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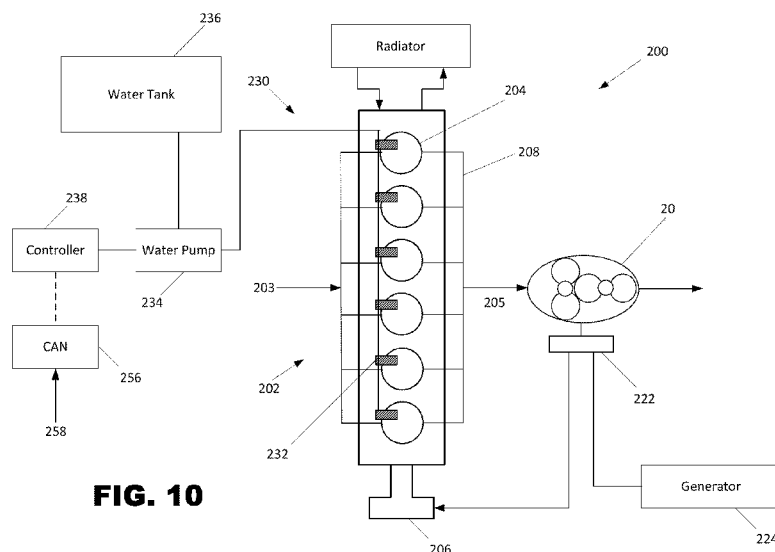
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**FIG. 10**

(57) Abstract: An exhaust gas energy recovery system includes an internal combustion engine, a volumetric fluid expander, and a water injection mechanism. The internal combustion engine includes an air inlet, at least one cylinder, and an exhaust gas outlet for conveying an exhaust gas stream at a first pressure. The volumetric fluid expander generates useful work at an output shaft by expanding the exhaust gas stream to a second pressure lower than the first pressure as the exhaust gas stream moves through the volumetric fluid expander. The water injection mechanism injects water into the system at a location between the air inlet of the engine and the expander to increase the volume of the exhaust received by the expander for increased power output at the expander.

VOLUMETRIC FLUID EXPANDER WITH WATER INJECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is being filed on June 30, 2016 as a PCT International Patent Application and claims the benefit of U.S. Patent Application Serial No. 14/790,745, filed on July 2, 2015, the disclosure of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to systems and methods for increasing the output of a volumetric fluid expander that utilizes exhaust gases as a working fluid.

BACKGROUND

[0003] 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

[0004] Various aspects are described in this disclosure, which include, but are not limited to, the following aspects. In general, an exhaust gas energy recovery system for an internal combustion engine having an air intake and an exhaust outlet is disclosed. The energy recovery system can include a water injection system that expands the volume of a working fluid (e.g. exhaust) received by a volumetric fluid expander. The water injection mechanism can include a water injector and a pump for providing pressurized water to the water injector. In one aspect, the water injector is positioned to inject water at a location between the air intake and the volumetric fluid expander to cause a volumetric expansion. Example locations are: at the air intake, upstream of a supercharger or turbocharger, in the

intake manifold, in the cylinders of the engine, in the exhaust manifold of the engine, and at a location between the engine and the fluid expander.

[0005] In one aspect of the disclosure, the volumetric fluid expander is provided to generate useful work by expanding a working fluid. In one application, the volumetric fluid expander 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 could be the case when the power plant is used as a generator. In one possible configuration and by non-limiting example, the volumetric fluid expander is used for an internal combustion engine with a water injection mechanism.

[0006] In one example, the working fluid is all or part of the exhaust gas stream from an internal combustion engine or a fuel cell. In another example, the working fluid is separate from and heated by a waste heat stream from an internal combustion engine or a fuel cell, such as is disclosed in Patent Cooperation Treaty International Publication Number WO 2013/130774. WO 2013/130774 discloses that the working fluid can be used in a Rankine cycle where the working fluid may be a solvent such as ethanol, n-pentane, or toluene. The entirety of WO 2013/120774 is hereby incorporated by reference herein.

[0007] As shown, the volumetric fluid expander includes a housing having an inlet port configured to admit the working fluid at a first pressure and an outlet port configured to discharge the working fluid at a second pressure lower than the first pressure. The expander also includes first and second twisted meshed rotors rotatably disposed in the housing that are configured to be rotated by the working fluid and to transfer the working fluid from the inlet to the outlet. Each rotor is provided with a plurality of lobes oriented such that when one lobe of the first rotor is leading with respect to the inlet port, one lobe of the second rotor is trailing with respect to the inlet port. The expander additionally includes an output shaft that is rotated by movement of the rotors such that energy recovered by the volumetric fluid expander can be transferred back to the power plant.

[0008] In another aspect of the disclosure, an exhaust gas energy recovery system is provided. The system includes an internal combustion engine, a volumetric fluid expander, and a water injection mechanism. The combustion engine includes at least one cylinder and an exhaust gas outlet for conveying an exhaust gas stream at a first pressure. The volumetric fluid expander includes a housing and an output shaft. The housing has an inlet and an outlet, and the inlet is in fluid communication with the exhaust gas outlet. The volumetric fluid expander is configured to generate useful work at the output shaft by

expanding the exhaust gas stream to a second pressure lower than the first pressure generally without reducing the volume of the exhaust gas stream as the exhaust gas stream moves from the housing inlet to the outlet. In some embodiments, the volumetric fluid expander includes first and second twisted meshed rotors rotatably disposed in the housing. The rotors have an equal number of lobes, and the lobes of the first rotor do not contact the lobes of the second rotor.

[0009] The water injection mechanism is configured to inject water into the cylinder at an exhaust cycle of the cylinder. In some embodiments, the water injection mechanism is configured to inject water into the cylinder before the exhaust cycle of the cylinder begins. The water injection mechanism may include a plurality of water injectors, a water pump device, a water reservoir tank, and a controller. The water injector is configured to inject water into the cylinder. The water pump device is connected to the water injector, and the water tank is connected to the water pump device. The controller may be configured to control the water injector to selectively inject water into the cylinder at or before the exhaust cycle of the cylinder.

[0010] The output shaft of the volumetric fluid expander may be coupled to an output shaft of the combustion engine, a hydraulic motor and/or a generator.

[0011] In yet another aspect of the disclosure, a method for recovering exhaust gas energy is provided. The method includes injecting, by a water injection mechanism, water into a cylinder of an engine at an exhaust cycle of the cylinder, wherein the injected water vaporizes within the cylinder; collecting, via an exhaust manifold of the engine, exhaust gas stream mixed with the vaporized water; supplying the exhaust gas stream into a volumetric fluid expander, the exhaust gas stream having a first pressure; and generating, by the volumetric fluid expander, useful work at an output shaft of the expander by expanding the exhaust gas stream to a second pressure lower than the first pressure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 is a cross-sectional side view of a first embodiment of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure.

[0013] Figure 2 is a schematic perspective top view of the volumetric fluid expander shown in Figure 1.

[0014] Figure 3 is a side perspective view of a second embodiment of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure.

[0015] Figure 4 is a cross-sectional side perspective view of the volumetric fluid expander shown in Figure 3.

[0016] Figure 5 is a schematic showing geometric parameters of the rotors of the volumetric fluid expanders shown in Figures 1 and 3.

[0017] Figure 6 is a schematic showing the rotors of the volumetric fluid expanders shown in Figures 1 and 3.

[0018] Figure 7 is a perspective view of a rotor usable in the volumetric fluid expanders shown in Figures 1 and 3.

[0019] Figure 8 is a schematic view of one embodiment of the energy recovery system with a volumetric fluid expander of the type shown in Figures 1 to 7 and a water injection mechanism.

[0020] Figure 9 is a schematic showing possible locations for the water injection mechanism shown in Figure 8.

[0021] Figure 10 is a schematic view of one embodiment of the energy recovery system with a volumetric fluid expander of the type shown in Figures 1 to 7 and a water injection mechanism.

[0022] Figure 11 is a schematic view of an example cylinder with the water injection mechanism of Figure 10.

DETAILED DESCRIPTION

[0023] 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.

Volumetric Fluid expander

[0024] Referring now to figures 1-4, two embodiments (Figures 1-2 and Figures 3-4) of a volumetric fluid expander 20 are shown. It is noted that the same reference numbers are utilized for both embodiments where the features are generally similar. The following description is fully applicable for each embodiment. The volumetric fluid expander 20

may also be referred to herein as an expander, expansion device or volumetric energy recovery device. An energy recovery system can be formed by coupling components with the output of the volumetric fluid expander that transfers energy back to the power plant directly or indirectly.

