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(54) VOLUMETRIC ENERGY RECOVERY SYSTEM WITH THREE STAGE EXPANSION

VOLUMETRISCHES ENERGIERÜCKGEWINNUNGSSYSTEM MIT DREISTUFIGER EXPANSION

SYSTÈME VOLUMÉTRIQUE DE RÉCUPÉRATION D’ÉNERGIE PAR DÉTENTE À TROIS ÉTAGES

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Description

[0001] 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

[0002] The present disclosure relates to a volumetric fluid expander used for power generation in the Rankine cycle.

BACKGROUND

[0003] The Rankine cycle is a power generation cycle that converts thermal energy to mechanical work. The Rankine cycle is typically used in heat engines, and accomplishes the above conversion by bringing a working substance from a higher temperature state to a lower temperature state. The classical Rankine cycle is the fundamental thermodynamic process underlying the operation of a steam engine.

[0004] In the Rankine cycle a heat "source" generates thermal energy that brings the working substance to the higher temperature state. The working substance generates work in the "working body" of the engine while transferring heat to the colder "sink" until the working substance reaches the lower temperature state. During this process, some of the thermal energy is converted into work by exploiting the properties of the working substance. The heat is supplied externally to the working substance in a closed loop, wherein the working substance is a fluid that has a non-zero heat capacity, which may be either a gas or a liquid, such as water. The efficiency of the Rankine cycle is usually limited by the working fluid.

[0005] The Rankine cycle typically employs individual subsystems, such as a condenser, a fluid pump, a heat exchanger such as a boiler, and an expander turbine. The pump is frequently used to pressurize the working fluid that is received from the condenser as a liquid rather than a gas. Typically, all of the energy is lost in pumping the working fluid through the complete cycle, as is most of the energy of vaporization of the working fluid in the boiler. This energy is thus lost to the cycle mainly because the condensation that can take place in the turbine is limited to about 10% in order to minimize erosion of the turbine blades, while the vaporization energy is rejected from the cycle through the condenser. On the other hand, the pumping of the working fluid through the cycle as a liquid requires a relatively small fraction of the energy needed to transport the fluid as compared to compressing the fluid as a gas in a compressor.

[0006] A variation of the classical Rankine cycle is the Organic Rankine cycle (ORC), which is named for its use of an organic, high molecular mass fluid, with a liquid-vapor phase change, or boiling point, occurring at a lower temperature than the water-steam phase change. As such, in place of water and steam of the classical Rankine cycle, the working fluid in the ORC may be a solvent, such as n-pentane or toluene. The ORC working fluid allows Rankine cycle heat recovery from lower temperature sources such as biomass combustion, industrial waste heat, geothermal heat, solar ponds, etc. The low-temperature heat may then be converted into useful work, which may in turn be converted into electricity.

[0007] In GB 2010 974 A there is disclosed a method for generating mechanical work via a closed-loop Rankine cycle as it is defined in the pre-characterizing portion of claim 1 and a system used to generate mechanical work via a closed-loop Rankine cycle as it is defined in the pre-characterizing portion of claim 8.

SUMMARY

[0008] In general terms, this disclosure is directed to a volumetric energy recovery system with a three stage expansion system. In particular, the present invention is a method for generating mechanical work via a closed-loop Rankine cycle as it is defined in claim 1 and a system used to generate mechanical work via a closed-loop Rankine cycle as it is defined in claim 8.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009]

Figure 1 is a schematic depiction of a first exemplary system employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure.

Figure 2 is a schematic depiction of a second exemplary system employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure.

Figure 3 is a schematic depiction of a third exemplary system employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure.

Figure 4 is a flowchart of an exemplary process in a Rankine cycle with a three stage expansion system.

Figure 5 is a flowchart of another exemplary process in a Rankine cycle with a three stage expansion system.

Figure 6 is a flowchart of yet another exemplary process in a Rankine cycle with a three stage expansion system.

Figure 7 is a side perspective view of an example of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure.

Figure 8 is a cross-sectional side perspective view of the volumetric fluid expander shown in Figure 7.

Figure 9 is a cross-sectional side view of an example of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure.

Figure 10 is a schematic perspective top view of the volumetric fluid expander shown in Figure 9.

Figure 11 is a schematic showing geometric parameters of the rotors of the volumetric fluid expanders shown in Figures 7 and 9.

Figure 12 is a schematic showing the rotors of the volumetric fluid expanders shown in Figures 7 and 9.

