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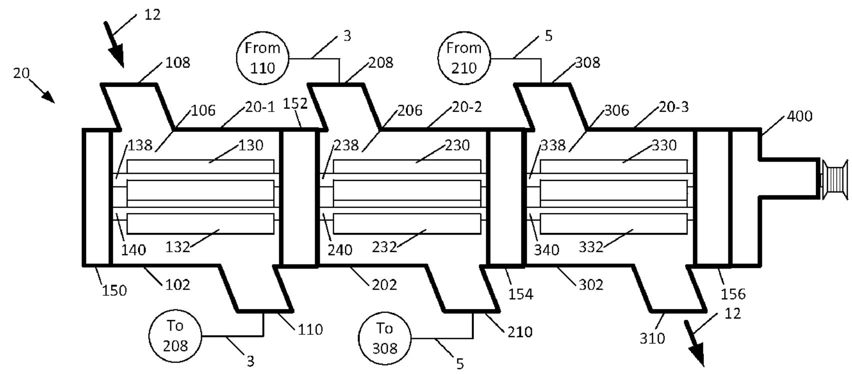
[Continued on next page]

(54) Title: MULTI-STAGE VOLUMETRIC FLUID EXPANSION DEVICE

FIG. 2



(57) **Abstract**: A multi-stage expansion device is disclosed. In one embodiment, the multi-stage expansion device has a housing within which a first stage, a second stage, and a third stage are housed. The housing may also be configured with internal working fluid passageways to direct a working fluid from the first stage to the second stage and/or from the second stage to the third stage. Each of the stages may include a pair of non-contacting rotors that are mechanically connected to each other and to a power output device such that energy extracted from the working fluid is converted to mechanical work at the output device. In one embodiment, a step up gear arrangement is provided between the rotors of the first and second stages. A step up gear arrangement may also be provided between the rotors of the second and third stage.

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MULTI-STAGE VOLUMETRIC FLUID EXPANSION DEVICE

RELATED APPLICATIONS

[0001] This application is being filed on 27 January 2014, as a PCT International Patent Application and claims priority to U.S. Patent Application Serial Number 61/757,533 filed on 28 January 2013, claims priority to U.S. Patent Application Serial Number 61/810,579 filed on 10 April, 2013, and claims priority to U.S. Patent Application Serial Number 61/816,143 filed on 25 April 2013. Each of applications 61/757,533, 61/810,579 and 61/816,143 are incorporated herein by reference in its entirety.

GOVERNMENT LICENSE RIGHTS

[0002] This invention was made with government support under Contract No. DE-EE0005650 awarded by the National Energy Technology Laboratory funded by the Office of Energy Efficiency & Renewable Energy of the United States Department of Energy. The government has certain rights in the invention

TECHNICAL FIELD

[0003] This present disclosure relates to volumetric fluid expansion devices that convert waste energy from a power plant to useful work for the purposes of increasing power plant efficiency.

BACKGROUND

[0004] Waste heat energy is necessarily produced in many processes that generate energy or convert energy into useful work, such as a power plant. Typically, such waste heat energy is released into the ambient environment. In one application, waste heat energy is generated from an internal combustion engine. Exhaust gases from the engine have a high temperature and pressure and are typically discharged into the ambient environment without any energy recovery process. Alternatively, some approaches have been introduced to recover waste energy and re-use the recovered energy in the same process or in separate processes. However, there is still demand for enhancing the efficiency of energy recovery.

SUMMARY

[0005] In one aspect of the disclosure, a multi-stage volumetric fluid expansion device is provided to generate useful work by expanding a working fluid. In one application, the volumetric fluid expansion device can be utilized to recover waste energy from a power plant, such as waste heat energy from a fuel cell or an internal combustion engine. The power plant may be provided in a vehicle or may be provided in a stationary application, such as a generator application.

[0006] The multi-stage volumetric fluid expansion device may be provides as part of a system for generating mechanical work via a closed-loop Rankine cycle. Such a system may also include a power plant that produces a waste heat stream, wherein the power plant has a waste heat outlet through which the waste heat stream exits and at least one heat exchanger in fluid communication with the waste heat stream. In operation, the heat exchanger heats the working fluid. The multi-stage fluid expansion device can be configured to generate mechanical work at an output device from the working fluid and be provided with a housing within which a first stage, a second stage, and a third stage are disposed. The first, second, and third stages can be configured to sequentially expand the working fluid and product mechanical work at the output device. A condenser may also be provided to partially or fully condense the working fluid while a pump may be provided to pump the condensed working fluid back to the heat exchanger.

[0007] The multi-stage expansion device first stage may include a first pair of non-contacting rotors disposed between a first inlet and a first outlet while the second stage may include a second pair of non-contacting rotors disposed between a second inlet and a second outlet. The third fluid expansion stage may include a third pair of non-contacting rotors disposed between a third inlet and a third outlet. In one aspect, the power output device is rotated by the first, second, and second third of rotors. In one embodiment, the second outlet and third inlet are joined within the housing to form a continuous working fluid passageway extending between the second inlet and the third outlet. In one embodiment, the first outlet and the second inlet are joined within the housing to form a continuous working fluid passageway extending between the first inlet and the third outlet.

[0008] In one aspect, the output device is mechanically coupled to the third stage, the second stage is mechanically coupled to the third stage, and the first stage is mechanically coupled to the second stage such that power developed by each of the first, second, and third stages is transmitted to the power output device. In one embodiment, a first step up gear arrangement provided between the first and second stages such that a first pair of rotors associated with the first stage rotate at a lower speed than a second pair of rotors associated with the second stage. Alternatively, the first and second pair of rotors can be mounted to a pair of common shafts. In one embodiment, a second step up gear arrangement is provided between the second and third stages such that the second pair of rotors rotate at a lower speed than a third pair of rotors associated with the third stage. Alternatively, the second and third pair of rotors can be mounted to a pair of common shafts. A step down gear arrangement may also be provided between the third stage and the power output device such that third pair of rotors rotate at a greater speed than the power output device. In one embodiment, the power output device is provided with a clutch to selectively engage and disengage the third stage from the power output device.

[0009] In one embodiment, the first pair of rotors have twisted non-contacting lobes, wherein one of the first pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the first pair of rotors. The second and third pairs of rotors may be similarly configured.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 is a cross-sectional side view of a vehicle having a volumetric fluid expansion device having features that are examples of aspects in accordance with the principles of the present disclosure.

[0011] Figure 2 is a schematic view of a first example of the volumetric fluid expansion device shown in Figure 1.

[0012] Figure 3 is a schematic view of a second example of the volumetric fluid expansion device shown in Figure 1.

[0013] Figure 4 is a schematic view of a third example of the volumetric fluid expansion device shown in Figure 1.

[0014] Figure 5 is a schematic view of a first example of a drivetrain arrangement suitable for use in the volumetric fluid expansion device shown in Figure 1.

[0015] Figure 6 is a schematic view of a second example of a drivetrain arrangement suitable for use in the volumetric fluid expansion device shown in Figure 1.

[0016] Figure 7 is a schematic view of a third example of a drivetrain arrangement suitable for use in the volumetric fluid expansion device shown in Figure 1.

[0017] Figure 8 is a perspective view of a rotor suitable for use in the volumetric fluid expansion device shown in Figure 1.

[0018] Figure 9 is a schematic end view of a stage inlet of the fluid expansion device shown in Figure 1.

[0019] Figure 10 is a schematic side view of a stage inlet of the fluid expansion device shown in Figure 1.

[0020] Figure 11 is a schematic showing geometric parameters of the rotors of the fluid expansion device shown in Figure 1.

[0021] Figure 12 is a schematic showing an example fluid expansion device in an organic Rankine cycle system having features that are examples of aspects in accordance with the principles of the present disclosure.

[0022] Figure 13 is a perspective view of the fluid expansion device shown in Figure 12.

[0023] Figure 14 is a perspective view of the drivetrain of the fluid expansion device shown in Figure 12.

[0024] Figure 15 is a cross-sectional side view of the fluid expansion device shown in Figure 12.

[0025] Figure 16 is a cross-sectional top view of the fluid expansion device shown in Figure 12.

[0026] Figure 17 is an end view of the first expansion stage of the fluid expansion device shown in Figure 12.

[0027] Figure 18 is an end view of the second expansion stage of the fluid expansion device shown in Figure 12.

[0028] Figure 19 is a schematic showing an example fluid expansion device in an organic Rankine cycle system having features that are examples of aspects in accordance with the principles of the present disclosure.

[0029] Figure 20 is a perspective view of the fluid expansion device shown in Figure 19.

[0030] Figure 21 is a perspective view of the drivetrain of the fluid expansion device shown in Figure 19.

[0031] Figure 22 is a cross-sectional side view of the fluid expansion device shown in Figure 19.

[0032] Figure 23 is a cross-sectional top view of the fluid expansion device shown in Figure 19.

[0033] Figure 24 is an end view of the second expansion stage of the fluid expansion device shown in Figure 19.

[0034] Figure 25 is an end view of the first expansion stage of the fluid expansion device shown in Figure 19.

[0035] Figure 26 is a perspective view of an example fluid expansion device having features that are examples of aspects in accordance with the principles of the present disclosure.

[0036] Figure 27 is a perspective view of the drivetrain of the fluid expansion device shown in Figure 23.

[0037] Figure 28 is a schematic view of a first example of a parallel drive volumetric fluid expansion device usable in the system shown in Figure 1.

[0038] Figure 29 is a schematic view of a second example of a parallel drive volumetric fluid expansion device usable in the system shown in Figure 1.

[0039] Figure 30 is a schematic view of a third example of a parallel drive volumetric fluid expansion device usable in the system shown in Figure 1.

[0040] Figure 31 is a schematic view of a fourth example of a parallel drive volumetric fluid expansion device usable in the system shown in Figure 1.

DETAILED DESCRIPTION

[0041] Various embodiments will be described in detail with reference to the drawings, wherein like reference numerals represent like parts and assemblies throughout the several views. Reference to various embodiments does not limit the scope of the claims attached hereto. Additionally, any examples set forth in this specification are not intended to be limiting and merely set forth some of the many possible embodiments for the appended claims. Referring to the drawings wherein like reference numbers correspond to like or similar components throughout the several figures.

[0042] Modern demands for fuel efficient vehicles and power plants have led to development of hybrid power-generation and propulsion systems. Generally, such systems combine a power-plant, such as an internal combustion engine or a fuel cell, and an electric motor to drive the vehicle. Each of the internal combustion engine and fuel cell emits high temperature exhaust as a byproduct of the power-generation cycle employed therein. The high temperature exhaust constitutes energy that is lost from the power-generation cycle, which, if recaptured, could be employed to improve efficiency of the cycle, and, therefore, of the propulsion system employing the same. Improvements in other applications are also desired, for example in marine agricultural and industries. Another example is stationary generator sets.

[0043] Referring to Figure 1, a vehicle 10 is shown having wheels 12 for movement along an appropriate road surface. The vehicle 10 includes a power-generation system 14. The system 14 includes a power-plant 16 employing a power-generation cycle. The power-plant 16 uses a specified amount of oxygen, which may be part of a stream of intake air, to generate power. The power-plant 16 also generates waste heat such in the form of a high-temperature exhaust gas in exhaust line 17 a byproduct of the power-generation cycle. In one embodiment, the power-plant 16 is an internal combustion (IC) engine, such as a spark-ignition or compression-ignition type which combusts a mixture of fuel and air to generate power. In one embodiment, the power-plant 16 may be or a fuel cell which converts chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent.

[0044] The vehicle 10 may also include an energy recovery device, for example volumetric fluid expansion device 20, which recovers waste heat from the power-plant 16 to improve the efficiency of the power-plant 16. In one aspect, the volumetric fluid expansion device 20 is a multi-stage fluid expansion device 20.

[0045] In one embodiment, and as shown in Figure 1, an organic Rankine cycle (ORC) is used to power the fluid expansion device 20. In such an embodiment, a piping system 1000 including a heat exchanger 18 is provided that transfers heat from the exhaust gas line 17 to a working fluid 12 that is then delivered to the volumetric fluid expansion device 20. The working fluid 12 may be a solvent such as ethanol, n-pentane, or toluene. A condenser 19 is also provided which creates a low pressure zone for the working fluid 12 and thereby provides a location for the working fluid 12 to condense. Once condensed, the working fluid 12 can be delivered to the heat exchanger 18 via a pump 17. A more detailed description of an ORC system being utilized to drive an energy recovery device 20 is provided in Patent Cooperation Treaty (PCT) International Application Publication Number WO 2013/130774 entitled VOLUMETRIC ENERGY RECOVERY DEVICE AND SYSTEMS. WO 2013/130774 is hereby incorporated herein by reference in its entirety. Additional ORC systems are disclosed in this application, as well as in a PCT Application (serial number unknown) entitled VOLUMETRIC ENERGY RECOVERY SYSTEM WITH THREE STAGE EXPANSION (Attorney Docket 15720.0275WOU1 / 13-rSPR-222 VTI) being filed concurrently with this application, the entirety of which is incorporated by reference herein. The volumetric fluid expansion device 20 may also be utilized in a direct exhaust gas heat recovery process wherein the exhaust gas is the working fluid 12, as disclosed in Patent Cooperation Treaty (PCT) International Application Number PCT/US2013/078037 entitled EXHAUST GAS ENERGY RECOVERY SYSTEM. PCT/US2013/078037 is herein incorporated by reference in its entirety.

Housing and Working Fluid Passageway Configurations

[0046] Referring to Figures 2-4, schematic representations of examples of multi-stage volumetric fluid expansion device 20 in accordance with the disclosure are presented. As shown, the multi-stage volumetric fluid expansion device 20 includes a first stage 20-1, a second stage 20-2, and a third stage 20-3. It should be understood that although three stages is shown, the device could be provided with fewer stages, such as two stages, or more stages, such as four, five, six, or more stages. In generalized terms, each of the stages 20-1, 20-2, 20-3 is or can be placed in fluid communication with the other such that the working fluid 12 passes sequentially through the stages 20-1, 20-2, 20-3 where energy from the fluid is transferred to useful work. The fluid expansion device 20 may also include a power output device 400 configured to transfer useful work from the stages 20-1, 20-2, 20-3 to a power input location of the vehicle 10 or power plant 16.

[0047] As shown, the first stage 20-1 includes a main housing 102 that defines a first working fluid passageway 106 extending between a first inlet 108 and a first outlet 110. Similarly, the second stage 20-2 includes a main housing 202 defining a working fluid passageway 206 extending between a second inlet 208 and a second outlet 210 while the third stage 20-3 has a main housing 302 defining a working fluid passageway 306 extending between a third inlet 308 and a third outlet 306. The fluid expansion device 20 can also be provided with compartments 150, 152, 154, and 156 to house bearings, timing gears, and/or step gears, as discussed later. The compartments 152 and 154 are configured to provide a boundary between the working fluid pathways 106/206 and 206/306 so as to prevent the working fluid 12 from bypassing from the first stage 20-1 to the second stage 20-2 and from the second stage 20-2 to the third stage 20-3 outside of the defined working fluid pathways 106, 206, 306.

[0048] Disposed within each of the working fluid passageways 106, 206, 306 is a pair of meshed rotors 130/132, 230/232, and 330/332, respectively. Each pair of meshed rotors 130/132, 230/232, and 330/332 is configured such that the rotors are overlapping and rotate synchronously in opposite directions. As the working fluid 12 passes through the inlet 108, 208, 308, across the meshed rotors 130/132, 230/232, 330/332, and to the respective outlet 110, 210, 310, the working fluid 12 undergoes a pressure drop which imparts rotational movement onto the rotors, thus creating mechanical work that can be input back into the power plant 16. Accordingly, each inlet port 108, 208, 308 is configured to admit the working fluid 12 at an entering pressure whereas the corresponding outlet port 110, 210, 310 is configured to discharge the working fluid 12 at a leaving pressure lower than the entering pressure. In such a configuration, the working fluid 12 enters inlet 108 at a first pressure and leaves outlet 110 and enters inlet 208 at a second pressure lower than the first. The working fluid then exits outlet 210 and enters inlet 308 at a third pressure lower than the second and subsequently exits outlet 310 at a fourth pressure lower than the third. In one embodiment, the pressure drop from the first inlet 108 to the third outlet 310 is about 10 bar wherein the pressure drop between the first inlet and the first outlet is about 5 bar, the pressure drop between the second inlet 208 and the second outlet 210 is about 3 bar, and the pressure drop between the third inlet 308 and the third outlet 310 is about 2 bar.

[0049] With reference to the example embodiment shown in Figure 2, each of the inlets 108, 208, 308 and each of the outlets 110, 210, 310 are shown as being completely separated. In this configuration, the second inlet 208 can be placed in fluid communication with the first outlet 110 while the third inlet 308 can be placed in fluid communication with the second outlet 210 via external piping 3, 5 to define a continuous internal working fluid passageway 106, 206, 306 extending through the housings 102, 202, 203. In such a configuration, the external flow paths provided by piping 3, 5 allow for the opportunity to route the working fluid 12 leaving the first stage 20-1 and/or the working fluid 12 leaving the second stage 20-2 through one or more heat exchangers 102 (or other equipment) before being directed into the inlet 208 of the second stage 20-2 or the inlet 308 of the third stage 20-3.

[0050] With reference to the example embodiment shown in Figure 3, and similar to the configuration shown at Figure 2, the first stage 108 is provided with a separated inlet 108 and a separated outlet 110. However, the housings 202, 302 of the second and third stages 20-2, 20-3 in this example are combined such that the outlet 210 of the second stage 20-2 is internally connected with the inlet 308 of the third stage 20-3. In this configuration, the second inlet 208 can be placed in fluid communication with the first outlet 110 via external piping 3 to define a continuous internal working fluid passageway 106, 206, 306 extending through the housings 102, 202, 203. In such a configuration, the external flow path provided by piping 3 allows for the opportunity to route the working fluid 12 leaving the first stage 20-1 through one or more heat exchangers 102 (or other equipment) before being directed into the inlet 208 of the second stage 20-2. As the working fluid 12 enters the second stage 20-2, at the second inlet 208, the working fluid 12 stays internal to the fluid expansion device 20 until reaching the third outlet 310. By creating an internal working fluid passageway 206/306 between the second outlet 210 and third inlet 308, potential leak paths for working fluid steam are reduced, packaging complexity is reduced, and pressure drop losses are minimized.

[0051] With reference to the example embodiment shown in Figure 4, and similar to the configuration shown at Figure 3, the second outlet 210 and the third inlet 208 are configured as a common internal working fluid passageway. However, the housings 102, 202 of the first and second stages 20-2, 20-3 in this example are also configured such that the outlet 110 of the first stage 20-1 is internally connected with the inlet 208 of the second stage 20-2 to form an internal passageway. In this configuration, as the working fluid 12 enters the first stage 20-1, at the first inlet 108, the working fluid 12 stays entirely internal to the fluid expansion device 20 until reaching the third outlet 310. By creating an entirely internal working fluid passageway 106/206/306 between the first inlet 108 and the third outlet 310, the potential leak paths for working fluid are even further reduced, which in turn also reduces pressure drop losses and packaging complexity.

Drivetrain Configurations

[0052] As shown, each of the rotors 130, 132, 230, 232, 330, and 332 (collectively referred to as rotors 30, 32), is attached to a respective rotor shaft 138, 140, 238, 240, 338, and 340 (collectively referred to as rotor shafts 38, 40). The rotor shafts 38, 40 are rigidly connected to the rotors 30, 32 and thus rotate as the rotors are rotated. The rotor shafts 138, 238, 338 can be individual separate shafts or form part of a common shaft 38. Likewise, rotor shafts 140, 240, and 340 can be individual separate shafts or form part of a common shaft 38.

[0053] Figure 5 shows an example drivetrain configuration for a three stage fluid expansion device 20 in which shafts 138, 238, 338 are portions of a common singular shaft 38 such that rotors 130, 230, and 330 are mounted to the same shaft 38 and all rotate together in the same direction. Similarly, shafts 140, 240, 340 are portions of a common singular shaft 40 such that rotors 130, 230, and 330 are mounted to the same shaft 40 and all rotate together in the same direction that is the opposite direction of rotation for shaft

38. In this arrangement, rotational energy from the working fluid 12 is imparted onto the same shafts 38, 40 (via the rotors) as the working fluid 12 passes through each stage 20-1, 20-2, 20-3.

[0054] In the example shown at Figure 5, bearings 260, 262 are provided in compartment 152 while bearings 360, 362 are provided in compartment 156. The bearings 260, 360 are configured to rotationally support shaft 38 while bearings 262, 362 are configured to rotationally support shaft 40. If desired, additional bearings may be provided in compartment 150 and/or compartment 154.