[0025] As shown, expansion device 20 has a housing 22 with a fluid inlet 24 and a fluid outlet 26 through which the fluid 12-1 undergoes a pressure drop to transfer energy to the output shaft 38. The inlet port 24 is configured to admit the working fluid 12-1 at a first pressure whereas the outlet port 26 is configured to discharge the working fluid 12-2 at a second pressure lower than the first pressure. The output shaft 38 is driven by synchronously connected first and second interleaved counter-rotating rotors 30, 32 which are disposed in a cavity 28 of the housing 22. Each of the rotors 30, 32 has lobes that are twisted or helically disposed along the length of the rotors 30, 32. Upon rotation of the rotors 30, 32, the lobes at least partially seal the fluid 12-1 against an interior side of the housing at which point expansion of the fluid 12-1 only occurs to the extent allowed by leakage which represents an 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 of the housing 22 of device 20 is constant as the fluid 12-1 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.

[0026] As additionally shown in Figure 2, each rotor 30, 32 has four lobes, 30-1, 30-2, 30-3, and 30-4 in the case of the rotor 30, and 32-1, 32-2, 32-3, and 32-4 in the case of the rotor 32. Although four 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, Figure 7 shows a suitable rotor 33 having three lobes 33-1, 33-2, and 33-3. Additionally, 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 12-1.

[0027] As shown, the first and second rotors 30 and 32 are fixed to respective rotor shafts, the first rotor being fixed to an output shaft 38 and the second rotor being fixed to a shaft 40. Each of the rotor shafts 38, 40 is mounted for rotation on a set of bearings (not shown) about an axis X1, X2, respectively. It is noted that axes X1 and X2 are generally parallel to each other.

[0028] The first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other. With renewed reference to Figure 1, the expander 20 also includes meshed timing gears 42 and 44, wherein the timing gear 42 is fixed for rotation with the rotor 30, while the timing gear 44 is fixed for rotation with the rotor 32. The timing gears 42, 44 are also configured to 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 42, 44. 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.

[0029] The output shaft 38 is rotated by the working fluid 12 as the fluid undergoes expansion from the higher first pressure working fluid 12-1 to the lower second pressure working fluid 12-2. As may additionally be seen in both Figures 1 and 2, the output shaft 38 extends beyond the boundary of the housing 22. Accordingly, the output shaft 38 is configured to capture the work or power generated by the expander 20 during the expansion of the fluid 12 that takes place in the rotor cavity 28 between the inlet port 24 and the outlet port 26 and transfer such work as output torque from the expander 20. Although the output shaft 38 is shown as being operatively connected to the first rotor 30, in the alternative the output shaft 38 may be operatively connected to the second rotor 32. The output shaft 38 can be coupled to the engine 202 such that the energy from the exhaust can be recaptured.

[0030] In one aspect of the geometry of the expander 20, each of the rotor lobes 30-1 to 30-4 and 32-1 to 32-4 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 34. As shown schematically at Figure 5, 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) = $(180/\pi \cdot \arctan(PD/Lead))$, 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 L1, L2 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 of the lobe from the rearward end of the rotor to the forward end of the rotor. As shown, the twist angle is about 120 degrees, although the twist angle may be fewer or more degrees, such as 160 degrees.

[0031] In another aspect of the expander geometry, the inlet port 24 includes an inlet angle 24-1, as can be seen schematically at Figure 4. In one example, the inlet angle 24-1 is defined as the general or average angle of an inner surface 24a of the inlet port 24, 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 24, for example as shown at Figures 1 and 4. In one example, the inlet angle 24-1 is defined as the general resulting direction of the fluid 12-1 entering the rotors 30, 32 due to contact with the anterior inner surface 24a, as can be seen at Figures 1 and 4. 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 24a of the inlet port 24 causes a substantial portion of the fluid 12-1 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.

[0032] Furthermore, and as shown in Figures 1 and 4, the inlet port 24 may be shaped such that the fluid 12-1 is directed to the first axial ends 30a, 32a 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 24b, as shown in Figures 1 and 4.

[0033] In another aspect of the expander geometry, the outlet port 26 includes an outlet angle 26-1, as can be seen schematically at Figures 1 and 4. In one example, the outlet angle 26-1 is defined as the general or average angle of an inner surface 26a of the outlet port 26. In one example, the outlet angle 26-1 is defined as the angle of the general

centerline of the outlet port 26, for example as shown at Figures 1 and 4. In one example, the outlet angle 26-1 is defined as the general resulting direction of the fluid 12-2 leaving the rotors 30, 32 due to contact with the inner surface 26a, as can be seen at Figures 1 and 4. 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 26a of the outlet port 26 receives the leaving fluid 12-2 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 Figures 1 and 4. 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 12-2 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 shaft 38 is maximized to the extent that backpressure caused by the outlet can be minimized such that the fluid can be rapidly discharged.

[0034] The efficiency of the expander 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 24 introduces the fluid 12-1 to both the leading and trailing faces of each rotor 30, 32, the fluid 12-1 performs both positive and negative work on the expander 20.

[0035] To illustrate, Figure 2 shows that lobes 30-1, 30-4, 32-1, and 32-2 are each exposed to the fluid 12-1 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 32-2a is the leading surface of lobe 32-2 while side 32-2b is the trailing surface.

[0036] In generalized terms, the fluid 12-1 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 12-1 causes the rotors to rotate in the desired direction: direction R1 for rotor 30 and direction R2 for rotor 32. As shown, fluid 12-1 will operate to impart positive work on the trailing surface 32-2b of rotor 32-2, for example on surface portion 47. The fluid 12-1 is also imparting positive work on the trailing surface 30-4b of rotor 30-1, for example of surface portion 46. However, the fluid 12-1 also impinges on the leading surfaces of the lobes, for example surfaces 30-1 and 32-1, as they pass through the inlet port opening 24b thereby causing negative work to be performed on each rotor 30, 32. By use of the term negative work, it is meant that the fluid 12-1 causes the rotors to rotate opposite to the desired direction, R1, R2.

[0037] Accordingly, it is desirable to shape and orient the rotors 30, 32 and to shape and orient the inlet port 24 such that as much of the fluid 12-1 as possible impinges on the trailing surfaces of the lobes with as little of the fluid 12-1 impinging on the on the leading lobes such that the highest net positive work can be performed by the expander 20.

[0038] One advantageous configuration for optimizing the efficiency and net positive work of the expander 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.

Volumetric Fluid Expander with Water Injection Mechanism

[0039] Referring to Figure 8, a schematic of an energy recovery system 200 is shown which includes the expander 20 and a water injection system 230 having one or more water injectors 232. The water injector 232 may be located at any point in the system upstream of the expander 20. In one aspect, water is injected by injector 232 into a relatively high temperature, low volumetric flow working fluid stream 12-0 to result in a relatively lower temperature, higher volumetric flow working fluid stream 12-1. As previously described, the expander receives working fluid stream 12-1 and discharges an expanded working fluid stream 12-2. In one aspect, the water injected by the injectors 232 can be recovered at a reservoir tank 236 downstream of the expander 20. The tank 236 can be configured to operate as a condenser such that the vaporized water can be removed returned to a liquid state. A pumping circuit including a pump 234 and piping 235 can be provided to deliver pressurized water from the condenser/water recovery tank 236 to the injector(s) 232. In one embodiment, the condenser/tank 236 can be located downstream of a vehicle emissions control system 209 which may include various components such as a catalytic converter.

[0040] As can be seen at Figure 9, the water injector(s) 232 can be placed at a variety of locations within a system 200. For example, injector(s) 232 can be placed upstream of a boost system 250, such as a supercharger or turbocharger. Injecting water at this location can increase the isentropic efficiency of the boost system. Water injector(s) 232b may also be placed in the intake air for an internal combustion engine and can be located downstream of the boost system 250, if provided. Water injector(s) 232c can also be placed immediately upstream of the expander 20. As is discussed with respect to Figures 10 and 11, injectors 232 may also be provided to inject water directly into the cylinders of the internal combustion engine 202. Injectors 232 can also be placed at a location between the cylinders of the engine and the expander 20, such as in the exhaust manifold of the engine 202.

[0041] Figures 10 and 11 show one embodiment of an energy recovery system 200 that can be configured not only to recover energy from the exhaust gases of the engine 202 but to reduce a cooling load of the engine 202. In this example, the system 200 includes a volumetric fluid expander 20 and a water injection mechanism 230. The engine 202 includes a plurality of cylinders 204, a crankshaft 206, and an exhaust manifold 208. The engine 202 can also be characterized as having an air inlet 203 and an exhaust outlet 205. The plurality of cylinders 204 accommodate pistons (not shown) and allow the pistons to

reciprocate therein. The crankshaft 206 is configured to translate linear motions of the reciprocating pistons into rotation. The exhaust manifold 208 may be configured as one pipe that is in fluid communication with the plurality of cylinders 204 and collects the exhaust gases from the cylinders 204. In this example, the exhaust manifold 208 is directly connected to the volumetric fluid expander 20 and in fluid communication with the device 20.