Figure 13 is a diagram depicting the Rankine cycle employed by the system shown in Figures 1-6.

DETAILED DESCRIPTION

[0010] 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 present disclosure. 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.

[0011] Referring to the drawings, a system is illustrated in which a plurality of volumetric fluid expansion stages 20 having dual interleaved rotors extracts energy from a waste heat stream from a power source, which is also referred to herein as a power plant, that would otherwise be wasted. As described below, the rotors can be configured to be either straight or twisted. The volumetric fluid expansion stage 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 expansion stage that transfers energy back to the power plant directly or indirectly.

Volumetric Energy Recovery System with Three Stage Expansion System

[0012] Figure 1 is a schematic depiction of a system 100 employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure. In this example, the system 100 employs a working fluid 12 as the working substance for closed loop circulation while using the Rankine cycle to generate mechanical work. The working fluid 12 can be of any type suitable for the Rankine cycle. In some examples, the working fluid is ethanol, n-pentane, or toluene. In this document, the working fluid 12 is designated as different reference numerals, such as 13, 14, 17, 22, 23, 16, 27, 28, 30 and 32, to represent different phases, temperatures and/or pressures or the fluid 12.

[0013] In some examples, the system 100 includes an engine 52; a plurality of heat exchangers 18-1, 18-2, 18-3, and 18-4 (collectively designated as 18); a three stage expansion system having a plurality of expansion stages 20-1, 20-2, and 20-3 (collectively designated as 20); a condenser 25; and a fluid pump 16.

[0014] The engine 52 can be an internal combustion engine that operates on combustion of a chemical fuel, such as diesel fuel or gasoline, and produces a great quantity of heat and exhaust gases. In some examples, the engine 52 can include a supercharger or turbocharger 102 to use forced induction.

[0015] The plurality of heat exchangers 18 is configured to transfer heat to and from the working fluid 12 passing therein.

[0016] The expansion stages 20 are configured to receive the working fluid 12 and generate mechanical work. In operation, as the working fluid 12 passes through the expansion stage 20, the temperature and pressure of the fluid 12 drop. In general, the expansion stages 20 rely upon the pressure of the fluid 12 to rotate an output shaft, thereby creating mechanical energy. The mechanical energy can be used or stored in several ways. For example, the torque created by the expansion stages 20 can be used by the engine 52. Each of the expansion stages 20 can return the extracted energy back to the engine 52 via an output shaft 38 of the device 20 (FIGS. 3-6). In other examples, the mechanical energy can be accumulated in a load storage device for subsequent release on demand. The mechanical energy can also be used for an electrical generator that is associated with the system 100 or for a hydraulic pump used by the engine 52, Accordingly, the volumetric fluid expansion stages 20 operate to increase the overall efficiency of the engine 52, to create useful mechanical work, and to recirculate the fluid 12. Examples of the expansion stages 20 are discussed below in further detail with reference to Figures 3-6.

[0017] The condenser 25 operates to condense the working fluid 12 from its gaseous state to a liquid state by cooling it.

[0018] The fluid pump 16 is configured to pump the working fluid 12 from low to high pressure while maintaining the working fluid 12 in its liquid state.

[0019] Referring to Figure 1, in operation, the engine 52 receives air through the turbo 102. The turbo 102 receives atmospheric air 103 at temperature T1 and a charge air cooler 104 cools the air 103 to air 106 at temperature T2 that is lower than temperature T1. The air 106 at temperature T2 is then delivered to and used by the engine 52 which thereafter emits exhaust gas 108 at temperature T3 that is higher than temperature T2.

[0020] The exhaust gas 108 at temperature T3 enters a first heat exchanger 18-1. The heat exchanger 18-1 utilizes a fluid 14 at temperature T9 flowing therein as a cooling fluid. The temperature T9 is lower than the temperature T3. As discussed below, the fluid 14 is discharged from a first expansion stage 20-1. The first heat exchanger 18-1 circulates the fluid 14 through its coils, thereby cooling the exhaust gas 108 as it flows past the coils and simultaneously heating the fluid 14 to produce a fluid 13 at temperature T11 that is higher than the temperature T9. The heated fluid 13 at the temperature T11 then passes through a second expansion stage 20-2.

[0021] The second expansion stage 20-2 receives the fluid 13 at the temperature T11 and discharges a fluid 17 at temperature T12 that is lower than T11. Furthermore, the fluid 17 has a lower pressure than the fluid 12. While reducing the temperature and pressure of the fluid 13 into the fluid 17, the second expansion stage 20-2 generates mechanical work that can be used or stored in various ways as discussed above.