[0055] The compartment 156 is also provided with a pair of timing gears 348 and 342, wherein the timing gear 348 is fixed for rotation with the shaft portion 338 and the timing gear 342 is fixed for rotation with the shaft portion 340. This configuration allows the rotors 30 and 32 to rotate in opposite directions in an overlapping and synchronized manner. The timing gears 348, 342 are also configured to precisely maintain the relative position of the rotors 30, 32 such that contact between the rotors is entirely prevented between the rotors 30, 32 which could cause extensive damage to the rotors 30, 32. Rather, a close tolerance between the rotors 30, 32 is maintained during rotation by the timing gears 348, 342. As the rotors 30, 32 are non-contacting, a lubricant in the fluid 12 is not required for operation of the expansion device 20, in contrast to typical rotary screw devices and other similarly configured rotating equipment having rotor lobes that contact each other. As the rotors are all connected to a common shaft, it is noted that timing gears 348, 342 could be alternatively mounted to the shaft in any of the compartments 150, 152, 154, and 156 with the same effect. The timing gears 348, 342 also operate such that rotational energy developed at shaft portion 338 can be transferred to shaft portion 340 and vice-versa. Accordingly, either shaft portion 338 or 340 may serve as an output shaft for the fluid expansion device 20.

[0056] As shown, a power output device 400 is provided to receive shaft portion 340 such that all rotational energy from the fluid expansion device 20 can be transferred to the power output device 400. As constructed, the power output device 400 is provided with an input gear 402 that is intermeshed with and is driven by a drive gear 344 fixed onto the shaft portion 340. In the embodiment shown, the drive gear 344 has a smaller diameter (i.e. fewer teeth) than the input gear 402. This configuration results in the drive gear 344 acting as a step down gear in which the input gear 402 is rotating at a lower speed than the drive gear 344. In one embodiment, the gear ratio is between about 0.25:1 and about 3:1, and more preferably between about 0.5:1 and about 2:1. The drive gear 344 and input gear 402 can be configured for a step up operation as well. It is also noted that the rotational direction of the output shaft 404 and output device 412 is opposite to the rotational direction of the shaft portion 340. Although not shown, it should be understood that bearings can be provided in power output device 400 to support output shafts 404 and 410, in addition to shaft 340, if desired.

[0057] The input gear 402 is fixed to an output shaft 404 that is in turn connected to a clutch assembly 406. The clutch assembly 406 is also connected to an output shaft 410 onto which an output device 412, for example a belt pulley, is mounted. The output device 412 (or the shaft portion 340) may be connected to the drivetrain of the power plant 16, for example by a belt, such that power developed by the fluid expansion device 20 can be input directly back into the power plant 16. Alternatively, the output device 412 (or the shaft portion 340) can be connected to a hydraulic pump or a generator such that energy can be respectively stored in an accumulator or battery. In operation, the clutch assembly 406 allows for output shafts 404 and 410 to be coupled and decoupled such that developed power from the fluid expansion device 20 is selectively allowed or prevented from being transmitted to the output device 412. When the clutch assembly 408 decouples the output device 412 from the output shaft 404, the fluid expansion device 20 is prevented from becoming a parasitic drag on the power plant 16 when the fluid expansion device 20 is not developing sufficient power, as may be the case at low engine idling speeds. In one embodiment, the clutch assembly 408 is an electromagnetic clutch assembly of the type disclosed in U.S. Patent 8,464,697 granted on June 18, 2013, the entirety of which is incorporated by reference herein.

[0058] In another embodiment, shafts 238 and 338 are portions of a common singular shaft 38 while shaft 138 is a separate shaft, wherein the shafts 38 and 138 are coupled by a gear set. The gear set can be configured to allow the shafts 38a, 138 to rotate at the same speed, at different speeds (with a step up or step down gear), and/or in opposite directions. In another embodiment, all three shafts 138, 238, and 338 are separate shafts that are coupled together by intermediate gear sets that allow for each shaft to be rotated at the same or different speeds and/or in an opposite direction. These variations apply equally for the shafts 140, 240, and 340. The shafts 38, 40 may also be supported by bearings at their ends and/or at intermediate points along the shafts 38, 40.

[0059] Figure 6 shows an example drivetrain that is similar in many respects to that shown in Figure 5. However, the example of Figure 6 is different in that the third stage is provided with independent shafts 338, 340 and in that the first and second stages 20-1, 20-2 share common shafts 38, 40. In this example, the common shaft 38 is formed by shaft portions 138 and 238 and is supported by bearings 160, 260 in compartments 152, 154, respectively. Similarly, the common shaft 40 is formed by shaft portions 140, 240 and is supported by bearings 162, 262. As shafts 338, 340 are independent shafts in this example; shaft 338 is supported by bearings 360, 364 while shaft 340 is supported by bearings 362, 366. With respect to compartment 154, timing gears 248, 242 are mounted to shaft portions 238, 240 respectively to fix the rotational relationship between the rotors 130/230 and the rotors 132/232, and operate in the same manner as already described for timing gears 348, 342. It is noted that bearings could be provided in compartment 152 in addition to or instead of bearings be provided in one of compartments 150, 154.

[0060] Also connected to the shaft portion 238 is a drive gear 244 that is intermeshed with and drives an input gear 346 fixed onto the shaft portion 338. In operation, the drive gear 244 and input gear 346 allow the power developed by the rotors of the first and second stages 20-1, 20-2 to be transferred to the third stage 20-3 of the fluid expansion device 20, and ultimately to the output device 412. Alternatively, the drive gear 244 could be mounted to shaft portion 240 and the input gear 346 could be mounted to the shaft portion 340.

[0061] In the embodiment shown, the drive gear 244 has a larger diameter (i.e. more teeth) than the input gear 346. This configuration results in the drive gear 244 acting as a step up gear in which the input gear 346 is rotating at a higher speed than the drive gear 244. In one embodiment, the gear ratio is between about 0.25:1 and about 3:1, and more preferably between about 0.5:1 and about 2:1. The drive gear 244 and input gear 346 can be alternatively configured for a step down operation as well. It is also noted that the rotational direction of the shaft portion 338 is opposite to the rotational direction of the shaft portion 238 which causes the rotor 330 to rotate in the opposite direction of rotors 130, 230 and likewise causes the rotor 332 to rotate in the opposite direction of rotors

132, 232. However, it is to be understood that the gearing could be set up such that the rotors 330, 332 rotate in the same direction as compared to rotors 130, 230 and 132, 232, respectively, such as by mounting drive gear 244 onto shaft portion 240 or by mounting input gear 346 onto shaft portion 340.

[0062] Figure 7 shows an example drivetrain that is similar in many respects to that shown in Figure 6. However, the example of Figure 7 is different in that each of the stages 20-1 and 20-2 are additionally provided with independent shafts such that all three stages 20-1, 20-2, and 20-3 are provided with independent shafts. Accordingly, the shaft 138 is supported by bearings 160 and 164, the shaft 140 is supported by bearings 162 and 166, the shaft 238 is supported by bearings 260 and 264, and the shaft 240 is supported by bearings 262 and 266. Additionally, a pair of timing gears 148, 142 is also provided to fix the rotational relationship between rotor 130 and rotor 132.

[0063] With respect to compartment 152, timing gears 148, 142 are respectively mounted to shafts 138, 140 to fix the rotational relationship between the rotor 130 and the rotor 132, and operate in the same manner as already described for timing gears 248/242 and 348/342. Also connected to the shaft portion 138 is a drive gear 144 that is intermeshed with and drives an input gear 246 fixed onto the shaft 240. In operation, the drive gear 144 and input gear 246 allow the power developed by the rotor of the first stage 20-1 to be transferred to the second stage 20-2 while the drive and input gears 244, 346 allow the power developed by the first and second stages 20-1, 20-2 to be transferred to the third stage 20-3 of the fluid expansion device 20, and ultimately to the output device 412 via input and drive gears 344, 402.

[0064] In the embodiment shown, the drive gear 144 has a larger diameter (i.e. more teeth) than the input gear 246. This configuration results in the drive gear 144 acting as a step up gear in which the input gear 246 is rotating at a higher speed than the drive gear 144. In one embodiment, the gear ratio is between about 0.25:1 and about 3:1, and more preferably between about 0.5:1 and about 2:1. Accordingly, it will be appreciated that, in relative terms, the rotors 130, 132 of the first stage 20-1 rotate at a lower speed than the rotors 230, 232 of the second stage 20-2, which in turn are rotating at a lower speed than the rotors 330, 332 of the third stage 20-3. As the gears 344/402 are configured in a step down arrangement, the rotors 330, 332 are rotating at a higher speed than the output device 412.

[0065] The drive gear 144 and input gear 246 can be alternatively configured for a step down operation as well. It is also noted that the rotational direction of the shaft portion 238 is opposite to the rotational direction of the shaft portion 140 which causes the rotor 230 to rotate in the same direction as rotor 130 and likewise causes the rotor 232 to rotate in the same direction as rotors 132. However, it is to be understood that the gearing could be set up such that the rotors 230, 232 rotate in an opposite direction as compared to rotors 132, 232, respectively.

[0066] A step up configuration between the first and second stage 20-1, 20-2 and between the second and third stage 20-2, 20-3 can be advantageous in embodiments where the volume of the working fluid 12 is expanding rapidly as the working fluid 12 is passing through each successive expansion stage. The volumetric flow rate can be different through each stage because the working fluid 12 has a greater volume when being introduced into rotors 230, 232 of the second stage 20-2 due to the fluid expansion caused by the first stage 20-1, and an even greater volume when being introduced into the rotors 330, 332 of the third stage 20-3 due to the fluid expansion caused by the second stage 20-2. Such a condition could easily exist in the housing and working fluid flow path configuration shown at Figure 4 and with respect to the working fluid flow path through the second and third stages 20-2, 20-3 of the configuration shown at Figure 3. Accordingly, the drivetrain configuration shown in Figure 5 can be particularly useful with the housing and working fluid flow path configuration shown in Figure 3 while the drivetrain configuration shown in Figure 7 can be particularly useful with the housing and working fluid flow path configuration shown in Figure 4. Likewise, the common shaft drivetrain configuration of Figure 5 may be suitable for the housing and working fluid flow path configuration of Figure 2 where it may be easier to mitigate changes in the volumetric flow rate between stages 20-1 and 20-2 and between 20-2 and 20-3. The volumetric flow rate may also be accommodated by configuring the second stage 20-2 to have larger rotors 230, 232 as compared to the rotors 130, 132 of the first stage 20-1 and by configuring the rotors 330, 332 of the third stage 20-3 to be larger than the rotors 230, 232 of the second stage 20-1.

Rotor Design

[0067] Each of the rotors 130/132, 230/232, 330/332, collectively referred to as rotors 30, 32 in this section and with reference to Figures 8-11, is provided with a plurality of lobes. As shown in Figures 8 and 9, each rotor 30, 32 can be provided with three lobes, 30-1, 30-2, 30-3 in the case of the rotor 30, and 32-1, 32-2, 32-3 in the case of the rotor 32. Although three lobes are shown for each rotor 30 and 32, each of the two rotors may have any number of lobes that is equal to or greater than two. For example, PCT Publication WO 2013/130774 shows a suitable rotor having four lobes. Additionally, the rotors of one or more of the stages 20-1, 20-2, 20-3 may have a different number of lobes than the rotors of the other stages 20-1, 20-2, 20-3 in the device 20.

[0068] As presented, the number of lobes is the same for each rotor 30 and 32. This is in contrast to the construction of typical rotary screw devices and other similarly configured rotating equipment which have a dissimilar number of lobes (e.g. a male rotor with "n" lobes and a female rotor with "n+1" lobes). Furthermore, one of the distinguishing features of the expansion device 20 is that the rotors 30 and 32 are identical, wherein the rotors 30, 32 are oppositely arranged so that, as viewed from one axial end, the lobes of one rotor are twisted clockwise while the lobes of the meshing rotor are twisted counter-clockwise. Accordingly, when one lobe of the rotor 30, such as the lobe 30-1 is leading with respect to the inlet port 24, a lobe of the rotor 32, such as the lobe 30-2, is trailing with respect to the inlet port 24, and, therefore with respect to a stream of the high-pressure fluid 12.

[0069] As previously mentioned, the first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other. In one embodiment, the lobes of each rotor 30, 32 are twisted or helically disposed along the length L of the rotors 30, 32. Upon rotation of the rotors 30, 32, the lobes at least partially seal the fluid 12 against an interior side of the housing at which point expansion of the fluid 12 only occurs to the extent allowed by leakage which represents and inefficiency in the system. In contrast to some expansion devices that change the volume of the fluid when the fluid is sealed, the volume defined between the lobes and the interior side 33 of the housing is constant as the fluid 12 traverses the length of the rotors 30, 32. Accordingly, the expansion device 20 is referred to as a "volumetric device" as the sealed or partially sealed fluid volume does not change wherein the working fluid 12 is generally not reduced or compressed.

[0070] The rotor shafts 38, 40 are rotated by the working fluid 12 as the fluid undergoes expansion from the higher first pressure working fluid 12 to the lower second pressure working fluid 12. Accordingly, the shafts 38, 40 are configured to capture the work or power generated by the expansion device 20 during the expansion of the fluid 12 that takes place between the inlet port 108, 208, 308 and the respective outlet port 110, 210, 310. As discussed previously, the work is transferred from the shafts 38, 40 as output torque from the expansion device 20 via output device 412.

<u>Inlet and Outlet Geometry</u>

[0071] In one aspect of the geometry of the expansion device 20, each of the rotor lobes 30-1 to 30-3 and 32-1 to 32-3 has a lobe geometry in which the twist of each of the first and second rotors 30 and 32 is constant along their substantially matching length L. Alternatively, the lobes 130, 132, 230, 232, 330, 332 can be provided without a twist although a drop in efficiency would be expected to occur. In one embodiment, lobes 130, 132 are provided as straight lobes while lobes 230, 232, 330, 332 are provided as twisted lobes. In one embodiment, the length L of all rotors 130, 132, 230, 232, 330, 332 is the same. In one embodiment, the length L of the rotors 130, 132 is less than a length L of the rotors 230, 232, which is in turn less than a Length L of the rotors 330, 332.

[0072] As shown schematically at Figure 11, one parameter of the lobe geometry is the helix angle HA. By way of definition, it should be understood that references hereinafter to "helix angle" of the rotor lobes is meant to refer to the helix angle at the pitch diameter PD (or pitch circle) of the rotors 30 and 32. The term pitch diameter and its identification are well understood to those skilled in the gear and rotor art and will not be further discussed herein. As used herein, the helix angle HA can be calculated as follows: Helix Angle (HA) = (180/.pi.* arctan (PD/Lead)), wherein: PD = pitch diameter of the rotor lobes; and Lead = the lobe length required for the lobe to complete 360 degrees of twist. It is noted that the Lead is a function of the twist angle and the length L of the lobes 30, 32, respectively. The twist angle is known to those skilled in the art to be the angular displacement of the lobe, in degrees, which occurs in "traveling" the length L of the lobe from the rearward end of the rotor to the forward end of the rotor. In one embodiment, the twist angle is about 120 degrees, although the twist angle may be fewer or more degrees, such as 160 degrees.

[0073] In another aspect of the expansion device geometry, the inlet ports 108, 208 and/or 308 can include an inlet angle 24-1, as can be seen schematically at Figure 10. In one example, the inlet angle 24-1 is defined as the general or average angle of an inner surface 24 of the inlet port 108, 208, 308, for example an anterior inner surface. In one example, the inlet angle 24-1 is defined as the angle of the general centerline of the inlet port 108, 208, 308. In one example, the inlet angle 24-1 is defined as the general resulting direction of the fluid 12 entering the rotors 30, 32 due to contact with the anterior inner surface 24, as can be seen at Figure 10. As shown, the inlet angle 24-1 is neither perpendicular nor parallel to the rotational axes X1, X2 of the rotors 30, 32. Accordingly, the anterior inner surface 24 of the inlet port 24 causes a substantial portion of the fluid 12 to be shaped in a direction that is at an oblique angle with respect to the rotational axes X1, X2 of the rotors 30, 32, and thus generally parallel to the inlet angle 24-1.

[0074] Furthermore, and as shown in Figure 10, the inlet port 108, 208, 308 may be shaped such that the fluid 12 is directed to the first axial ends 30a, 30b of the rotors 30, 32 and directed to the rotor lobe leading and trailing surfaces (discussed below) from a lateral direction. However, it is to be understood that the inlet angle 24-1 may be generally parallel or generally perpendicular to axes X1, X2, although an efficiency loss may be anticipated for certain rotor configurations. Furthermore, it is noted that the inlet port 24 may be shaped to narrow towards the inlet opening adjacent the rotor 30, 32.

[0075] In another aspect of the expansion device geometry, the outlet ports 110, 210, and/or 310 include an outlet angle 26-1, as can be seen schematically at Figure 10. In one example, the outlet angle 26-1 is defined as the general or average angle of an inner surface 26 of the outlet port 110, 210, and/or 310. In one example, the outlet angle 26-1 is defined as the angle of the general centerline of the outlet port 110, 210, 310. In one example, the outlet angle 26-1 is defined as the general resulting direction of the fluid 12 leaving the rotors 30, 32 due to contact with the inner surface 26a, as can be seen at Figure 10. As shown, the outlet angle 26-1 is neither perpendicular nor parallel to the rotational axes X1, X2 of the rotors 30, 32. Accordingly, the inner surface 26 of the outlet port 110, 210, 310 receives the leaving fluid 12 from the rotors 30, 32 at an oblique angle which can reduce backpressure at the outlet port 26. In one example, the inlet angle 24-1 and the outlet angle 26-1 are generally equal or parallel, as shown in Figure 10. In one example, the inlet angle 24-1 and the outlet angle 26-1 are oblique with respect to each other. It is to be understood that the outlet angle 26-1 may be generally perpendicular to axes X1, X2, although an efficiency loss may be anticipated for certain rotor configurations. It is further noted that the outlet angle 26-1 may be perpendicular to the axes X1, X2. As configured, the orientation and size of the outlet port 26-1 are established such that the leaving fluid 12 can evacuate each rotor cavity 28 as easily and rapidly as possible so that backpressure is reduced as much as possible. The output power of the fluid expansion device 20 is maximized to the extent that backpressure caused by the outlet 110, 210, 310 can be minimized such that the fluid can be rapidly discharged into the lower pressure fluid at the condenser.

[0076] The efficiency of the expansion device 20 can be optimized by coordinating the geometry of the inlet angle 24-1 and the geometry of the rotors 30, 32. For example, the helix angle HA of the rotors 30, 32 and the inlet angle 24-1 can be configured together in a complementary fashion. Because the inlet port 108, 208, 309 introduces the fluid 12 to both the leading and trailing faces of each rotor 30, 32, the fluid 12 performs both positive and negative work on the expansion device 20.

[0077] To illustrate, Figure 9 shows that lobes 30-2, 30-3, 32-2, and 32-3 are each exposed to the fluid 12 through the inlet port opening 24b. Each of the lobes has a leading surface and a trailing surface, both of which are exposed to the fluid at various points of rotation of the associated rotor. The leading surface is the side of the lobe that is forward most as the rotor is rotating in a direction R1, R2 while the trailing surface is the side of the lobe opposite the leading surface. For example, rotor 30 rotates in direction R1 thereby resulting in side 30-1a as being the leading surface of lobe 30-1 and side 30-1b being the trailing surface. As rotor 32 rotates in a direction R2 which is opposite direction R1, the leading and trailing surfaces are mirrored such that side 32-1a is the leading surface of lobe 32-1 while side 32-1b is the trailing surface.

[0078] In generalized terms, the fluid 12 impinges on the trailing surfaces of the lobes as they pass through the inlet port opening 24b and positive work is performed on each rotor 30, 32. By use of the term positive work, it is meant that the fluid 12 causes the rotors to rotate in the desired direction: direction R1 for rotor 30 and direction R2 for rotor 32. As shown, fluid 12 will operate to impart positive work on the trailing surface 30-1b of rotor

30-1. The fluid 12 is also imparting positive work on the trailing surface 32-2b of rotor 32-2. However, the fluid 12 also impinges on the leading surfaces of the lobes, for example surfaces 30-3a and 32-1a, as they pass through the inlet port opening thereby causing negative work to be performed on each rotor 30, 32. By use of the term negative work, it is meant that the working fluid 12 causes the rotors to rotate opposite to the desired direction, R1, R2.

[0079] Accordingly, it is desirable to shape and orient the rotors 30, 32 and to shape and orient the inlet ports 108, 208, 308 such that as much of the fluid 12 as possible impinges on the trailing surfaces of the lobes with as little of the fluid 12 impinging on the on the leading lobes such that the highest net positive work can be performed by the fluid expansion device 20.

[0080] One advantageous configuration for optimizing the efficiency and net positive work of the expansion device 20 is a rotor lobe helix angle HA of about 35 degrees and an inlet angle 24-1 of about 30 degrees. Such a configuration operates to maximize the impingement area of the trailing surfaces on the lobes while minimizing the impingement area of the leading surfaces of the lobes. In one example, the helix angle is between about 25 degrees and about 40 degrees. In one example, the inlet angle 24-1 is set to be within (plus or minus) 15 degrees of the helix angle. In one example, the helix angle is between about 25 degrees and about 40 degrees. In one example, the inlet angle 24-1 is set to be within (plus or minus) 15 degrees of the helix angle HA. In one example, the inlet angle is within (plus or minus) 10 degrees of the helix angle. In one example, the inlet angle 24-1 is set to be within (plus or minus) 5 degrees of the helix angle HA. In one example, the inlet angle 24-1 is set to be within (plus or minus) fifteen percent of the helix angle HA while in one example, the inlet angle 24-1 is within ten percent of the helix angle. Other inlet angle and helix angle values are possible without departing from the concepts presented herein. However, it has been found that where the values for the inlet angle and the helix angle are not sufficiently close, a significant drop in efficiency (e.g. 10-15% drop) can occur.

