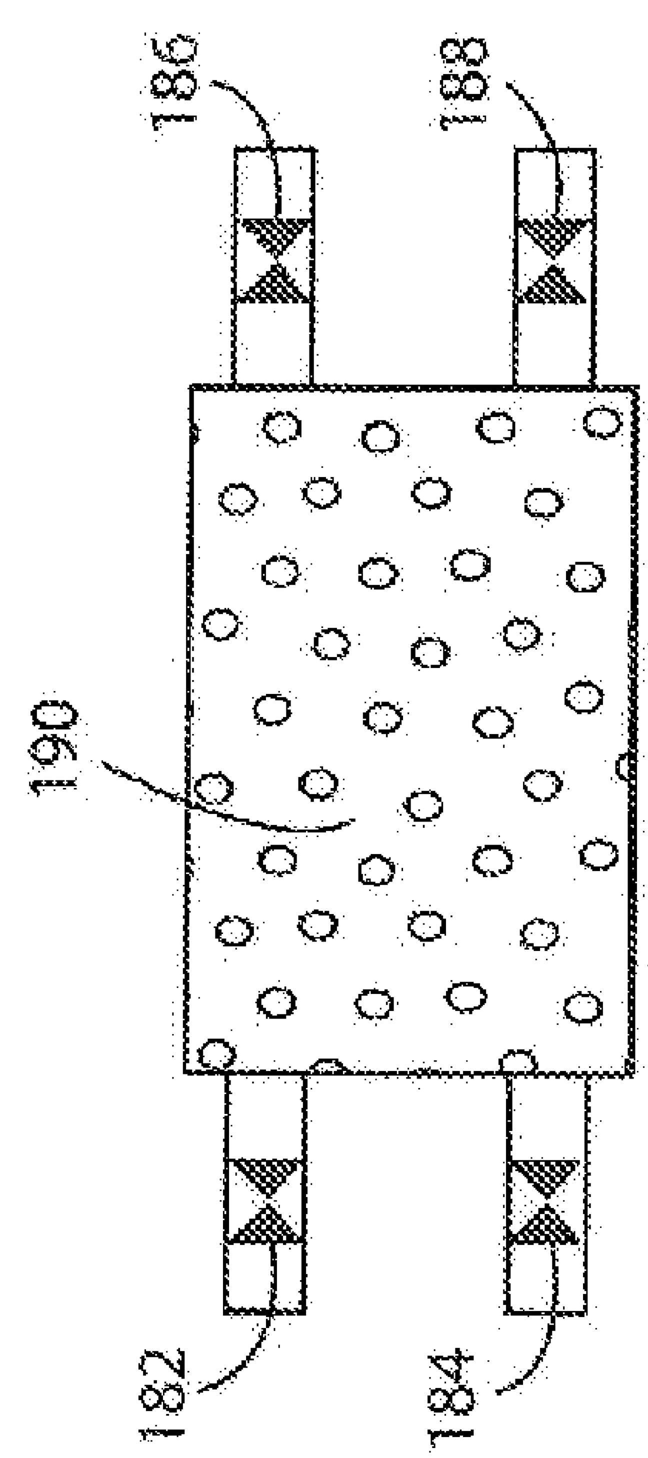


FIG. 1C

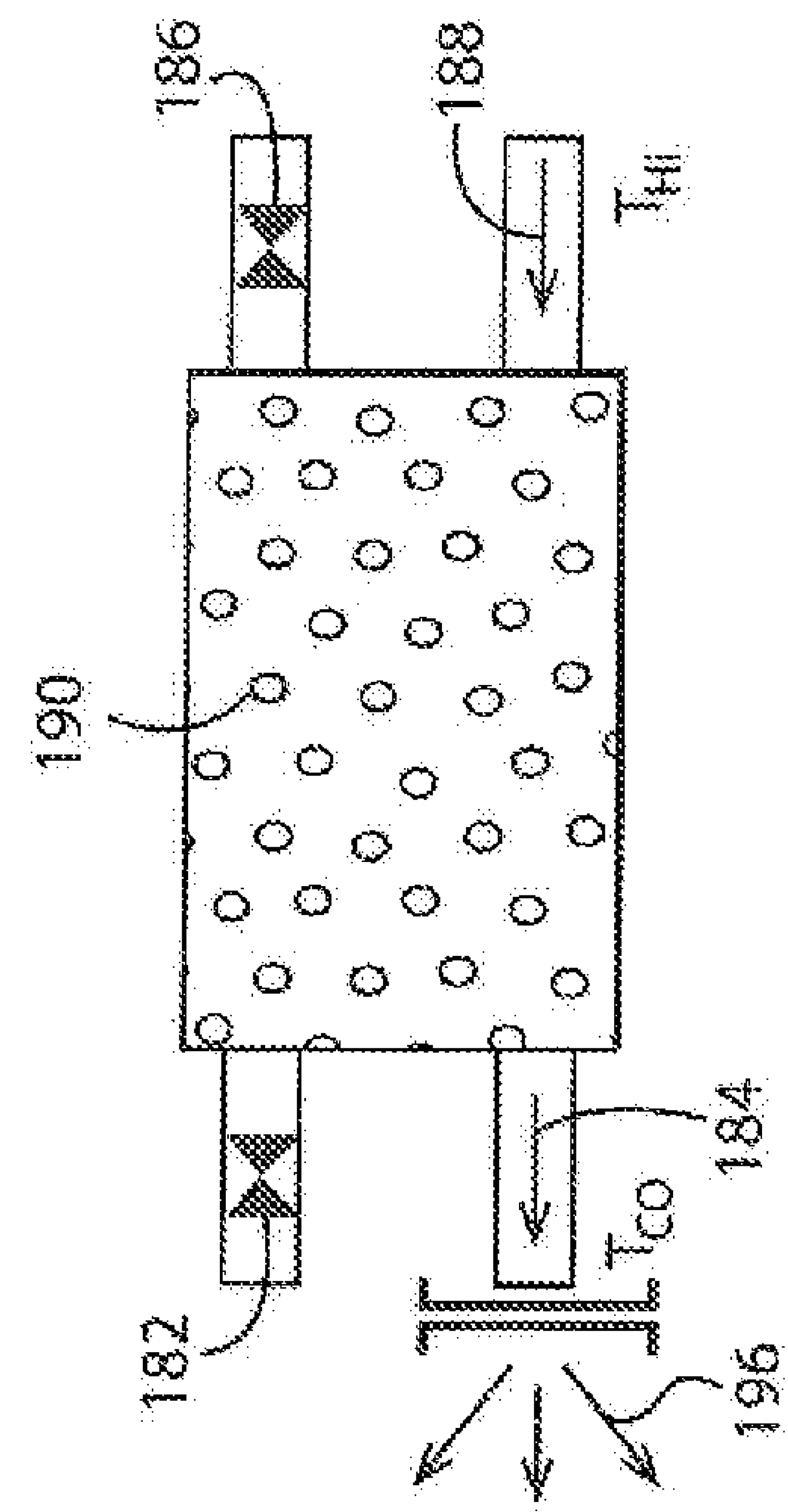
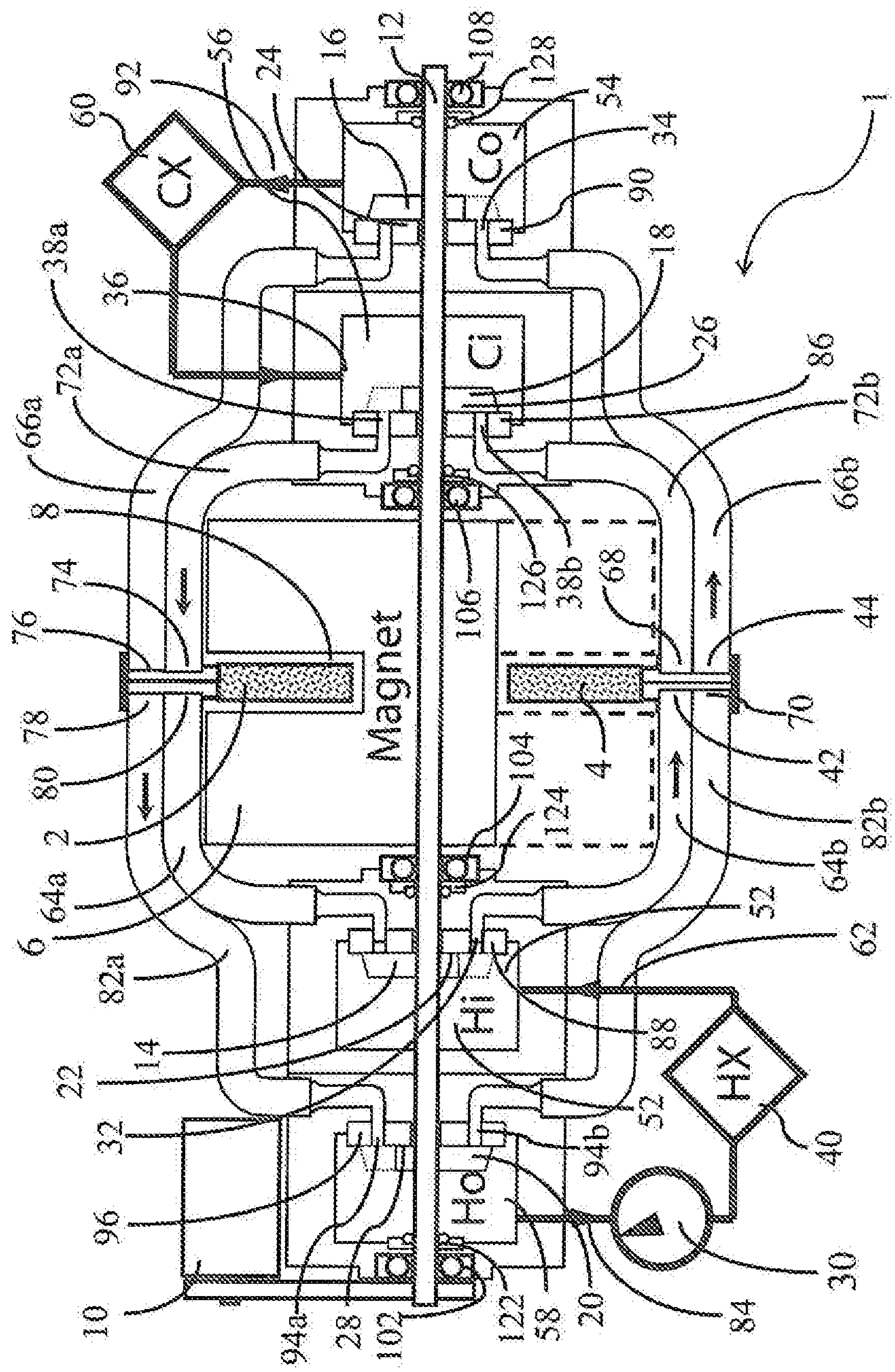


FIG. 1D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Co
Ci
Magnet
Hi
Ho
HX
1
2
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6
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36
38a
38b
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66a
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72a
72b
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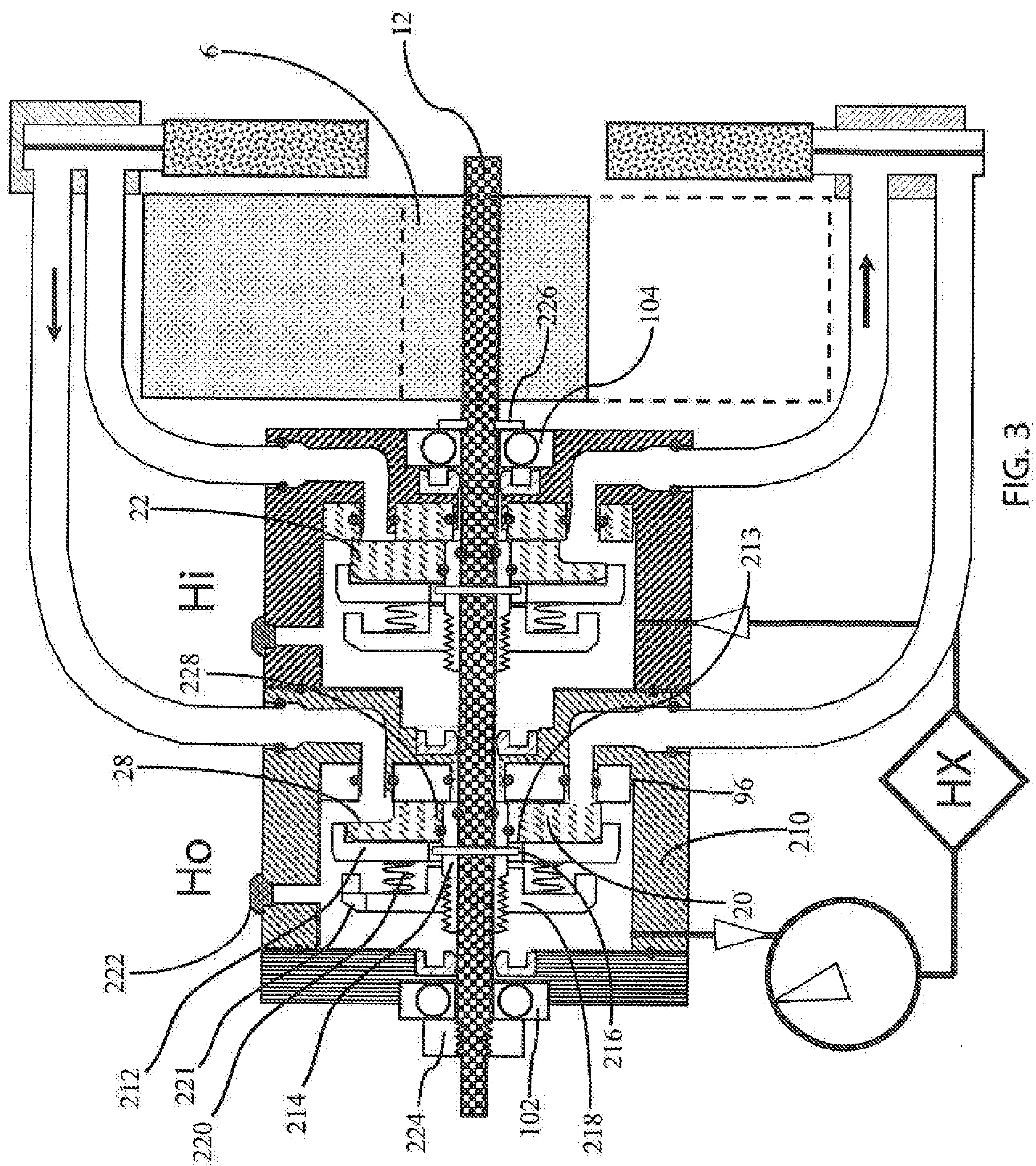
128

FIG. 2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6
226
104
22
Hi
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96
Ho
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HX
222
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221
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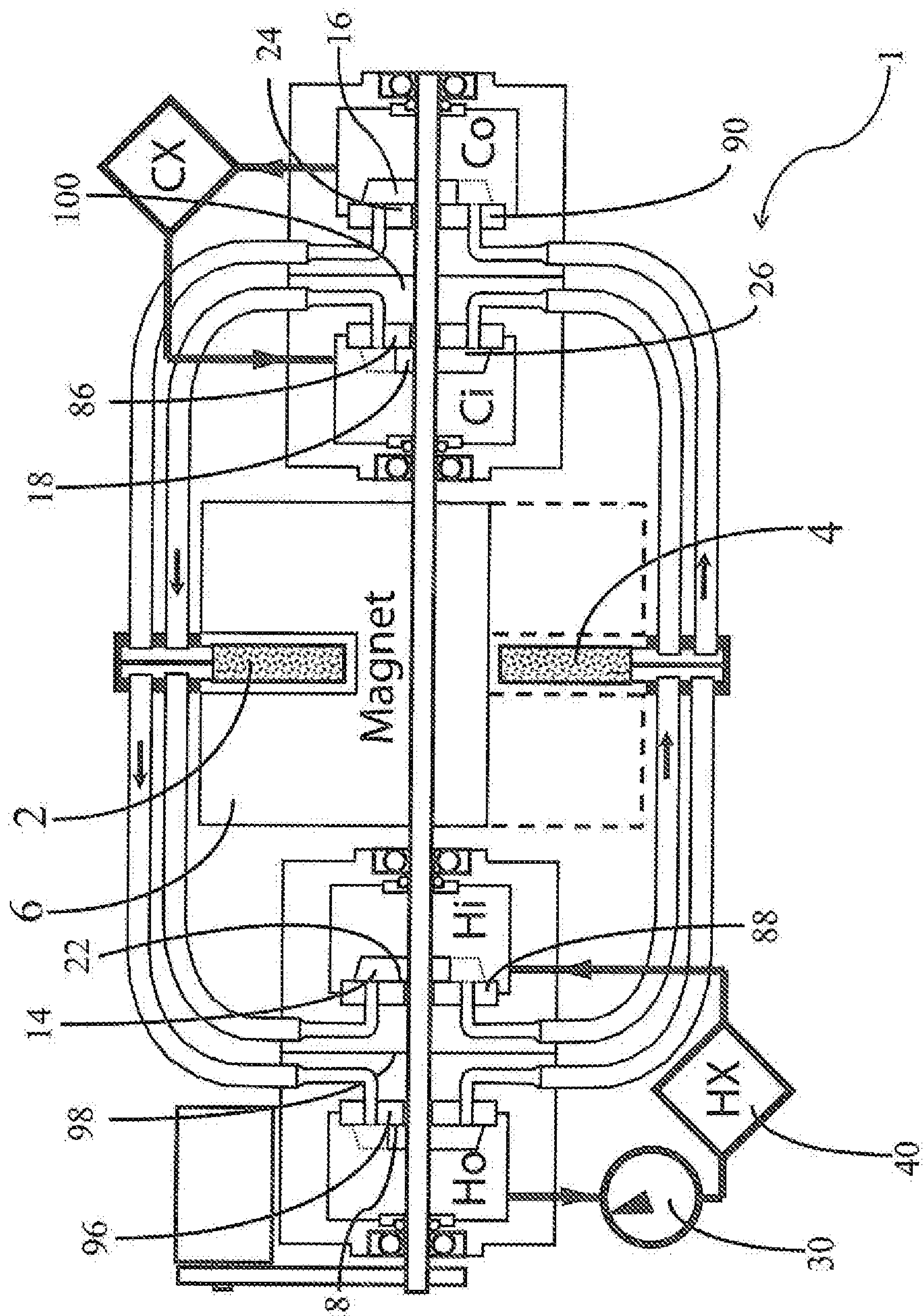
214
224
102
218
216