[0042] The volumetric fluid expander 20 operates to recover energy from exhaust gases of the engine 202. The exhaust gases discharged from the cylinders 204 through the exhaust manifold 208 have a higher pressure than ambient pressure, and, thus, contain energy that can be recovered by the volumetric fluid expander 20. To recuperate energy from the exhaust gases, the volumetric fluid expander 20 is configured to receive the exhaust gases from the engine 202, and expand the exhaust gases so that the exhaust gases have a lower pressure when they are discharged from the expander 20 than the exhaust gases entering the expander 20. The volumetric fluid expander 20 recuperates energy from the exhaust gases as the exhaust gases expand within the expander 20, and generates a mechanical work out of the recovered energy.

[0043] In some embodiments, the volumetric fluid expander as described herein is used for the volumetric fluid expander 20. For example, the volumetric fluid expander 20 includes a housing, a plurality of rotors, and an output shaft. The housing has inlet and outlet ports. The inlet port is in fluid communication with the exhaust manifold to receive the exhaust gases from the cylinders 204. The outlet port discharges the exhaust gases that have been expanded within the expander 20. The plurality of rotors is arranged within the housing and operates to expand the exhaust gases. As shown above with reference to Figure 2 or 6, the plurality of rotors may include two twisted meshed rotors. The two rotors are rotatably disposed within the housing and have a plurality of lobes, respectively. The output shaft is connected to one of the rotors and operates to be rotated by the exhaust gases as the exhaust gases pass through the rotors and expand in volume. Such a mechanical work generated by the rotation of the output shaft may be delivered to any elements or devices as necessary. For example, the recuperated energy may be accumulated in an energy storage device, such as a battery or an accumulator, and the energy storage device may release the stored energy on demand. In other examples, the recovered energy may return to the engine 202 by coupling the output shaft of the expander 20 to the crankshaft 206 of the engine 202, as shown in Figure 10. A power transmission link 222 may be employed between the volumetric fluid expander 20 and the

engine 202 to provide a better match between rotational speeds of the engine 202 and the output shaft of the expander 20.

[0044] The volumetric fluid expander 20 of this type is advantageous in combination with the disclosed water injection system because multiphase flow that may be caused by the water injection system does not adversely affect the expander or its constituent components. In comparison, some other types of systems, such as a centrifugal turbine system, are not able to accommodate multiphase flow without damage and/or significant reductions in efficiency.

[0045] Referring to Figures 10 and 11, a specific implementation is shown in which water is injected directly into the cylinders of an internal combustion engine. In such an embodiment, the water injection mechanism 230 operates to inject water into each of the plurality of cylinders 204 at or shortly before an exhaust cycle or stroke of the cylinder so that the injected water vaporizes within the cylinder 204 due to a high temperature environment in the cylinder 204. As the injected water vaporizes in the cylinder, it undergoes expansion in volume. The vaporized water, as well as the exhaust gases generated by the engine strokes, are discharged from the cylinder 204 and flow into the volumetric fluid expander 20 through the exhaust manifold 208. By adding the expanded volume of the water into the exhaust gases generated by the engine strokes, the vaporized water increases a volume of the entire exhaust gases that are discharged from the exhaust manifold 208 into the volumetric fluid expander 20, and, therefore, enhances the performance of the volumetric fluid expander 20.

[0046] In this example, the water injection mechanism 230 includes a plurality of water injectors 232, a water pump device 234, a water tank 236, and a controller 238. A water injector 232 is installed for each cylinder 204 and is configured to inject water into the cylinder 204. The water pump device 234 is connected to the water injectors 232 and configured to selectively supply water to the water injectors 232. The water pump device 234 is in fluid communication with the water tank 236 and operates to provide water from the water tank 236 to the water injectors 232. In some embodiments, the controller 238 may be connected to the water pump device 234 and configured to activate the water pump device 234 to provide water to the water injectors 232 in such a manner that the water injectors 232 inject water into the cylinders 204 at or before the exhaust cycle of the cylinders 204. Additionally or alternatively, the controller 238 may be configured to activate the water pump device 234 and each water injector 232 to selectively inject water into the cylinder 204 at or before the exhaust cycle of the cylinder 204.

[0047] Figure 11 is a schematic view of an example cylinder 204 with the water injection mechanism 230. Figure 11 shows that the water injection mechanism 230 is injecting water into the cylinder 204 through the water injector 232 at the exhaust stroke of the cylinder 204. The cylinder 204 includes a piston assembly 240, an inlet valve 242, an exhaust valve 244, and the water injector 232. As explained above, the water injection mechanism 230 is configured to control the water injector 232 to inject water at or shortly before the exhaust stroke of the cylinder 204. As illustrated in Figure 11, at the exhaust cycle, the piston assembly pushes up a piston head 246 within the cylinder 204 while the inlet valve 242 remains closed and the exhaust valve 244 opens. During the exhaust cycle (or shortly before the exhaust cycle), water 252 is injected into the cylinder 204. The injected water vaporizes within the cylinder 204 due to a high temperature of the exhaust gases generated by the engine strokes (in particular, a power stroke of the cylinder), and, therefore, expands in volume. The vaporized, and thus expanded, water is then mixed with the exhaust gases within the cylinder 204. The open exhaust valve 244 allows the exhaust gases, which are mixed with the vaporized water, to escape the cylinder 204 and to flow into the volumetric fluid expander 20. As discussed above, the increased volume of the entire exhaust gases enhances the operation of the volumetric fluid expander 20.

[0048] The water injection mechanism 230 also functions to reduce a cooling load of the engine 202 because the water injected to the cylinder 204 functions as part of an engine cooling system. The water introduced into the cylinder 204 cools down engine components such as engine heads and pistons. As a result, the water injection mechanism 230 may share a cooling load with the engine cooling system such as a radiator or a heat exchanger.

[0049] In some embodiments, the water injection mechanism 230 may selectively operate only when the exhaust gases alone from the engine 202 is not sufficient for operating the volumetric fluid expander 20. Typically, an engine operating at a low RPM does not generate a sufficient volume of exhaust gases for operation of the volumetric fluid expander 20 that is directly connected to the exhaust manifold 208 of the engine 202. In this case, the water injection mechanism 230 operates to inject water into the cylinders 204 to increase a volume of the entire exhaust gases, which have been mixed with vaporized water. When the engine operates at a high RPM in which a sufficient volume of exhaust gases is generated from the engine, the water injection mechanism 230 need not operate.

[0050] In one possible, but non-limiting, embodiment, an engine running below a threshold output value (e.g. about 1,500 RPM which may be around 15% load of the engine with an exhaust gas temperature in the range of about 200 °C to about 250 °C) may generate exhaust gases that would not be sufficient to operate the volumetric fluid expander 20 at a desired efficiency or output. Accordingly, when the engine is running below the threshold output value, the water injection mechanism 230 may be operated to add a volume of vaporized water into the exhaust gases, as discussed above. In contrast, where an engine operates at or above the threshold output value (e.g. about 2,000 RPM which may be around 50% load of the engine with an exhaust gas temperature exceeding 350oC), the engine may generate exhaust gases that would be sufficient to operate the volumetric fluid expander 20 at a desired efficiency or output.

[0051] The water injection mechanism 230 in all of the configurations shown at Figures 8-11 may be activated or operated based on one or more operating parameters 258 of the engine via the controller 238 and/or CAN 256. In some embodiments, the operating parameters 258 provide an indication of whether the engine is running below or above the threshold output value, and thus whether the exhaust gas output conditions (e.g. volume) are sufficient. Examples of the operating parameters 258 include measured or calculated engine speed, exhaust temperature, exhaust pressure, and/or expander rotational speed. In some embodiments, the parameters 258 may be obtained from a vehicle control system using, for example, controller area network (CAN) bus 256. The operating parameters may be utilized in an algorithm to activate or deactivate the pump 234, open and close the injectors 232, and/or to control the speed of the pump 234. It is also noted that the pump speed can be controlled to maintain a specified pressure at the injector.

[0052] 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 following claims.