[0022] The fluid 17, with a lower temperature and pressure than the fluid 13, immediately flows through a third expansion stage 20-3 which is again used to create mechanical energy as it discharges a fluid 21 at temperature T4 that is lower than the temperature T12. Furthermore, the fluid 21 has a lower pressure than the fluid 17. Because the fluid 17 has a lower temperature and pressure than the fluid 13 as it enters the third expansion stage 20-3, the third expansion stage 20-3 cannot produce as much mechanical energy as the second expansion stage 20-2. As such, the fluid 21 exiting the third expansion stage 20-3 has a lower temperature and pressure than the fluids 17 and 13. In some examples, the fluid 21 exiting the third expansion stage 20-3 has a mixed phase fluid comprising of a mixture of gas and liquid.

[0023] The fluid 21 at the temperature T4 then passes through a second heat exchanger 18-2, which is typically referred to as a recuperator, before flowing into the condenser 25. The recuperator 18-2 is placed between the third expansion stage 20-3 and the condenser 25 to further reclaim waste heat from the fluid 21 released from the third expansion stage 20-3. A fluid 23 exiting the recuperator 18-2 has temperature T10 that is lower than the temperature T4.

[0024] The fluid 23 is then sent to the condenser 25 that is used to convert the fluid 23, which, in some examples, can be a mixture of gas and liquid, to a saturated liquid 31 at temperature T5. As shown in the Rankine cycle of Figure 7, the temperature T5 remains substantially the same at the condenser 25, and thus the temperature T5 is substantially the same as T10.

[0025] The fluid 31 at the temperature T5 is pumped from low to high pressure by the pump 16. In this process, the temperature T5 of the fluid 31 increases, as shown in the Rankine cycle of Figure 7. Therefore, a fluid 27 discharged from the pump 16 has the temperature T13 that is higher than the temperature T5 of the fluid 31, and flows into the recuperator 18-2.

[0026] The recuperator 18-2 utilizes the fluid 27 at the temperature T13 to take heat from the fluid 21, which is released from the third expansion stage 20-3. Accordingly, the recuperator 18-2 transfers heat from the fluid 21 at the temperature T4 to the fluid 27 at the temperature T13, thereby producing a fluid 33 at temperature T6 that is higher than the temperature T13. The fluid 33 flows to a third heat exchanger 18-3.

[0027] The third heat exchanger 18-3 transfers heat from the exhaust gas 108, which is released from the first heat exchanger 18-1, to the fluid 33, thereby producing a fluid 35 at temperature T7 that is higher than T6. The fluid 35 thereafter flows to a fourth heat exchanger 18-4.

[0028] The fourth heat exchanger 18-4 transfers heat from the exhaust gas 108 at the temperature T3, which flows through the fourth heat exchanger 18-4 from the engine 52, to the fluid 35 at the temperature T7. As a result, the fourth heat exchanger 18-4 produces a fluid 36 at temperature T8 that is greater than T7. The exhaust gas 108 is simultaneously cooled to a lower temperature than T3 as it flows through the fourth heat exchanger 18-4 and released to the atmosphere.

[0029] The fluid 36 at the temperature T8 is received by the first expansion stage 20-1 that discharges a fluid 14 at temperature T9 that is lower than T8 and generates mechanical work as described above. The fluid 14 has a lower pressure than the fluid 36. The fluid 14 leaving the first expansion stage 20-1 at temperature T9 flows directly to the first heat exchanger 18-1 where it is reheated directly by exhaust gas 108 supplied from the engine 52. The entire process is then repeated in a cycle as described above.

[0030] As illustrated above, the second heat exchanger 18-2, which is also referred to as the recuperator, the third heat exchanger 18-3, and the fourth heat exchanger 18-4 are connected in series. In some examples, the second, third and fourth heat exchangers 18-2, 18-3 and 18-4 are replaced by one or two heat exchanger devices, which operate the same as the combination of the first, second and third heat exchangers 18-2, 18-3 and 18-4.

[0031] Figure 2 is a schematic depiction of a second exemplary system 100 employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure. As many of the concepts and features are similar to the first example shown in Figure 1, the description for the first example is hereby incorporated by reference for the second example. Where like or similar features or elements are shown, the same reference numbers will be used where possible. The following description for the second example will be limited primarily to the differences between the first and second examples.