FIG. 3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Ci
Magnet
Hi
Ho
HX
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98
100

FIG. 4

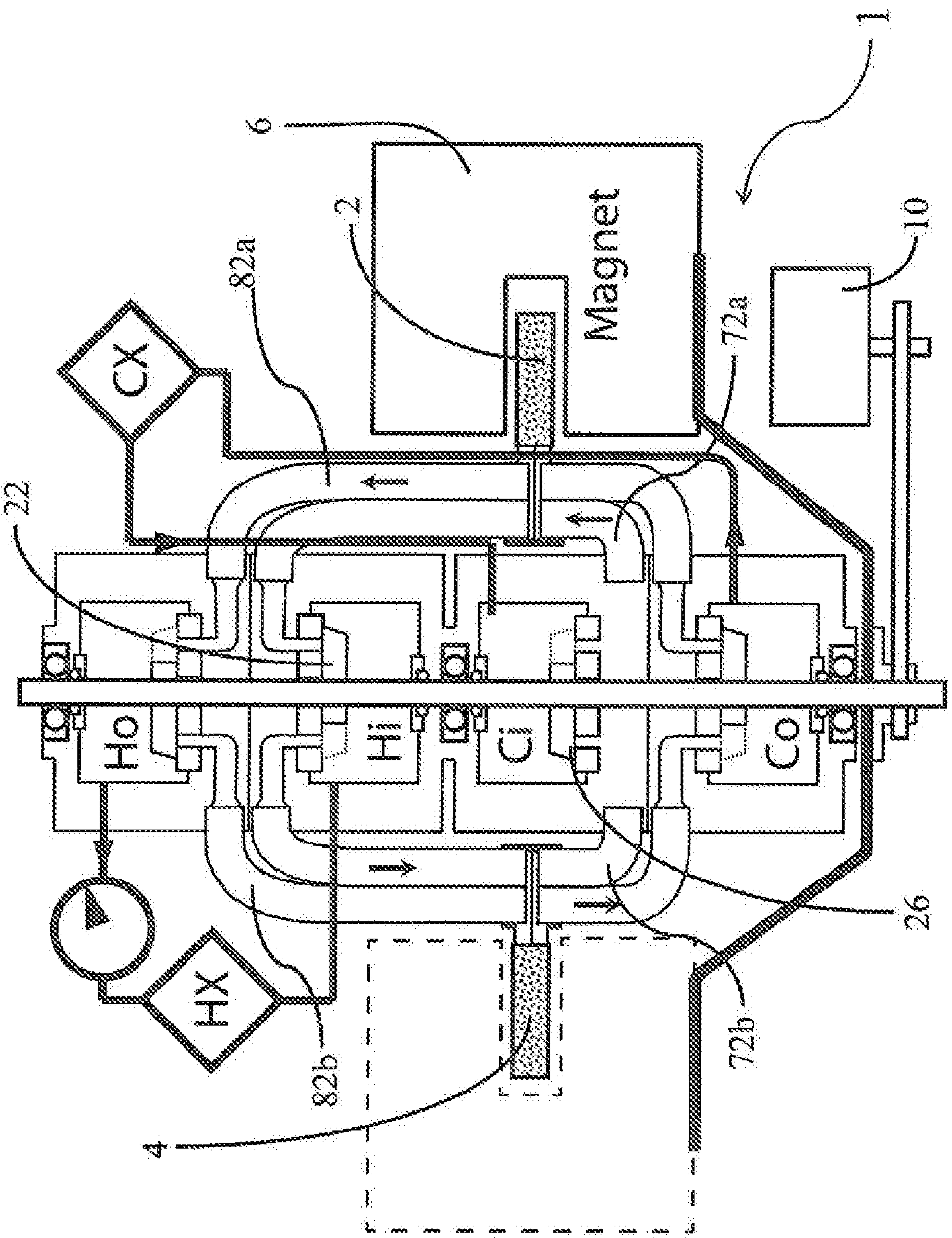
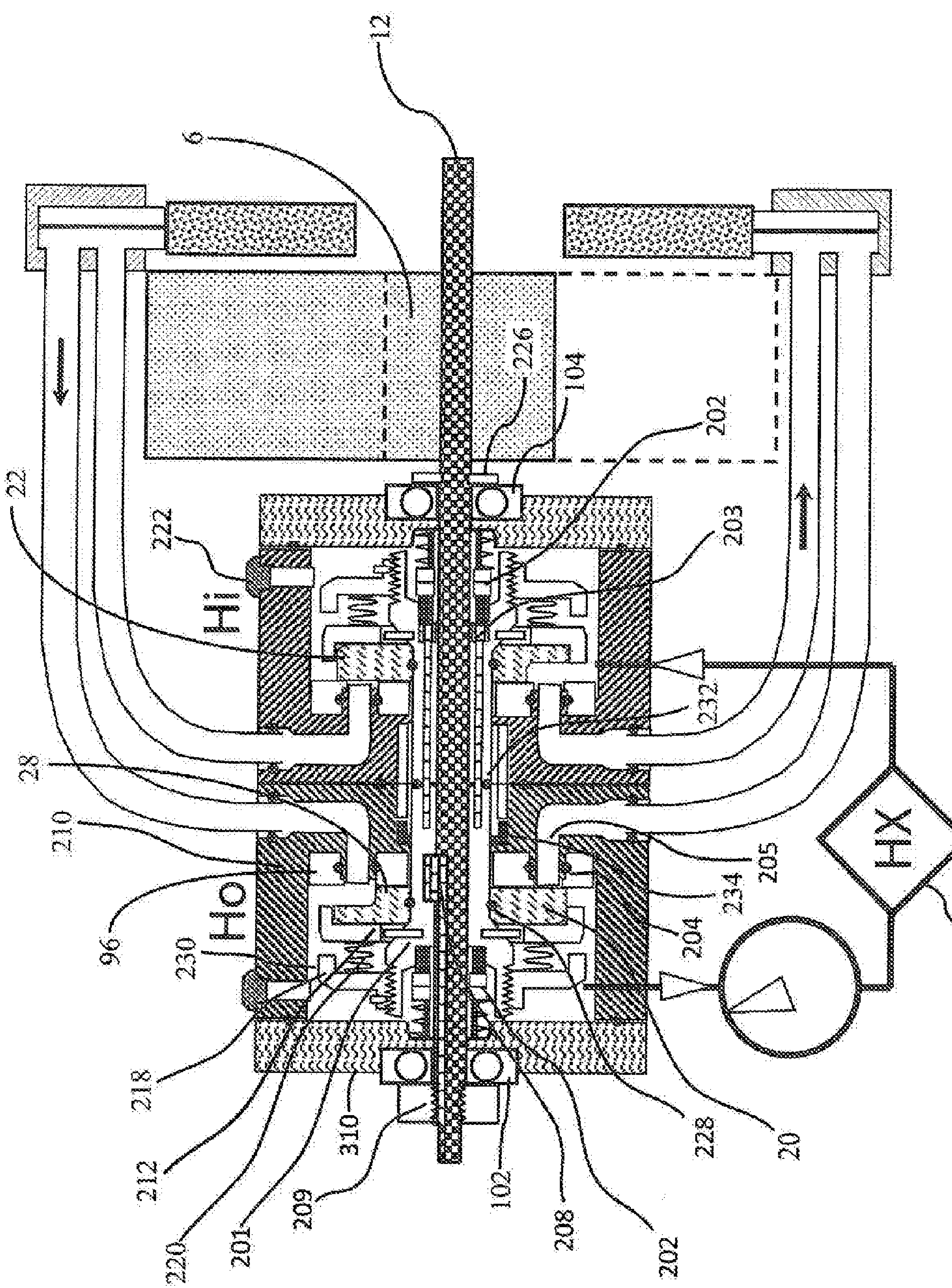


FIG. 5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6
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202
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96
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22
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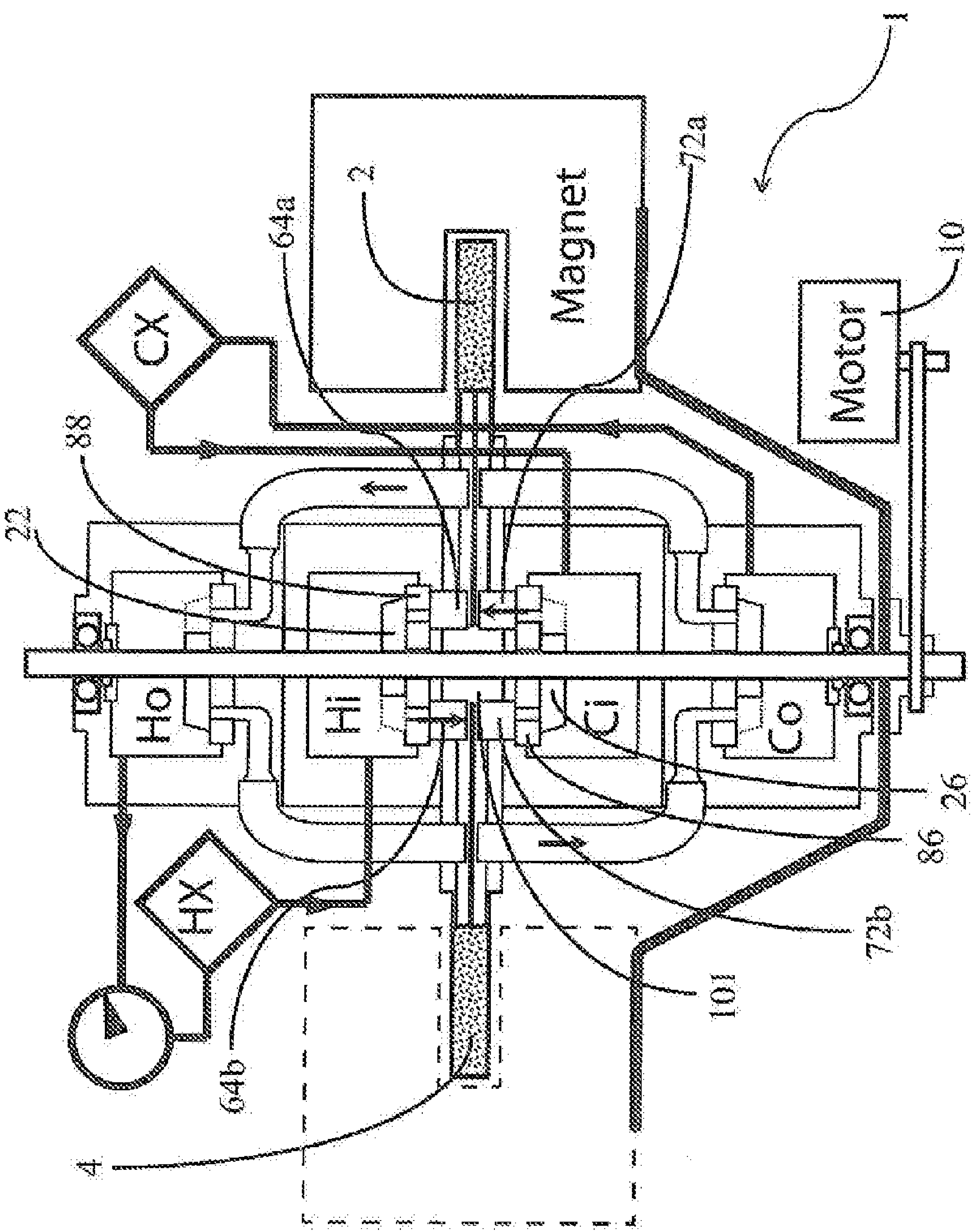
Hi
HO
HX
40

FIG. 6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72a
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Motor
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Hi
Ci
Co
HX
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4
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72b
86
26