WHAT IS CLAIMED IS:

1. An exhaust gas energy recovery system for an internal combustion engine having an air intake and an exhaust outlet, the energy recovery system comprising:
 - (a) a volumetric fluid expander in fluid communication with the exhaust outlet, the volumetric fluid expander being configured to receive and expand exhaust from the exhaust outlet to a lower pressure, the volumetric fluid expander including first and second twisted meshed rotors rotatably disposed in a housing, wherein the rotors have an equal number of lobes, and wherein the lobes of the first rotor do not contact the lobes of the second rotor; and
 - (b) a water injection mechanism including a water injector and a pump for providing pressurized water to the water injector, the water injector being positioned to inject water at a first location or a second location, the first location being between the exhaust outlet and the volumetric fluid expander to cause a volumetric expansion, the second location being upstream of a supercharger associated with the internal combustion engine.
2. The exhaust gas energy recovery system of claim 1, further comprising:
 - (a) a water recovery condenser located downstream of the volumetric fluid expander and in fluid communication with the pump, the water recovery condenser being for collecting at least some of the water injected by the water injector.
3. The exhaust gas energy recovery system of claim 2, wherein the water recovery condenser is located downstream of a catalytic converter associated with the internal combustion engine.
4. The exhaust gas energy recovery system of claim 1, further comprising:
 - (a) a controller to operate the pump, wherein the controller is configured to control the speed of the pump based on an operating parameter of at least one of the internal combustion engine and the volumetric fluid expander.

5. The exhaust gas energy recovery system of claim 4, wherein the operating parameter is one or more of an exhaust temperature, an exhaust pressure, and a rotational speed of the expander.
6. A method for recovering exhaust gas energy, the method comprising:
 - injecting, by a water injection mechanism, water into a cylinder of an engine at or before an exhaust cycle of the cylinder, wherein the injected water vaporizes within the cylinder;
 - collecting, via an exhaust manifold of the engine, exhaust gas stream mixed with the vaporized water;
 - supplying the exhaust gas stream into a volumetric fluid expander, the exhaust gas stream having a first pressure;
 - generating, by the volumetric fluid expander, useful work at an output shaft of the expander by expanding the exhaust gas stream to a second pressure lower than the first pressure; and
 - collecting at least some of the injected water from the exhaust gas stream and returning the water to the water injection mechanism.
7. The method of claim 6, wherein the step of injecting, by the water injection mechanism, water into the cylinder comprises providing:
 - a water injector configured to inject water into the cylinder;
 - a water pump device connected to the water injector;
 - a water tank connected to the water pump device; and
 - a controller configured to control the water injector to selectively inject water to the cylinder at or before the exhaust cycle of the cylinder.
8. The method of claim 7, wherein the step of providing the controller configured to control the water injector comprises activating the water injector and the water pump device to selectively inject water to the cylinder based on an operating parameter of the engine.
9. The method of claim 7, wherein the step of generating, by the volumetric fluid expander, useful work comprises providing:

first and second twisted meshed rotors rotatably disposed in a housing of the volumetric fluid expander, wherein the rotors have an equal number of lobes, and wherein the lobes of the first rotor do not contact the lobes of the second rotor.

10. The method of claim 8, wherein the step of generating, by the volumetric fluid expander, useful work comprises transferring the generated useful work to an output shaft of the engine.

11. The method of claim 8, wherein the step of generating, by the volumetric fluid expander, useful work comprises transferring the generated useful work to a generator or a hydraulic pump.

12. An exhaust gas energy recovery system comprising:

- a. an internal combustion engine having a cylinder and an exhaust gas outlet for conveying an exhaust gas stream at a first pressure;
- b. a volumetric fluid expander including:
 - i. a housing having an inlet and an outlet, the housing inlet being in fluid communication with the exhaust gas outlet;
 - ii. an output shaft;
 - iii. wherein the volumetric fluid expander is configured to generate useful work at the output shaft by expanding the exhaust gas stream to a second pressure lower than the first pressure generally without reducing the volume of the exhaust stream as the exhaust stream moves from the housing inlet to the outlet;
- c. a water injection mechanism configured to inject water into at least one of the cylinder, a boost system located upstream of the, and the volumetric fluid expander inlet; and
- d. a water recovery condenser for collecting at least some of the injected water downstream of the location where the water is injected.

13. The system of claim 12, wherein the water injection mechanism is configured to inject water into the cylinder at or before the exhaust cycle of the cylinder begins.

14. The system of claim 13, wherein the water injection mechanism comprises:
a plurality of water injectors, each configured to inject water into each of the plurality of cylinders;
a water pump device connected to the plurality of water injectors;
a water tank connected to the water pump device; and
a controller configured to control the water injector to selectively inject water to the cylinder at or before the exhaust cycle of the cylinder.
15. The system of claim 12, wherein the controller controls the water injector to selectively inject water based on an operating parameter of the engine.
16. The system of claim 12, wherein the volumetric fluid expander includes first and second twisted meshed rotors rotatably disposed in the housing, wherein the rotors have an equal number of lobes, and wherein the lobes of the first rotor do not contact the lobes of the second rotor.
17. The system of claim 12, wherein the volumetric fluid expander output shaft is mechanically coupled to an output shaft of the combustion engine.
18. The system of claim 12, wherein the water injection mechanism is configured to inject water into an air intake of the boost system.
19. The system of claim 12, wherein the water injection mechanism is configured to inject water into the volumetric fluid expander inlet.
20. The system of claim 12, wherein the water recovery condenser is located downstream of a vehicle emissions control system.