[0032] In this example, the system 100 removes the first heat exchanger 18-1. In the first example, the fluid 14 at the temperature T9 is discharged from the first expansion stage 20-1 and enters the first heat exchanger 18-1 before flowing into the second expansion stage 20-2. In contrast, in this example, the fluid 14 at the temperature T9 discharged from the first expansion stage 20-1 is directly delivered to the second expansion stage 20-2. Furthermore, in the first example, the exhaust gas 108 at the temperature T3 supplied from the engine 52 passes through the first heat exchanger 18-1 and the third heat exchanger 18-3 in series. However, in this example, the exhaust gas 108 at the temperature T3 flows directly from the engine 52 to the third heat exchanger 18-3.

[0033] Figure 3 is a schematic depiction of a third exemplary system 100 employing a Rankine cycle using a three stage expansion system in accordance with the principles of the present disclosure. As many of the concepts and features are similar to the second example shown in Figure 2, the description for the second example is hereby incorporated by reference for the third example. Where like or similar features or elements are shown, the same reference numbers will be used where possible. The following description for the third example will be limited primarily to the differences between the second and third examples.

[0034] In this example, the recuperator 18-2 is directly connected to both the third heat exchanger 18-3 and the fourth heat exchanger 18-4 while the third heat exchanger 18-3 and the fourth heat exchanger 18-4 are arranged in parallel. The system 100 can include a splitter valve 19 (also known as a distributor valve), which operates to divide the fluid discharged from the recuperator 18-2 to flow into both the third heat exchanger 18-3 and the fourth heat exchanger 18-4 at the same time. Therefore, the fluid 33 at the temperature T6 discharged from the recuperator 18-2 is drawn into both the third heat exchanger 18-3 and the fourth heat exchanger 18-4. The third heat exchanger 18-3 transfers heat from the exhaust gas 108 of the engine 52 to the fluid 33, and discharges the fluid 29 at temperature T14, which is greater than the temperature T6. The fluid 29 flows directly to the first expansion stage 20-1. Similarly, the fourth heat exchanger 18-4 transfers heat from the exhaust gas 108 of the engine 52 to the fluid 33, and discharges the fluid 36, which is then drawn to the first expansion stage 20-1.

[0035] Although this example describes that the two heat exchangers 18-3 and 18-4 are arranged in parallel through one splitter valve 19, more than two heat exchangers can be arranged in parallel through one or more splitter valves, provided that the heat exchangers discharge the fluid 36 that is drawn into the first expansion stage 20-1.

[0036] Additional examples are directed to a method of using a three stage expansion system in a Rankine cycle as described in Figures 1 and 2.

[0037] Figure 4 is a flowchart of an exemplary method 300 for circulating the working fluid 12 in a Rankine cycle with a three stage expansion system. At process 302, the working fluid 12 is heated to at least a partial vapor state. The process can be performed by a heat exchanging device, such as the first heat exchanger 18-1, the second heat exchanger 18-2, the third heat exchanger 18-3, or the fourth heat exchanger 18-4, or any combination thereof. At process 304, the working fluid 12 passes through the first expansion stage 20-1, which expands the working fluid 12 and generates useful work from expansion. At process 306, the working fluid 12 discharged from the first expansion stage 20-1 passes through the second expansion stage 20-2. The second expansion stage 20-2 generates useful work by expanding the working fluid 12. The working fluid 12 is then discharged from the second expansion stage 20-2. At process 308, the working fluid 12 passes the third expansion stage 20-3, which generates useful work by expanding the working fluid 12. At process 310, the working fluid 14, which has been used to generate useful work by the first, second and third expansion stages 20-1, 20-2 and 20-3, is then condensed to a liquid state, and returns to the process 302.

[0038] Figure 5 is a flowchart of an exemplary method 200 for circulating the working fluid 12 in a Rankine cycle with a three stage expansion system. For example, the process 200 can be performed in the system 100 in accordance with the second example described above with reference to Figure 2. In this example, the working fluid 36 at the temperature T8 enters the first expansion stage 20-1 (202). At process 202, the pressure and temperature of the working fluid 36 decrease as the working fluid 36 passes through the first expansion stage 20-1 that simultaneously generates mechanical energy, which is also referred to herein as useful work. The first expansion stage 20-1 then discharges the working fluid 14 at the temperature T9. The working fluid 14 flows into the second expansion stage 20-1 (204). At process 204, the pressure and temperature of the working fluid 14 decrease as the working fluid 14 passes through the second expansion stage 20-2 that simultaneously generates mechanical energy. The second expansion stage 20-2 then discharges the working fluid 17 at the temperature T12. The working fluid 17 flows into the third expansion stage 20-3 (206). At process 206, the pressure and temperature of the working fluid 17 decrease as the working fluid 17 passes through the third expansion stage 20-3 that simultaneously generates mechanical energy. The third expansion stage 20-3 then discharges the working fluid 21 at the temperature T4.