FIG. 7

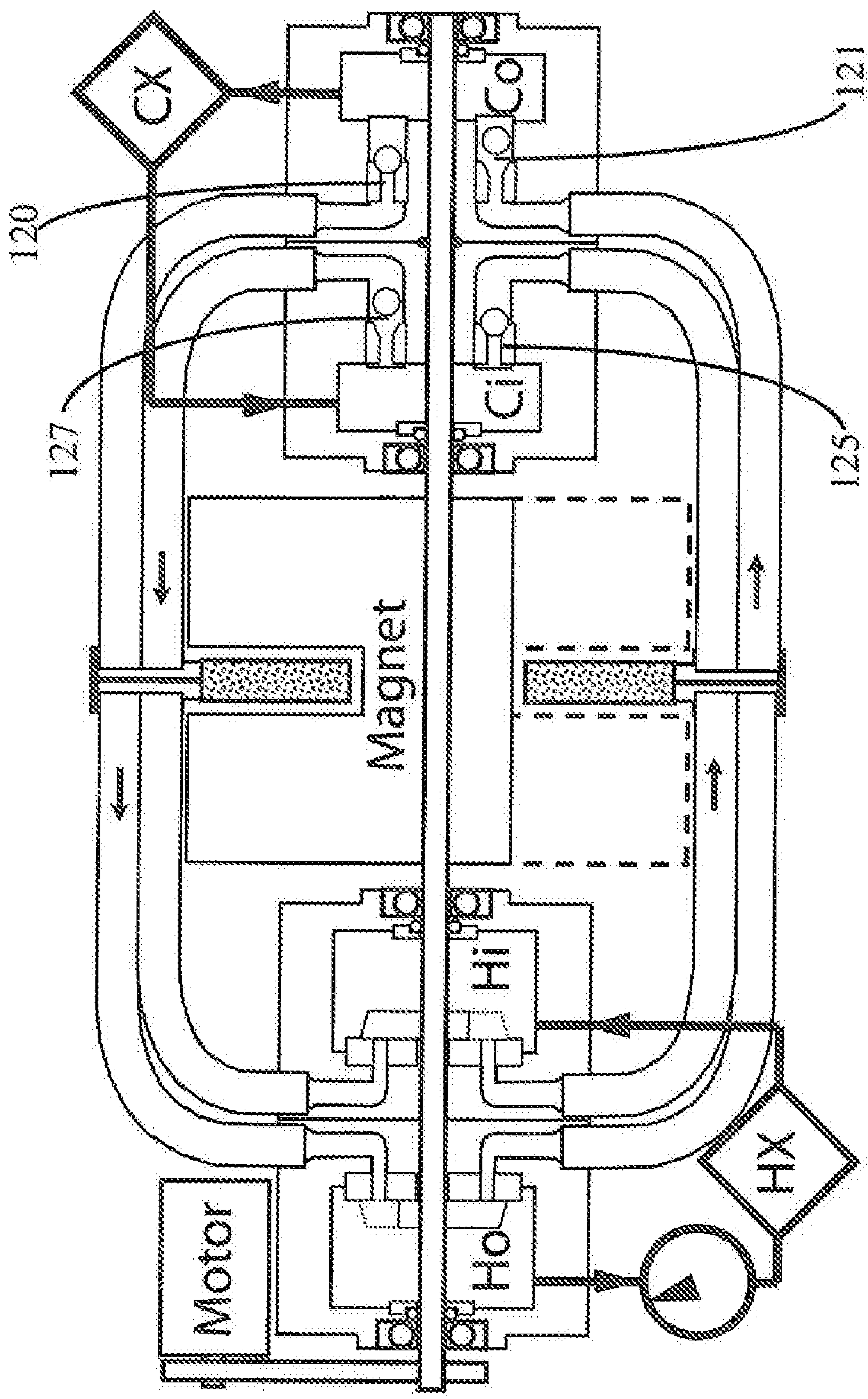


FIG. 8

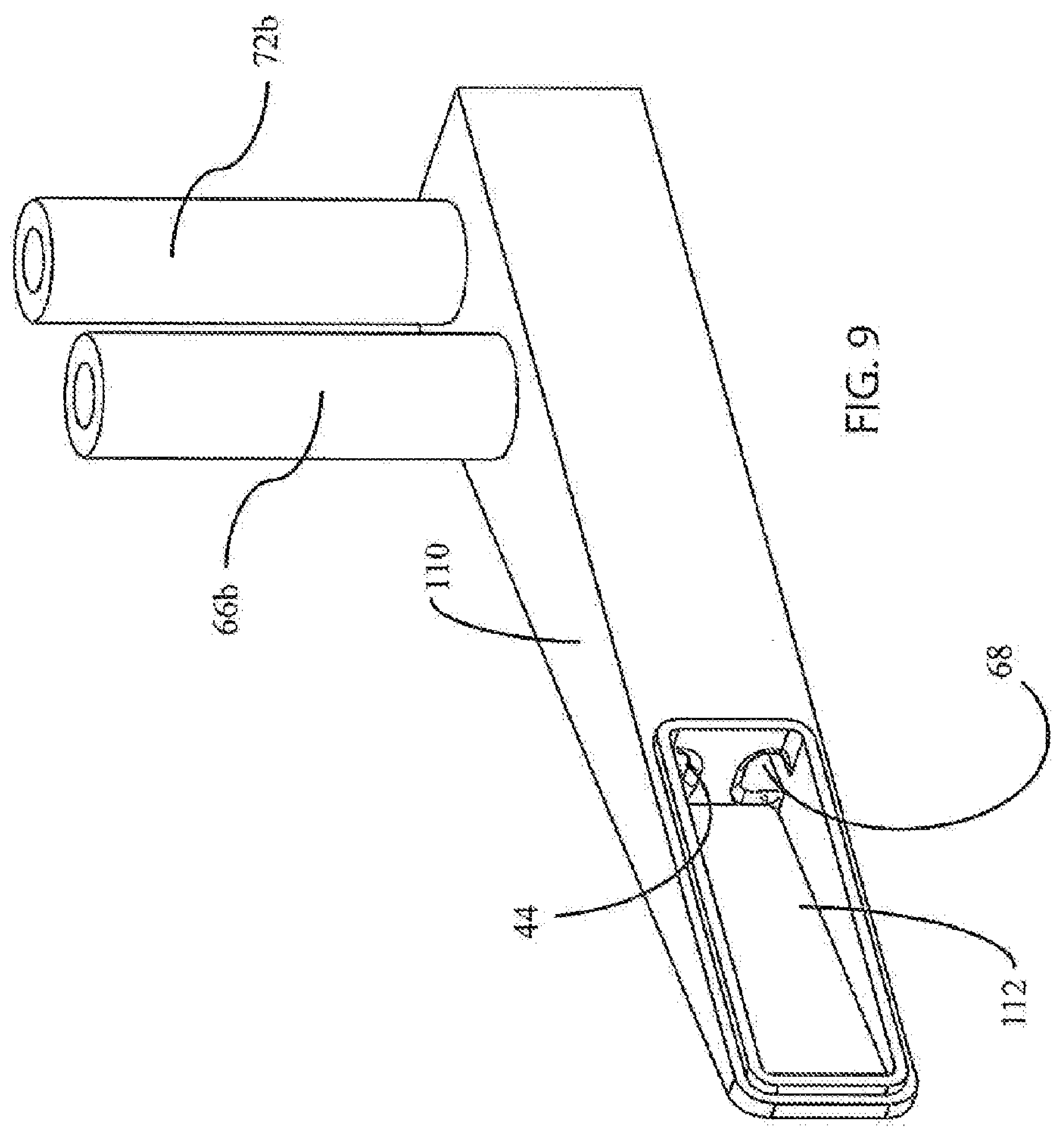
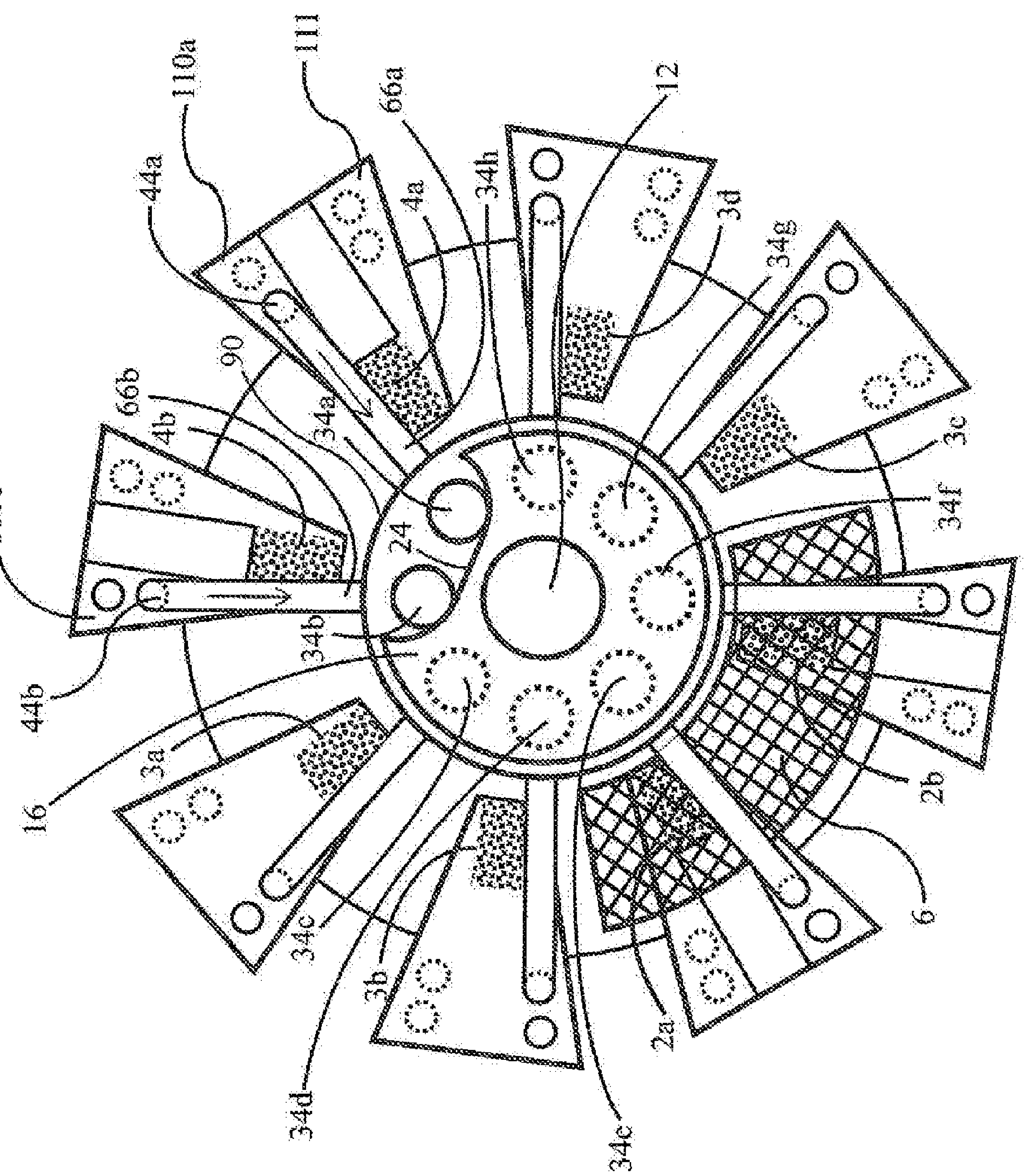
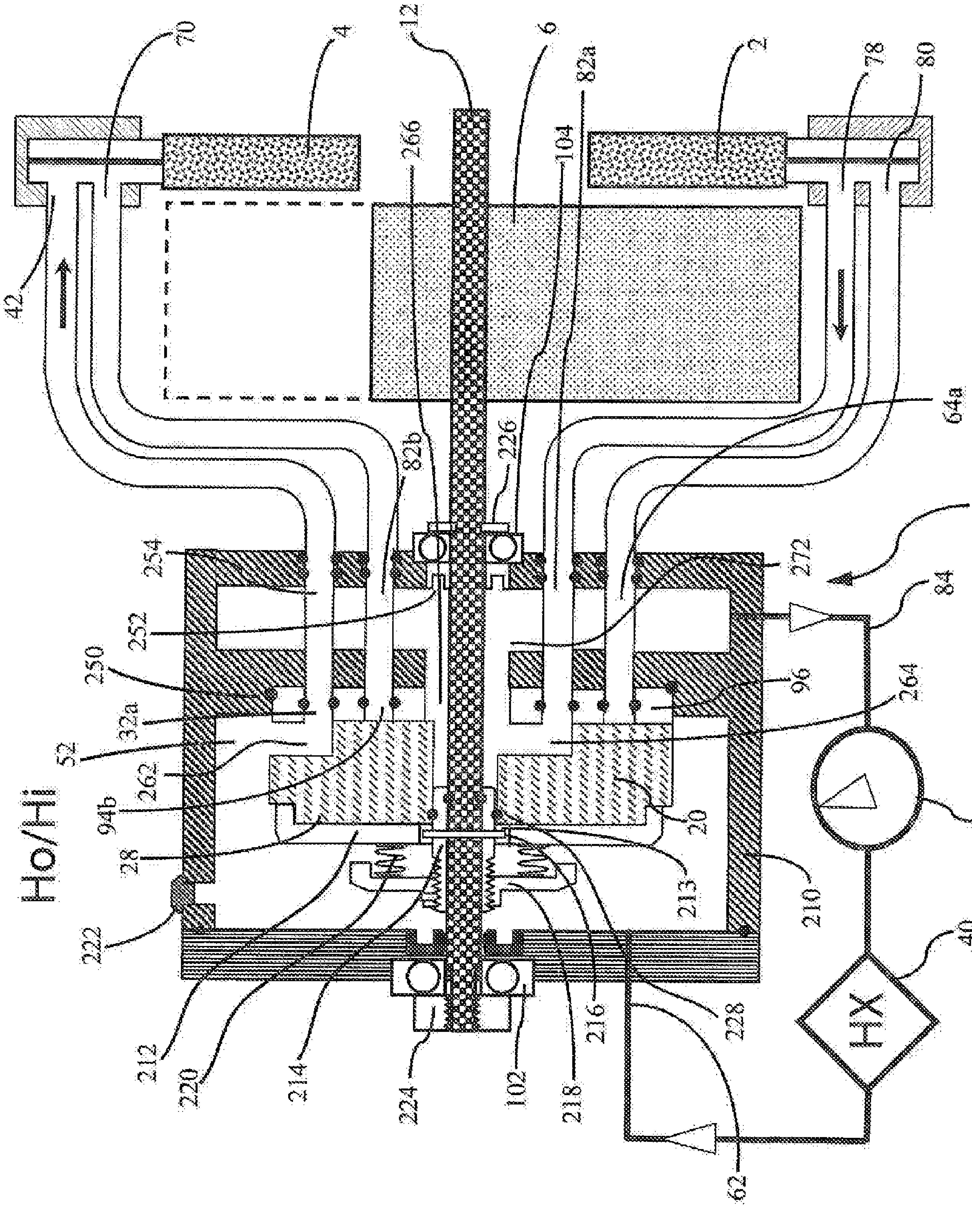


FIG. 9



110a
111
66a
4a
34h
12
3d
34g
3c
34f
44a
90
66b
4b
110b
34a
24
34b
44b
16
3a
34c
3b
34d
34c
2a
6
2b

FIG. 10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HX
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32a
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82b
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94b
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272