FIG. 1

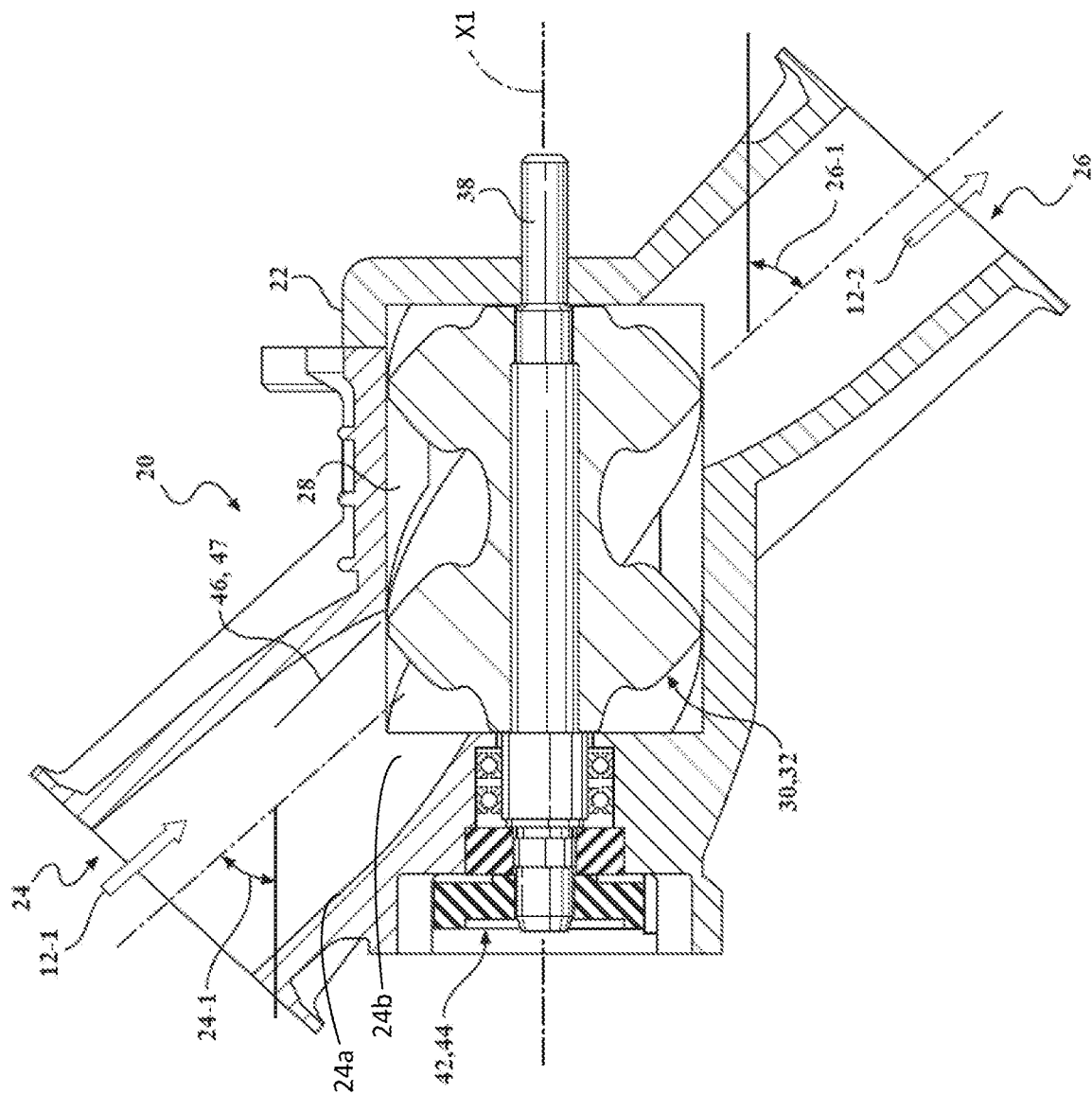
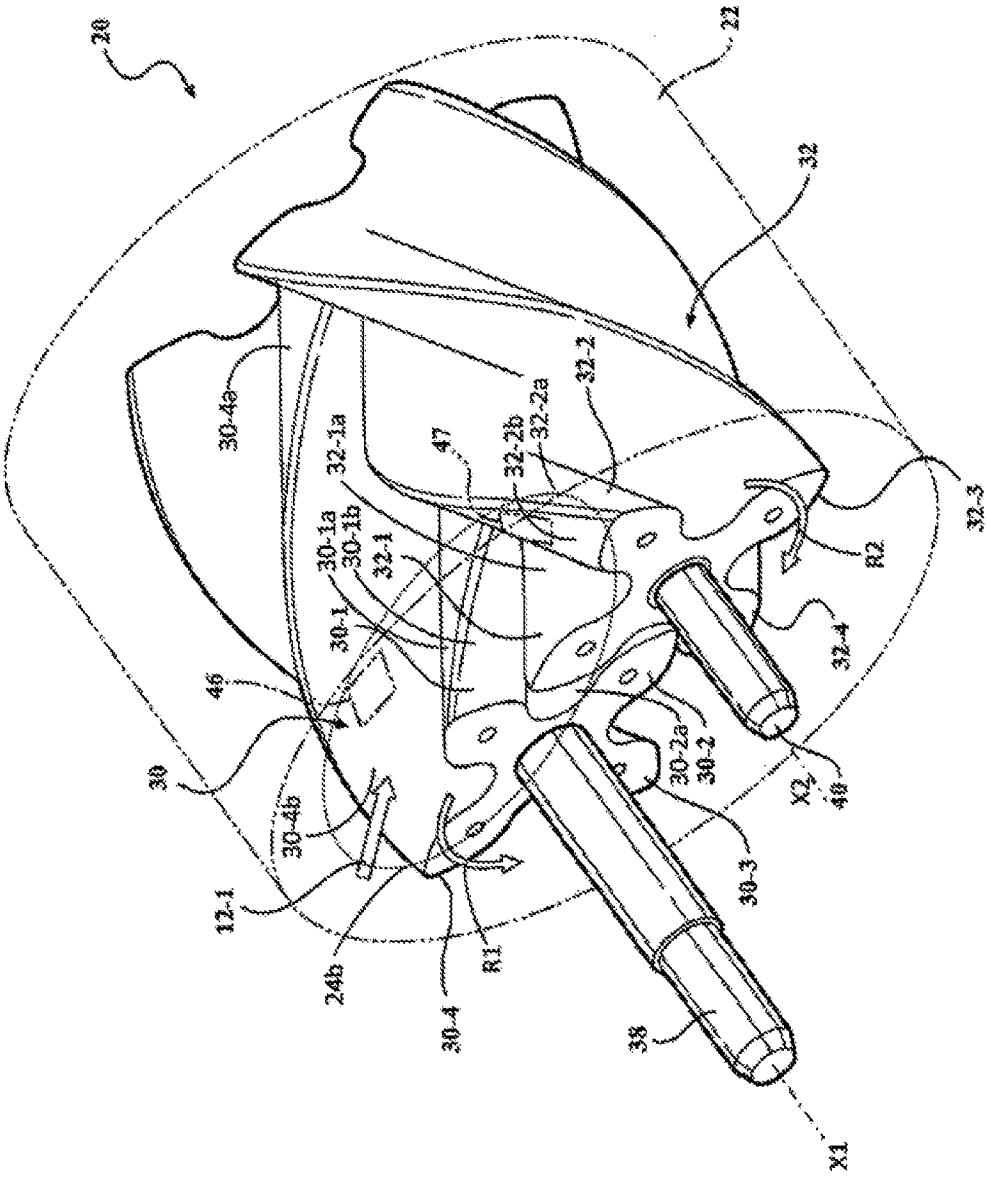