Example Embodiments

[0081] Referring to Figures 12-18, an example embodiment of a fluid expansion device 20 in accordance with the present disclosure is shown. In this example, the overall configuration is generally similar to the housing and working fluid passageway arrangement of Figure 3 and the drivetrain arrangement presented in Figure 6. Therefore, the similarities between the systems will not be discussed further here. Accordingly, the fluid expansion device 20 shown in Figures 12-18 has an inlet 108 and an outlet 310, and further includes a first stage outlet 110 that is separated from a second stage inlet 208.

[0082] Figure 12 shows the fluid expansion device 20 being used in an organic Rankine cycle in which a working fluid is sequentially heated at heat exchangers 18-1, 18-2, and 18-3 and introduced to the first stage 20-1 of the fluid expansion device. As shown, the working fluid leaves the first stage 20-1 and is again heated by a heat exchanger 15 and then introduced back into the fluid expansion device 20 where the working fluid passes internally from the second stage 20-2 to the third stage 20-3. After passing through the third stage 20-3, the working fluid is transported to heat exchanger 18-1 and then to condenser 19. A pump 17 is provided to pump the working fluid back to the heat exchanger 18-1. Heat exchanger 18-1 operates as a recuperator to simultaneously cool the working fluid before reaching the condenser 19 and preheating the working fluid after the condenser 19. The heat exchangers 15 and 18-2 are sequentially heated by exhaust directly from the power plant 16 while the heat exchanger 18-3 is heated by exhaust gas downstream from a turbocharger 13.

[0083] With reference to Figures 14-18, the internal components of the volumetric fluid expansion device 20 are shown in greater detail. As shown, the rotors 130, 132 of the first expansion stage are each provided with four straight lobes. The rotors 230, 232, which are mounted to the same common shafts 38, 40 as the rotors 130, 132, are shown as each being provided with three twisted lobes. Additionally, the rotors 230, 232 are shown as having a greater overall length than that of the rotors 130, 132. The rotors 330, 332 are provided with an even greater length than that of the rotors 230, 232, but with the same helix angle. Accordingly, the rotors 330, 332 extend through a greater twist angle than rotors 230, 232.

[0084] As can be seen at Figures 15-18, the compartment 154 is formed by the third housing 302 and an internal housing part 203 associated with the second housing 102. The internal housing part 203 also forms a portion of the working fluid passageway 206/306 between the rotors 230, 232 and the rotors 330, 332. As shown, the second housing 202 is secured to the third housing 302, and the internal housing part 203 sandwiched there between, via a plurality of mechanical fasteners 207. The first housing 102 is also secured to the second housing 202 via a plurality of mechanical fasteners 107.

[0085] As shown, the compartment 156 is formed by a housing part 303 and a portion of the power output device 400. The housing part 303 also forms a portion of the working fluid passageway 306 near the outlet 310. The housing part 303 is secured to the third housing 103 via a plurality of mechanical fasteners 307 and is secured to the power output device 400 via a plurality of mechanical fasteners 407. It is noted that gaskets may be provided at the interfaces between the power output device and the housing part 303, between the housing part 303 and the third housing 302, between the third housing 302 and the internal housing part 203, between the third housing 302 and the second housing 202, and between the second housing 202 and the first housing 102.

[0086] Referring to Figures 19-22, another example embodiment of a fluid expansion device 20 in accordance with the present disclosure is shown. In this example, the overall configuration is generally similar to the housing and working fluid passageway arrangement of Figure 4 and the drivetrain arrangement presented in Figure 7. Additionally, the construction of the housing components is generally similar to that shown in Figures 12-18. Therefore, the similarities between the systems will not be discussed further here.

[0087] Figure 19 shows the fluid expansion device 20 being used in an organic Rankine cycle 1000 in which a working fluid is sequentially heated at heat exchangers 18-1, 18-2, and 18-3 and introduced to the first stage 20-1 of the fluid expansion device. As shown, the working fluid passes from the inlet 108 and internally through all three stages 20-1, 20-2, 20-3 before reaching the outlet 310. After passing through the third stage 20-3, the working fluid is transported to heat exchanger 18-1 and then to condenser 19. A pump 17 is provided to pump the working fluid back to the heat exchanger 18-1. Heat exchanger 18-1 operates as a recuperator to simultaneously cool the working fluid before reaching the condenser 19 and preheating the working fluid after the condenser 19. The heat exchanger 18-2 is heated by exhaust directly from the power plant 16 while the heat exchanger 18-3 is heated by exhaust gas downstream from a turbocharger 13.

[0088] With reference to Figures 14-18, the internal components of the volumetric fluid expansion device 20 are shown in greater detail. As shown, each of the rotors 130, 132, 230, 232, 330, 332 are mounted to an independent shaft and are provided with four twisted lobes having a matching helix angle. As with the previous example, the rotors 230, 232 are shown as having a greater overall length than that of the rotors 130, 132 while the rotors 330, 332 are provided with an even greater length than that of the rotors 230, 232. Accordingly, the rotors 330, 332 extend through a greater twist angle than rotors 230, 232 which in turn extend through a greater twist angle than rotors 130, 132.

[0089] As can be seen at Figures 15-18, the compartment 152 is formed by the second housing 202 and an internal housing part 103 associated with the first housing 102. The internal housing part 103 also forms a portion of the working fluid passageway 106/206 between the rotors 130, 132 and the rotors 230, 232. As shown, the second housing 202 is secured to the first housing 102, and the internal housing part 103 sandwiched there between, via a plurality of mechanical fasteners. It is noted that gaskets may be provided at the interfaces between the second housing 202 and the housing part 103. The compartment 150 is formed by a cavity in the first housing 102 and a cover plate 105 extending over the cavity. The cover plate 105 is secured to the first housing 102 by a plurality of fasteners 109.

[0090] Figures 23-24 show an embodiment of a fluid expansion device in which each of rotors 130, 230, and 330 are mounted to a common shaft 38 and each of rotors 132, 232, and 332 are mounted to a common shaft 340. Additionally, each stage 20-1, 20-2, and 20-3 is provided with its own independent inlet and outlet 108/110, 208/210, and 308/310, respectively. Accordingly, the embodiment shown at Figures 23-24 is similar to the drivetrain arrangement shown in Figure 5 and the housing and fluid pathway configuration of Figure 2. Therefore, the similarities between the systems will not be discussed further here.

[0091] As shown at Figure 23, and most easily seen at Figure 24 for the components relating to shaft 40, the rotors 130, 132 of the first expansion stage are each provided with four straight lobes. The rotors 130, 132, 230, and 232 are shown as each being provided with three twisted lobes. Additionally, the rotors 230, 232 are shown as having a greater overall length than that of the rotors 130, 132. The rotors 330, 332 are provided with an even greater length than that of the rotors 230, 232, but with the same helix angle. Accordingly, the rotors 330, 332 extend through a greater twist angle than rotors 230, 232. In the example shown in Figure 23, the power output device 400 is directly mounted to the third housing 302 without the use of housing part 303 and is also provided without a clutch mechanism 408. Additionally, the first housing 102 is mounted to the second housing directly via fasteners 107.

[0092] The various embodiments described above are provided by way of illustration only and should not be construed to limit the claims attached hereto. Those skilled in the art will readily recognize various modifications and changes that may be made without following the example embodiments and applications illustrated and described herein, and without departing from the true spirit and scope of the disclosure.

Example Parallel Drive Embodiments

[0093] Referring to Figures 28-21, examples a fluid expansion device 20 in accordance with the present disclosure is shown. In these examples, the overall configurations of the expanders are generally similar to the housing and working fluid passageway arrangements previously described at least in that the rotor and housing designs are similar, and in that a working fluid 12 flows from the first stage 20-1, through the second stage 20-2, and then through the third stage 20-3. Additionally, the drivetrain configurations between the stages are also generally the same as previously described. Therefore, the similarities between the systems in this regard will not be discussed further here. However, the examples shown in Figures 28-31 differ from the previously discussed embodiments in that the output gears (144, 244, 344) of at least two of the three stages 20-1, 20-2, 20-3 are in placed in a parallel arrangement to drive either the power output device 400 or the third expander stage, as described below.

[0094] With reference to the example shown in Figure 28, each of the output gears (144, 244, 344) of the three stages 20-1, 20-2, 20-3 are placed in a parallel arrangement such that each of the drive gears 144, 244, and 344 acts on the input gear 402 of the power output device 400. In the embodiment shown, drive gear 144 drives the input gear 402 via a gear train 420 while drive gear 244 drives the input gear via a gear train 422. Additionally, drive gear 344 outputs to a gear train 424 that acts on drive gear 244. However, it is to be understood that gear trains 420, 422, and 424 can be configured to each act directly on input gear 402 and/or act on each other via one or more of the drive gears, as desired. By use of the term "gear train" it is meant to include any gear assembly including one or more gears that act on each other. As with the other gearing mechanisms disclosed, the gear trains 420, 422, and 422 may be configured to accomplish either a step down gear ratio function or a step up gear ratio function.

[0095] With reference to the example shown in Figure 29, the output gears 244 and 344 of the second and third stages 20-2 and 20-3 are placed in a parallel arrangement such that each of the drive gears 244 and 344 acts on the input gear 146 of the first expander stage 20-1. In the embodiment shown, drive gear 244 drives the input gear 146 via a gear train 245 while drive gear 344 drives the input gear 146 via a gear train 345. As shown, the drive gear 144 of the first stage acts on the input gear 402 of the output device 400.

[0096] With reference to the example shown in Figure 30, the first stage 20-1 has an independently formed housing while the second and third stages 20-2, 20-3 are coupled together in a similar fashion to the drivetrain arrangement shown in Figure 7 and the housing arrangement shown in Figure 3. In this example, the drive gears 144 and 244 act on the input gear 402 via respective gear trains 420, 422. However, it is to be understood that the gear trains 420, 422 could be configured to act on each other such that only one of the gear trains 420, 422 acts directly on the input gear 402. It is also noted that the device 20 could be configured such that rotors 230 and 330 are on a common shaft 38 and such that rotors 232 and 332 are on a common shaft 40, as is shown for the second and third stages 20-2, 20-3 at Figure 5.

[0097] With reference to the example shown in Figure 31, the third stage 20-3 has an independently formed housing while the first and second stages 20-2, 20-3 are coupled together with an internal working fluid flow path and a drivetrain having a similar arrangement to that shown in Figure 7, but in a reverse configuration. In this example, the drive gears 144 and 344 act on the input gear 402 via respective gear trains 420, 424. However, it is to be understood that the gear trains 420, 424 could be configured to act on each other such that only one of the gear trains 420, 424 acts directly on the input gear 402. It is also noted that the device 20 could be configured such that rotors 130 and 230 are on a common shaft 38 and such that rotors 132 and 132 are on a common shaft 40, as is shown for the first and second stages 20-1, 20-2 at Figures 5 and 6.

[0098] With respect to above described parallel drive examples, it should be appreciated that fewer or more than three stages can be arranged in such a configuration, for example, two stages, four stages, six stages, and/or eight stages. In one example, two three stage expanders 20 are provided to simultaneously drive the input gear 402.

What is claimed is:

1. A multi-stage volumetric fluid expansion device comprising:
   a. a first fluid expansion stage having a first pair of non-contacting rotors disposed between a first inlet and a first outlet, the first fluid expansion stage being configured to generate useful work at the first pair of rotors by expanding a working fluid from a first pressure to a second pressure that is lower than the first pressure;
   b. a second fluid expansion stage having a second pair of non-contacting rotors disposed between a second inlet and a second outlet, the second fluid expansion stage being configured to generate useful work at the second pair of rotors by receiving the working fluid from the first fluid expansion stage outlet and expanding the working fluid to a third pressure that is lower than the second pressure; and
   c. a power output device rotated by the first and second pair of rotors.

2. The multi-stage volumetric fluid expansion device of claim 1, further comprising:
   a. a housing within which the first and second pairs of rotors is disposed, wherein the first outlet and the second inlet are joined within the housing to form a continuous working fluid passageway extending between the first inlet and the second outlet .

3. The multi-stage volumetric fluid expansion device of claim 1, wherein:
   a. one of the first pair of rotors and one of the second pair of rotors are mounted to a first common rotor shaft and the other of the first pair of rotors and the other of the second pair of rotors are mounted to a second common rotor shaft;
   b. wherein the power output device is rotated by the first rotor shaft.

4. The multi-stage volumetric fluid expansion device of claim 3, wherein:
   a. the first shaft is provided with a drive gear and the power output device is provided with an input gear that is driven by the drive gear.

5. The multi-stage volumetric fluid expansion device of claim 4, wherein:

a. the drive gear and input gear are configured in a step down arrangement such that the first and second pair of rotors rotates at a higher rotational speed than the power output device.

6. The multi-stage volumetric fluid expansion device of claim 5, wherein:
   a. the power output device is provided with a clutch to selectively engage and disengage the first rotor shaft from the power output device.

7. The multi-stage volumetric fluid expansion device of claim 2, wherein:
   a. one of the first pair of rotors is mounted to a first rotor shaft and the other of the first pair of rotors is mounted to a second rotor shaft; and
   b. one of the second pair of rotors is mounted to a third rotor shaft and the other of the second pair of rotors is mounted to a fourth shaft;
   c. wherein the power output device is rotated by the fourth rotor shaft.

8. The multi-stage volumetric fluid expansion device of claim 4, wherein:
   a. the first shaft is provided with a first drive gear and the fourth shaft is provided with a first input gear that is driven by the first drive gear.

9. The multi-stage volumetric fluid expansion device of claim 5, wherein:
   a. the first drive gear and first input gear are configured in a step up arrangement such that the first pair of rotors rotates at a lower rotational speed than the second pair of rotors.

10. The multi-stage volumetric fluid expansion device of claim 9, wherein:
    a. the fourth shaft is provided with a second drive gear and the power output device is provided with an second input gear that is driven by the second drive gear.

11. The multi-stage volumetric fluid expansion device of claim 10, wherein:
    a. The second drive gear and the second input gear are configured in a step down arrangement such that the second pair of rotors rotates at a higher rotational speed than the power output device.

12. The multi-stage volumetric fluid expansion device of claim 11, wherein:
    a. the power output device is provided with a clutch to selectively engage and disengage the fourth rotor shaft from the power output device.

13. The multi-stage volumetric fluid expansion device of claim 1, wherein:
    a. the second pair of rotors have twisted non-contacting lobes, wherein one of the second pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the second pair of rotors.

14. A multi-stage volumetric fluid expansion device comprising:
    a. a first fluid expansion stage having a first pair of non-contacting rotors disposed between a first inlet and a first outlet, the first fluid expansion stage being configured to generate useful work at the first pair of rotors by expanding a working fluid from a first pressure to a second pressure that is lower than the first pressure;
    b. a second fluid expansion stage having a second pair of non-contacting rotors disposed between a second inlet and a second outlet, the second fluid expansion stage being configured to generate useful work at the second pair of rotors by receiving the working fluid from the first fluid expansion stage outlet and expanding the working fluid to a third pressure that is lower than the second pressure;
    c. a third fluid expansion stage having a third pair of non-contacting rotors disposed between a third inlet and a third outlet, the third fluid expansion stage being configured to generate useful work at third pair of rotors by receiving the working fluid from the second fluid expansion stage outlet and expanding the working fluid to a fourth pressure that is lower than the third pressure;
    d. a power output device rotated by the first, second, and second third of rotors.

15. The multi-stage volumetric fluid expansion device of claim 14, further comprising:
    a. a housing within which the first, second, and third pairs of rotors is disposed, wherein the second outlet and third inlet are joined within the housing to form

a continuous working fluid passageway extending between the second inlet and the third outlet.

16. The multi-stage volumetric fluid expansion device of claim 15, wherein:
    a. the first outlet and the second inlet are joined within the housing to form a continuous working fluid passageway extending between the first inlet and the third outlet.

17. The multi-stage volumetric fluid expansion device of claim 14, wherein:
    a. one of the first pair of rotors, one of the second pair of rotors, and one of the third pair of rotors are mounted to a first common rotor shaft and the other of the first pair of rotors, the other of the second pair of rotors, and the other pair of rotors are mounted to a second common rotor shaft;
    b. wherein the power output device is rotated by the first rotor shaft.

18. The multi-stage volumetric fluid expansion device of claim 15, wherein:
    a. one of the first pair of rotors and one of the second pair of rotors is mounted to a first common rotor shaft and the other of the first pair of rotors and the other of the second pair of rotors is mounted to a second common rotor shaft; and
    b. one of the third pair of rotors is mounted to a third rotor shaft and the other of the third pair of rotors are mounted to a fourth rotor shaft;
    c. wherein the power output device is rotated by the fourth rotor shaft.

19. The multi-stage volumetric fluid expansion device of claim 16, wherein:
    a. one of the first pair of rotors is mounted to a first rotor shaft and the other of the first pair of rotors is mounted to a second rotor shaft;
    b. one of the second pair of rotors is mounted to a third rotor shaft and the other of the second pair of rotors is mounted to a fourth rotor shaft; and
    c. one of the third pair of rotors is mounted to a fifth rotor shaft and the other of the third pair of rotors is mounted to a sixth rotor shaft;
    d. wherein the power output device is rotated by the sixth rotor shaft.

20. The multi-stage volumetric fluid expansion device of claim 17, wherein:

a. the first rotor shaft is provided with a drive gear and the power output device is provided with an input gear that is driven by the drive gear;
b. the drive gear and input gear being configured in a step down arrangement such that the first, second, and third pairs of rotors rotate at a higher rotational speed than the power output device.

21. The multi-stage volumetric fluid expansion device of claim 20, wherein:
a. the power output device is provided with a clutch to selectively engage and disengage the first rotor shaft from the power output device.

22. The multi-stage volumetric fluid expansion device of claim 17, wherein:
a. the first rotor shaft is provided with a first drive gear and the third rotor shaft device is provided with an input gear that is driven by the drive gear;
b. the drive gear and input gear being configured in a step down arrangement such that the first, second, and third pairs of rotors rotate at a higher rotational speed than the power output device.

23. The multi-stage volumetric fluid expansion device of claim 20, wherein:
a. the power output device is provided with a clutch to selectively engage and disengage the first rotor shaft from the power output device.

24. The multi-stage volumetric fluid expansion device of claim 18, wherein:
a. the first shaft is provided with a first drive gear and the fourth shaft is provided with a first input gear that is driven by the first drive gear;
b. the first drive gear and first input gear being configured in a step up arrangement such that the first and second pair of rotors rotates at a lower rotational speed than the third pair of rotors.

25. The multi-stage volumetric fluid expansion device of claim 24, wherein:
a. the fourth shaft is provided with a second drive gear and the power output device is provided with a second input gear that is driven by the second drive gear;

b. the second drive gear and the second input gear being configured in a step down arrangement such that the third pair of rotors rotates at a higher rotational speed than the power output device.

26. The multi-stage volumetric fluid expansion device of claim 25, wherein:
  a. the power output device is provided with a clutch to selectively engage and disengage the fourth rotor shaft from the power output device.

27. The multi-stage volumetric fluid expansion device of claim 19, wherein:
  a. the first shaft is provided with a first drive gear and the third shaft is provided with a first input gear that is driven by the first drive gear;
  b. the first drive gear and first input gear being configured in a step up arrangement such that the first pair of rotors rotates at a lower rotational speed than the second pair of rotors.

28. The multi-stage volumetric fluid expansion device of claim 27, wherein:
  a. the fourth shaft is provided with a second drive gear and the sixth shaft is provided with a second input gear that is driven by the second drive gear;
  b. the first drive gear and first input gear being configured in a step up arrangement such that the second pair of rotors rotates at a lower rotational speed than the third pair of rotors.

29. The multi-stage volumetric fluid expansion device of claim 28, wherein:
  a. The sixth shaft is provided with a third drive gear and the power output device is provided with a third input gear that is driven by the third drive gear;
  b. the third drive gear and the third input gear being configured in a step down arrangement such that the third pair of rotors rotates at a higher rotational speed than the power output device.

30. The multi-stage volumetric fluid expansion device of claim 29, wherein:
  a. the power output device is provided with a clutch to selectively engage and disengage the sixth rotor shaft from the power output device.

31. The multi-stage volumetric fluid expansion device of claim 14, wherein:
    a. the first pair of rotors have twisted non-contacting lobes, wherein one of the first pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the first pair of rotors;
    b. the second pair of rotors have twisted non-contacting lobes, wherein one of the second pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the second pair of rotors; and
    c. the third pair of rotors have twisted non-contacting lobes, wherein one of the third pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the third pair of rotors.