FIG. 11

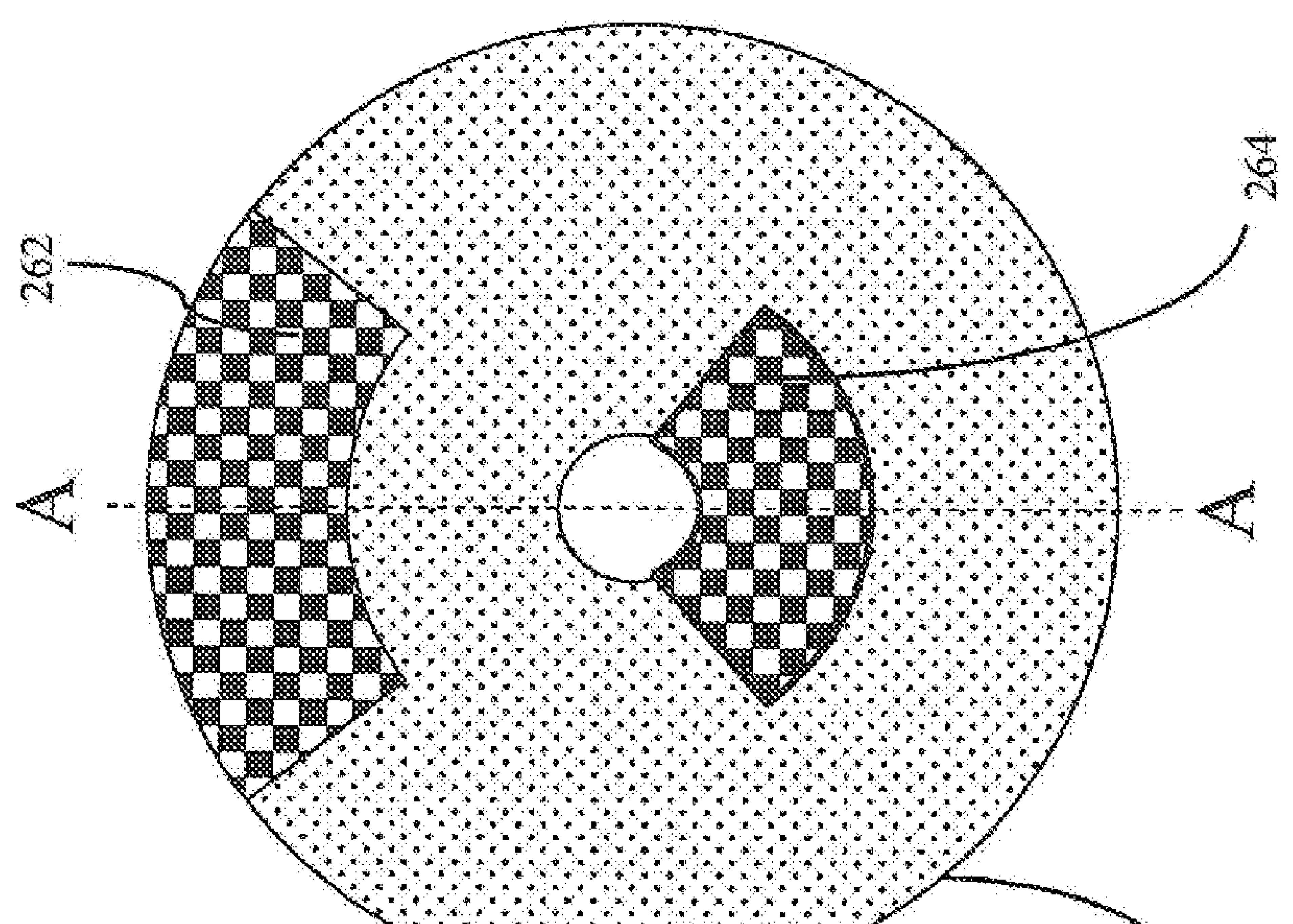


FIG. 12A

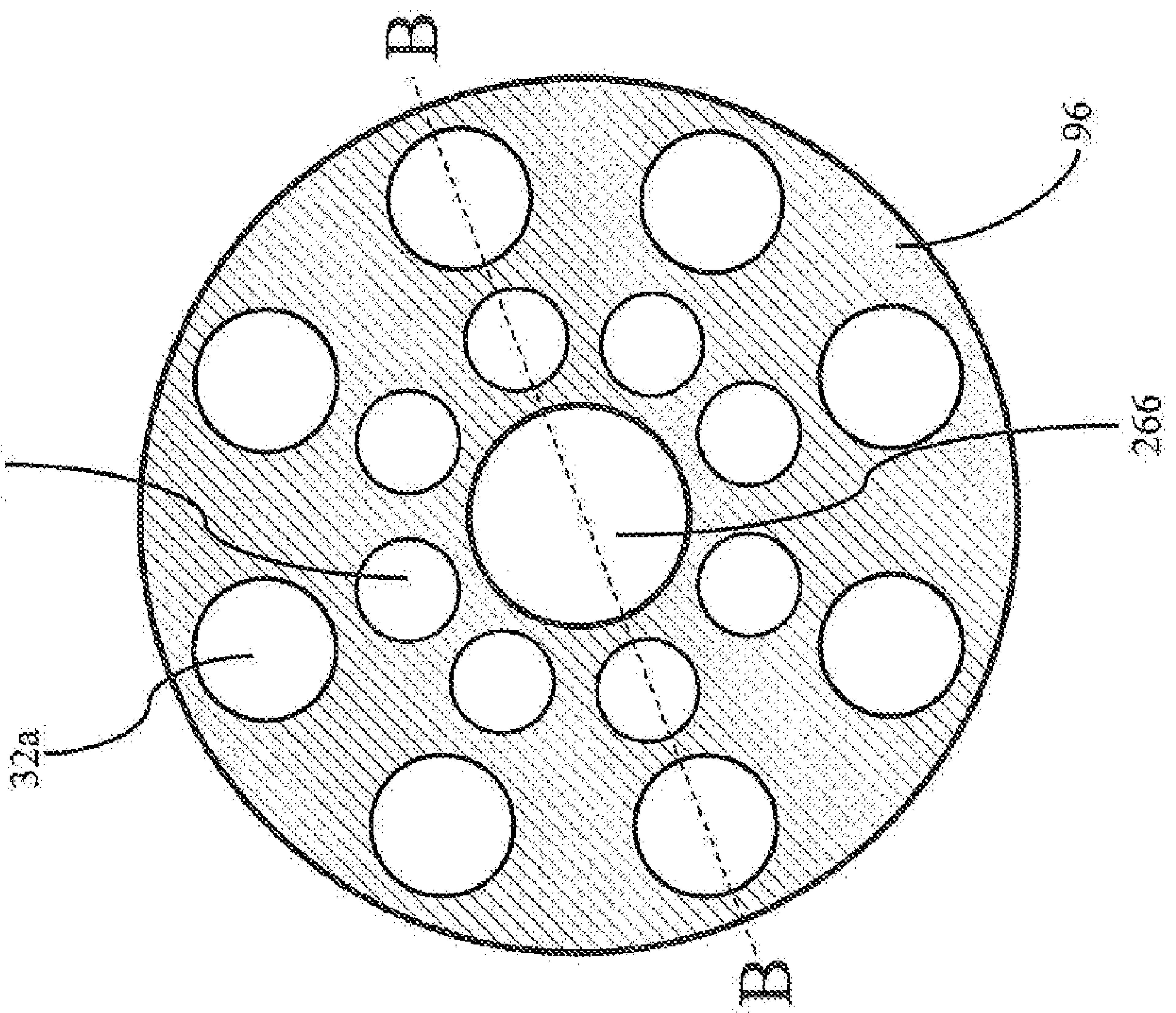


FIG. 13A

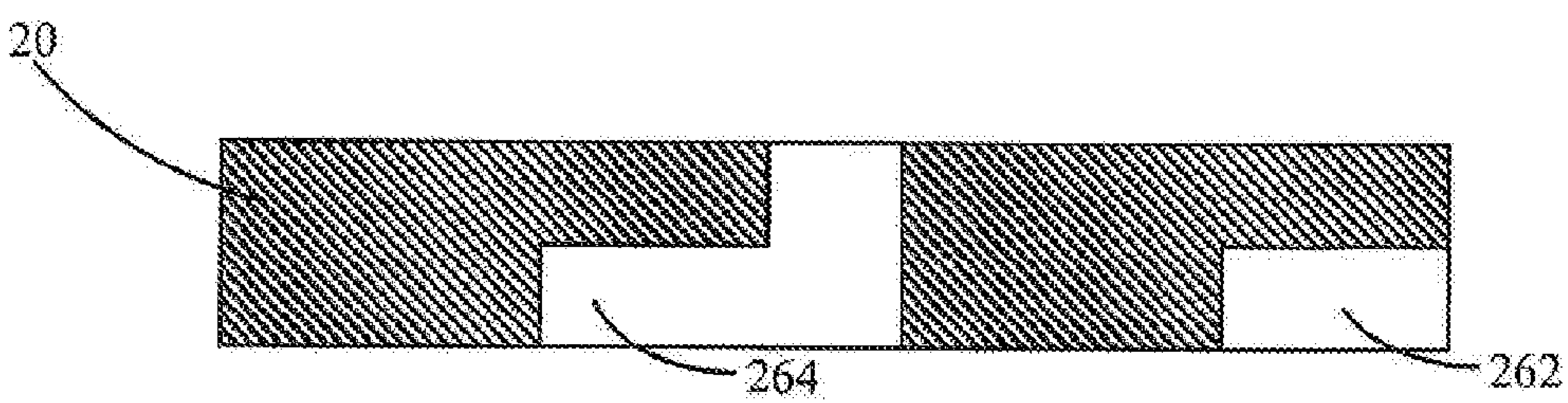


FIG. 12B

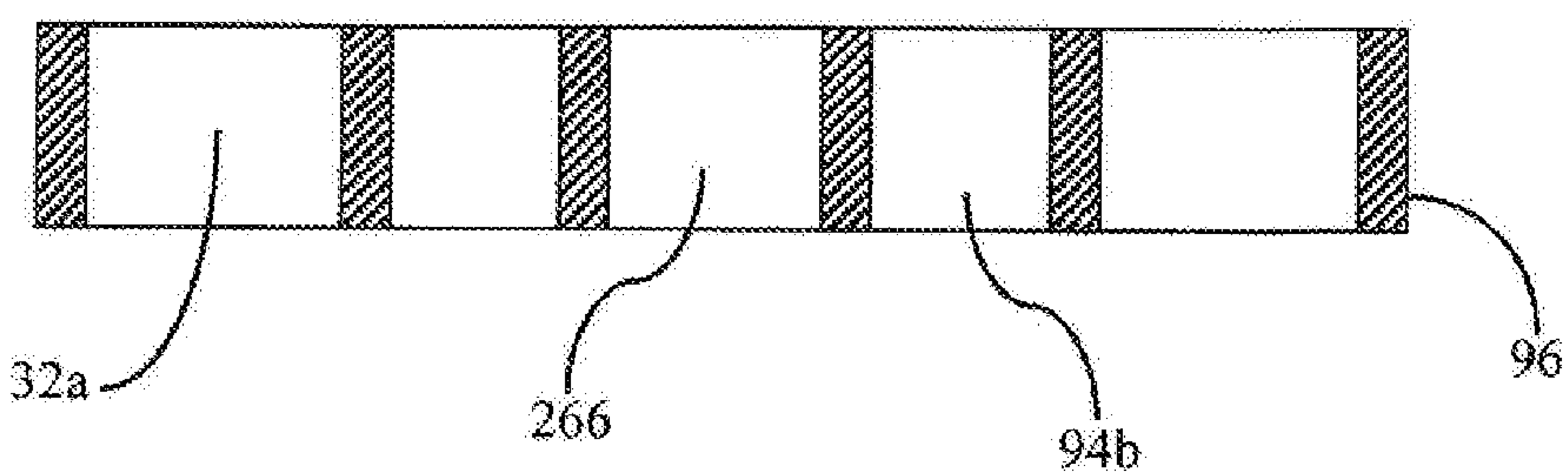


FIG. 13B

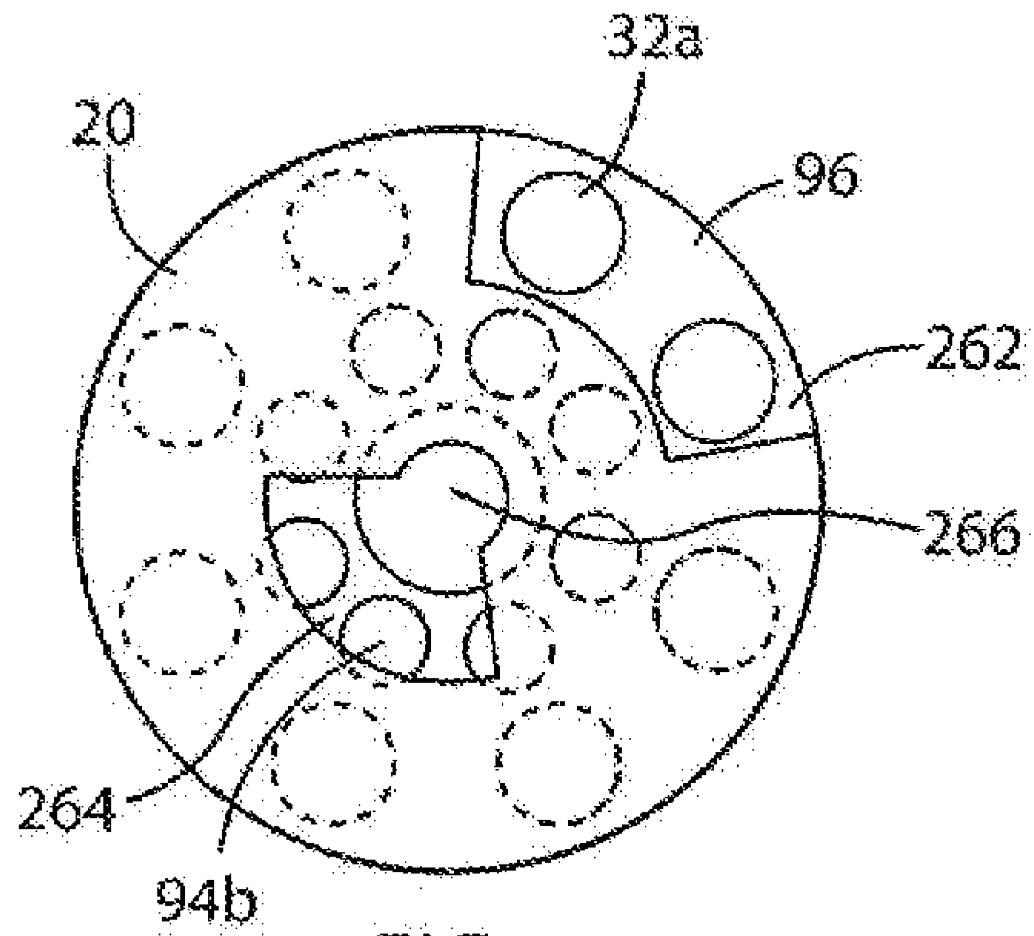


FIG. 14

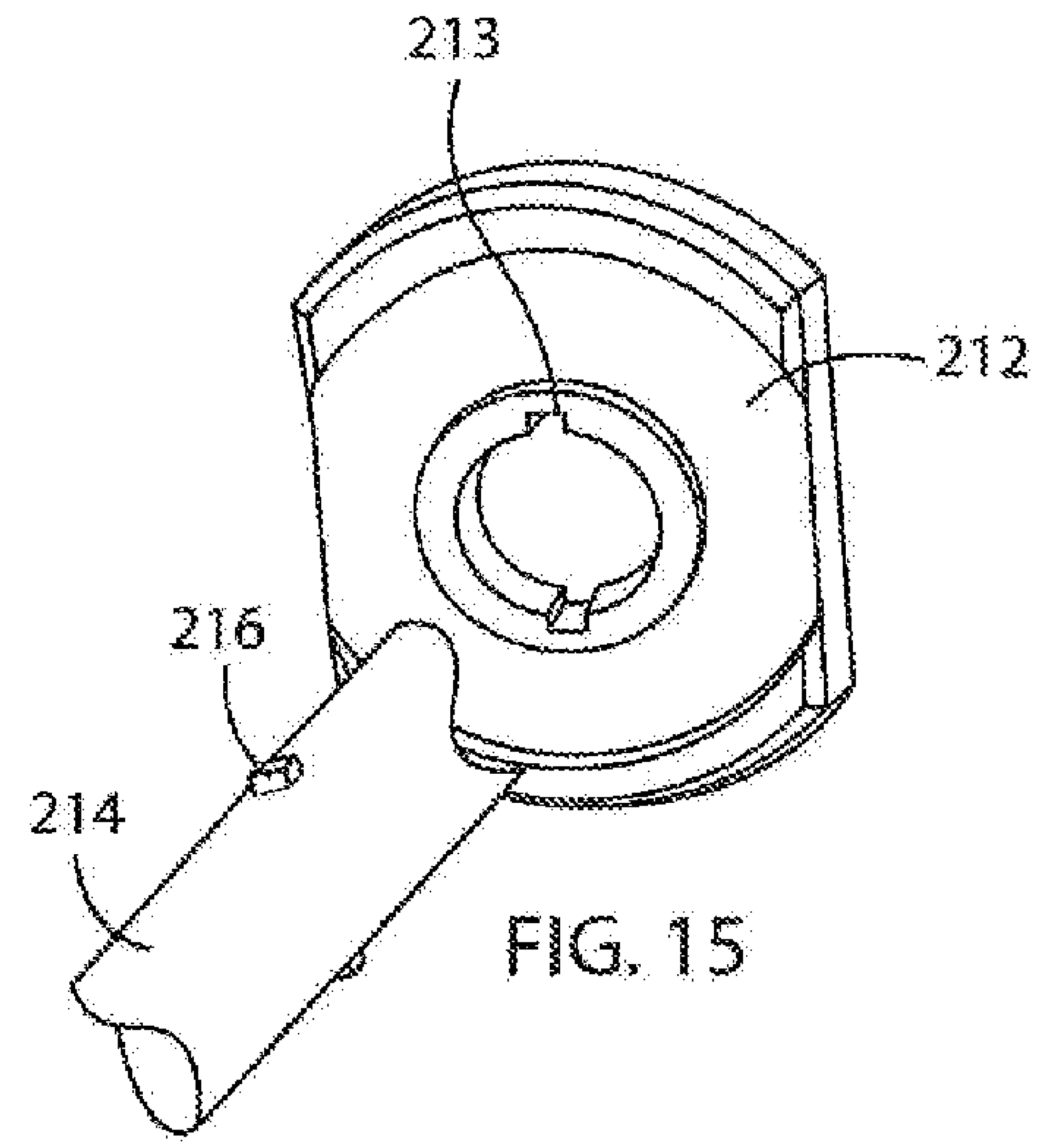


FIG. 15

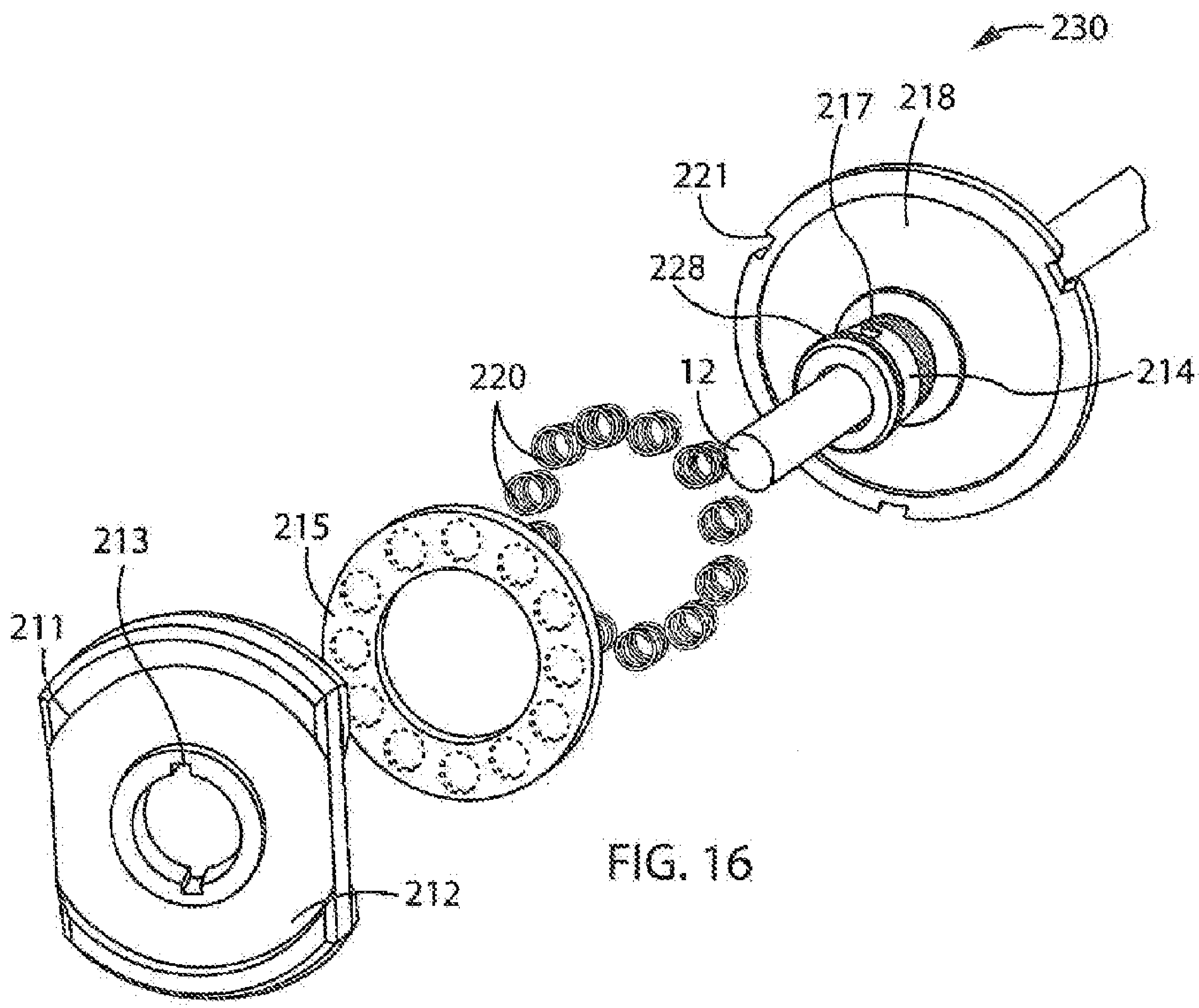
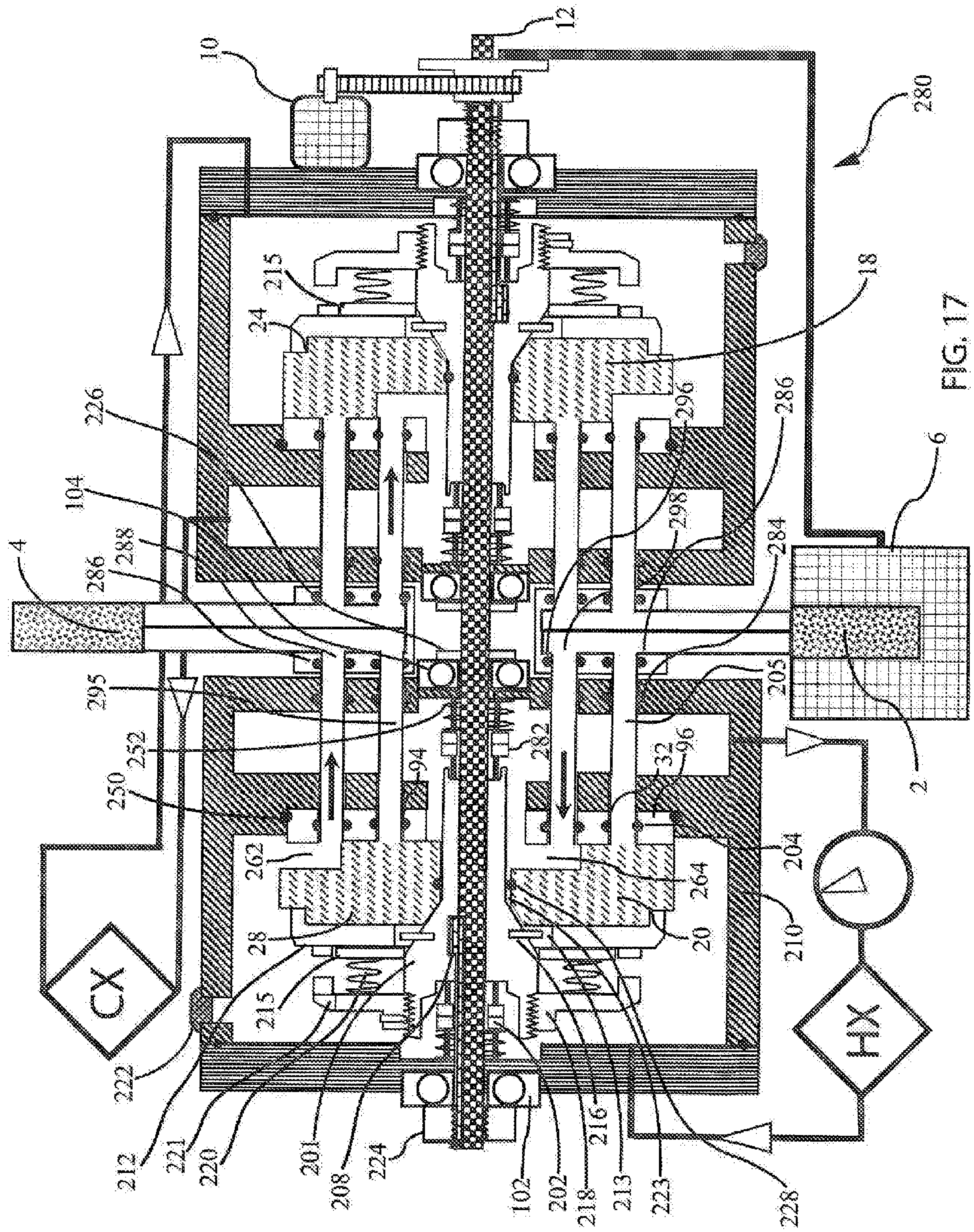