FIG. 2



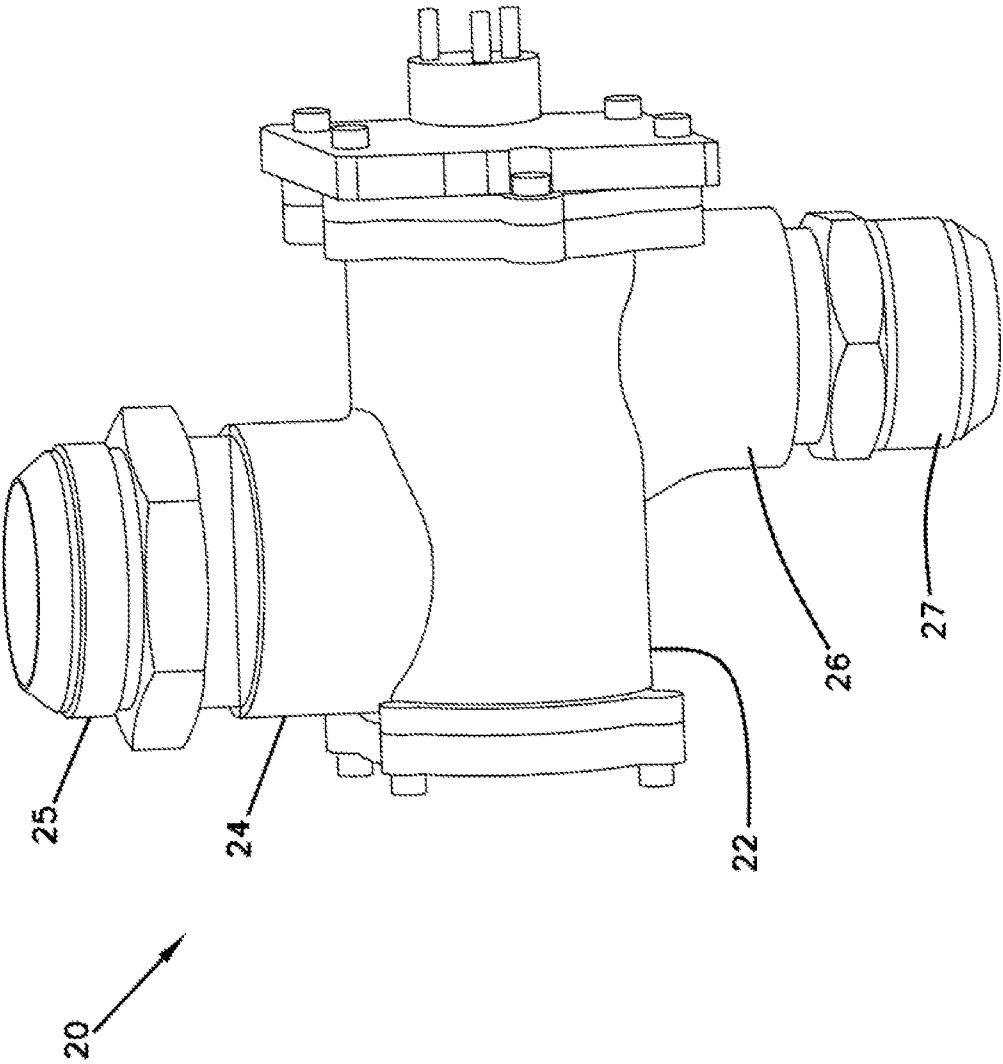


FIG. 3

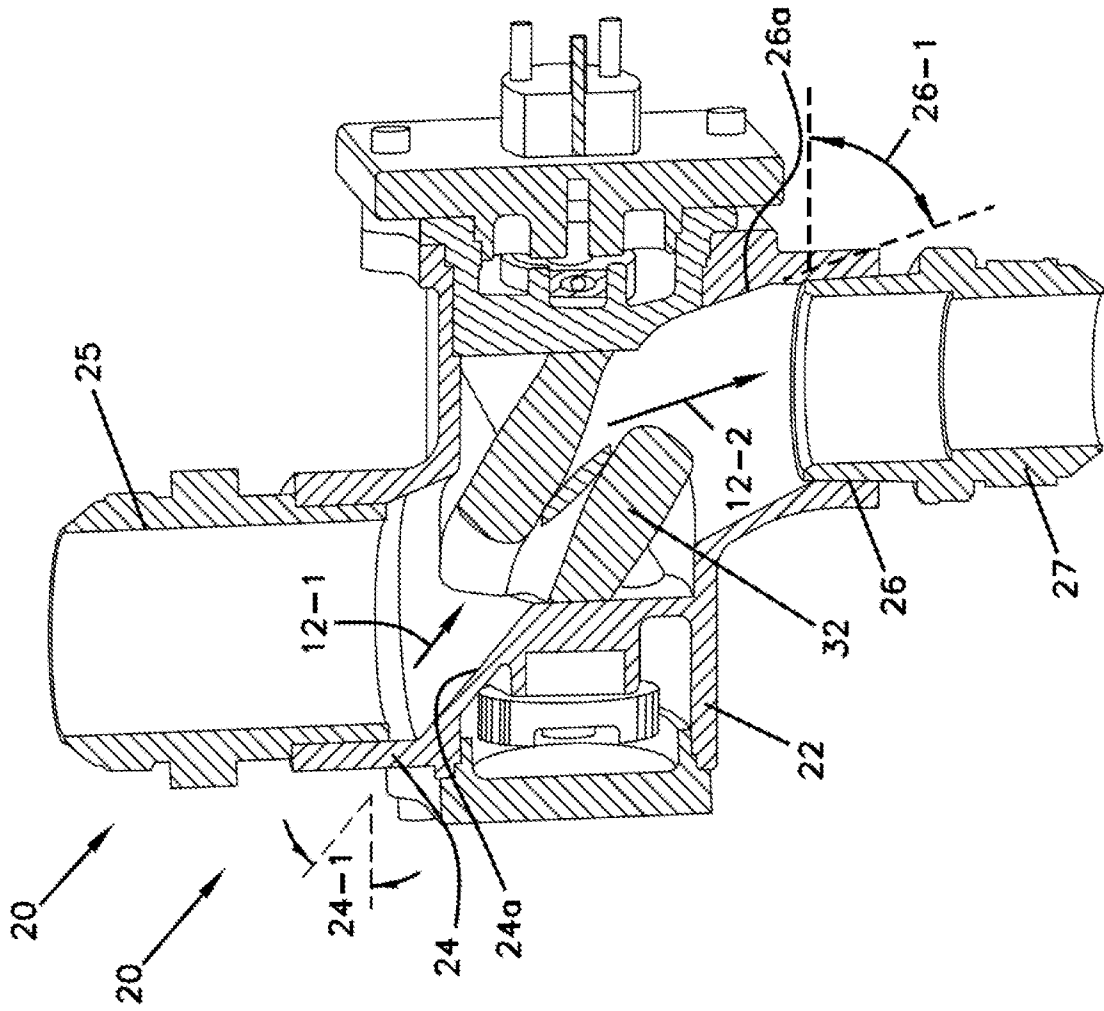
**FIG. 4**

FIG. 5

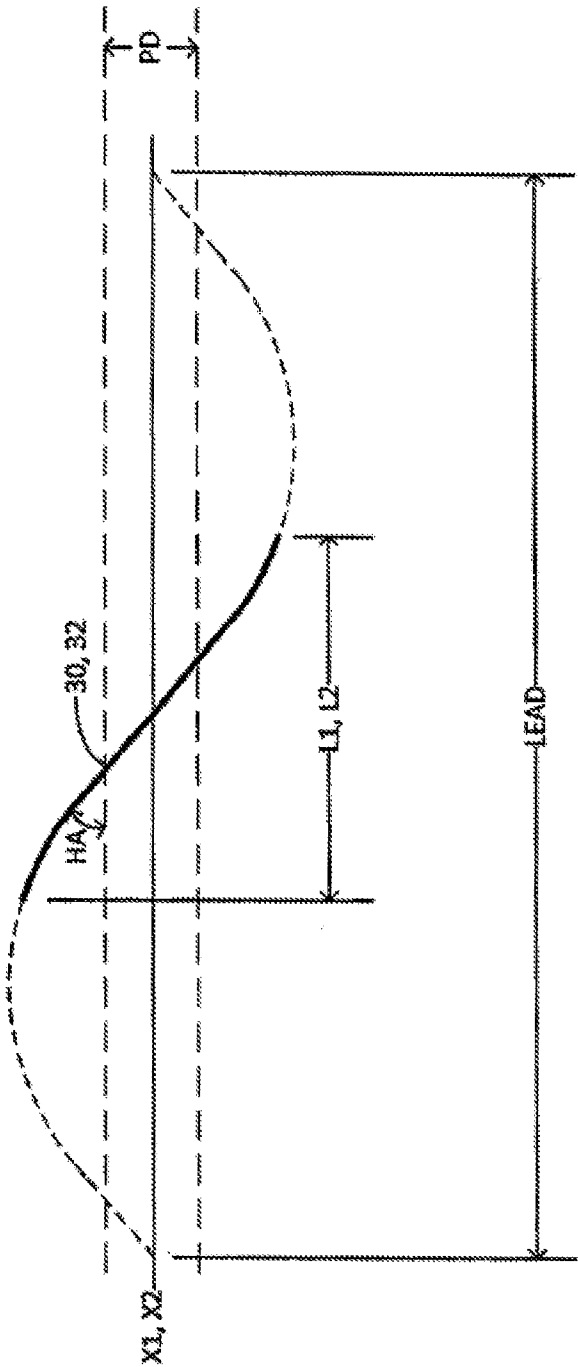


FIG. 6