32. A system for generating mechanical work via a closed-loop Rankine cycle, the system comprising:
    a. a power plant that produces a waste heat stream, wherein the power plant has a waste heat outlet through which the waste heat stream exits;
    b. at least one heat exchanger in fluid communication with the waste heat stream, the heat exchanger being configured to heat a working fluid;
    c. a multi-stage fluid expansion device configured to generate mechanical work at an output device from the working fluid, the expansion device having a housing within which a first stage and a second stage are disposed, the first stage being configured to expand the working fluid, the second stage being configured to receive the working fluid from the first stage and to expand the working fluid;
    d. a condenser constructed and arranged to condense the working fluid;
    e. a pump constructed and arranged to pump the condensed working fluid to the at least one heat exchanger.

33. The system for generating mechanical work of claim 32, wherein:
    a. the multi-stage fluid expansion device housing further includes a third stage disposed within the housing that is configured to receive the working fluid from the second stage and to expand the working.

34. The system for generating mechanical work of claim 33, further comprising:

a. a second heat exchanger located between the first and second stages.

35. The system for generating mechanical work of claim 33, wherein:
    a. The housing defines an internal working fluid pathway within which the working fluid can pass internally from the first stage to the second stage and from the second stage to the third stage.

36. The system for generating mechanical work of claim 35, wherein:
    a. the output device is mechanically coupled to the third stage, the second stage is mechanically coupled to the third stage, and the first stage is mechanically coupled to the second stage such that power developed by each of the first, second, and third stages is transmitted to the power output device.

37. The system for generating mechanical work of claim 35, further comprising:
    a. a first step up gear arrangement provided between the first and second stages such that a first pair of rotors associated with the first stage rotate at a lower speed than a second pair of rotors associated with the second stage; and
    b. a second step up gear arrangement provided between the second and third stages such that the second pair of rotors rotate at a lower speed than a third pair of rotors associated with the third stage.

38. The system for generating mechanical work of claim 37, further comprising:
    a. a step down gear arrangement provided between the third stage and the power output device such that third pair of rotors rotate at a lower speed than the power output device.

39. The multi-stage volumetric fluid expansion device of claim 38, wherein:
    a. the power output device is provided with a clutch to selectively engage and disengage the third stage from the power output device.

40. The multi-stage volumetric fluid expansion device of claim 38, wherein:

a. the first pair of rotors have twisted non-contacting lobes, wherein one of the first pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the first pair of rotors;
b. the second pair of rotors have twisted non-contacting lobes, wherein one of the second pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the second pair of rotors; and
c. the third pair of rotors have twisted non-contacting lobes, wherein one of the third pair of rotors has a number of twisted lobes that equals a number of twisted lobes of the other of the third pair of rotors.

41. A multi-stage volumetric fluid expansion device comprising:
a. a first fluid expansion stage having a first pair of non-contacting rotors disposed between a first inlet and a first outlet, the first fluid expansion stage being configured to generate useful work at a first output shaft by expanding a working fluid from a first pressure to a second pressure that is lower than the first pressure;
b. a second fluid expansion stage having a second pair of non-contacting rotors disposed between a second inlet and a second outlet, the second fluid expansion stage being configured to generate useful work at a second output shaft by receiving the working fluid from the first fluid expansion stage outlet and expanding the working fluid to a third pressure that is lower than the second pressure; and
c. a power output device having an input gear that is rotated by the first and second output shafts.

42. The multi-stage volumetric fluid expansion device of claim 41 wherein:
a. the first output shaft acts on the power output device input gear via a first gear train and the second output shaft acts on the power output device input gear via a second gear train in parallel to the first gear train.

43. A multi-stage volumetric fluid expansion device comprising:
a. a first fluid expansion stage having a first pair of non-contacting rotors disposed between a first inlet and a first outlet, the first fluid expansion stage

being configured to generate useful work at a first output shaft by expanding a working fluid from a first pressure to a second pressure that is lower than the first pressure;

b. a second fluid expansion stage having a second pair of non-contacting rotors disposed between a second inlet and a second outlet, the second fluid expansion stage being configured to generate useful work at a second output shaft by receiving the working fluid from the first fluid expansion stage outlet and expanding the working fluid to a third pressure that is lower than the second pressure; and

c. a third fluid expansion stage having a third pair of non-contacting rotors disposed between a second inlet and a second outlet, the second fluid expansion stage being configured to generate useful work at a third output shaft by receiving the working fluid from the first fluid expansion stage outlet and expanding the working fluid to a third pressure that is lower than the second pressure;

d. wherein at least two of the first, second, and third output shafts are arranged in parallel to act on an input gear of the fluid expansion device.

44. The multi-stage volumetric fluid expansion device of claim 43 wherein:

a. the input gear of the fluid expansion device is a power output device input gear;

b. the first output shaft acts on the power output device input gear via a first gear train;

c. the second output shaft acts on the power output device input gear via a second gear train; and

d. the third output shaft acts on the power output device input gear via a third gear train.

45. The multi-stage volumetric fluid expansion device of claim 43 wherein:

a. the input gear of the fluid expansion device is a first stage input gear;

b. the first output shaft acts on a power output device input gear via a first gear train;

c. the second output shaft acts on the first stage input gear via a second gear train; and
d. the third output shaft acts on the first stage input gear via a third gear train.

46. The multi-stage volumetric fluid expansion device of claim 43 wherein:
a. the input gear of the fluid expansion device is a power output device input gear;
b. the first output shaft acts on the power output device input gear via a first gear train;
c. the second output shaft acts on the power output device input gear via a second gear train; and
d. the third output shaft acts on a second stage input gear via a third gear train.

47. The multi-stage volumetric fluid expansion device of claim 46 wherein:
a. the working fluid is directed through an internal passageway in a housing of the volumetric fluid expansion device from the second stage to the third stage.

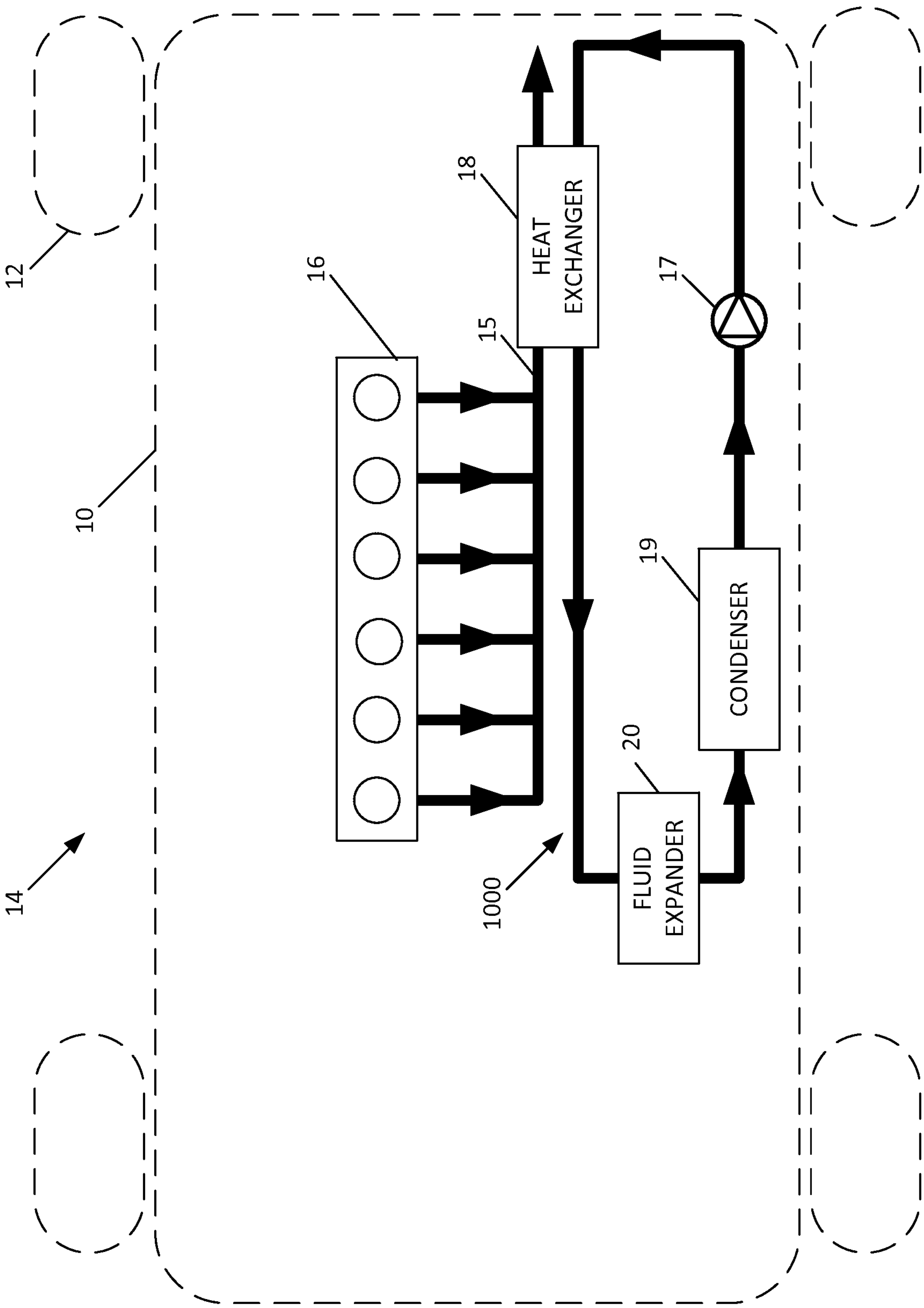
48. The multi-stage volumetric fluid expansion device of claim 47 wherein:
a. the second pair of rotors and the third pair of rotors are mounted to a common pair of shafts.

49. The multi-stage volumetric fluid expansion device of claim 43 wherein:
a. the input gear of the fluid expansion device is a power output device input gear;
b. the first output shaft acts on the power output device input gear via a first gear train;
c. the second output shaft acts on a first stage input gear via a second gear train; and
d. the third output shaft acts on the power output device input gear via a third gear train.

50. The multi-stage volumetric fluid expansion device of claim 49 wherein:

a. the working fluid is directed through an internal passageway in a housing of the volumetric fluid expansion device from the first stage to the second stage.

51. The multi-stage volumetric fluid expansion device of claim 50 wherein:
    a. the first pair of rotors and the second pair of rotors are mounted to a common pair of shafts.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CONDENSER
FLUID
EXPANDER

FIG. 1

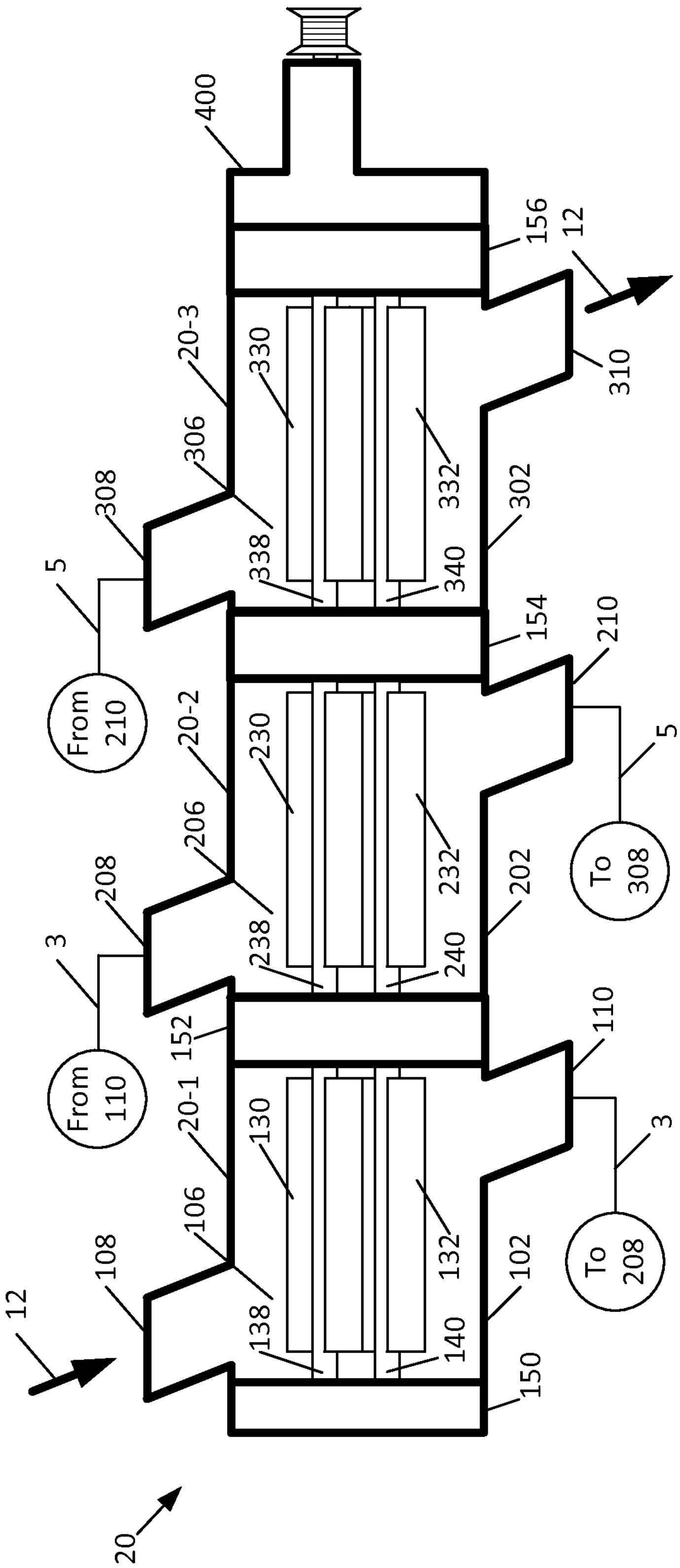
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FIG. 2

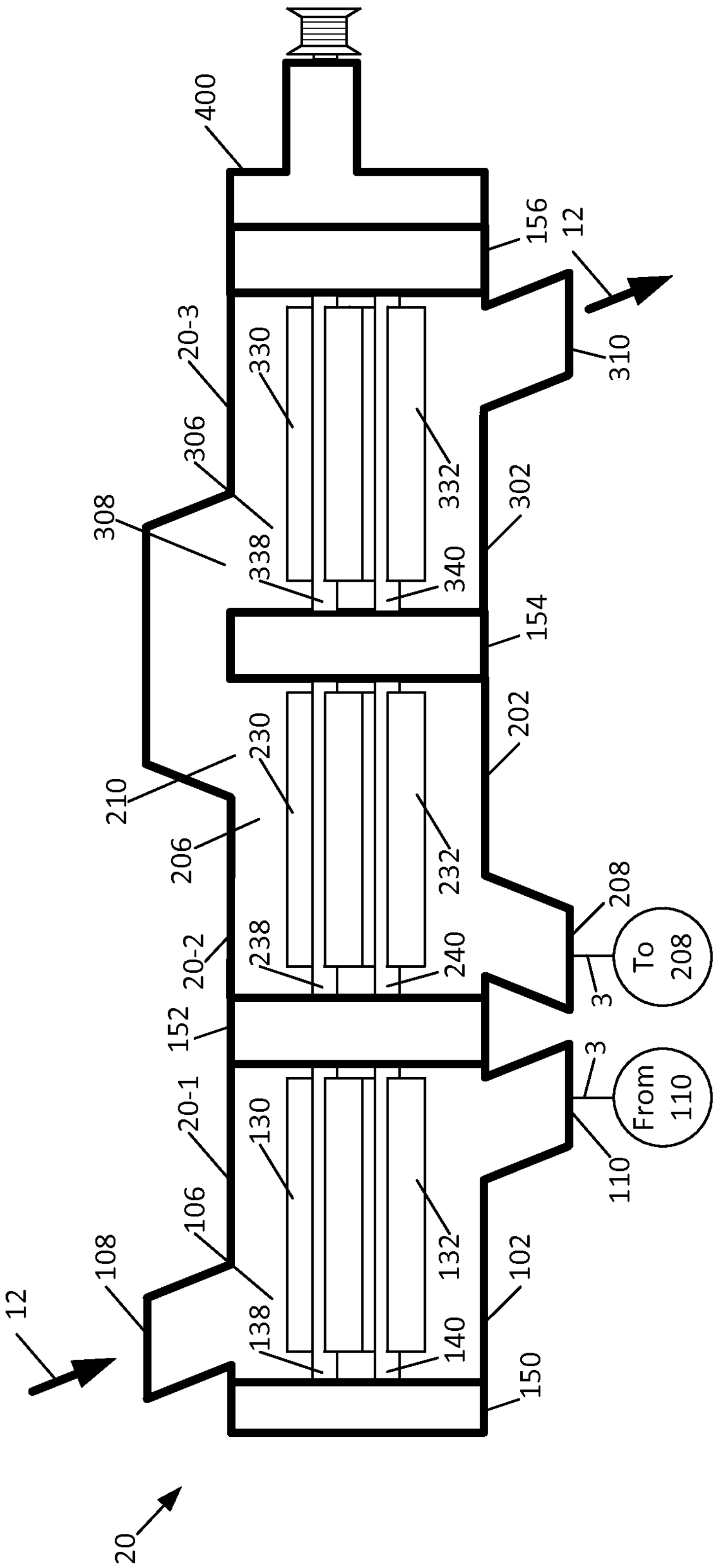
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FIG. 3

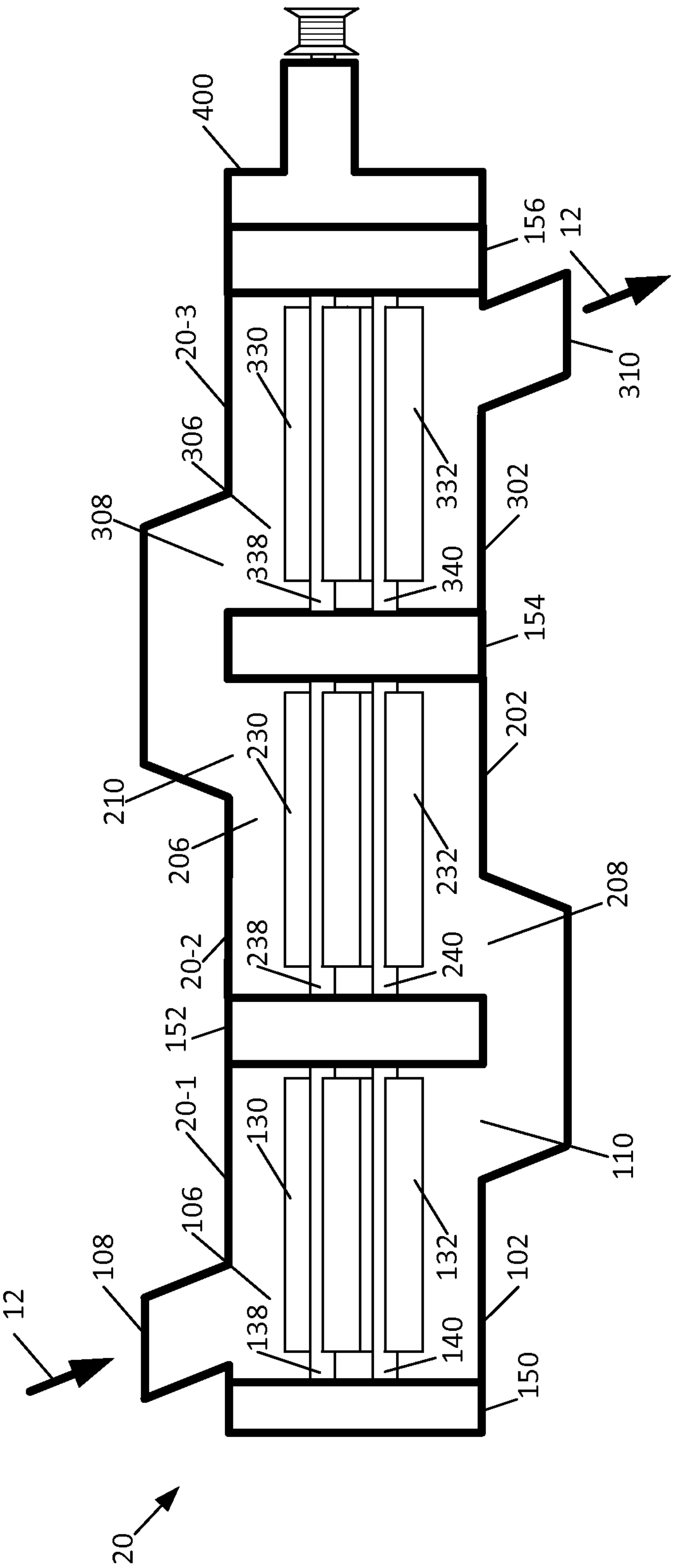
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FIG. 4