FIG. 16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CX
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FIG. 17

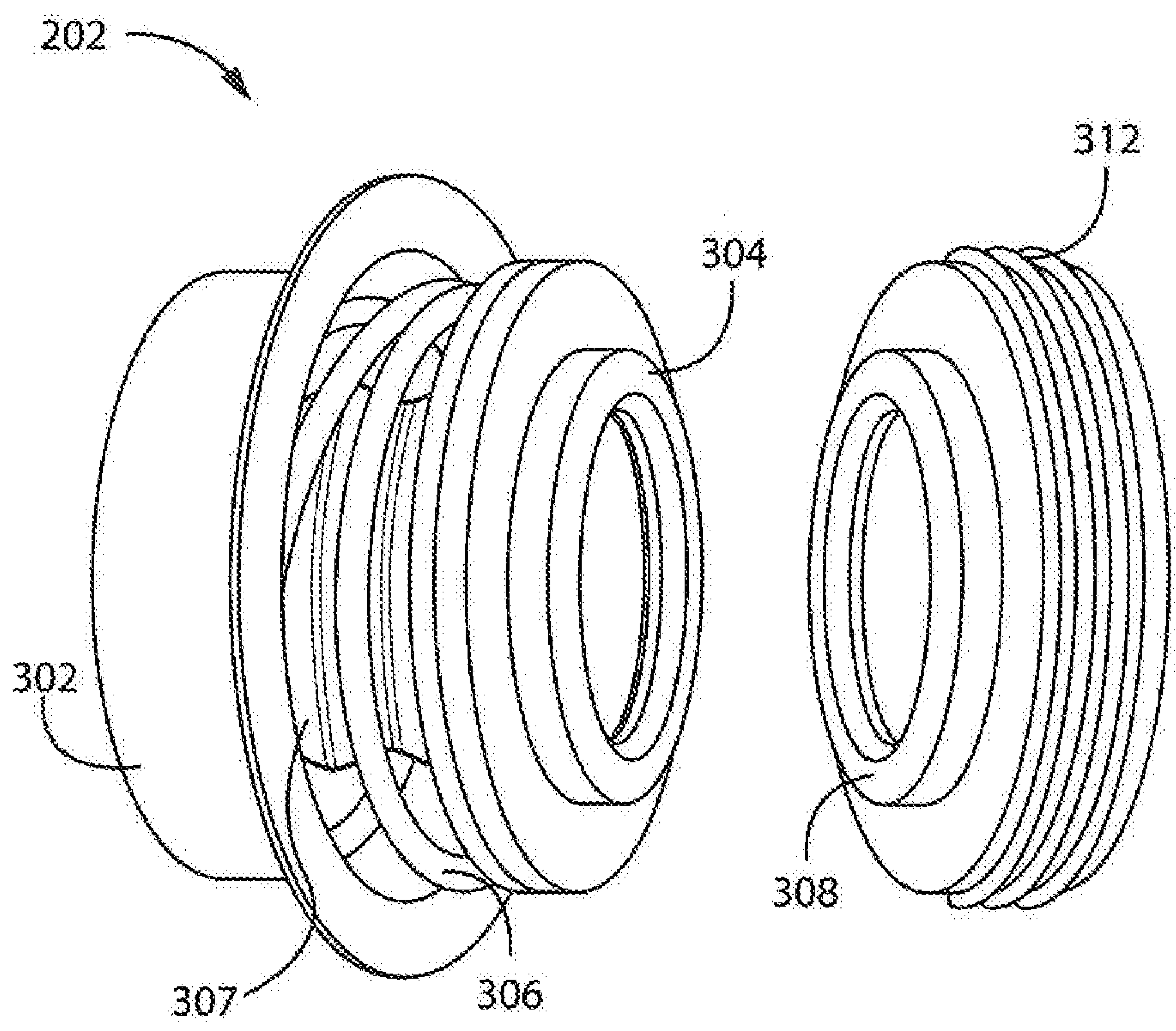

FIG. 18

MAGNETIC REFRIGERATION SYSTEM WITH IMPROVED COAXIAL VALVE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. provisional application Ser. No. 62/091,849, filed Dec. 15, 2014, and hereby incorporated by reference, and is a continuation-in-part of U.S. non-provisional application Ser. No. 14/556,424, filed Dec. 1, 2014, and hereby incorporated by reference, which claims priority to U.S. provisional application Ser. No. 61/917,025, filed Dec. 17, 2013, and also incorporated by reference.

BACKGROUND OF THE INVENTION

[0002] Magnetic refrigeration (MR) is an emerging cooling technology that is based on the magnetocaloric effect; a property exhibited by certain materials which heat up when placed in a magnetic field and cool down when the field is removed. Magnetic refrigeration offers a number of distinct advantages over vapor compression, which is currently the most widely used method for cooling. First, MR uses no hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), nor any other gaseous materials; the refrigerant in the MR system is in the form of a porous solid. The absence of any gases greatly reduces the potential for leaks, a common problem in vapor compression systems. As a result, MR systems can have greater reliability with reduced maintenance and downtime. The elimination of HFCs and CFCs has benefits for the environment, as these gases are ozone-depleting and contribute to global warming. Finally, theoretical studies demonstrate that MR systems can be more energy-efficient than vapor compression systems, particularly under off-peak load conditions.

[0003] General background on magnetic refrigeration may be found at K. Gsehneidner and V. Pecharsky. "Thirty years of near room temperature magnetic cooling: Where we are today and future prospects", Int. J. of Refrig. 31: 945-961, 2008 and K. Engelbrecht, G. Nellis, S. Klein, and C. Zimm, "Recent Developments in Room Temperature Active Magnetic Regenerative Refrigeration", HVAC&R Research, 13(4); 525-542, 2007, both of which are hereby incorporated by reference. Modern room-temperature MR systems implement the so-called Active Magnetic Regenerator (AMR) cycle to perform cooling, as disclosed in U.S. Pat. No. 4,332,135, hereby incorporated by reference. This cycle has four stages, as shown schematically in FIGS. **1**A, **1**B, **1**C, and **1**D. The MR system in these figures consists of a porous bed of magnetocaloric material (MCM) **190** and a heat transfer fluid which exchanges heat with the MCM as it flows through the bed **190**. The left side of the bed **190** is the cold side, while the hot side is on the right side. The timing and direction (hot-to-cold or cold-to-hot) of the fluid flow is coordinated with the application and removal of the magnetic field **192**. In the first stage of the cycle ("magnetization"), FIG. **1**A, while the fluid in the bed **190** is stagnant, a magnetic field **192** is applied to the MCM causing it to heat. In the next stage (the "hot blow"), FIG. **1**B, while the magnetic field **192** over the bed **190** is maintained, fluid at a temperature T_{Ci} (the cold inlet temperature) is pumped through the bed from the cold side to the hot side though the cold inlet **182**. This fluid pulls heat from the MCM in the bed and rises in temperature as it passes through the bed **190**. During the hot blow, the fluid exits the bed **190** at the temperature T_{Ho} (the hot outlet temperature) through the hot outlet **186** and is circulated through a hot-side heat exchanger **194**, where it gives up heat to the ambient environment and returns to the temperature T_{Hi} (the hot inlet temperature)$<T_{Ho}$. In the next stage ("demagnetization"), FIG. **1**C, the fluid flow is terminated and the magnetic field is removed. This causes the bed **190** to cool further. In the final stage (the "cold blow"), FIG. **1**D, fluid at a temperature T_{Hi} is pumped through the bed **190** from the hot side via the hot inlet **188** to the cold side in the continued absence of the magnetic field. The fluid is cooled as it passes through the MCM in the bed **190**, reaching a temperature T_{Co} (the cold outlet temperature)$<T_{Ci}$. The colder fluid exiting the bed **190** during the cold blow via the cold outlet **184** is circulated through a cold-side heat exchanger **196**, picking up heat from the refrigerated environment. The fluid exits the cold-side heat exchanger **196** at temperature T_{Ci} and completes the AMR cycle. The heat absorbed by the cold fluid in the cold-side heat exchanger **196** during the cold blow allows the refrigerated environment to maintain its colder temperature.

[0004] Although FIGS. **1**A, **1**B, **1**C and **1**D illustrate the operation of a single-bed MR system, one of ordinary skill in the art would see that multiple beds, each undergoing the same AMR cycle, may be combined in a single system to increase the cooling power, reduce the system size, or otherwise improve the performance of the cycle.

[0005] To implement the AMR, cycle, a magnetic refrigerator needs one or more porous beds of magnetocaloric material, a heat, transfer fluid, a pump to drive the fluid through the beds, a means for applying and removing a magnetic field to the beds, and a flow control system which coordinates the timing and direction of the fluid flow through a bed with the application and removal of the magnetic field over the bed. In one implementation of the AMR cycle in a magnetic refrigerator, a magnet assembly with a gap, such as that disclosed in U.S. Pat. No. 7,148,777, hereby incorporated by reference, rotates over fixed beds of magnetocaloric material. The fixed beds fit into the gap of the magnet assembly and the magnetic field is applied to a given bed when the magnet assembly gap rotates over it. The field is maintained over the bed as it remains within the magnet gap. As the magnet rotates away from the given bed, the magnetic field is removed. This implementation, referred to as a "rotating magnet" magnetic refrigerator or RMMR, is described in U.S. Pat. No. 6,668,560, hereby incorporated by reference.

[0006] Each bed in an RMMR has four fluid ports, as shown in FIGS. **1**A, **1**B, **1**C and **1**D. Two of these ports, the hot inlet port **188** and the hot outlet port **186**, are located on the hot side of the bed **190**, while two other ports, the cold inlet port **182** and cold outlet port **184**, are located on the cold side of the bed **190**. The inlet ports **188** and **182** deliver fluid to the magnetocaloric material in the bed **190**, while the outlet ports **186** and **184** collect fluid emerging from the magnetocaloric material. By using separate inlet and outlet ports, the mixing of inlet and outlet fluid streams, which are generally at different temperatures, is minimized. This improves MR system performance by preventing the thermal loss associated with mixing.

[0007] To control the fluid flow, the RMMR typically uses four valves, referred to as the hot inlet (Hi) valve, the hot outlet (Ho) valve, the cold inlet (Ci) valve, and the cold outlet (Co) valve. When a bed is within the gap of the rotating magnet assembly, the cold inlet valve delivers flow to the cold inlet port of the bed; simultaneously, the hot outlet valve collects fluid from the hot outlet port of the bed. The hot inlet valve blocks flow to the hot inlet port of the bed, while the cold outlet valve blocks flow from the cold outlet port. In this manner, flow can only proceed through the bed from the cold inlet port to the hot outlet port, the desired flow path for a magnetized bed undergoing the hot blow stage of the AMR cycle. When the magnet rotates away from the bed, so that the bed is now demagnetized, the cold inlet valve now blocks flow from entering the cold inlet port, while the hot outlet valve blocks flow from emerging through the hot outlet port. The hot inlet valve opens and directs hot inlet fluid to the hot inlet port of the bed, while the cold outlet valve opens, allowing fluid to exit the bed through the cold outlet port. In this manner, flow can only proceed through the bed from the hot inlet port to the cold outlet port, the desired flow path for a demagnetized bed undergoing the cold blow stage of the AMR cycle. It is clear that for the proper functioning of the MR system, the opening and closing of the valves must be coordinated with the angular position of the magnet assembly relative to a bed.

[0008] Rotary valves, such as those disclosed in U.S. Pat. No. 6,668,560, hereby incorporated by reference, may be used for implementing the flow control described above. Generally, rotary valves employ two elements, a stator containing an annular arrangement of holes and a rotor containing a slot, extending over a certain angular distance. The rotor slot is centered over the same path as the holes in the stator, so that the slot of the rotor overlaps one or more of the holes in the stator. When the rotor slot overlaps a stator hole, a continuous fluid path is established through the valve; when the rotor slot does not overlap a stator hole, flow cannot proceed through the valve and flow is blocked. The contact faces of the rotor and stator are typically highly polished, so that no fluid can leak between them. In the valve, the stator has a plurality of ports. Each of these valve ports is connected to a fluid conduit (e.g., a pipe), the other end of which is connected to a bed port. Each hole in the stator is connected to one of these valve ports. Another end of the chamber contains a single axial port, which is connected to a fluid conduit (e.g., a pipe). The other end of this conduit is connected to a heat exchanger. The rotor is attached to a rotary shaft which rotates the rotor with respect to the stator. When the rotor is positioned so that its slot overlaps a stator hole, then a continuous fluid path is provided between a bed port on one side of the valve and the heat exchanger on the other side; otherwise, flow to or from the bed port is blocked. As the rotor rotates, the slot alternately allows and blocks flow from or to the bed port. The position of the rotor in the cold inlet valve is set so that when a bed is within the gap of the magnet assembly, the rotor slot overlaps the hole connected to the cold inlet port of the bed (through the associated cold inlet valve port). The position of the rotor in the hot outlet valve is set so that at this same time, its rotor slot overlaps the hole connected to the hot outlet bed port (through the associated hot outlet valve port). In this manner, a continuous fluid path from the cold-side heat exchanger, through the bed from its cold inlet port to its hot outlet port, to the hot-side heat exchanger, is established. The angular extent of the rotor slots is chosen so that holes in the cold inlet and hot outlet valves remain uncovered as long as the bed remains within the gap of the magnet assembly. The positions of the rotors in the hot inlet and cold outlet valves are set so that the holes connecting to the hot inlet and cold outlet ports of the magnetized bed are blocked.

[0009] With the valves and magnet assembly driven off the same motor, the rotors will rotate in exact coordination with the magnet assembly. In particular, as the magnet assembly rotates away from a given bed so that the bed becomes demagnetized, the rotors in the cold inlet and hot outlet valves will now block the holes connected to the cold inlet and hot outlet ports of the bed. The rotors in the hot inlet and cold outlet valves rotate so that the rotor slots uncover the holes connected to the hot inlet and cold outlet ports of the now demagnetized bed. Thus, flow is established from the hot-side heat exchanger, through the demagnetized bed from its hot inlet to its cold outlet, to the cold-side heat exchanger.

[0010] In past RMMRs, and as described in U.S. Pat. No. 6,668,560, hereby incorporated by reference, the four valves are placed at four positions outside of the sweep of the magnet assembly, and the valve shafts are driven by the magnet assembly shaft through belts and pulleys which connect the valve shafts to the magnet assembly shaft, which is in turn driven by a motor. In contrast, in the current invention, the valves are located coaxial with the magnet assembly shaft on each side of the magnet assembly, so that the valves can be directly driven by the magnet assembly shaft.

SUMMARY OF THE INVENTION

[0011] The present inventors have determined that substantial inefficiencies can arise in conventional magnetic refrigeration systems as a result of variations in the length, configuration and construction of the inter-communicating conduits used to conduct fluid within the complex circuits of the device. These variations can significantly underutilize the magnetocaloric beds reducing efficiency. Accordingly, the present invention provides a magnetic refrigeration system in which the conduits between the valve system and the magnetocaloric beds are balanced with respect to flow either when multiple conduits are active or over successive intervals of conduit activation. A rotary design with concentric positioning of the valves facilitates this balancing which considers not only steady-state resistance to flow but also dynamic effects caused by variations in conduit volume and/or elasticity. An improved valve design balances the forces needed to seal valve surfaces, reduces influence of wear on leakage, makes assembly and adjustment of the valve easier, reduces potential for bypass flows, reduces stress on and corrosion of the drive shaft, and can allow a more compact system.

[0012] In one embodiment, the invention provides an active magnetic regenerative refrigerator (AMR) apparatus, comprising: a first AMR bed with a first end and a second end; a first heat exchanger (HEX) with an inlet and an outlet; a shaft rotatable along an axis; a magnet attached to the shaft to apply a time-varying magnetic field to the first AMR bed with rotation of the shaft; a first valve switchably connecting the outlet of the first HEX to the first end of the AMR bed for fluid flow therebetween when the field on the first AMR bed is in a low state relatively removed from the magnet; a second valve switchably connecting the inlet of the first HEX to the first end of the AMR bed for fluid flow therebetween when the field on the first AMR bed is in a high state relatively proximate to the magnet. The first and second valves include: (a) at least one pair of valve plates in rotational sliding communication and positioned coaxially about the shaft, where a first valve plate is attached to rotate with the shaft with respect to the second valve plate, the valve plates including valve ports that move into alignment and out of alignment to allow fluid flow through the valve ports when in alignment and to block fluid flow through the valve ports when out of alignment, where at least one of the valve plates is mounted for movement along the axis of the shaft with respect to an other of the valve plates; and (b) a spring urging the valve plates axially into contact with each other.

[0013] The spring may be a compression spring positioned between a spring support and a contacted valve plate of the valve plates and the position of the spring support may be adjustable to control a force of the spring on the contacted valve plate.