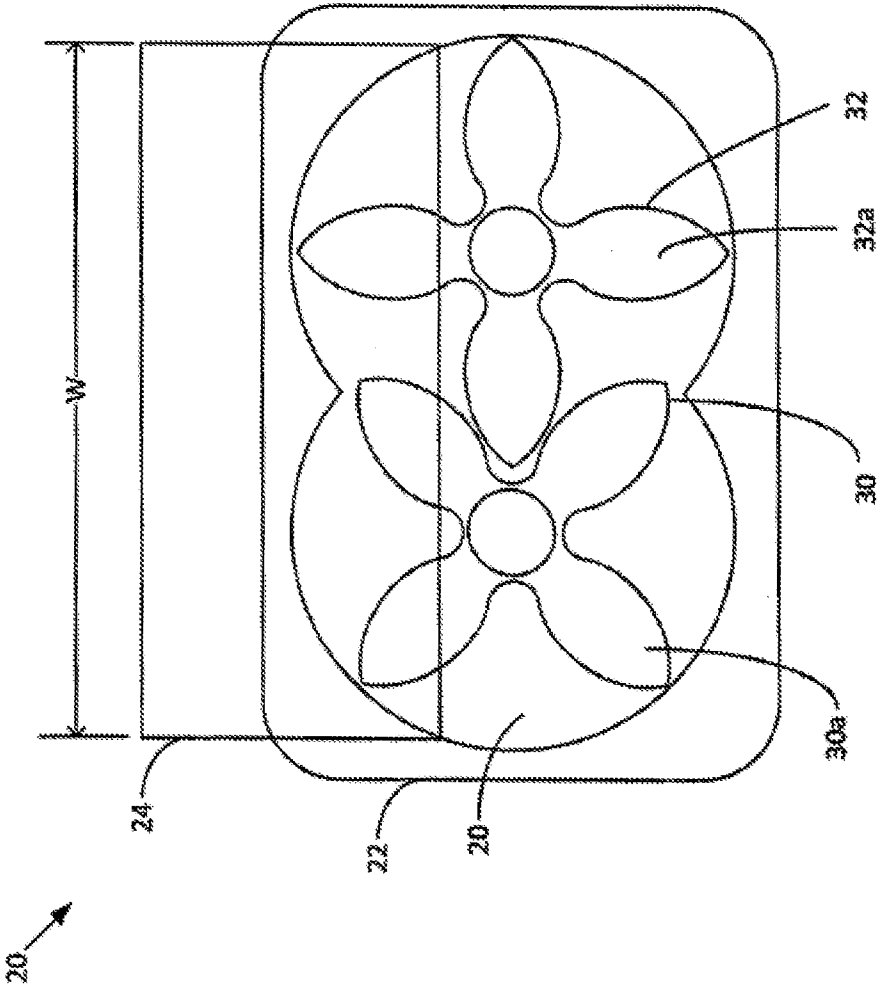


FIG. 7

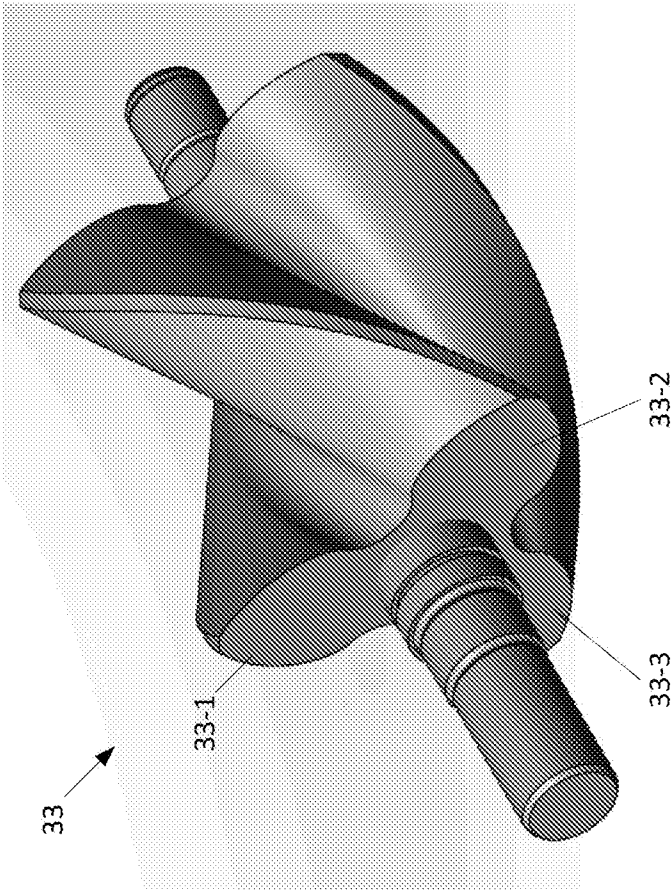


FIG. 8

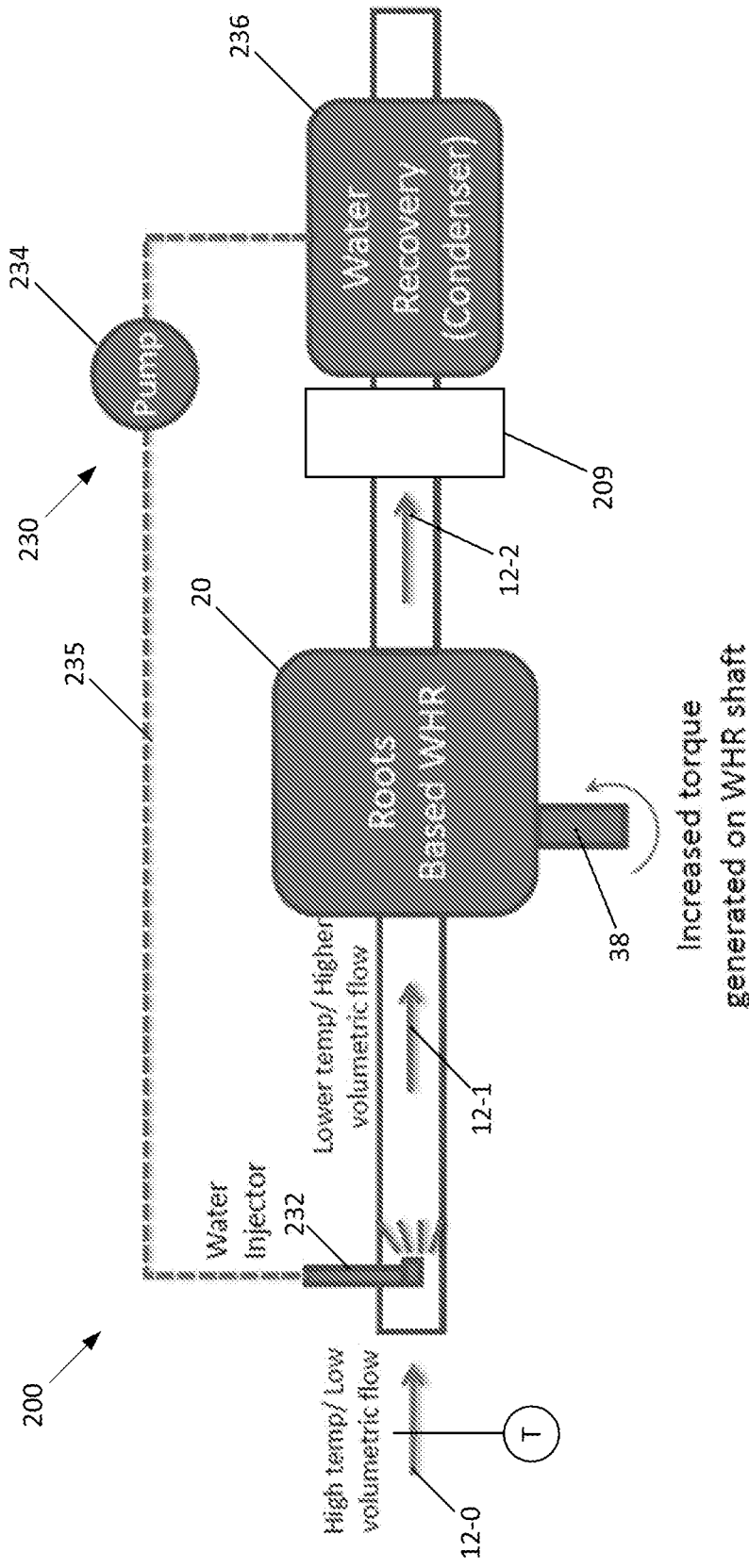
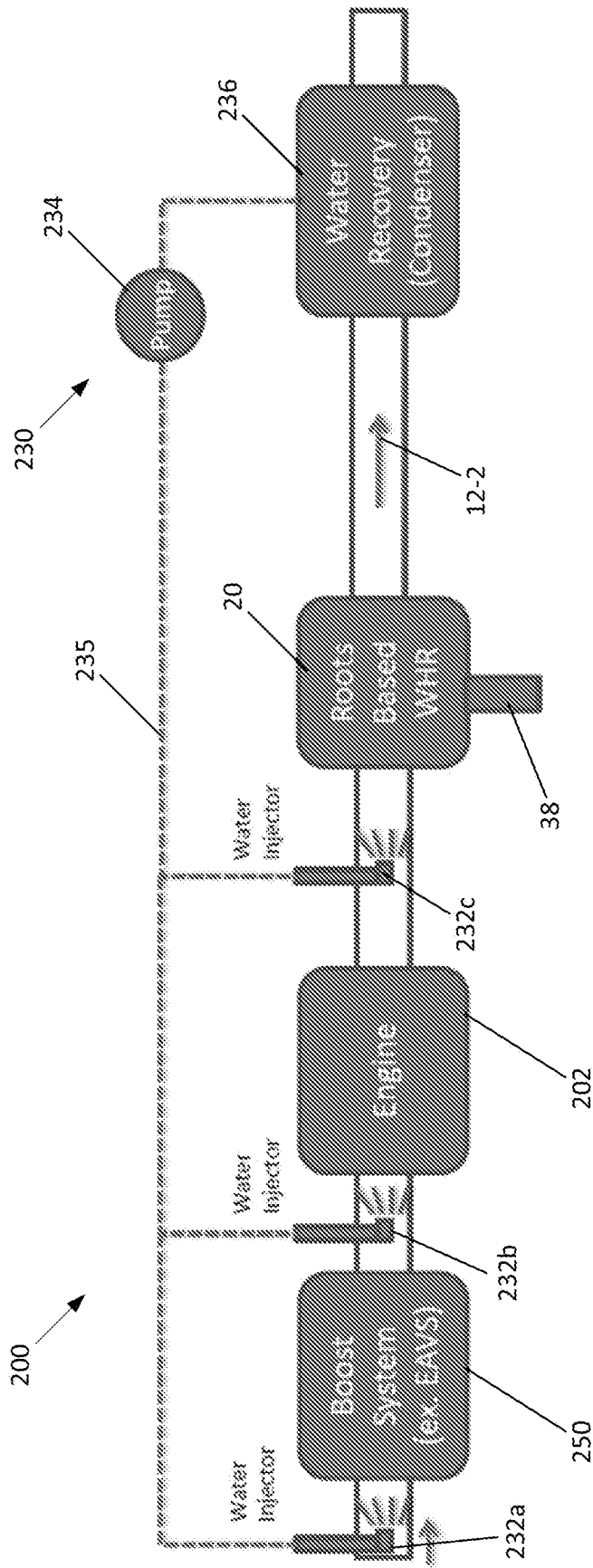