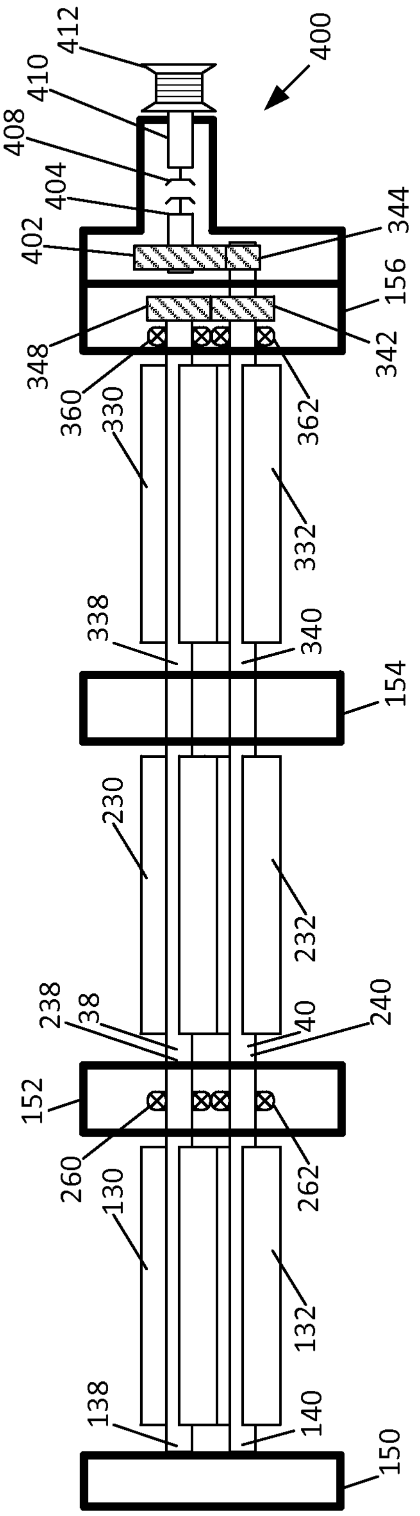
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FIG. 5

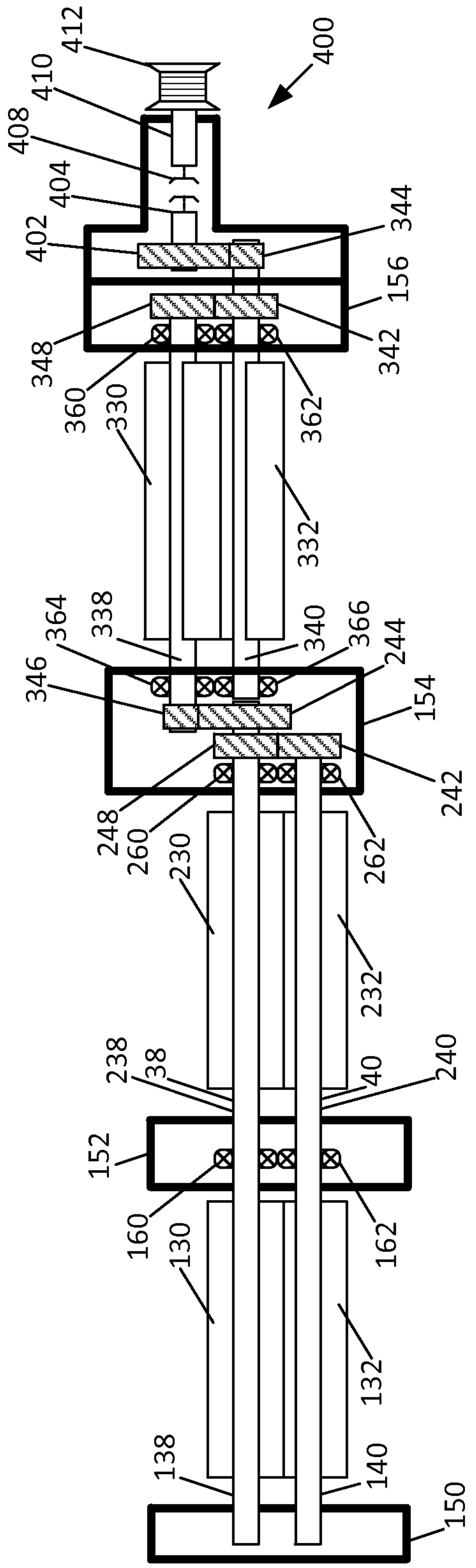
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FIG. 6

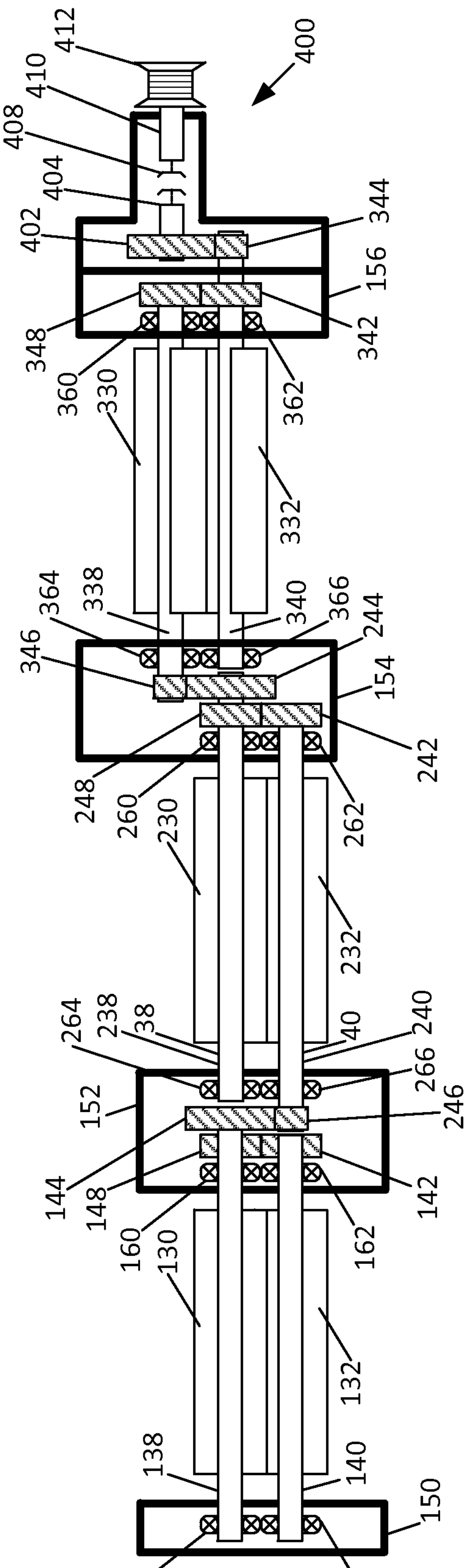
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FIG. 7

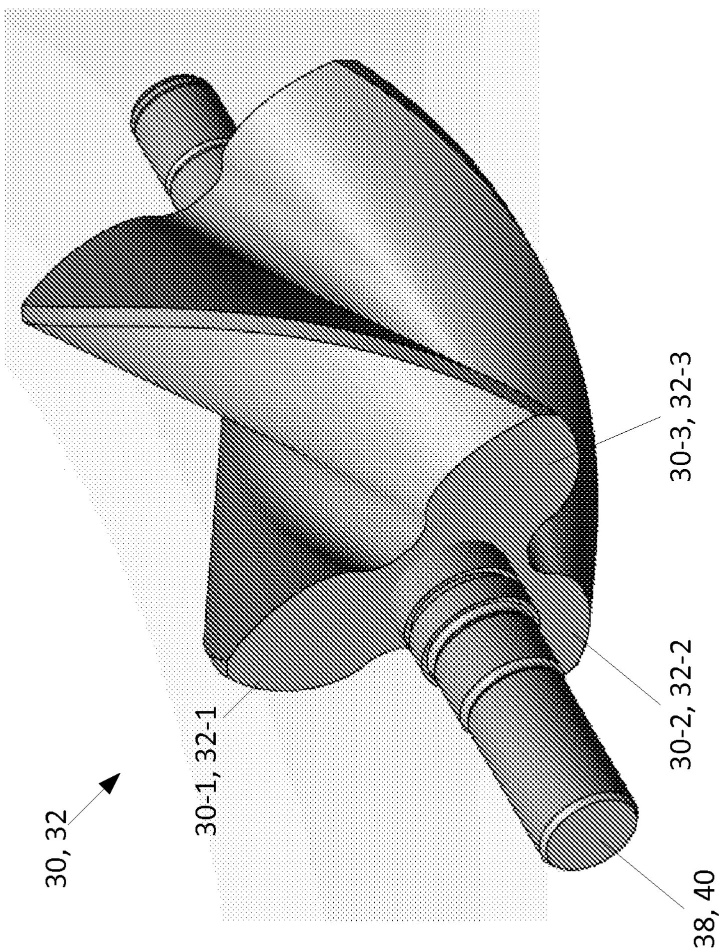
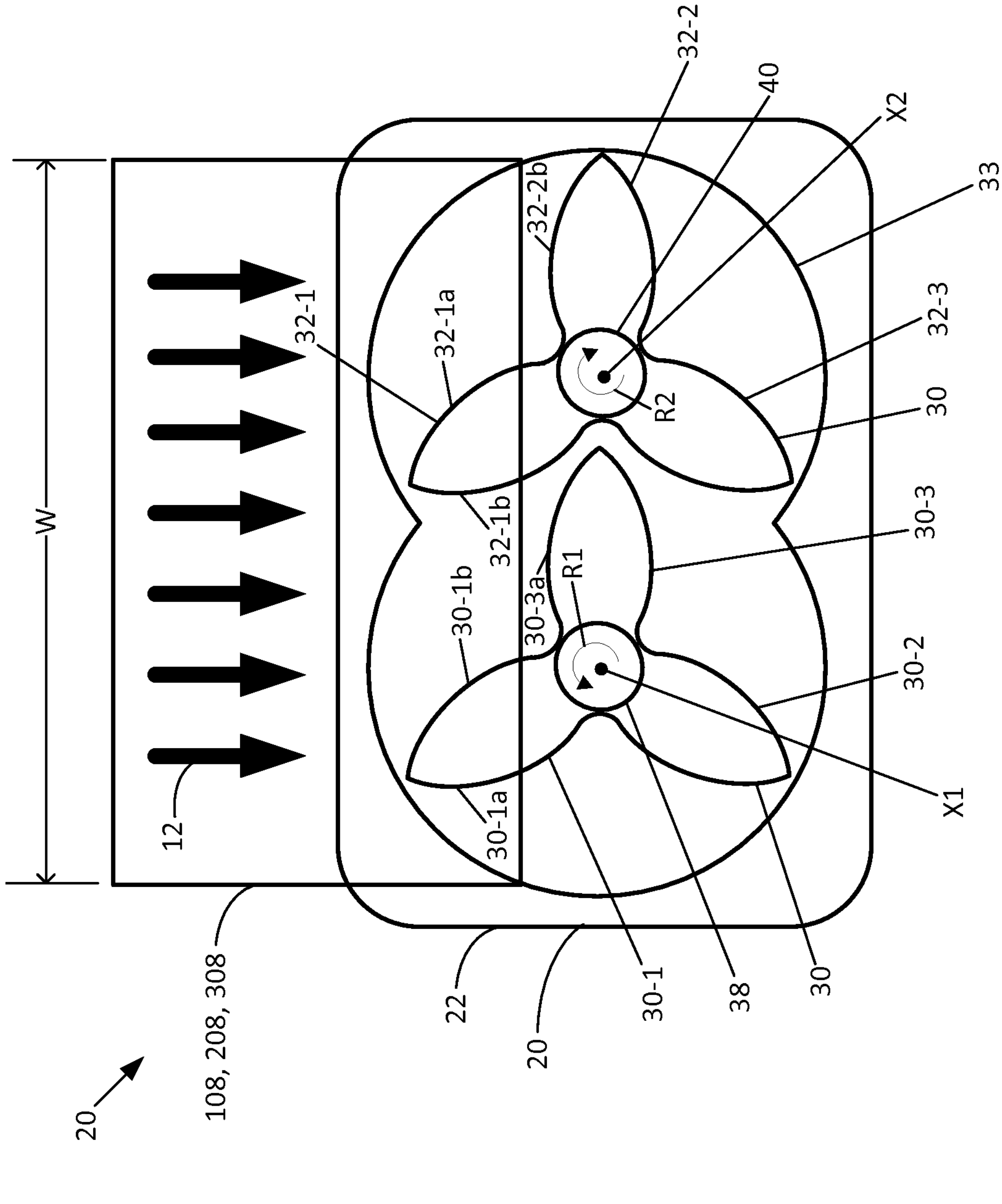


FIG. 8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X2
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R2

FIG. 9

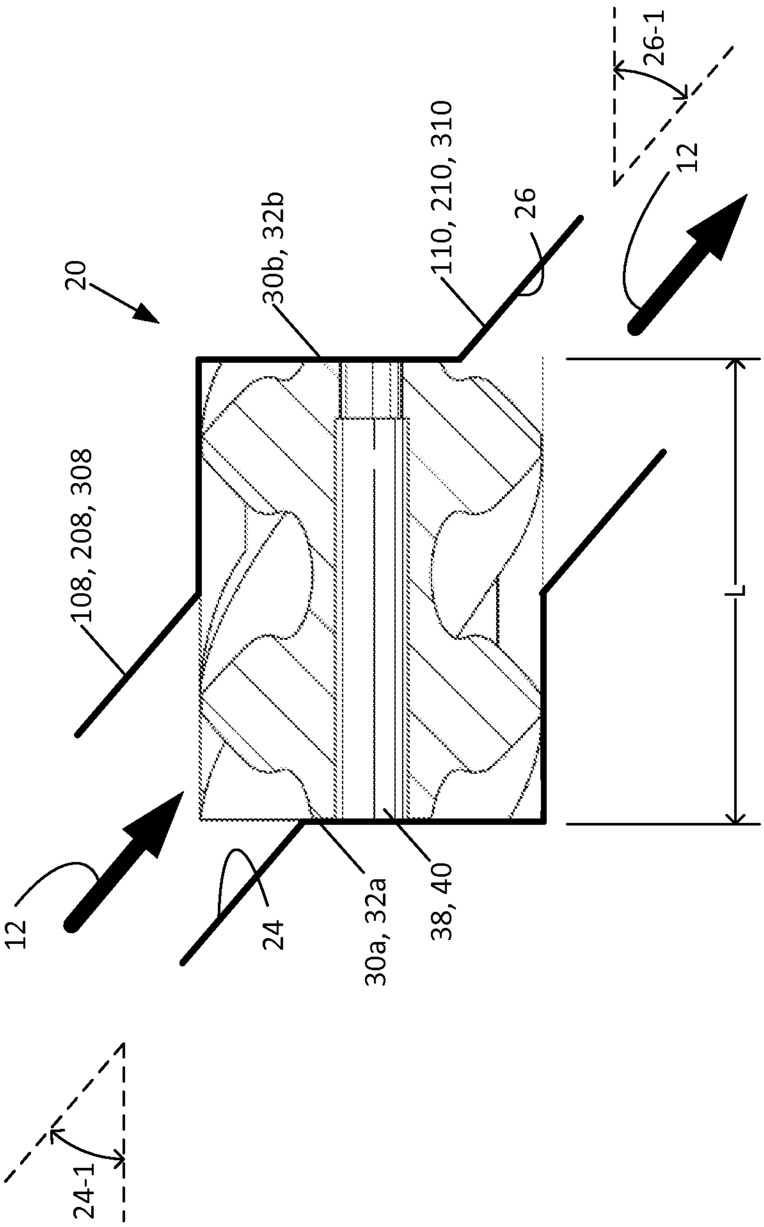
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FIG. 10