[0014] The valve plates may be held within as plenum receiving a fluid controlled by the valve and where the spring support may be adjustable by rotation on a threaded element coaxial about the shaft and where the plenum includes a sealable opening allowing access to the spring support for rotation of the spring support with respect to the threaded element to move the spring support axially along the shaft.

[0015] The first valve plate may attach to the shaft through a joint allowing angulation of the first valve plate in addition to axial movement of the first valve plate while preventing relative motion of the valve plate and shaft in rotation about an axis of the shaft.

[0016] The joint may provide an interengaging axial slot and radial pin.

[0017] The shaft may communicate with the first valve plate by means of a key joining a key way and key seat on the shaft and valve plate where the key extends to an end of the shaft to allow extraction of the key in a first direction from a first end of the shaft and extraction of the shaft in a second direction opposite the first direction.

[0018] The shaft may pass through a plenum receiving fluid from a valve and may be separated from the plenum by a sleeve assembly.

[0019] The sleeve assembly may include a first and second sleeve portion over different axial portions of the shaft each portion including a sliding seal communicating with a corresponding sliding seal of the other portion allowing relative rotational movement of the first sleeve portion with respect to the second sleeve portion about the axis.

[0020] The sliding seal may include a spring biasing the first and second seal portion into engagement to prevent leakage therebetween.

[0021] The first and second valves may comprise one pair of valve plates in rotational sliding communication and positioned coaxially on the rotatable shaft.

[0022] The valve plates may cooperate to in a first position present a passage of fluid to a first plenum communicating with an outer periphery of at least one valve plate and in a second position to present a fluid passage to a fluid and a second plenum separated from the first plenum communicating with an inner periphery of at least one valve plate.

[0023] The AMR apparatus may further include a second heat exchanger (HEX) with an inlet and outlet; including a third valve that fluidly connects the inlet of the second HEX to the second end of the AMR bed when the field on the first AMR bed is in a low state; a fourth valve that fluidly connects the outlet of the second HEX to the second end of the AMR bed when the field on the first AMR bed is in a high state.

[0024] The third and fourth valves may be check valves.

[0025] At least one valve plate may be a carbon material.

[0026] In another embodiment, the invention provides a magnetic refrigeration system having at least a first and second bed of magnetocaloric material, each bed having a first and second opposed side between which fluid may flow. At least one manifold communicates a hot inlet conduit and a hot outlet conduit to the first side of each bed and communicates a cold inlet conduit and a cold outlet conduit to the second side of each bed. A magnet assembly is movable to apply a greater magnetic field to the first bed than the second bed in a first state and a greater magnetic field to the second bed than the first bed in a second state, and a valve system communicates with the conduits and synchronizes to the magnet assembly to permit circulation of fluid through the first and second beds to remove heat from the first bed by providing flow through at least one first conduit pair (each pair being a series-connected cold inlet conduit and hot outlet conduit) and to add heat to the second bed in the first state by providing flow through at least one second conduit pair (each pair being a series-connected hot inlet conduit and cold outlet conduit). Each of the first and second conduit pairs are adapted to provide substantially equal fluid flow through each first conduit pair when connected for flow by the valve system.

[0027] It is thus a feature of at least one embodiment of the invention to address cooling inefficiencies that can result from relatively minor flow imbalances.

[0028] Each first conduit pair may have substantially equal flow resistance and each second conduit pair has substantially equal flow resistance. In this respect, each first and second conduit pair may have a substantially identical length.

[0029] It is thus a feature of at least one embodiment of the invention to balance flow resistances in the conduit such as affects steady-state flow.

[0030] The conduit pairs carrying greater flow may be made shorter than conduit pairs carrying lesser flow.

[0031] It is thus a feature of at least one embodiment of the invention to provide a system that may be better tailored to permitting an equal flow in the hot and cold cycle portions.

[0032] Alternatively or in addition, each first and second conduit pair may have substantially equal internal volume.

[0033] It is thus a feature of at least one embodiment of the invention to address flow imbalances caused by dynamic "inductive" effects related to the inertial mass of flowing material in the conduit pairs.

[0034] Alternatively or in addition, each conduit pair has substantially equal change in internal volume as a function of change in pressure.

[0035] It is thus a feature of at least one embodiment of the invention to compensate for flow imbalances caused by dynamic "capacitive" effects related to the elasticity of the conduit.

[0036] The change in internal volume of each conduit pair to a bed of magnetocaloric material, when subjected to the increase from a minimum to a maximum fluid pressure during the operation of the magnetic refrigeration system, may be less than 5% of the total fluid volume delivered to a single bed during the time interval in one AMR cycle that the conduit pair is delivering flow to that bed.

[0037] It is thus a feature of at least one embodiment of the invention to limit potential backflow and inefficiencies caused by stored pressure in possibly elastic conduits.

[0038] Each of the hot inlet conduits, hot outlet conduits, cold inlet conduits, and cold outlet conduits may be adapted to provide substantially equal resistance to fluid flow.

[0039] It is thus a feature of at least one embodiment of the invention to provide balanced resistance according to the function of the conduit.

[0040] The valve system may provide four valves including a hot outlet valve, a hot inlet valve, a cold outlet valve and a cold inlet valve, where in the first state, the hot outlet valve connects the hot outlet conduit of the first bed to the inlet of a hot heat exchanger and the cold inlet valve connects the cold inlet conduit of the first bed to an outlet of a cold heat exchanger and the hot inlet valve connects the hot inlet conduit of the second bed to an outlet of the hot heat exchanger and the cold outlet valve connects the cold outlet conduit of the second bed to an inlet of the cold heat exchanger. And further where in the second state the hot outlet valve connects the hot outlet conduit of the second bed to the inlet of the hot heat exchanger and the cold inlet valve connects the cold inlet conduit of the second bed to the outlet of the cold heat exchanger and the hot inlet valve connects the hot inlet conduit of the first bed to the outlet of the hot heat exchanger and the cold outlet valve connects the cold outlet conduit of the first bed to the inlet of the cold heat exchanger.

[0041] It is thus a feature of at least one embodiment of the invention to provide for balanced flow in a system that preserves unidirectional flow through each conduit to eliminate losses from backflow.

[0042] The hot outlet valve and the hot inlet valve may include movable elements opening and closing the valves and in mechanical communication with the magnet assembly, and where the cold inlet valve and cold outlet valve are one-way valves actuated by fluid flow. Alternatively, the cold outlet valve and the cold inlet valve may include movable elements opening and closing the valves and in mechanical communication with the magnet assembly, and where the hot inlet valve and hot outlet valve may be one-way valves actuated by fluid flow

[0043] It is thus a feature of at least one embodiment of the invention to simplify the valve structures by using some one-way type valves.

[0044] The first and second bed may arranged around a central axis and the magnet assembly may be attached to a shaft rotatable with respect to the first and second bed along the central axis and the hot outlet valve and hot inlet valve may be disk valves having rotor portions attached coaxially about the shaft to move with respect to stationary stator portions positioned coaxially about the shaft.

[0045] It is thus a feature of at least one embodiment of the invention to employ an axially balanced rotating architecture to facilitate balancing of the conduit structure.

[0046] The hot outlet valve and hot inlet valve may have stator portions fixed with respect to the beds and rotor portions fixed with respect to the magnet where the stator portions are mounted between the rotor portions.

[0047] It is thus a feature of at least one embodiment of the invention to adopt a valve orientation and inherent sealing between the valve rotor and stator to balance the forces necessary to seal the rotors to the stators.

[0048] The magnetic refrigeration system may include a plurality of magnetic beds arranged about the central axis, each having a manifold communicating a hot inlet conduit and a hot outlet conduit to the first side of each bed and communicating a cold inlet conduit and cold outlet conduit to the second side of each bed where the valve assembly provides valves attached to the shaft communicating with either inlet conduits or outlet conduits.

[0049] It is thus a feature of at least one embodiment of the invention to provide balanced flow in a multi-bed system where inefficiencies from unbalanced flow may be aggravated.

[0050] The valves may provide substantially unobstructed communication with multiple inlet conduits or outlet conduits at one or more positions of the shaft.

[0051] It is thus a feature of at least one embodiment of the invention to ensure equal flow sharing among conduits when multiple conduits are operated in parallel.

[0052] The magnetic refrigeration system may further include a positive displacement pump circulating the fluid through the valve system and inlet and outlet conduits.

[0053] It is thus a feature of at least one embodiment of the invention to provide a pump that can handle quick changes in flow rate necessary for switching among multiple beds and to provide a conduit system compatible with this rapid switching.

[0054] These particular objects and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0055] FIGS. **1**A-**1**D are schematics illustrating an Active Magnetic Regenerator (AMR) cycle to perform cooling;

[0056] FIG. **2** shows an overview of the component arrangement of a first embodiment of the invention with four disk valves;

[0057] FIG. **3** shows a first embodiment of an improved valve assembly providing reduced wear effects and simplified adjustment;

[0058] FIG. **4** shows an overview of the component arrangement of a second embodiment of the invention with stators for the hot inlet valve and the hot outlet valve mounted to a common assembly;

[0059] FIG. **5** shows an overview of a component arrangement of an third embodiment of the invention with the magnet at a larger radius;

[0060] FIG. **6** shows a second embodiment of the improved valve assembly providing balanced sealing forces and simplified assembly and maintenance;

[0061] FIG. **7** shows an overview of the component arrangement of an fourth embodiment of the invention with stators of the hot inlet and cold inlet valves mounted to a common assembly;

[0062] FIG. **8** shows an overview of the component arrangement of a fifth embodiment of the invention with check valves on the cold side;

[0063] FIG. **9** shows an enlarged view of a flow connection at one side of a bed;

[0064] FIG. **10** shows an end view of an eight bed configuration of the second embodiment shown in FIG. **4**;

[0065] FIG. **11** shows a third embodiment of the improved valve assembly where the inlet and outlet functions are combined in a single valve assembly;

[0066] FIGS. **12**A-**12**B shows end views of rotor discs that could be used in the improved valve assembly of FIG. **11**;

[0067] FIGS. **13**A-**13**B shows end views of valve stators that could be used in the improved valve assembly of FIG. **11**;

[0068] FIG. **14** shows in a top view of how the rotor and stator disks can be stacked in the improved valve assembly of FIG. **11**;

[0069] FIG. **15** shows details of a bushing and valve cup that could be used in the improved valve assembly of FIG. **11**;

[0070] FIG. **16** shows an exploded view of the valve tensioning assembly that could be used in the improved valve assembly of FIG. **3** or **11**;

[0071] FIG. **17** shows a fourth embodiment of the improved inlet and outlet valve assembly providing balanced sealing forces, simplified assembly and maintenance, and a drive shaft that is protected from the heat transfer fluid; and

[0072] FIG. **18** shows a rotary face seal that can be used in the improved valve assembly of FIG. **6** or **17**.

DETAILED DESCRIPTION OF THE INVENTION

[0073] The invention comprises a "rotating magnet" magnetic refrigerator (RMMR) which uses rotary disk valves to control flow to and from the beds where these valves are located coaxially with the shaft rotating the magnet assembly, and where a compression mechanism on the valve disks is adjustable after assembly of the valves, and maintains sealing as the disks wear. An overview of the arrangement of components of a first embodiment of this invention is shown in FIG. **2**. FIG. **2** shows a cross section of a two-bed system **1**, where a first bed **2** (magnetized) is within the gap **8** of the magnet assembly **6** while a second bed **4** (demagnetized) is outside the gap **8** of the assembly. A motor **10** (which may be an electric motor) rotates the central shaft **12**, which is mounted to bearings **102**, **104**, **106** and **108**, and passes through rotary seals **122**, **124**, **126** and **128**. This central shaft **12** also drives the rotors **14**, **16**, **18**, **20** in each of the coaxial valves **22**, **24**, **26**, **28**. A pump **30** drives fluid flow through the system **1**.

[0074] In the configuration shown in FIG. **2**, the rotor **14** in the hot inlet (Hi) valve **22** uncovers the hole **32** connected to the hot inlet port **42** of the demagnetized (lower) bed **4**. At the same time, the rotor **16** in the cold outlet (Co) valve **24** uncovers the hole **34** connected to the cold outlet port **44** of the bed **4**. Thus, pressurized fluid emerging from the hot-side heat exchanger (HHEX) **40** at temperature T_{Hi} is carried by a pipe **62** into a chamber **52** at one end of the hot inlet valve **22**, through the uncovered hole **32** in stator **88** of the hot inlet valve **22** and is driven into a hot inlet pipe **64*b*** and through the bed **4** from its hot inlet port **42** to its cold outlet port **44**. After passing through the cold (demagnetized bed) **4**, this fluid, now at temperature T_{Co}, is carried by a cold outlet pipe **66*b*** and collected by the open cold outlet valve **24** through the hole **34** in the stator **90**, and directed via the chamber **54** at one end of the valve **24** through pipe **92** to the cold-side heat exchanger (CHEX) **60** where the fluid absorbs heat from the refrigerated environment and rises in temperature to T_{Ci}. The cold inlet port **68** and cold inlet pipe **72*b*** of the demagnetized bed **4** are blocked by the rotor **16** position in the cold inlet (Ci) valve **26** covering the hole **38*b***, and the hot outlet port **70** and hot outlet pipe **82*b*** of the demagnetized bed **4** are also blocked by the rotor **20** position in the hot outlet (Ho) valve **28** covering the hole **94*b***. Fluid at temperature T_{Ci} emerging from the other end of the cold-side heat exchanger **60** enters the single port **36** in the chamber **56** at one end of the cold inlet valve **26**. This fluid is directed through the cold inlet rotor **18** and through the hole **38*a*** in the stator **86** into a cold inlet pipe **72*a*** and to the cold inlet port **74** of the magnetized (upper) bed **2**. The fluid passes through the magnetized bed **2** from the cold inlet port **74** to the hot outlet port **78** and rises in temperature to T_{Ho}. Flow through the cold outlet port **76** and cold outlet pipe **66*a*** of the bed **2** is blocked by the cold outlet valve **24**. Flow through the hot inlet port **80** and hot inlet pipe **64*a*** of the bed **2** is blocked by the hot inlet valve **22**. Hot outlet fluid at temperature T_{Ho} from the port **78** of the bed **2** is carried by a hot outlet pipe **82*a*** through a hole **94*a*** in the stator **96** into the hot outlet valve **28**, exits the valve **28** via the chamber **58** and returns via a pipe **84** to the pump **30**, where it gets directed through the other end of the HHEX **40**, completing the flow circuit.

[0075] Although the figures show pipes that carry the fluid flow between components of the invention, any suitable conduits that carry the fluid between the components might be used. For example, the conduits might be fluid passages in an injection-molded assembly, or the conduits might be fluid passages in an assembly made by additive manufacturing, or the conduits could be pipes as shown in the drawings.

[0076] The improvements to the valves of the first embodiment of this invention are shown in the detailed view of the hot side valves in FIG. **3**. Both the hot inlet valve **22** and hot outlet valve **28** are of similar construction. The hot outlet valve **28** contains a stator **96** that is fixed in position and sealed against the valve housing **210**. The hot outlet valve also contains a rotor **20** that rotates with the magnet **6** about the axis of the shaft **12**. The rotor **20** is centered by an o-ring **228** between its inner diameter (ID) and a bushing **214**, and is mounted to a rigid valve cup **212**. The bushing **214** is individually assembled on the drive shaft **12**, and held in place by a pin **216** that extends through the shaft **12**, bushing **214** and into a slot **213** in the rigid cup **212**. The pin **216** provides precise axial location of the bushing **214**, and also transfers rotary torque from the shaft **12** to the rotating components of the valve. A threaded nut **218** supports springs **220** that apply compression force against the rigid cup **212**. The rigid cup can move along the axis of the shaft **12** and bushing **214** as the pin **216** slides in the slot **213** and thus transmit compressive force to the rotor **20**, but the engagement of the pin **216** in the slot **213** and in the shaft **12** ensures that rotary torque is transmitted from the shaft **12** to the rigid cup **212** and the rotor **20**. An external access port **222** allows adjustment of compression without disassembly of the valve. External access ports **222** and slots **221** in the threaded nut **218** allow adjustment of compression without disassembly of the valves. The adjustment is done by rotation of the shaft **12** while the threaded nut **218** is held fixed by a tool inserted through the access port **222**. Bearings **102** and **104** are incorporated into the valve housings. This allows a compact design, allows compression loading of the outer nut **224** against the outer bearing **102** and guarantees alignment in the valve bodies. The inner bearing **104** is seated against a retaining ring **226** that is attached to the shaft **12**.

[0077] As the valve rotor **20** and valve stator **96** of the valve **28** wear during operation of the valve, their combined thickness will be reduced. However, the springs **220** will accommodate this change in thickness and maintain sealing of the valve disks without need for external adjustment.

[0078] An overview of the arrangement of components of a second embodiment of this invention is shown in FIG. **4**. The valves perform the same time-sequenced flow allocation between the same conduits as the first embodiment. The difference is that the stator **86** and rotor **18** of the cold inlet valve **26** are inverted left to right, and the stator **88** and rotor **14** of the hot inlet valve **22** are inverted left to right, allowing the stator **88** for the hot inlet valve **22** and the stator **96** for the hot outlet valve **28** to be mounted to a common assembly **98**; the stator **86** for the cold inlet valve **26** and the stator **90** for the cold outlet valve **24** also can be mounted to a common assembly **100**. The magnet assembly **6**, the beds **2**, **4**, and the pump **30** are in similar positions in the first and second embodiments.

[0079] By mounting the stators **88** and **96** on opposed walls, the forces needed to compress the rotors **14** and **20** to their stators **88** and **96** are counter-acting, and the forces needed to compress the rotors **16** and **18** to their stators **90** and **86** are counteracting, thus reducing loads on the shaft **12** and simplifying the design.