FIG. 9



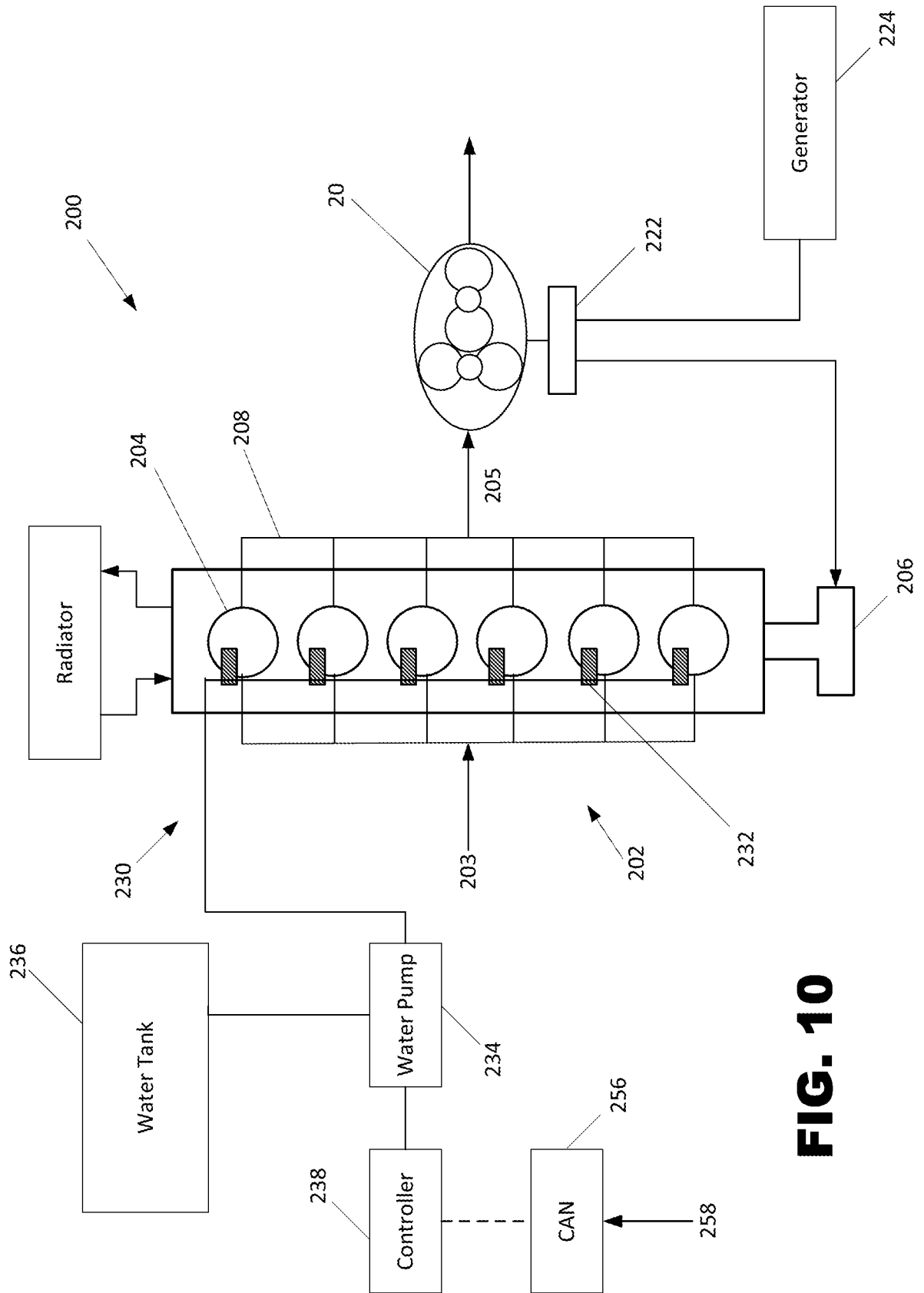


FIG. 10

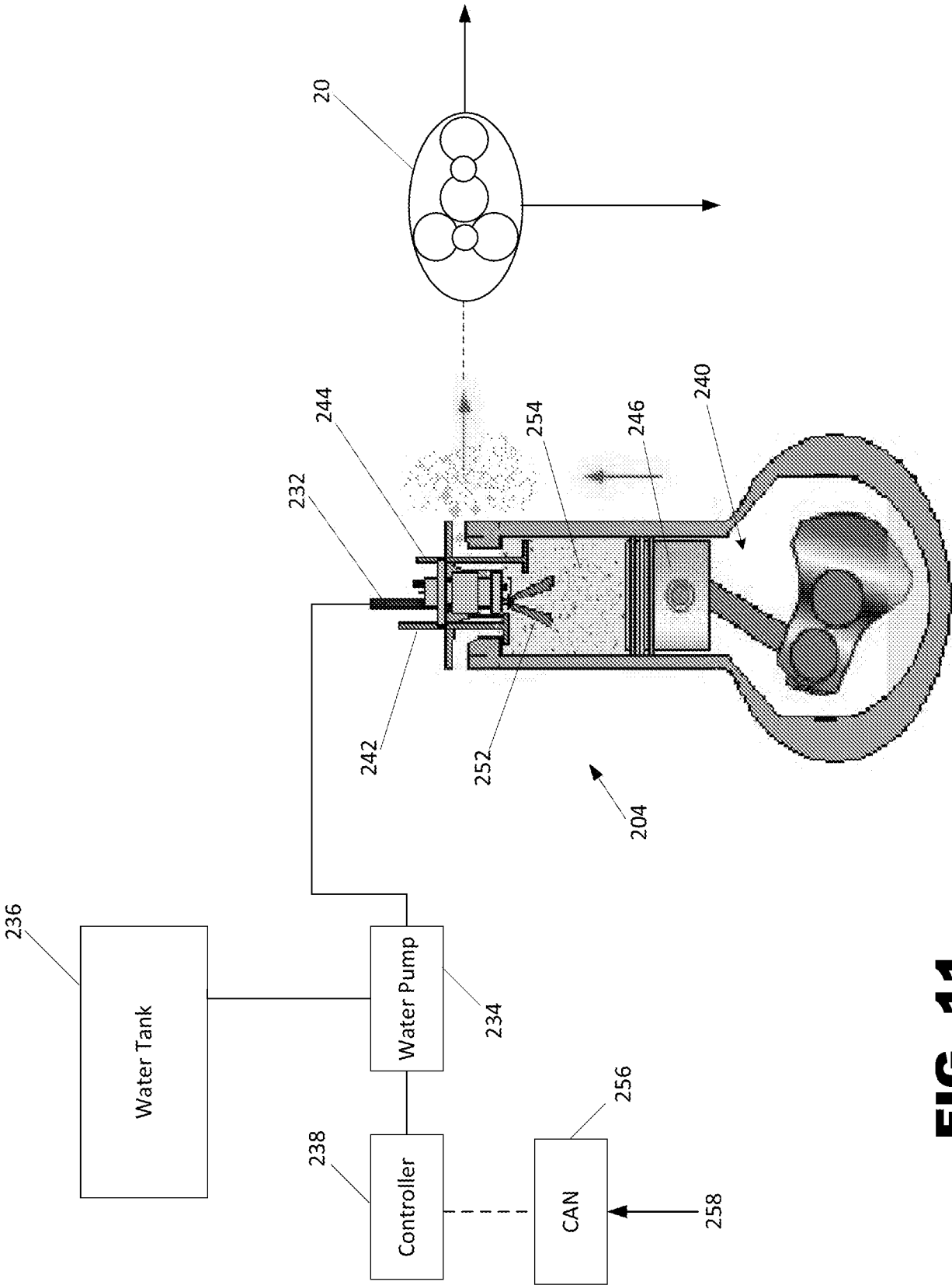


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/040499**A. CLASSIFICATION OF SUBJECT MATTER****F01K 23/06(2006.01)I, F01N 5/02(2006.01)I, F01K 19/00(2006.01)I**

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 23/06; F02B 37/013; F01K 25/08; F01N 3/00; F01K 23/10; F02B 37/00; F02D 23/00; F02M 25/07; F01N 5/02; F01K 19/00

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: waste heat recovery, engine, volumetric fluid expander, cylinder, exhaust gas outlet, housing, shaft, pump, water injection mechanism, water recovery condenser

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2014-107414 A1 (EATON CORPORATION et al.) 10 July 2014 See abstract; paragraphs [0008], [0024], [0039]-[0040], [0043], [0048]; claims 1-2, 5, 8-19; and figures 1-3, 8-9.	1-20
Y	US 3935848 A (GAMELL, JOSEPH A.) 03 February 1976 See abstract; column 3, line 26 - column 4, line 16; and figure 2.	1-20
Y	US 2015-0007569 A1 (EATON CORPORATION) 08 January 2015 See abstract; paragraph [0023]; and figure 1.	2-3, 12-20
A	US 2012-0111001 A1 (ESPINOSA, NICOLAS) 10 May 2012 See abstract; paragraphs [0008]-[0011]; and figure 1.	1-20
A	US 2009-0205326 A1 (WATSON, DAVID EUGENE) 20 August 2009 See abstract; paragraphs [0030]-[0040]; and figures 1-3.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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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

12 September 2016 (12.09.2016)

Date of mailing of the international search report

12 September 2016 (12.09.2016)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/040499

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