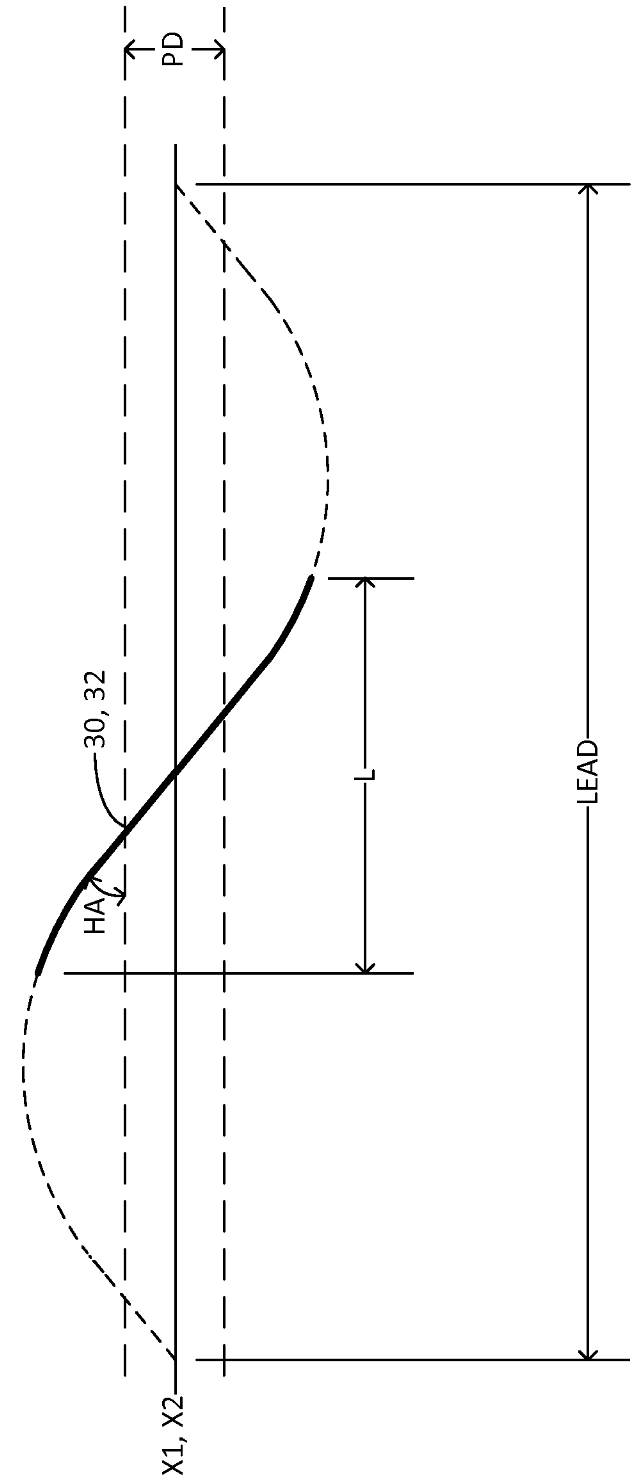

FIG. 11

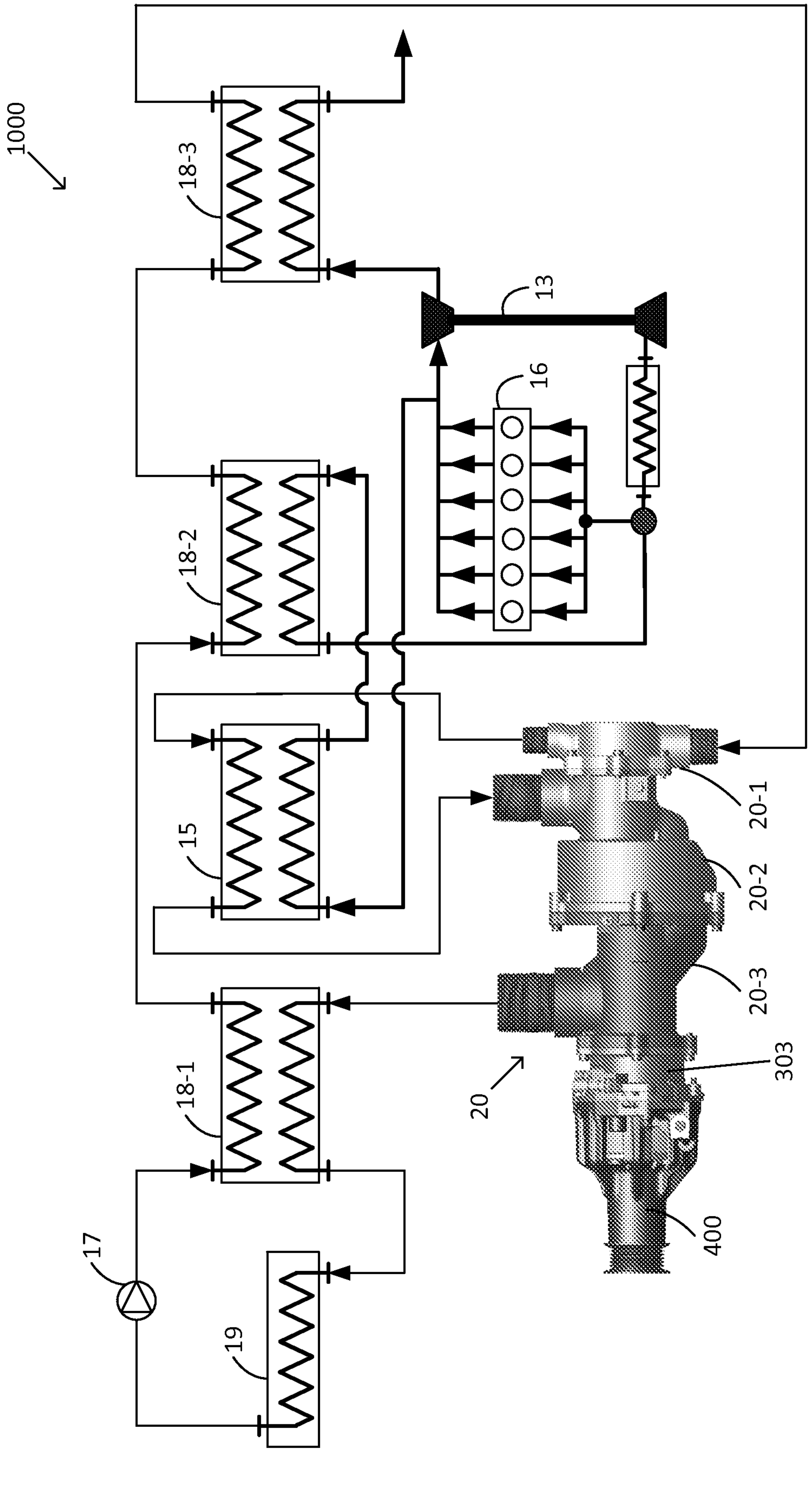

FIG. 12

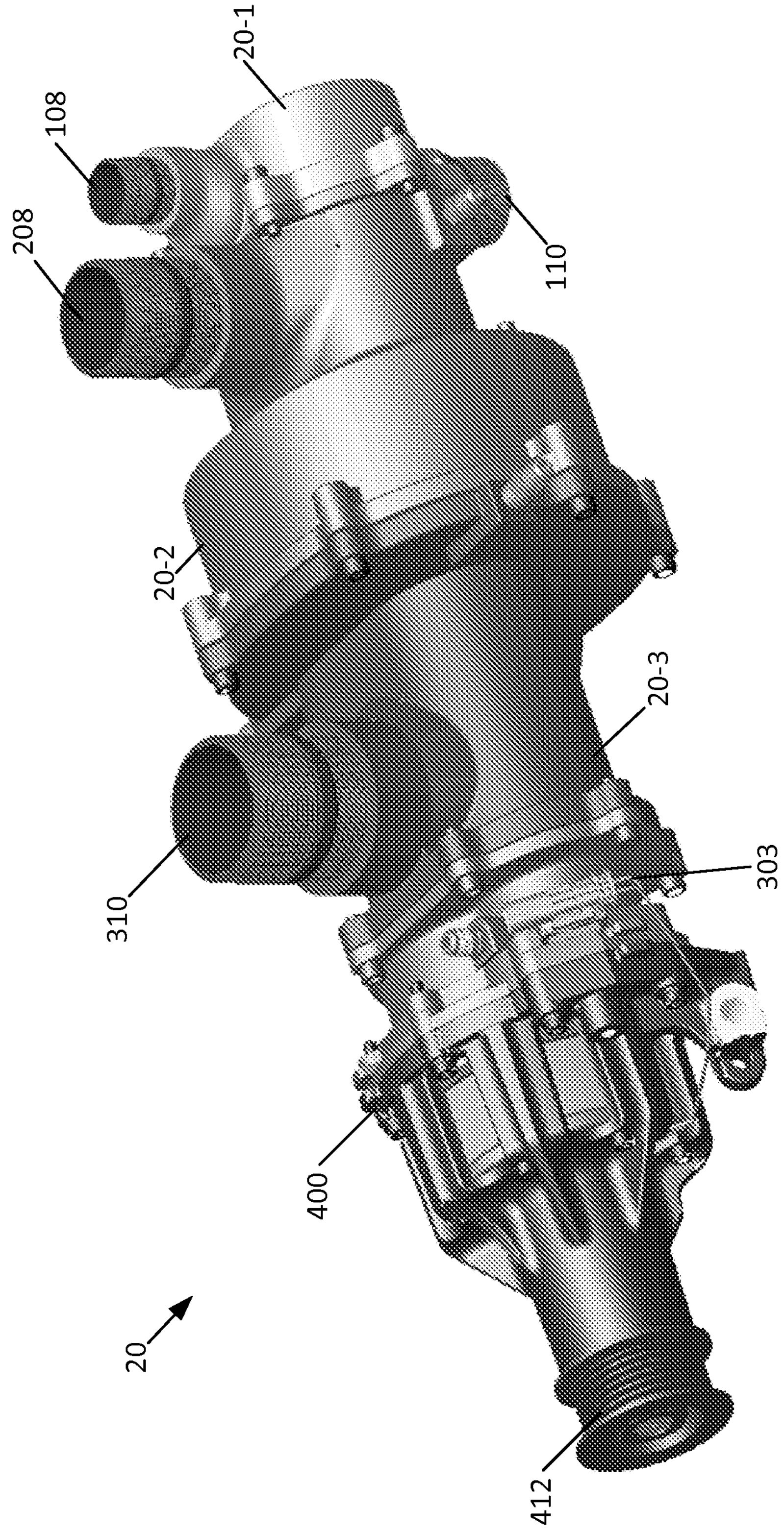

FIG. 13

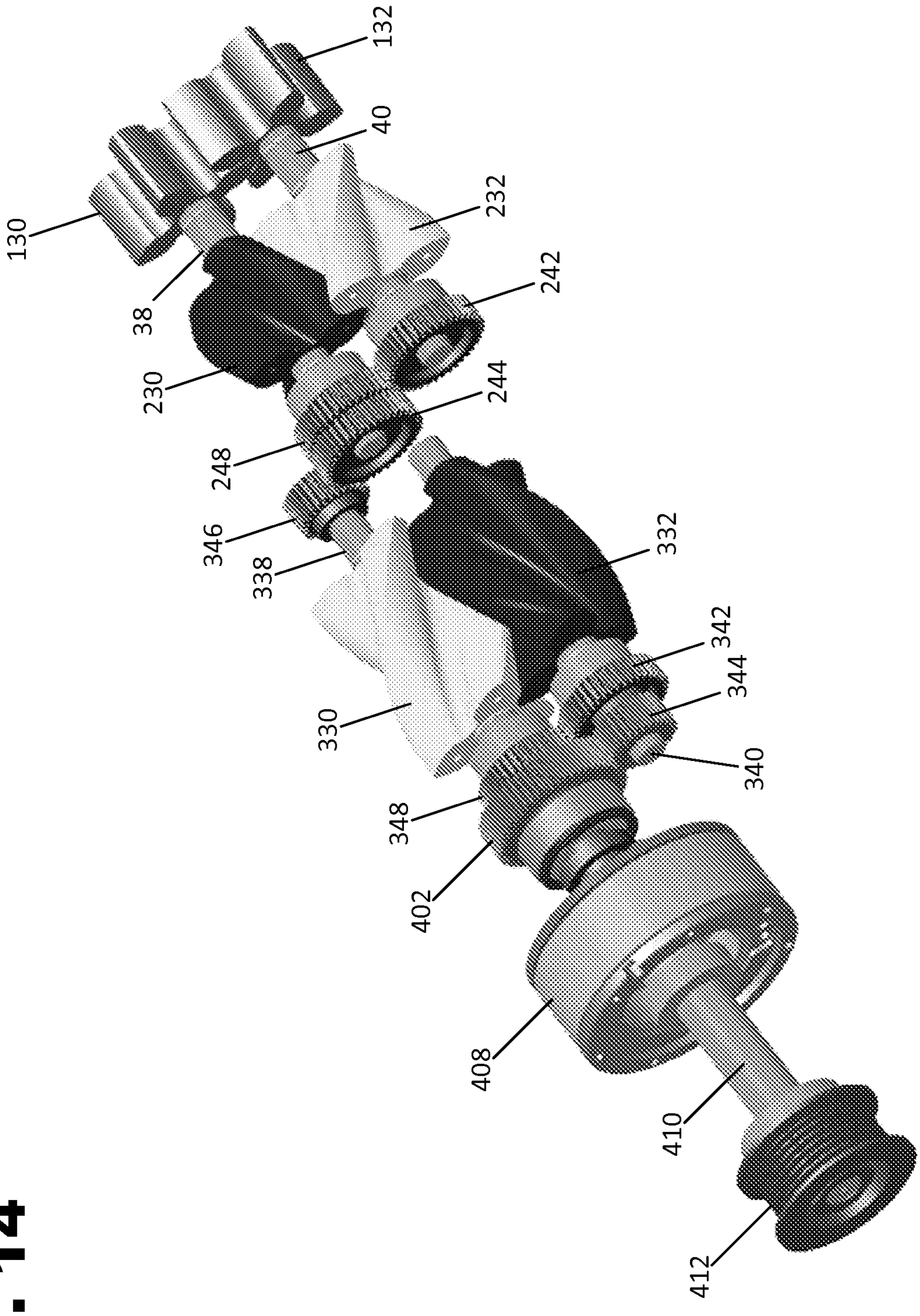
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FIG. 14

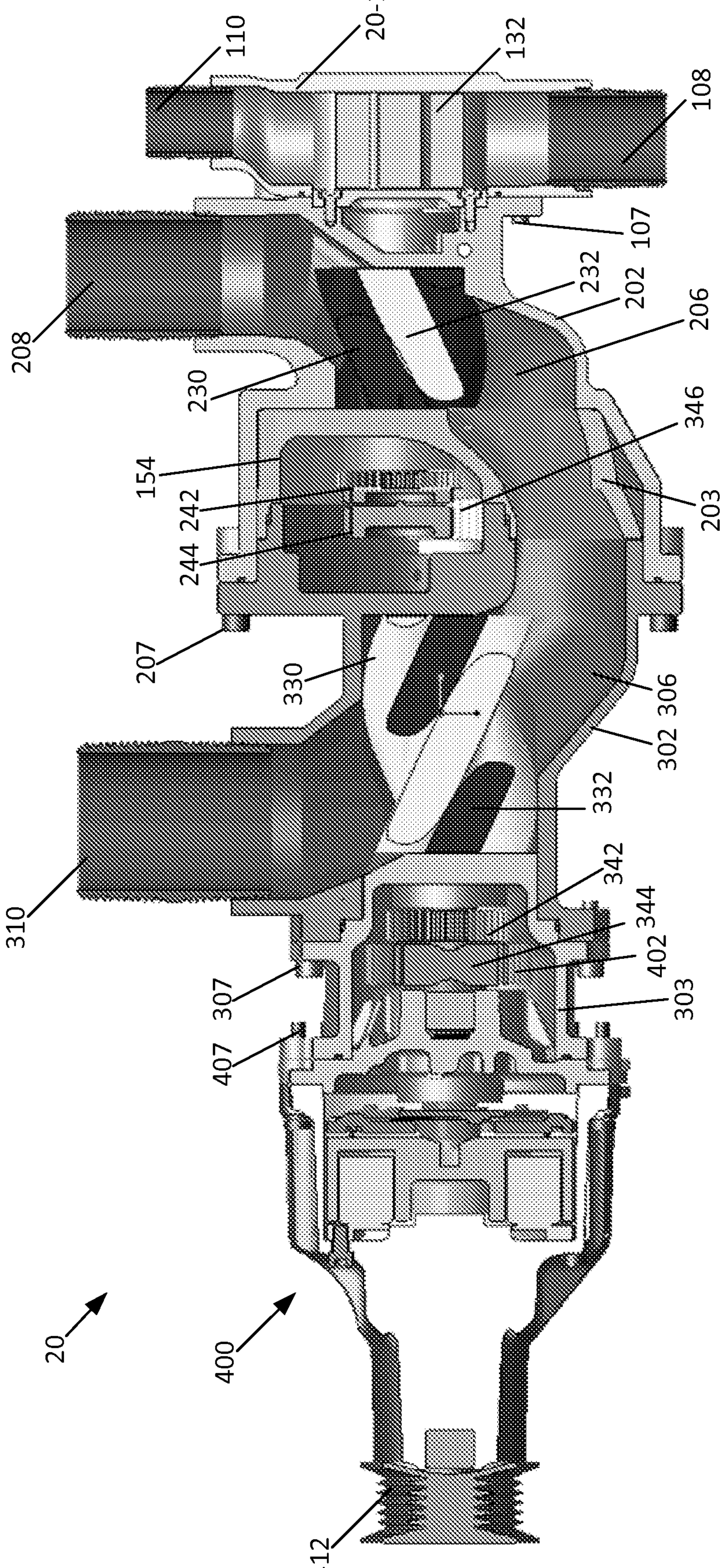
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FIG. 15

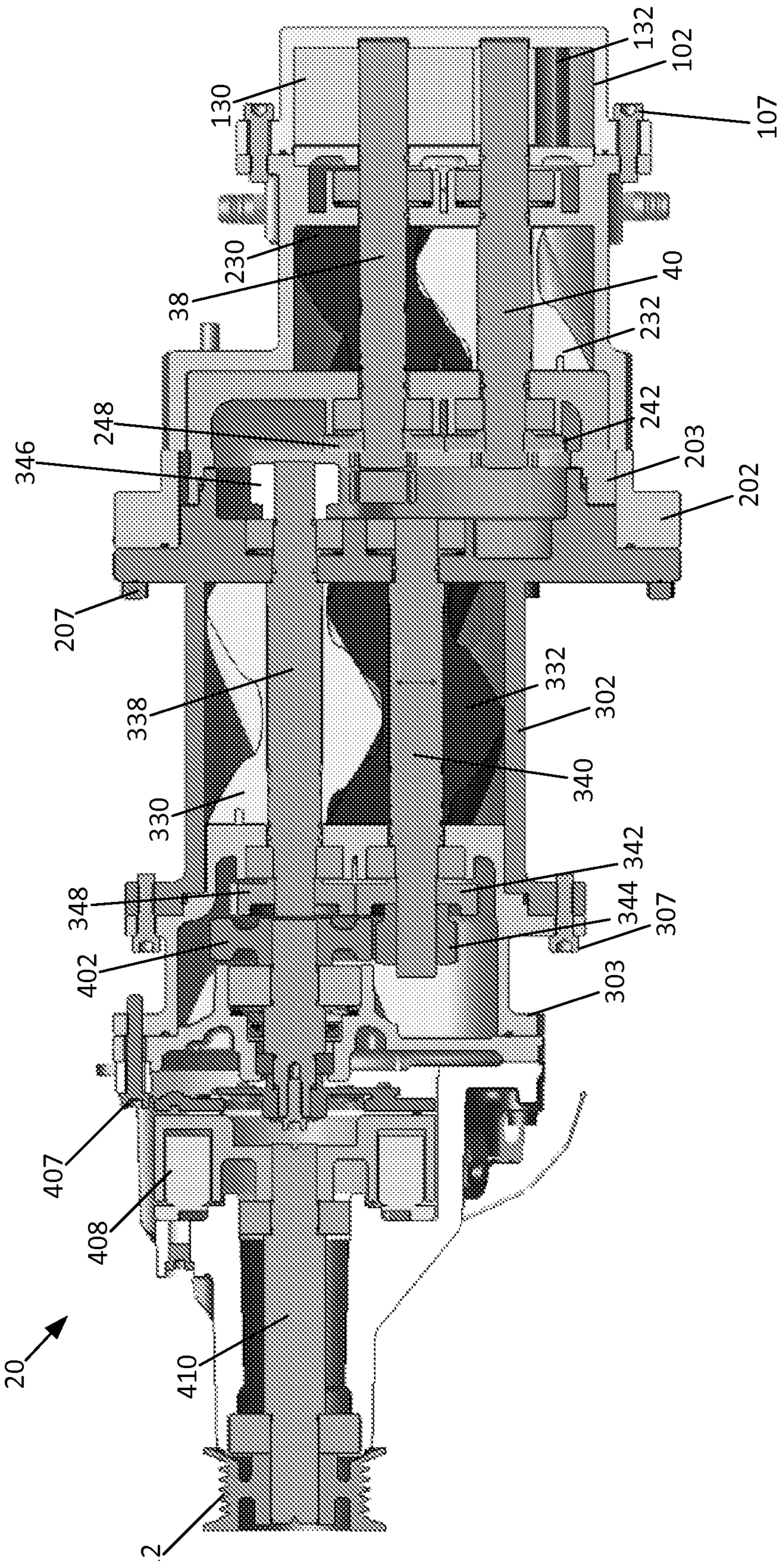
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FIG. 16

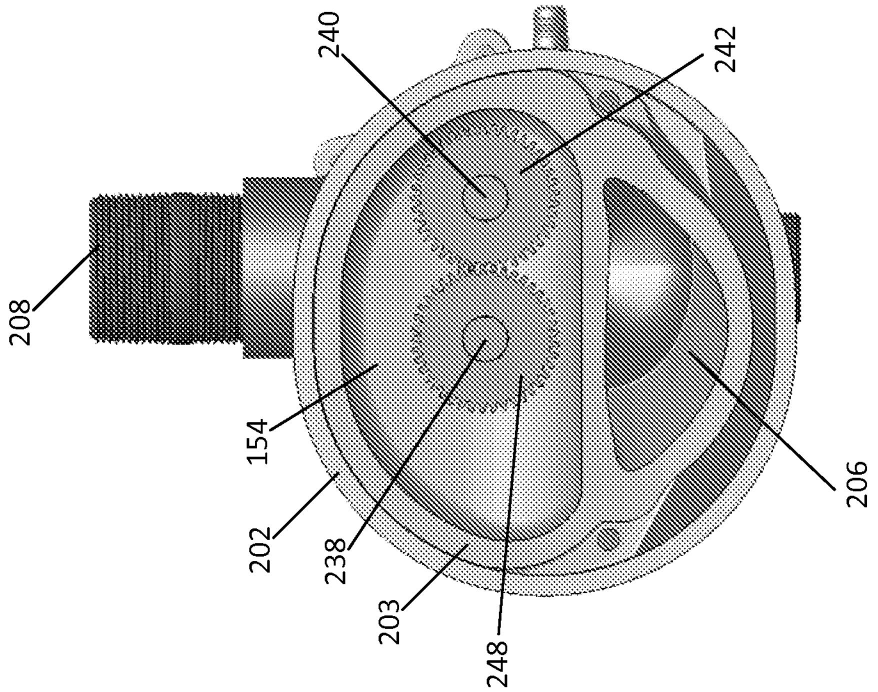
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FIG. 18

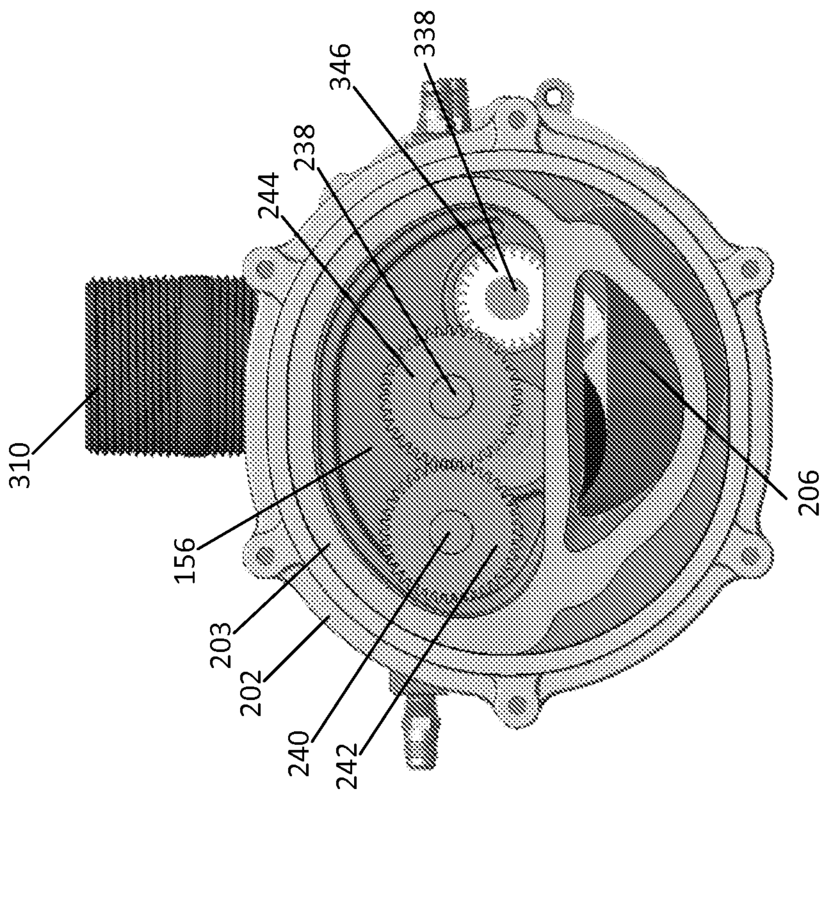
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FIG. 17