[0080] An overview of the component arrangement of another embodiment of this invention is shown in FIG. **5**. The third embodiment has the same components as the second embodiment, and the components such as the motor **10** perform the same functions in the same manner as the second embodiment. The difference is that magnet assembly **6** and beds **2**, **4** in the first and second embodiments are located between the hot inlet valve **22** and cold inlet valve **26** at a similar radius, while the magnet assembly **6** and beds **2** and **4** of the third embodiment are located outside the valves **22**, **26** at a larger radius, allowing the length of the assembly **1** to be reduced. Note that in FIG. **5**, the hot outlet pipes **82***a*, **82***b* are each the same length and shape, and the cold inlet pipes **72***a*, **72***b* are also each the same length and shape, although the hot outlet pipe **82***a* is a different length and shape from the cold inlet pipe **72***a*.

[0081] In FIGS. **2**, **4** and **5**, all the pipes of the same function, such as hot outlet, are the same length, although pipes of different function, such as hot outlet and cold inlet, may be of different length. More generally, conduit pairs, such as cold inlet pipe **72***a* in series with and hot outlet pipe **82***a*, and cold inlet pipe **72***b* in series with hot outlet pipe **82***b* (first conduit pairs), or being hot inlet pipe **64***a* in series with cold outlet pipe **66***a* and hot inlet pipe **64***b* in series with cold outlet pipe **66***b* (second conduit pairs), are configured for equal or balanced flow among all similar conduit pairs. This is provided by ensuring that the conduit pairs provide equal steady-state flow resistance, but also by addressing dynamic factors such as flow inductance by setting equal the total internal volume of the conduit pairs, and flow capacitance by ensuring that the change in internal volume with changes in pressure is equal for the conduit pairs. These values may also be identical but need not be identical when the first conduit pairs are compared to the second conduit pairs.

[0082] The improvements to the valves of the second embodiment of this invention are shown in the detailed view of the hot side valves in FIG. **6**. Both the hot inlet valve **22** and hot outlet valve **28** are of similar construction. The hot outlet valve **28** contains a stator **96** that is fixed in position and sealed against the valve housing **210**. Each port in the stator is mated with a stub-tube **205** protruding from the floor of the valve housing. Each stub tube has an o-ring seal **204** to the stator. The hot outlet valve also contains a rotor **20** that rotates with the magnet **6** about the axis of the shaft **12**. The rotor **20** is centered by an o-ring **228** between its ID and an inner rotating assembly **201**, and is mounted to a rigid valve cup **212**. The drive shaft **12** passes coaxially through the inner assembly **201** that is connected to the rotor **20** and the compression assembly **230**. The compression assembly **230** is comprised of a threaded nut **218** that supports springs **220** that apply compression force against the rigid cup **212** and rotor **20**. The rigid cup **212** may be a carbon composite material. External access ports **222** allow adjustment of compression without disassembly of the valves. The inner rotatable assembly **201** has commercial ceramic (or other material) rotary face seals **202** mounted at each end to seal the fluid inside the valve body comprised of valve housing **210** and end plate **310** and prevent fluid from reaching the drive shaft **12**. In this way the driveshaft remains 'dry' and can be separated from the valve without breaking the seal in the bodies. This feature allows the hot inlet and outlet valves to be assembled, or removed and replaced without disturbing the cold inlet and outlet valves, or the bed and magnet assembly.

[0083] The inner rotating assembly consists of two pieces, sealed in the center by an o-ring **232** and held in place by threaded screws **203**. A special key **208** is fitted into a slot of the driveshaft and mates with a slot in the inner bore of the inner rotatable assembly **201**. The key **208** provides torque transfer from the driveshaft **12** to the inner rotatable assembly **201**. The key **208** also provides precise axial position control of the inner rotatable assembly **201** relative to the driveshaft **12**. The shank of the key **208** is designed so that it fits flush in its slot (within the diameter of the shaft **12**). This allows the seals **202** to run adjacent to the key **208** without interference. The key **208** is co-threaded with the drive shaft **12**, so that its axial position is rigidly locked when the outer nut **209** is assembled. The key **208** rigidly couples the inner rotatable assembly **201** to the drive shaft **12**. This allows the inner rotatable assembly **201** position to be accurately determined. It also allows unbalanced compression forces on the opposing valve surfaces while maintaining correct axial positions.

[0084] Bearings **102** and **104** are incorporated into the valve housings. This allows a compact design, allows compression loading of the outer nut **209** against the outer bearing **102** and guarantees alignment in the valve bodies. The inner bearing **104** is seated against a retaining ring **226** that is attached to the shaft **12**.

[0085] As the valve rotor **20** and valve stator **96** of the valve **28** wear during operation of the valve, their combined thickness will be reduced. However, the springs **220** will accommodate this change in thickness and maintain sealing of the valve disks without need for external adjustment. Even as the valves wear and potentially accumulate damage, leakage that bypasses the heat exchanger **40** would require both valves **22** and **28** and optional auxiliary seals **234** to leak, as can be seen in FIG. **6**.

[0086] Another embodiment of this invention is shown in FIG. **7**. The fourth embodiment has the same components as the third embodiment, and the components such as the motor **10** perform the same functions in the same manner as the third embodiment. The difference is that the stators **88**, **86** of the hot inlet **22** and cold inlet **26** valves are mounted to a common assembly **101**, allowing for shorter hot inlet piping **64***a*, **64***b* and cold inlet piping **72***a*, **72***b* to the beds **2**, **4** than is possible for the first three embodiments.

[0087] Additional variants for the above embodiments may be created by replacing the cold side inlet and outlet valves by one-way valves. Examples of one-way valves that might be used in the invention are check valves and reed valves. A one-way valve, also known as a check valve, allows fluid flow in only one direction and blocks fluid flow in the opposite direction. For example, a ball check valve uses a spherical ball to block the flow of fluid in one direction. A conically tapered seat will place the ball within the valve opening to prevent flow in one direction, but allow flow in the opposite direction when the ball is displaced from its seat. Placement of the ball within the seat may be aided by a spring. Other types of one-way valves include diaphragm check valves, swing check valves, tilting disc check valves, stop-check valves, lift-check valves, in-line check valves, duckbill valves, pneumatic non-return valves, etc. One-way valves can be smaller and less expensive than rotary disk valves.

[0088] An example of another embodiment using one-way valves is shown in FIG. **8**, where the cold side valves **24**, **26** of embodiment 2 in FIG. **4** have been replaced by check valves **120**, **121**, **125**, and **127** in FIG. **8**.

[0089] FIG. **9** shows details on how the connection might be made between one end of a bed and the inlet and outlet pipes coming from a valve. The cold inlet pipe **72***b* and cold outlet pipe **66***b* come in from the top of the figure and enter a bed plenum assembly **110**. The cold inlet pipe **72***b* terminates at a cold inlet port **68** and the cold outlet pipe **66***b* terminates in a cold outlet port **44** that connect at a rectangular opening **112** that can be attached to one side of a bed, such as the bed **4** of FIG. **2**. The bed is not shown in FIG. **9**.

[0090] Although two-bed embodiments are shown in FIGS. **2** through **8**, it is usually advantageous to fit additional beds in the path swept by the magnet gap. The additional beds increase the cooling power and can make more efficient use of the magnet assembly. The valves may be designed to allow flow in a given direction to multiple beds at the same time. For example, an eight-bed version of the first embodiment is shown as an end view from the cold end in FIG. **10**. Not shown are the cold inlet pipes, the hot inlet and outlet pipes, the valve housings and seals, the HEX's, the pump, the motor, and the bearings. The magnet assembly **6** and the cold outlet valve rotor **16** are connected to the shaft **12** and rotate with it. The magnet assembly is shown over two magnetized beds **2***a*, **2***b*, which are both under flow from their cold ends to their hot ends. Two demagnetized beds **4***a*, **4***b* are in the lowest field region and both are under flow from their hot ends to their cold ends, and four remaining beds **3***a*, **3***b*, **3***c*, and **3***d* at intermediate fields are not under flow. Each bed is attached to a cold side plenum assembly **110** and a hot side plenum assembly **111**. Together these plenums create a manifold about the bed. The cold outlet valve rotor **16** is shown exposing two holes **34***a*, **34***b* in the cold outlet valve stator **90**, allowing flow to leave the demagnetized beds **4***a*, **4***b* through the cold outlet ports **44***a*, **44***b* and the cold outlet pipes **66***a*, **66***b* which are attached to the cold side plenum assemblies **110***a*, **110***b*. Meanwhile, the cold outlet valve rotor **16** is blocking the holes **34***c*, **34***d*, **34***e*, **34***f*, **34***g* and **34***h*, thereby blocking flow from the cold outlet ports of beds **2***a*, **2***b*, **3***a*, **3***b*, **3***c*, and **3***d*.

[0091] Note that the flow situation of FIG. **10** can be implemented using cold inlet, cold outlet, hot inlet and hot outlet valve rotors that each exposes two holes in their matching stator at a time.

[0092] Although FIG. **10** shows a situation where two beds are simultaneously under flow from cold to hot and two beds are under flow from hot to cold, there are four beds that are not under flow and thus are not contributing to the cooling of the device. If the cold outlet and hot inlet valve rotors expose more holes in their matching stators than the cold inlet and hot outlet valves, then more beds will be subjected to hot to cold flow than will be subjected to cold to hot flow.

[0093] FIGS. **3** and **6** show improved valve assemblies where the hot inlet and hot outlet flow control functions are controlled by two distinct valve assemblies that are driven by a single shaft. Use of separate valve assemblies for hot inlet and outlet flows minimizes the possibility of thermal heat leakage or fluid leakage that bypasses the hot heat exchanger. However, use of two separate valve assemblies doubles the parts count and increases the cost of manufacture, and also increases the length of the system along the shaft axis. FIG. **11** shows an improved valve configuration that combines the switching of hot inlet and hot outlet flows in a single hot inlet/outlet valve assembly **270**. The hot valve **28** contains a stator **96** that is fixed in position and sealed against the valve housing **210**. The hot valve also contains a rotor **20** that rotates with the magnet **6** about the axis of the shaft **12**. The rotor **20** is centered by an o-ring **228** between its ID and a bushing **214**, and is mounted to a rigid valve cup **212**. The bushing **214** is assembled on the drive shaft **12**, and held in place by a pin **216** that extends through the shaft **12**, bushing **214** and into a slot **213** in the rigid cup **212**. The pin **216** provides precise axial location of the bushing **214**, and also transfers rotary torque from the shaft **12** to the rotating components of the valve. A threaded nut **218** supports springs **220** that apply compression force against the rigid cup **212**. The rigid cup can move along the axis of the shaft **12** and bushing **214** as the pin **216** slides in the slot **213** and thus transmit compressive force to the rotor **20**, but the engagement of the pin **216** in the slot **213** and in the shaft **12** ensures that rotary torque is transmitted from the shaft **12** to the rigid cup **212** and the rotor **20**. An external access port **222** allows adjustment of compression without disassembly of the valve. Bearings **102** and **104** are incorporated into the valve housing. This allows a compact design, allows compression loading of the outer nut **224** against the outer bearing **102** and guarantees alignment in the valve body. The inner bearing **104** is seated against a retaining ring **226** that is attached to the shaft **12**.

[0094] As the valve rotor **20** and valve stator **96** of the valve **28** wear during operation of the valve, their combined thickness will be reduced. However, the springs **220** will accommodate this change in thickness and maintain sealing of the valve disks without need for external adjustment.

[0095] A motor (not shown) rotates the central shaft **12**. In the position shown in FIG. **11**, hot outlet fluid at temperature T_{Ho} from the port **78** of the bed **2** that is inside the magnet **6** is carried by a hot outlet pipe **82***a* at an intermediate radius through a hole **94***a* in the stator **96** into the hot outlet valve **28**, flows through a slot **264** in the rotor **20** to a hole **266** in the inner radius of the stator **96**, and flows just outside the shaft **12** into an inner plenum **272**. The fluid exits the inner plenum **272** through a pipe **84** to the inlet of the pump **30**, which pumps the fluid through the hot HEX **40** and through a pipe **62** into the outer plenum **52** of the valve **28**. The fluid in the outer plenum **52** can enter the slot **262** in the rotor **20** and proceed through a hole **32***a* at an outer radius in the stator disk **96** and through a pipe **254** to the hot inlet **42** of the bed **4** that is outside the magnet **6**.

[0096] In the rotational position shown in FIG. **11**, flow through the hot inlet port **80** and hot inlet pipe **64***a* of the magnetized bed **2** is blocked by the hot valve rotor **20** covering the hole **32***b*. The hot outlet port **70** and hot outlet pipe **82***b* of the demagnetized bed **4** are also blocked by the rotor **20** position covering the hole **94***b*.

[0097] FIGS. **12**A and **13**A shows plan views of a rotor disk **20** and stator disk **96**, respectively, that can be used in the hot inlet/outlet valve assembly **270** shown in FIG. **11**. Slots **264** and **266** in the rotor disk are shown. Also shown are holes **32***a*, **94***b*, and **266** in the stator disk. FIG. **12**B shows a cross section of the rotor disk **20** taken at the line A-A shown in FIG. **12**A, and FIG. **13**B shows a cross section of the stator disk **96** taken at the line B-B shown in FIG. **13**A. Slots **264** and **266** in the rotor disk are shown in FIG. **12**B. Holes **32***a*, **94***b*, and **266** in the stator disk are also shown in FIG. **13**B. FIG. **14** shows in an end view how the rotor disk **20** and stator disk **96** can be stacked with their surfaces in contact, allowing flow to be directed between the slots and different holes as the rotor **20** rotates with respect to the stator **96**.

[0098] FIG. **15** shows details of a bushing, pin and valve cup that can be used in the improved valve assemblies of FIG. **3** or **11**. The bushing **214** is assembled on the drive shaft **12** (not shown in FIG. **15**), and held in place by a pin **216** that extends through the shaft **12**, bushing **214** and into a slot **213** in the rigid cup **212**. The pin **216** provides precise axial location of the bushing **214** with respect to the shaft **12**, and also transfers rotary torque from the shaft **12** to valve cup **212** and other rotating components of the valve.

[0099] FIG. **16** shows an exploded view of the compression assembly that can be used in the improved valve assemblies of FIG. **3** or **11**. The valve compression assembly **230** is comprised of a threaded nut **218** (or spring support) that supports springs **220** that apply compression force against the rigid cup **212** (or contacted valve plate) connected to rotor **20** (not shown). The springs **220** are held in place by the ring **215** which fits inside the rim **211** on the rigid cup **212**. It is understood that the ring **2015** could be moved to the opposite side of the springs **220** while performing a similar function. Referring also to FIG. **17**, the springs **220**, which may be compression springs, are positioned between the ring **215** on one side and the threaded nut **218** on the opposite side, and the position of the threaded nut **218** may be adjustable to control a force of the springs **220** on the rigid cup **212** applied via the ring **215**. It is understood that the springs **220** may be replaced with any elastic object used to store mechanical energy as is known in the art.

[0100] The rigid cup **212** may be held within the plenum receiving a fluid controlled by the valve and where the springs **220** may be adjustable by rotation on a threaded element coaxial about the shaft **12**. The plenum may include a sealable opening allowing access to the threaded nut **218** for rotation of the threaded nut **218** with respect to the threaded element to move the threaded nut **218** axially along the shaft **12**. The rigid cup **212** may cooperate to, in a first position present a passage of fluid to a first plenum communicating with an outer periphery of at least one rigid cup **212** and in a second position to present a fluid passage to a fluid and a second plenum separated from the first plenum communicating with an inner periphery of at least one rigid cup **212**.

[0101] Referring also to FIG. **15**, a joint between the drive shaft **12** and the rigid cup **212** may provide an interengaging axial slot **213** and radial pin **216**. The bushing **214** is individually assembled on the drive shaft **12**, and held in place by a pin **216** inserted in the hole **217** in the bushing **214**. The pin extends through the shaft **12**, bushing **214** and into a slot **213** in the rigid cup **212**. The pin **216** provides precise axial location of the bushing **214**, and also transfers rotary torque from the shaft **12** to the rotating components of the valve. The rigid cup **212** can move along the axis of the shaft **12** and bushing **214** as the pin slides in the slot **213** and thus transmit compressive force to the rotor **20**, but the engagement of the pin in the slot **213** and in the shaft **12** ensures that rotary torque is transmitted from the shaft **12** to the rigid cup **212** and the rotor **20**. An external access port **222** (not shown) allows adjustment of compression without disassembly of the valve. Slots **221** in the threaded nut **218** allow adjustment of compression without disassembly of the valves. The adjustment is done by rotation of the shaft **12** while the threaded nut **218** is held fixed by a tool inserted through the access port **222**. The rigid cup **212** may attach to the drive shaft **12** through the joint allowing angulation of the rigid cup **212** in addition to axial movement of the rigid cup **212** while preventing relative motion of the rigid cup **212** and shaft **12** in rotation about an axis of the shaft **12**. It s also possible to construct an improved valve assembly that combines the switching of hot inlet and hot outlet flows in a single hot valve and the switching of cold inlet and cold outlet flows in a single cold valve, for which the driveshaft remains 'dry'. A detailed view of this improved dry shaft combined inlet and outlet valve assembly **280** is shown in FIG. **17**. Both the hot valve **28** and cold valve **24** are of similar construction. The hot valve **28** contains a stator **96** that is fixed in position and sealed against the valve housing **210**. Each outer circle port **32** in the stator is mated with a tube **205** protruding from the floor of the valve housing. Each inner circle port **94** in the stator is mated with a tube **295** protruding from the floor of the valve housing. Each tube has an o-ring seal **204** to the stator and an o-ring seal **284** to the housing **210**. The hot valve also contains a rotor **20** that rotates with the magnet **6** about the axis of the shaft **12**. The rotor **20** is centered by an o-ring **228** in a clearance **223** between the ID of the rotor **20** and the OD of an inner rotating assembly **201**, and is mounted to a rigid valve cup **212**. The drive shaft **12** passes coaxially through the inner assembly **201** that is connected to the rotor **20** and the compression assembly **230**. The compression assembly **230** is comprised of a threaded nut **218** that supports springs **220** that apply compression force against the rigid cup **212** and rotor **20**. External access ports **222** and slots **221** in the threaded nut **218** allow adjustment of compression without disassembly of the valves. The adjustment is done by rotation of the shaft **12** while the threaded nut **218** is held fixed by a tool inserted through the access port **222**. The centering action of the o-ring **228** in the clearance **223** and the application of axial force by the springs **220** keeps the rotor **20** sealed against the stator **96** even if the valve components were constructed with eccentricities or wear during operation. The inner rotatable assembly **201** has two commercial ceramic rotary face seals **202** and **282** mounted at each end to seal the fluid inside the valve body and prevent it from reaching the drive shaft **12**. In this way the driveshaft remains 'dry' and can be separated from the valve without breaking the seal in the bodies. This feature allows the hot inlet and outlet valves to be assembled, or removed and replaced without disturbing the cold inlet and outlet valves, or the bed and magnet assembly.