[0039] The working fluid 21 enters the second heat exchanger or recuperator 18-2 (208). At process 208, the temperature of the working fluid 21 is reduced to the temperature T10 by the recuperator 18-2. The working fluid 23 at the temperature T10 then enters the condenser 25, which liquidizes the fluid 23 and discharges the working fluid 31 at the temperature T5 (210). As shown in Figure 7, the temperature T5 of the fluid 31 is substantially the same as the temperature T10 of the fluid 23. At process 212, the working fluid 31 is pumped by the pump 16. The working fluid 27 pumped from the pump 16 has the temperature T13 that is higher than the temperature T5 of the fluid 31, as shown in Figure 7. At process 214, the working fluid 27 is heated by the recuperator 18-2 to have increased temperature. The recuperator 18-2 produces the working fluid 33 at the temperature T6 that is higher than T13. At process 216, the working fluid 33 is further heated by the third heat exchanger 18-3 to have increased temperature. The third heat exchanger 18-3 discharges the working fluid 35 at the temperature T7 higher than T6. At process 218, the working fluid 35 is again heated by the fourth exchanger 18-4 to have increased temperature. The fourth heat exchanger 18-4 discharges the working fluid 36 at the temperature T8 higher than T7. The working fluid 36 is fed back into the third expansion stage 18-3 at process 202, as described above.

[0040] Figure 6 is a flowchart of another exemplary method 200 for circulating a working fluid 12 in a Rankine cycle with a three stage expansion system. For example, the process 200 can be performed in the system 200 in accordance with the first example described above with reference to Figure 1. As the method in this example is substantially similar to the first example shown in Figure 8, the description for the first example is hereby incorporated by reference for this example. Where like or similar features or elements are shown, the same reference numbers will be used where possible. The following description will be limited primarily to the differences between the first and second examples.

[0041] In this example, the method 200 further includes a step of increasing the temperature of the working fluid at the first heat exchanger 18-1 between processes 202 and 204 (220). At process 220, the working fluid 14, which has passed the first expansion stage 20-1, is drawn into the first heat exchanger 18-1 to increase its temperature before entering the second expansion stage 20-2. As the working fluid 14 passes through the first heat exchanger 18-1, the temperature increases from T9 to T11. Thus, the first heat exchanger 18-1 discharges the working fluid 13 at the temperature T11, which subsequently flows into the second expansion stage 20-2 for process 204.

Volumetric Fluid Expander

[0042] Figures 7-12 illustrate an expander used in the system shown in Figures 1-3. Figure 7 is a side perspective view of an example of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure. Figure 8 is a cross-sectional side perspective view of the volumetric fluid expander shown in Figure 7. Figure 9 is a cross-sectional side view of another example of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure. In general, the volumetric energy recovery device 20 relies upon the kinetic energy and static pressure of the working fluid 12-1 to rotate an output shaft 38. Where the device 20 is used in an expansion application, such as with a Rankine cycle, additional energy is extracted from the working fluid via fluid expansion. In such instances, the device 20 may be referred to as an expander or expansion device, as so presented in the following paragraphs. However, it is to be understood that the device 20 is not limited to applications where a working fluid is expanded across the device.

[0043] The expansion device 20 has a housing 22 with a fluid inlet 24 and a fluid outlet 26 through which the working 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 from the heat exchanger 18 (shown in Figures 1-3), 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 working fluid 12-1 against an interior side of the housing at which point expansion of the working fluid 12-1 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 working 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 working fluid 12-1 traverses the length of the rotors 30, 32. Accordingly, the expansion device 20 may be referred to as a "volumetric device" as the sealed or partially sealed working fluid volume does not change.

[0044] As additionally shown in Figure 10, 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. Additionally, the number of lobes is the same for both rotors 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 counterclockwise. 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 working fluid 12-1.

[0045] 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. The first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other.

[0046] The first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other. With renewed reference to Figure 9, 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.