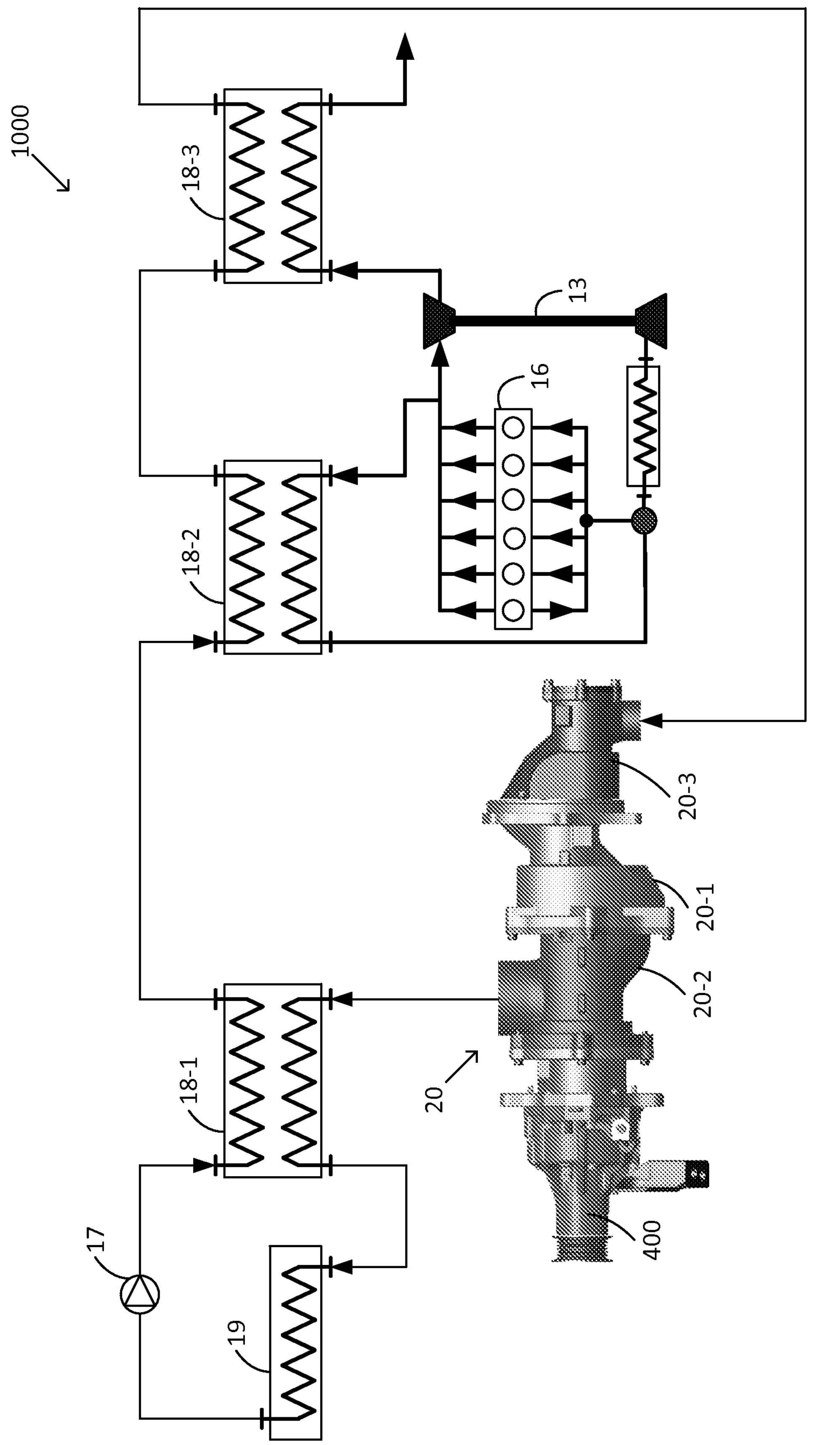

FIG. 19

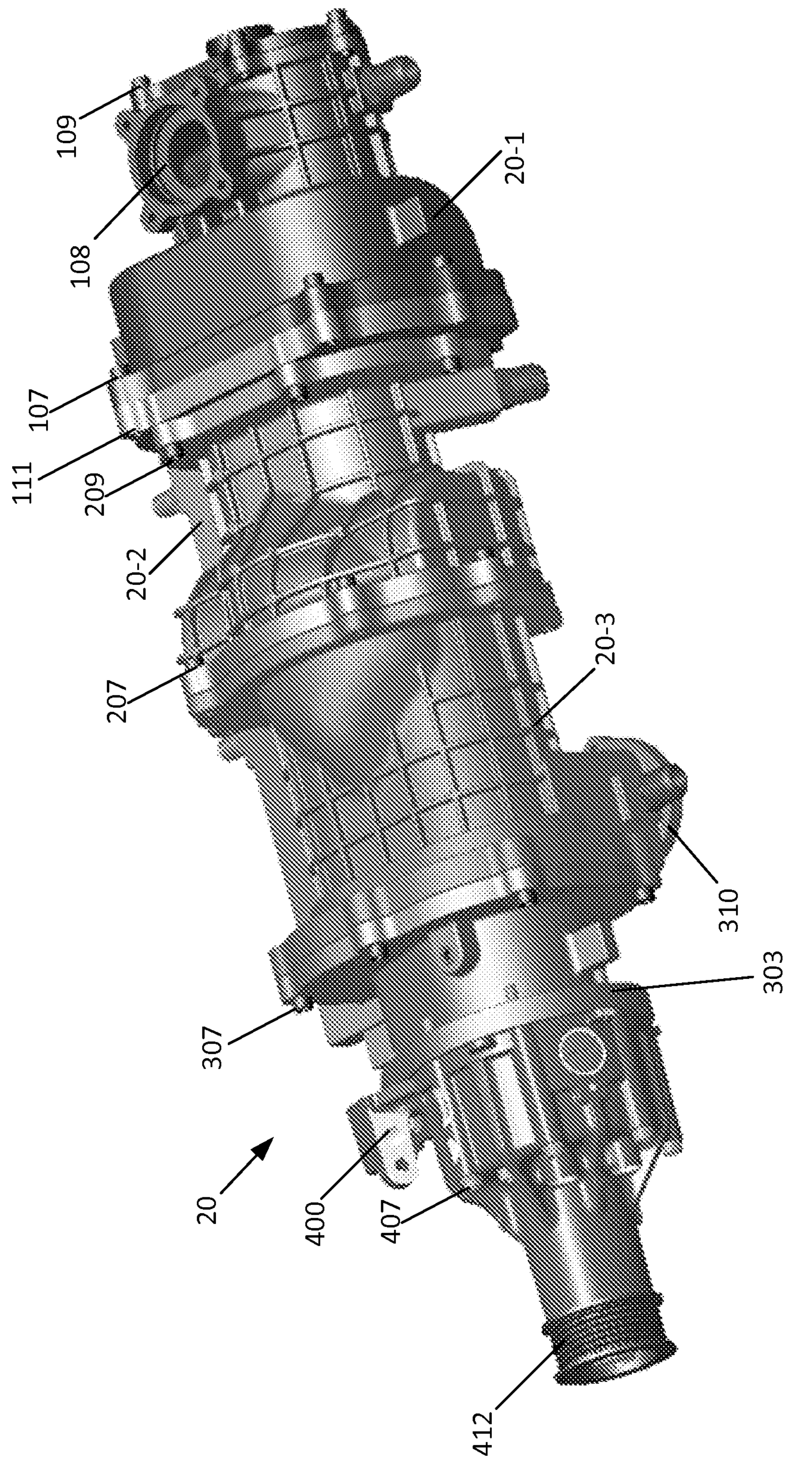

FIG. 20

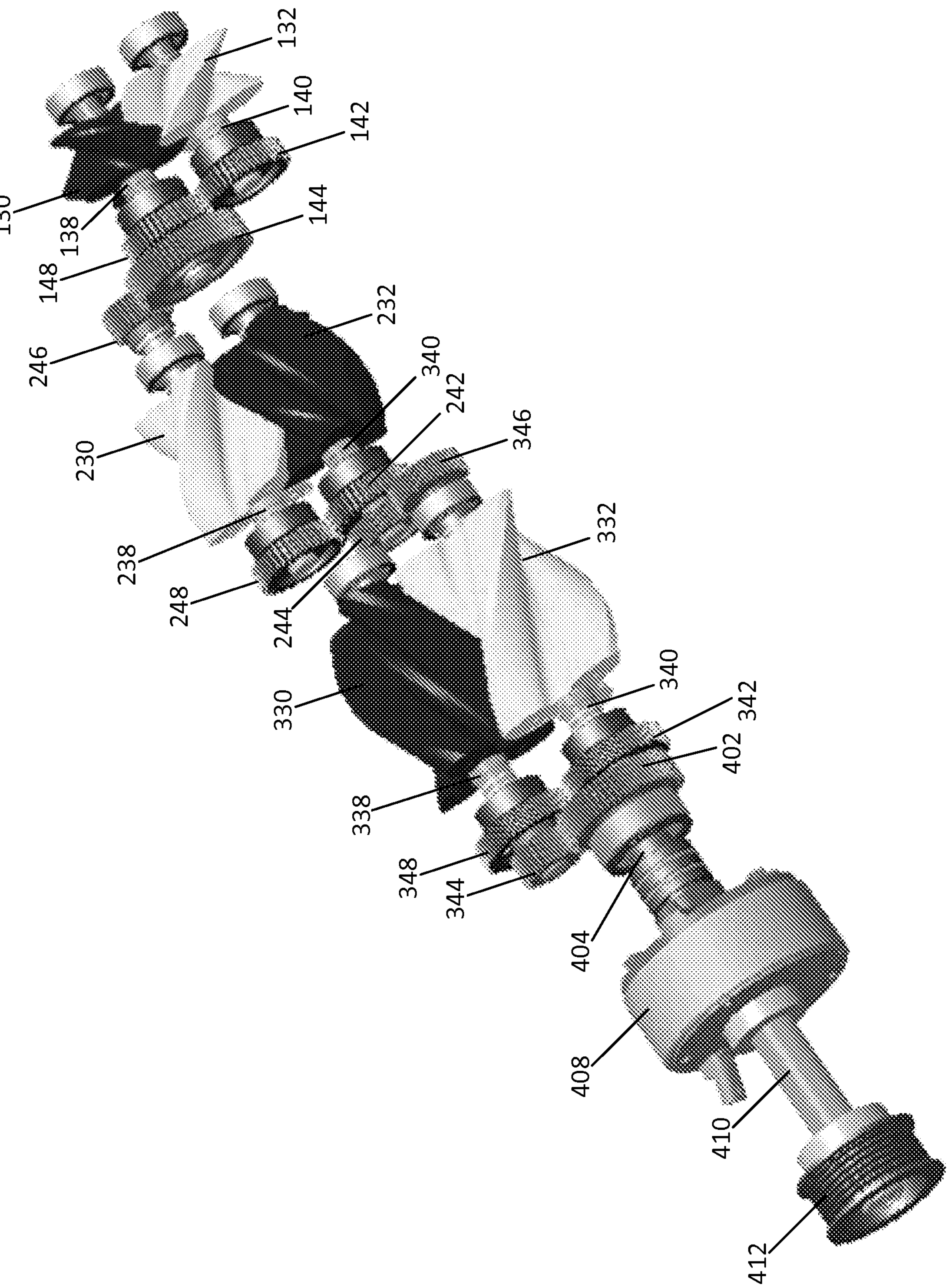
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FIG. 21

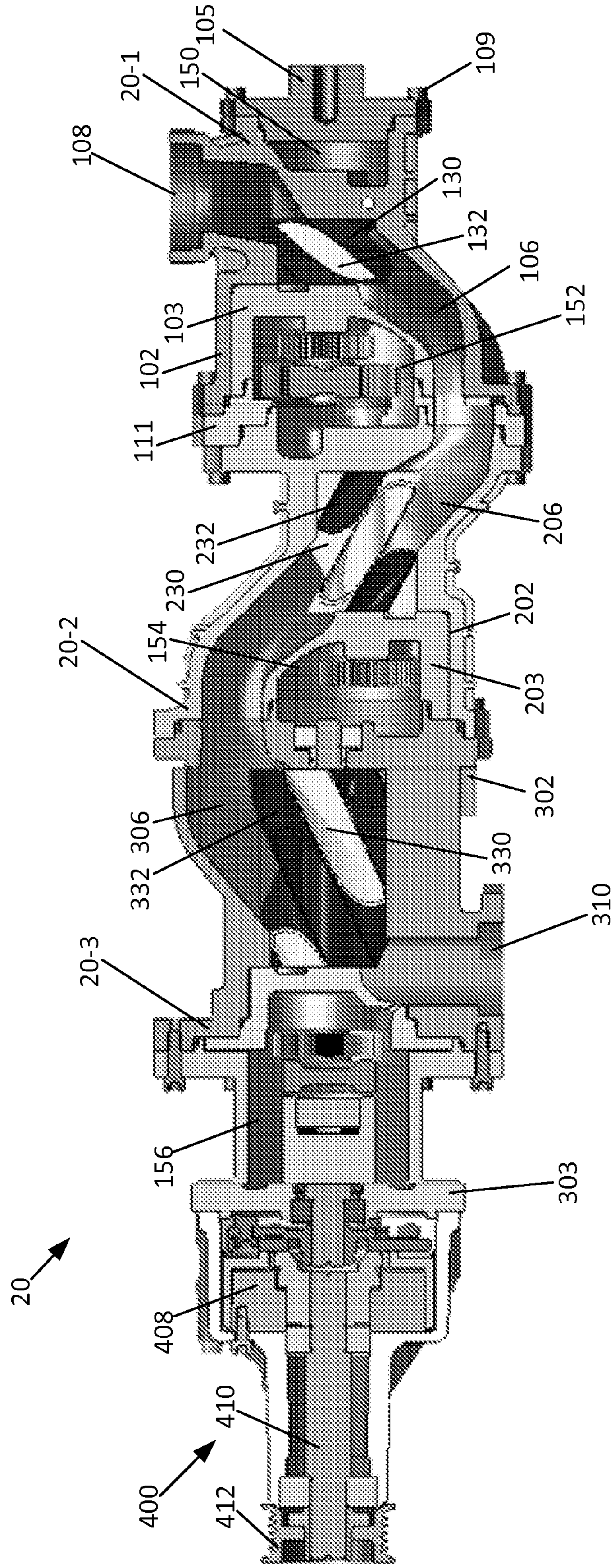
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FIG. 22

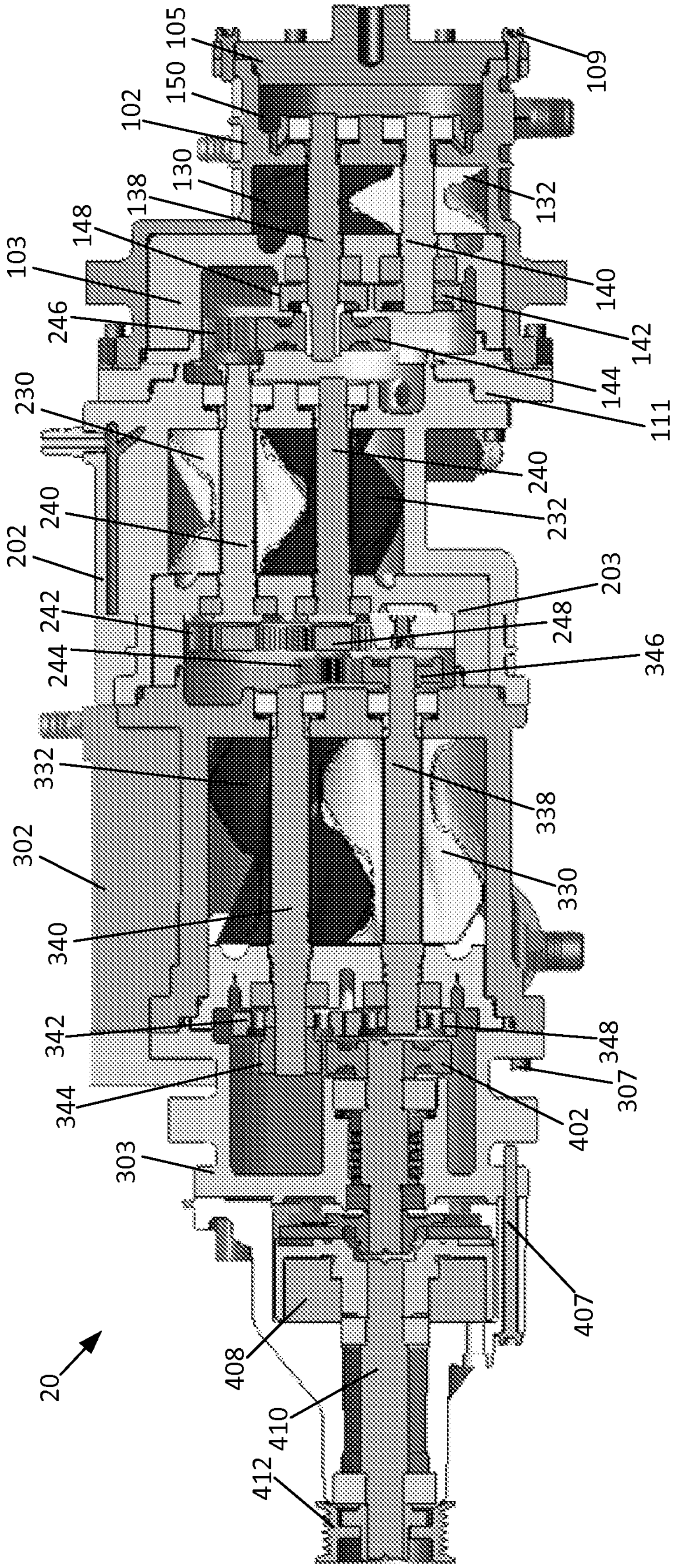
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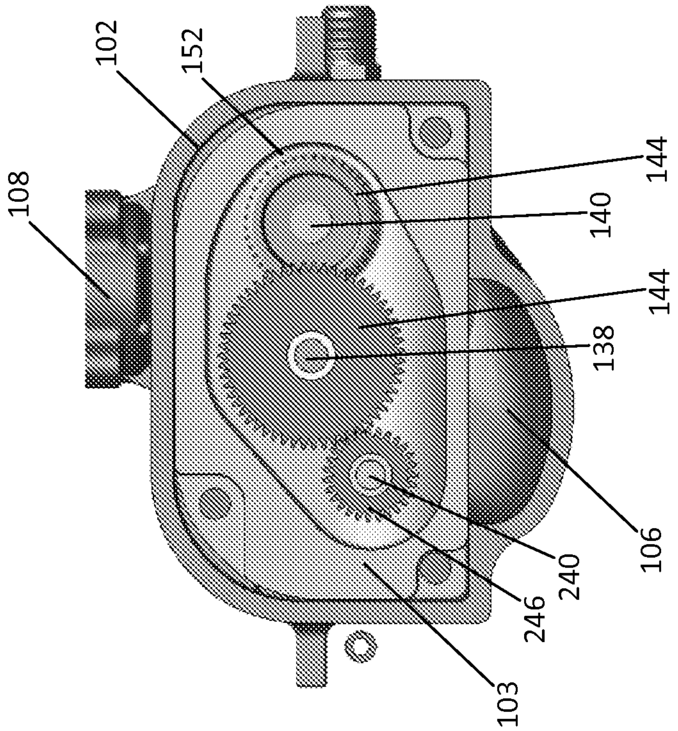
FIG. 23

FIG. 25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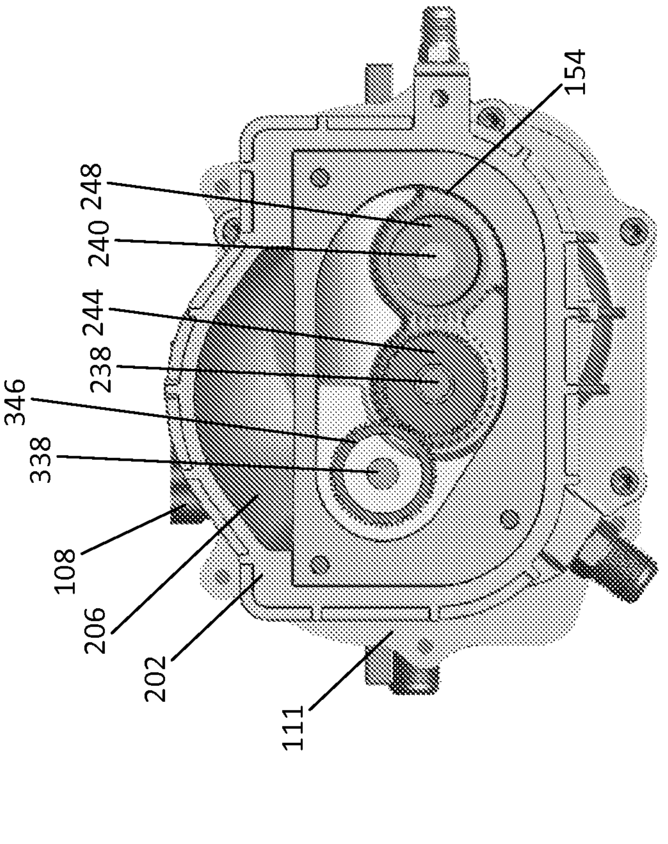
103