[0102] The shaft **12** may communicate with the rigid cup **212** by means of a special key **208** joining a key way and key seat on the shaft **12** and rigid cup **212**. The special key **208** is fitted into a slot of the driveshaft and mates with a slot in the inner bore of the inner rotatable assembly **201**. The key **208** provides torque transfer from the driveshaft **12** to the inner rotatable assembly **201**. The key **208** also provides precise axial position control of the inner rotatable assembly **201** relative to the driveshaft **12**. The shank of the key **208** is designed so that it fits flush in its slot (within the diameter of the shaft **12**). This allows the seal **202** to run adjacent to the key **208** without interference. The key **208** is co-threaded with the drive shaft **12**, so that its axial position is rigidly locked when the outer nut **209** is assembled. The key **208** rigidly couples the inner rotatable assembly **201** to the drive shaft **12**. This allows the position of the inner rotatable assembly **201** to be accurately determined. It also allows unbalanced compression forces on the opposing valve surfaces while maintaining correct axial positions. Removal of the valve assembly **28** from the shaft **12** can be accomplished by unscrewing the nut **224** from the shaft **12**, then sliding the housing **210** with the key **208** and the valve internal components along the shaft **12** in a direction away from the retaining ring **226**, with the tubes

205 and **295** sliding out of the o-rings **286** and **296**. The key **208** extends to an end of the shaft **12** to allow extraction of the key **208** in a first direction from a first end of the shaft **12** and extraction of the shaft **12** in a second direction opposite the first direction.

[0103] Bearings **102** and **104** are incorporated into the hot valve housing. This allows compact design, allows compression loading of the outer nut **209** against the outer bearing **102** and guarantees alignment in the valve body. The inner bearing **104** is seated against a retaining ring **226** that is attached to the shaft **12**.

[0104] The outer circle of tubes **205** connect to inlet ports **288** of the beds, and are sealed by o-rings **286**. The inner circle of tubes **295** connect to outlet ports **298** of the beds, and are sealed by o-rings **296**.

[0105] The cold valve **24** can use the same method of construction as the hot valve, as is shown in FIG. **17**. A motor **10** drives the rotation of the shaft **12**, which in turn drives the rotation of both the rotor **20** of the hot valve **28** and the rotor **18** of the cold valve **24**. The motor also drives the rotation of the magnet **6**. Alternately, the cold flows can be controlled by one-way valves in a manner similar to that shown in FIG. **8**.

[0106] An advantage of the flow configuration shown in FIG. **17** is that all of the tubes (such as **205** and **295**) carrying flow from the valves to the individual beds can be short and of equal length and shape. This feature of the tubes reduces pressure drop and aids in achieving uniform flow timing and distribution between the beds. The design configuration of FIG. **17** that combines the inlet and outlet valve functions in a single coaxial assembly will allow the construction of cooling units with a shorter overall length than that achievable with separate inlet and outlet valves in a coaxial assembly. The same advantage applies to the design configuration shown in FIG. **11**. A shorter length cooling unit is more easily incorporated in products that need to fit in locations with limited space.

[0107] Referring to FIGS. **6**, **17** and **18**, the shaft **12** may pass through a plenum receiving fluid from a valve and may be separated from the plenum by a rotary seal **202** or sleeve assembly. The rotary seal **202** may include a first and second sleeve portion over different axial portions of the shaft each portion including a sliding seal communicating with a corresponding sliding seal of the other portion allowing relative rotational movement of the first sleeve portion with respect to the second sleeve portion about the axis. The sliding seal may include a spring **306** biasing the first and second seal portion into engagement to prevent leakage therebetween.

[0108] FIG. **18** shows details of a rotary seal **202** that can he used in the dry shaft improved valve assemblies of FIG. **6** or **17**. The seal **202** contains of a fixed cup **302** that is glued to the fixed end plate **310** (FIG. **6**) of the valve. The fixed cup **302** is also connected by a bellows seal **307** and spring **306** to a fixed seal ring **304**. The fixed seal ring **304** engages and seals with a rotating seal ring **308** that is sealed to a rotary seal gasket **312** that seals against the rotating assembly **201** (FIG. **6**) of the valve. This sealing arrangement keeps fluid inside the valve from leaking from the interior of the valve body or reaching the dry shaft **12** (FIG. **6**) of the valve. The seal **282** of FIG. **17** is of identical construction to seal **202**.

[0109] The magnet assemblies shown in the above embodiments are a single lobe design, with one high field region, and an opposite low field region. However, it may be advantageous to employ magnet assemblies with multiple high field regions and multiple low field regions. For such cases, coaxial disk valves could be implemented with additional slots that direct cold to hot flow simultaneously to beds in multiple high field regions, and direct hot to cold flow simultaneously to beds in multiple low field regions.

[0110] By placing the valves in rotational sliding communication and coaxially with the main drive shaft, the need for connecting belts and pulleys between this shaft and the valve shafts is eliminated. These belts and pulleys waste energy provided by the motor, so their elimination improves the energy-efficiency of the MR system. The belts and pulleys take up space, so their elimination also results in a smaller, more compact system.

[0111] Moreover, the coaxial valve placement reduces the length of the fluid conduits (commonly called pipes) connecting the valves and the fixed beds. Note that this invention allows the use of separate inlet and outlet pipes on both the cold and hot sides for each bed. By using separate inlet and outlet pipes with unidirectional flow in each pipe, all the fluid that enters the pipe eventually will reach the destination bed or destination heat exchanger. Thus the fluid contained in the pipes will contribute to the operation of the AMR cycle and not represent “dead volume”. However, even with separate inlet and outlet pipes, the shorter pipe lengths possible with the coaxial valves still offer two advantages. First, the shorter length reduces the pressure drop experienced by the fluid as it flows through the pipe through the conduit, that is, the fluid resistance of the pipe to steady flow is reduced. This reduces the load on the pump and further improves the energy efficiency of the system. Second, the shorter pipe lengths reduce the magnitude of bypass flow, a phenomenon in which fluid bypasses the beds and proceeds directly from the hot inlet valve to the hot outlet valve. Bypass flow does not contribute to refrigeration and therefore wastes energy provided by the pump; its reduction therefore improves the energy efficiency of the MR system.

[0112] Bypass flow is caused, in part, by periodic expansion of a deformable plumbing element under pressurization, followed by fluid expulsion under depressurization, a form of fluid capacitance for the plumbing element. To explain this bypass flow mechanism, we refer to FIG. **2**. The hot inlet fluid is at the highest pressure in the fluid circuit. Under this pressure, the pipe **64*b*** connecting the hot inlet valve **22** to the hot inlet port **42** of the demagnetized bed **4** will expand slightly, storing some fluid that would otherwise pass through the bed **4**. After the cold blow is completed, the Hi and Co valves **22**, **24** seal off the hot inlet pipe **64*b*** of this bed **2**, preventing the stored fluid from leaving the hot inlet pipe **64*b***. When the valves rotate for the hot blow, the hot outlet pipe **82*b*** connected to the bed **4** can now carry flow, so the pressurized fluid stored in the hot inlet pipe **64*b*** can be expelled through the hot outlet pipe **82*b*** and into the hot outlet valve **28**, allowing the hot inlet pipe **64*b*** to return to its original shape. This cyclical process of pressurization, expansion, and fluid storage during the cold blow, followed by fluid expulsion and depressurization during the following hot blow, produces bypass flow. The amount of fluid that can be stored during the cold blow increases with the length of pipe connecting the hot inlet valve to the hot inlet port of a bed. The coaxial valve placement minimizes this conduit length, minimizing the increase in fluid volume during pressurization, thus minimizing bypass flow and improving system performance. For best operation of an AMR system, the change in internal fluid volume of a conduit to a bed when subjected to the increase from the minimum to the maximum fluid pressures during the

AMR cycle should be less than 5% of the total fluid volume delivered to a single bed during the time interval in one AMR cycle that the conduit pair is delivering flow to that bed.

[0113] An additional advantage of the coaxial valve arrangement is that it allows the conduits of a similar flow function connecting the beds to the valves to be symmetrically placed around the shaft axis and to be of identical shape and length. There are four flow functions for conduits connecting the beds to the valves: hot inlet, hot outlet, cold inlet, and cold outlet. Two pipes that each conduct hot inlet flow both have a similar function, although they might be connected to different beds. For an example of symmetrical placement and identical shape, in FIG. **2**, if the two beds **2** and **4** shown in the figure are located at a 180 degree rotational angle from each other around the axis of the shaft **12**, and the ports **38***a* and **38***b* in the cold inlet valve are also located at a 180 degree angle from each other around the same axis, then the two cold inlet pipes **72***a* and **72***b* can be identical components of identical shape and length, but mounted at a 180 degree angle from each other around the axis of the shaft **12**. In addition to saving fabrication cost, the identical shape and length of conduits of a similar flow function ensures that the resistance of the conduits to steady flow will be equal. In addition, if the conduits of a similar flow function are of identical shape and length and wall thickness, then the conduits of similar function will have equal change in internal fluid volume when subjected to the increase from the minimum to the maximum fluid pressures during the AMR cycle. Finally, if the conduits of a similar flow function have the same internal cross section as well as identical shape and length, the conduits will have equal internal fluid volume, the mass of fluid stored in the conduits will be identical, and thus the dynamic pressure drop needed to accelerate fluid flow at the start of the fluid blow will be equal. The equivalent characteristics of conduits of a similar flow function thus ensure that the pressure drop due to flow friction, and the flow transient effects due to conduit expansion and fluid inertia, will be identical for all the beds. This helps ensure that all the beds get similar flow versus time profiles during an AMR cycle, which can improve efficiency and temperature span.

[0114] The flow from the hot outlet valve to the pump in the first three embodiments (FIGS. **2**, **4**, and **5**) only occurs in one direction, from the valve to the pump, and is thus unidirectional flow.

[0115] Although this invention enables conduits of a similar flow function to be of equal length, conduits of dissimilar flow function, such as hot outlet and hot inlet, may be of different length.

[0116] The flow from an outlet valve to the pump in the embodiments described above only occurs in one direction, from the valve to the pump, and is thus unidirectional flow. This means that the fluid contained in the pipe **84** between the hot outlet valve **28** and the pump **30** in FIG. **2**, for example, does not contribute to dead volume losses, and thus the pump **30** can be located outside the coaxial valve and bed assembly. This allows the use of any convenient type of pump. In particular, positive displacement pumps, such as gear pumps, screw pumps, piston pumps, diaphragm pumps, rotary vane pumps and scroll pumps can be used. Positive displacement pumps produce a flow that is nearly constant over a wide range of operating pressures. The use of a positive displacement pump allows the flow rate to quickly reach intended levels as the flow is switched between different AMR beds. In addition, efficient positive displacement pumps can be made over a wide range of flow capacity and pressure capacity, while centrifugal pumps, a common form of non-positive displacement pump, are only efficient at relatively large flow capacity or low pressure capacity. Efficient heat transfer in AMR beds requires a large internal heat transfer area, which tends to lead to high operating pressures, which are not well suited to efficient operation of centrifugal pumps for small to medium scale systems.

[0117] If hot to cold flow or cold to hot flow occurs to only one bed at a time, the use of a positive displacement pump may require either precise valve timing to ensure flow is not blocked for a period of time, or alternately, the use of a fluid accumulator at the pump outlet.

[0118] Although the description of the present invention above has been based on the use of rotary disk valves, it is clear that other valve types that also rely on rotary motion to open and close desired fluid paths could be used and fall within the scope of the present invention.

[0119] Certain terminology is used herein for purposes of reference only, and thus is not intended to be limiting. For example, terms such as “upper”, “lower”, “above”, and “below” refer to directions in the drawings to which reference is made. Terms such as “front”, “back”, “rear”, “bottom” and “side”, describe the orientation of portions of the component within a consistent but arbitrary frame of reference which is made clear by reference to the text and the associated drawings describing the component under discussion. Such terminology may include the words specifically mentioned above, derivatives thereof, and words of similar import. Similarly, the terms “first”, “second” and other such numerical terms referring to structures do not imply a sequence or order unless clearly indicated by the context.

[0120] When introducing elements or features of the present disclosure and the exemplary embodiments, the articles “a”, “an”, “the” and “said” are intended to mean that there are one or more of such elements or features. The terms “comprising”, “including” and “having” are intended to be inclusive and mean that there may be additional elements or features other than those specifically noted. It is further to be understood that the method steps, processes, and operations described herein are not to be construed as necessarily requiring their performance in the particular order discussed or illustrated, unless specifically identified as an order of performance. It is also to be understood that additional or alternative steps may be employed.

[0121] It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein and the claims should be understood to include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims. All of the publications described herein, including patents and non-patent publications, are hereby incorporated herein by reference in their entireties.

We claim:

1. An active magnetic regenerative refrigerator (AMR) apparatus, comprising:

a first AMR bed with a first end and a second end;

a first heat exchanger (HEX) with an inlet and an outlet;

a shaft rotatable along an axis;

a magnet attached to the shaft to apply a time-varying magnetic field to the first AMR bed with rotation of the shaft;

a first valve switchably connecting the outlet of the first HEX to the first end of the AMR bed for fluid flow therebetween when the field on the first AMR bed is in a low state relatively removed from the magnet;

a second valve switchably connecting the inlet of the first HEX to the first end of the AMR bed for fluid flow therebetween when the field on the first AMR bed is in a high state relatively proximate to the magnet; and

wherein the first and second valves include:

(a) at least one pair of valve plates in rotational sliding communication and positioned coaxially about the shaft, wherein a first valve plate is attached to rotate with the shaft with respect to the second valve plate, the valve plates including valve ports that move into alignment and out of alignment to allow fluid flow through the valve ports when in alignment and to block fluid flow through the valve ports when out of alignment, wherein at least one of the valve plates is mounted for movement along the axis of the shaft with respect to another of the valve plates; and

(b) a spring-like object urging the valve plates axially into contact with each other.

2. The AMR apparatus of claim **1** wherein the spring-like object is a compression spring positioned between a spring support and a contacted valve plate of the valve plates and wherein the position of the spring support is adjustable to control a force of the spring on the contacted valve plate.

3. The AMR apparatus of claim **2** wherein the valve plates are held within a plenum receiving a fluid controlled by the valve and where in the spring support is adjustable by rotation on a threaded element coaxial about the shaft and wherein the plenum includes a sealable opening allowing access to the spring support for rotation of the spring support with respect to the threaded element to move the spring support axially along the shaft.

4. The AMR apparatus of claim **2** wherein the first valve plate attaches to the shaft through a joint allowing angulation of the first valve plate in addition to axial movement of the first valve plate while preventing relative motion of the valve plate and shaft in rotation about an axis of the shaft.

5. The AMR apparatus of claim **4** wherein the joint provides an interengaging axial slot and radial pin.

6. The AMR apparatus of claim **1** wherein the shaft communicates with the first valve plate by means of a key joining a key way and key seat on the shaft and valve plate wherein the key extends to an end of the shaft to allow extraction of the key in a first direction from a first end of the shaft and extraction of the shaft in a second direction opposite the first direction.

7. The AMR apparatus of claim **1** wherein the shaft passes through a plenum receiving fluid from a valve and is separated from the plenum by a sleeve assembly.

8. The AMR apparatus of claim **7** wherein the sleeve assembly includes a first and second sleeve portion over different axial portions of the shaft each portion including a sliding seal communicating with a corresponding sliding seal of the other portion allowing relative rotational movement of the first sleeve portion with respect to the second sleeve portion about the axis.

9. The AMR apparatus of claim **8** wherein the sliding seal includes a spring biasing the first and second seal portion into engagement to prevent leakage therebetween.

10. The AMR apparatus of claim **1** wherein the first and second valves comprise one pair of valve plates in rotational sliding communication and positioned coaxially on the rotatable shaft.

11. The AMR apparatus of claim **10** wherein the valve plates cooperate to in a first position present a passage of fluid to a first plenum communicating with an outer periphery of at least one valve plate and in a second position to present a fluid passage to a fluid and a second plenum separated from the first plenum communicating with an inner periphery of at least one valve plate.

12. The AMR apparatus of claim **1** further including a second heat exchanger (HEX) with an inlet and outlet:

including a third valve that fluidly connects the inlet of the second HEX to the second end of the AMR bed when the field on the first AMR bed is in a low state;

a fourth valve that fluidly connects the outlet of the second HEX to the second end of the AMR bed when the field on the first AMR bed is in a high state.

13. The AMR apparatus of claim **12** wherein the third and fourth valves are check valves.

14. The AMR apparatus of claim **1** wherein at least one valve plate is a carbon material.

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