FIG. 24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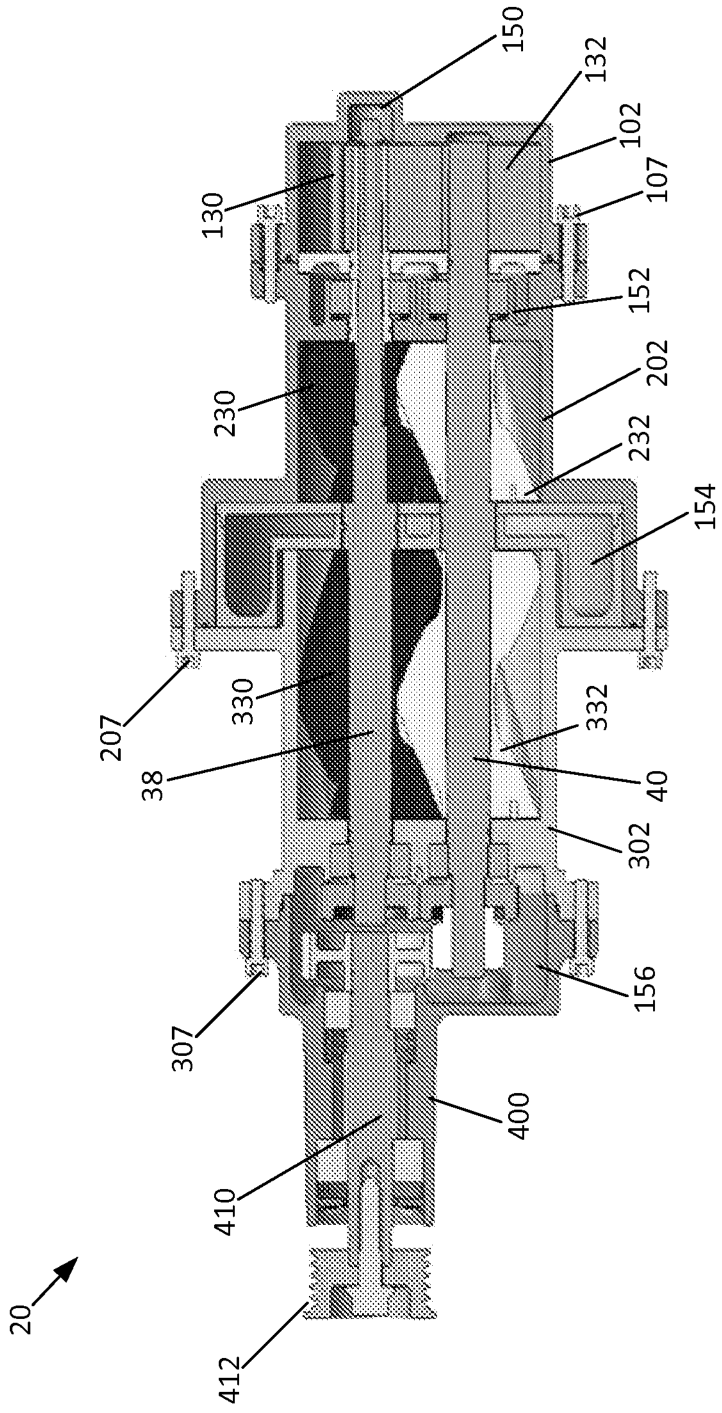
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FIG. 26

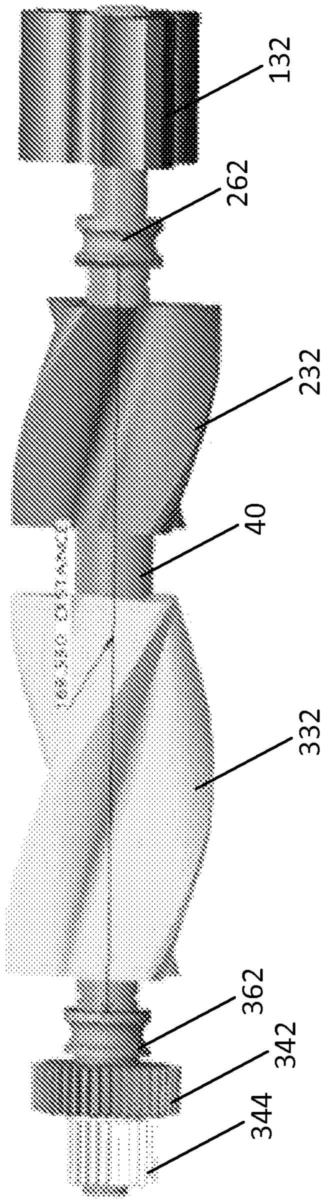

FIG. 27

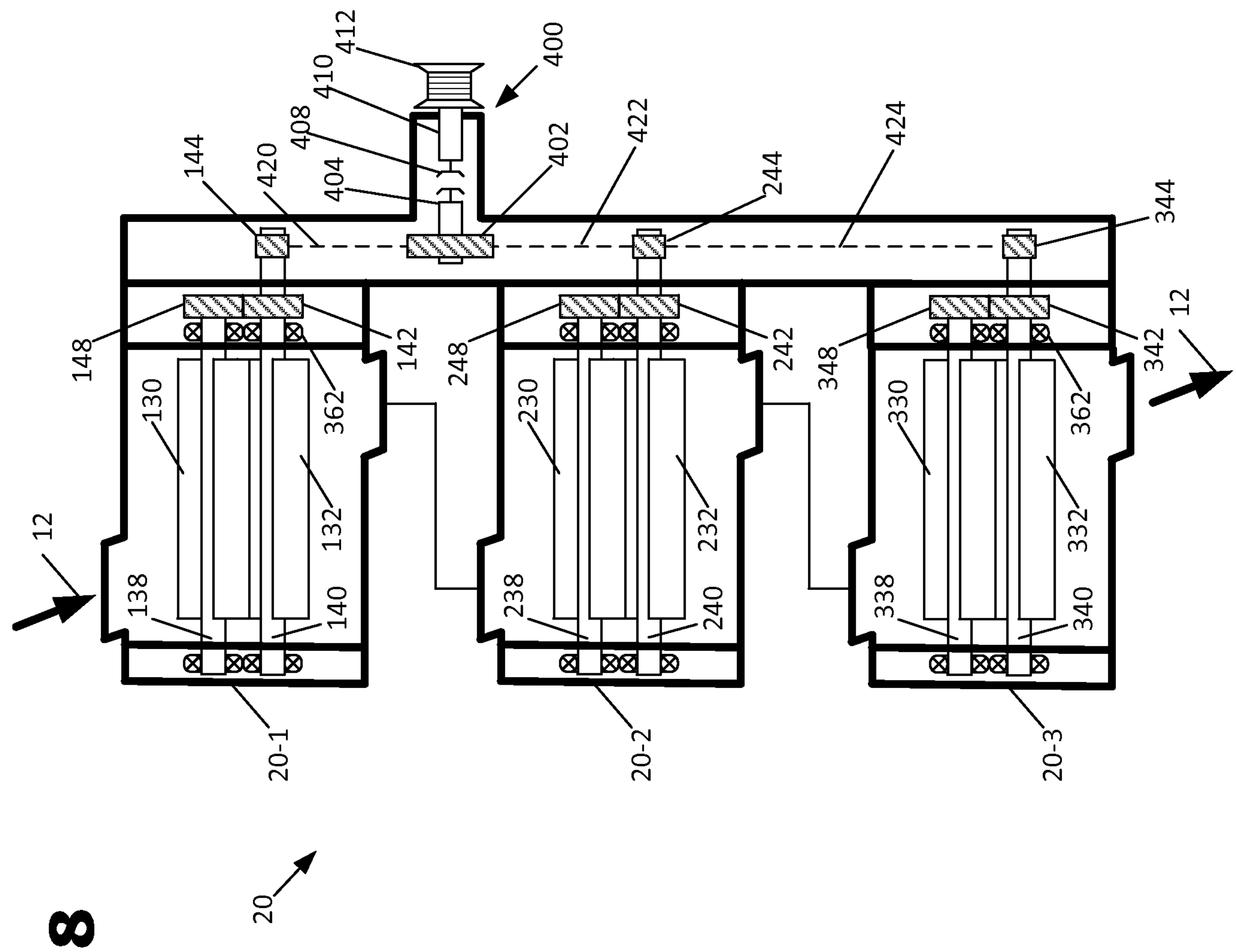
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FIG. 28

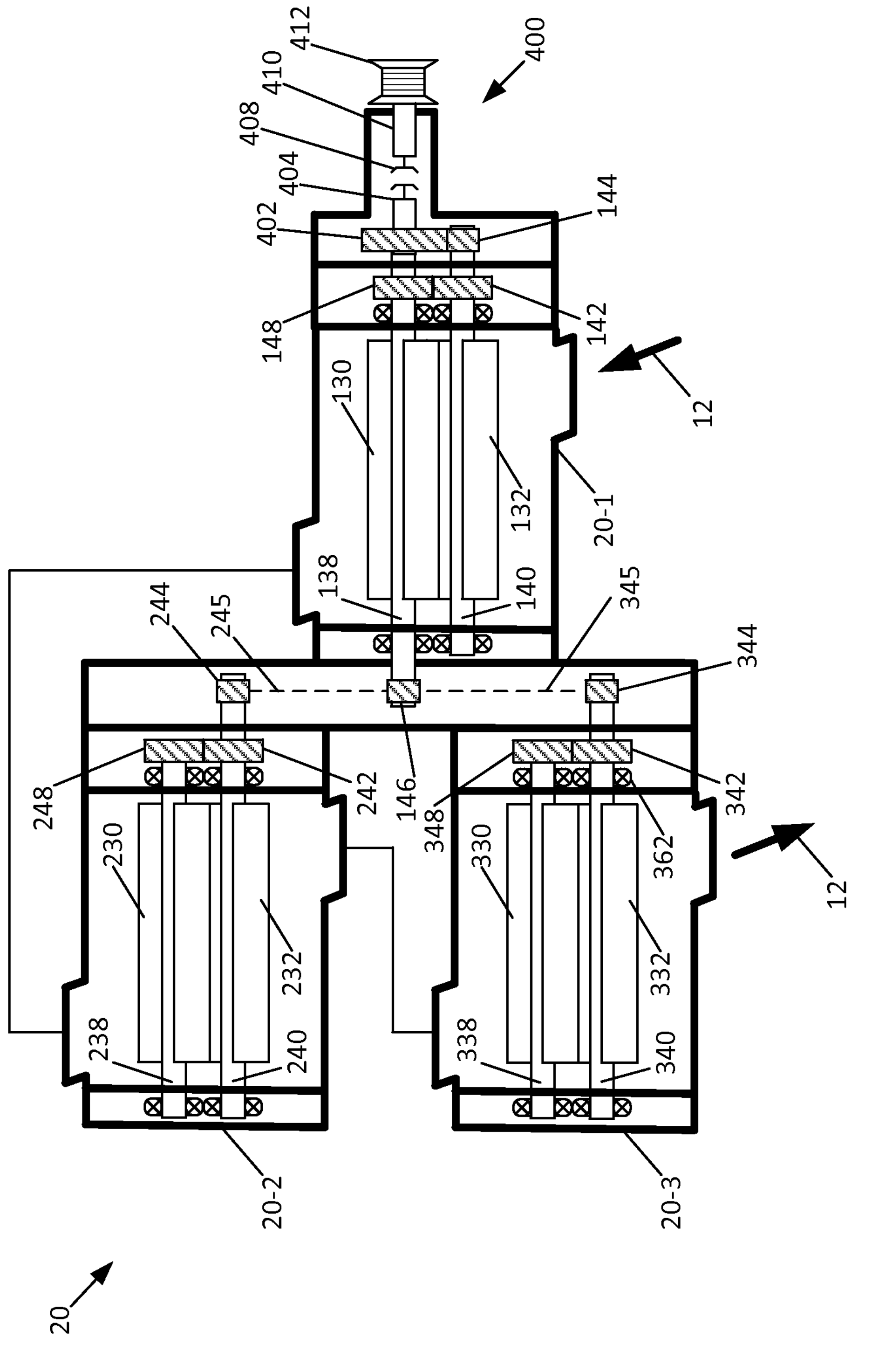
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FIG. 29

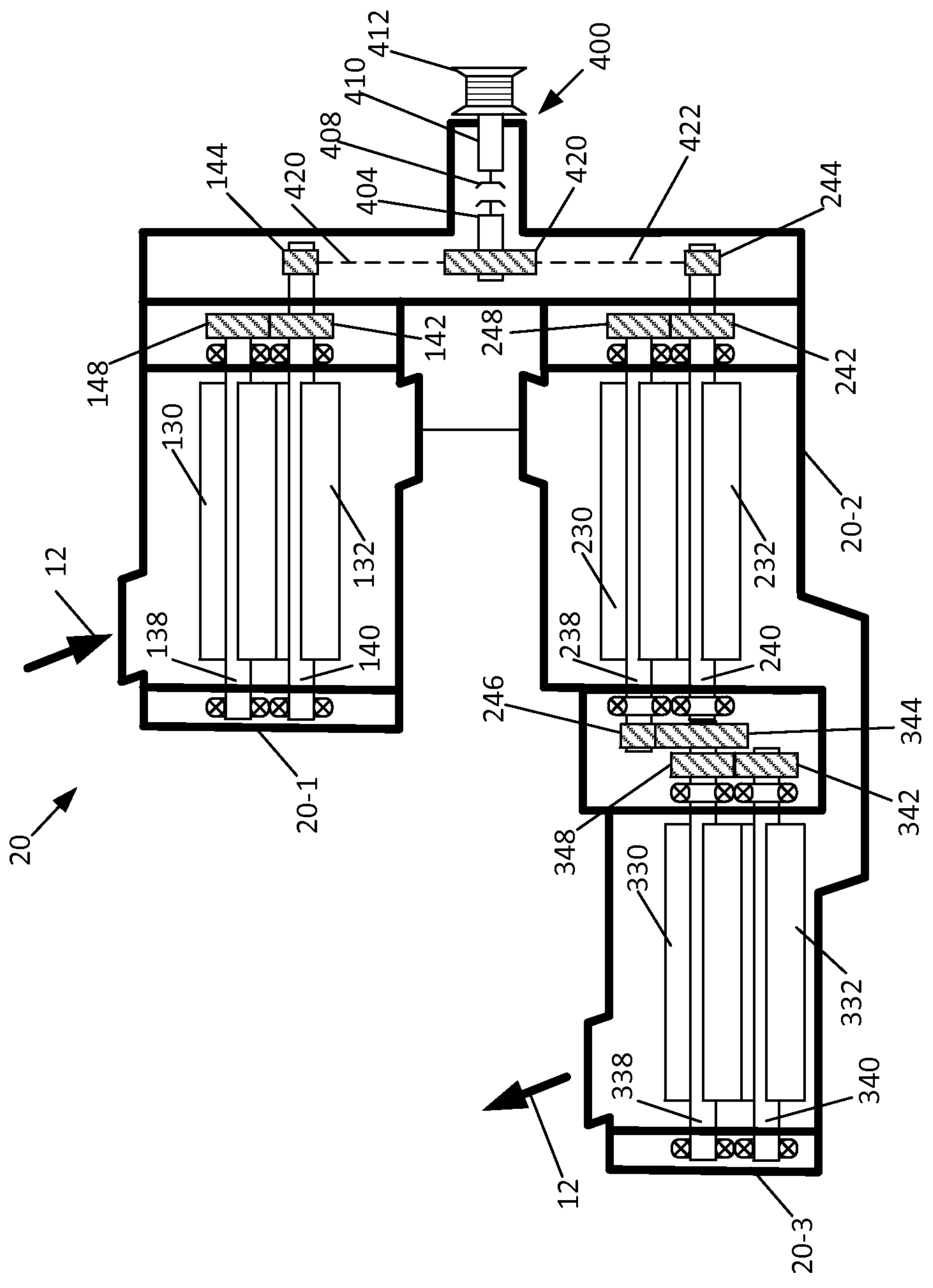
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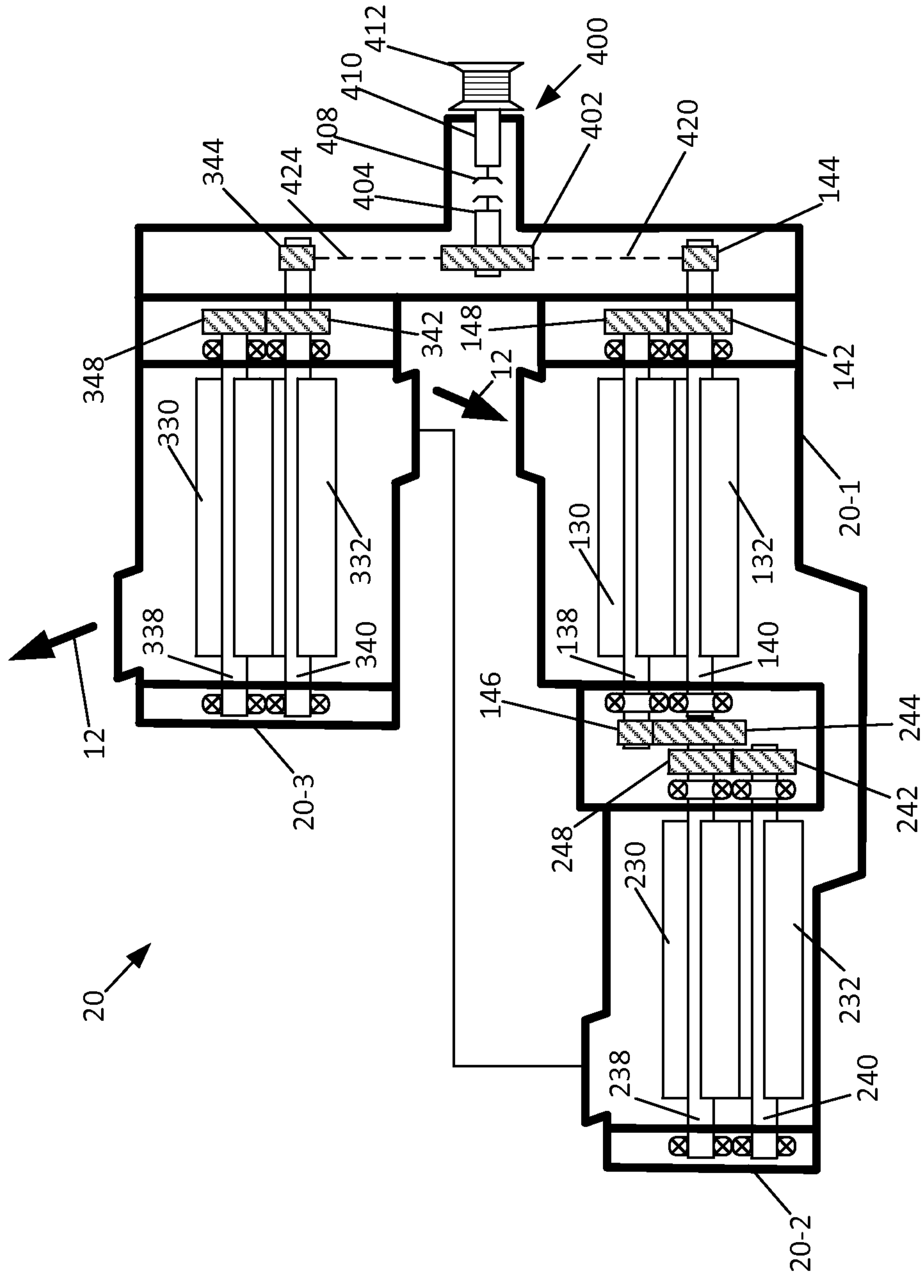
FIG. 30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20-2

FIG. 31

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/013401

A. CLASSIFICATION OF SUBJECT MATTER
INV. F01K7/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2012/143799 A1 (EXERGY ORC S R L [IT]; SPADACINI CLAUDIO [IT]; RIZZI DARIO [IT]; BARBA) 26 October 2012 (2012-10-26)	1-12, 14-30, 32-39, 41-51
Y	abstract; figures 1, 2 page 5, line 30 - page 6, line 34 page 9, line 15 - page 11, line 29 -----	13,31,40
Y	US 2010/192574 A1 (LANGSON RICHARD K [US]) 5 August 2010 (2010-08-05) abstract; figures 2, 6-9 paragraphs [0004], [0011], [0032] - [0039], [0043], [0044] -----	13,31,40
A	DE 10 2010 034230 A1 (DAIMLER AG [DE]) 9 February 2012 (2012-02-09) the whole document -----	1-51

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 May 2014	19/05/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Varelas, Dimitrios

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/013401

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		EP 2699767 A1	26-02-2014
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DE 102010034230 A1	09-02-2012	CN 103270247 A	28-08-2013
		DE 102010034230 A1	09-02-2012
		EP 2601389 A2	12-06-2013
		JP 2013536351 A	19-09-2013
		WO 2012019706 A2	16-02-2012