[0047] The output shaft 38 is rotated by the working fluid 12 as the working 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 9 and 10, 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 working 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 52 such that the energy from the exhaust can be recaptured.

[0048] 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 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 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.

[0049] In another aspect of the expander geometry, the inlet port 24 includes an inlet angle 24-1, as can be seen schematically at Figure 9. 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 Figure 9. In one example, the inlet angle 24-1 is defined as the general resulting direction of the working fluid 12-1 entering the rotors 30, 32 due to contact with the anterior inner surface 24a, as can be seen at Figure 9. 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 working 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.

[0050] Furthermore, and as shown in Figure 9, the inlet port 24 may be shaped such that the working 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 Figure 9.

[0051] Referring to Figure 12, it can be seen that the inlet port 24 has a width W that is slightly less than the combined diameter distance of the rotors 30, 32. The combined rotor diameter is equal to the distance between the axes X1 and X2 plus the twice the distance from the centerline axis X1 or X2 to the tip of the respective lobe. In some examples, width W is the same as or more than the combined rotor diameter.

[0052] In another aspect of the expander geometry, the outlet port 26 includes an outlet angle 26-1, as can be seen schematically at Figure 9. 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 Figure 9. In one example, the outlet angle 26-1 is defined as the general resulting direction of the working fluid 12-2 leaving the rotors 30, 32 due to contact with the inner surface 26a, as can be seen at Figure 9. 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 working 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 Figure 9. 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 working 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 working fluid can be rapidly discharged into the lower pressure working fluid at the condenser.

[0053] 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 working fluid 12-1 to both the leading and trailing faces of each rotor 30, 32, the working fluid 12-1 performs both positive and negative work on the expander 20.

[0054] To illustrate, Figure 10 shows that lobes 30-1, 30-4, 32-1, and 32-2 are each exposed to the working 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 working 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.

[0055] In generalized terms, the working 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 working 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, working 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 working 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 working 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 working fluid 12-1 causes the rotors to rotate opposite to the desired direction, R1, R2.

[0056] 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 working fluid 12-1 as possible impinges on the trailing surfaces of the lobes with as little of the working fluid 12-1 impinging on the on the leading lobes such that the highest net positive work can be performed by the expander 20.

[0057] 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.

Rankine Cycle Operation

[0058] Figure 13 shows a diagram 48 depicting a representative Rankine cycle applicable to the system 100, as described with respect to Figures 1-6. The diagram 48 depicts different stages of the Rankine cycle showing temperature in Celsius plotted against entropy "S", wherein entropy is defined as energy in kilojoules divided by temperature in Kelvin and further divided by a kilogram of mass (kJ/kg*K). The Rankine cycle shown in Figure 7 is specifically a closed-loop Organic Rankine Cycle (ORC) that may use an organic, high molecular mass working fluid, with a liquid-vapor phase change, or boiling point, occurring at a lower temperature than the water-steam phase change of the classical Rankine cycle. Accordingly, in the system 100, the working fluid 12 may be a solvent, such as ethanol, n-pentane or toluene.

[0059] In the diagram 48 of Figure 13, the term "$\dot{Q}$" represents the heat flow to or from the system 100, and is typically expressed in energy per unit time. The term "$\dot{W}$" represents mechanical power consumed by or provided to the system 100, and is also typically expressed in energy per unit time. As may be additionally seen from Figure 13, there are four distinct processes or stages 48-1, 48-2, 48-3, and 48-4 in the ORC. During stage 48-1, the working fluid 12 in the form of a wet vapor enters and passes through the condenser 25, in which the working fluid is condensed at a constant temperature to become a saturated liquid. Following stage 48-1, the working fluid 12 is pumped from low to high pressure by the pump 16 during the stage 48-2. During stage 48-2, the working fluid 12 is in a liquid state.

[0060] From stage 48-2 the working fluid is transferred to stage 48-3. During stage 48-3, the pressurized working fluid 12 enters and passes through the heat exchanger 18 where it is heated at constant pressure by an external heat source to become a two-phase fluid, i.e., liquid together with vapor. From stage 48-3 the working fluid 12 is transferred to stage 48-4. During stage 48-4, the working fluid 12 in the form of the two-phase fluid expands through the expander 20, generating useful work or power. The expansion of the partially vaporized working fluid 12 through the expander 20 decreases the temperature and pressure of the two-phase fluid, such that some additional condensation of the two-phase working fluid 12 may occur. Following stage 48-4, the working fluid 12 is returned to the condenser 25 at stage 48-1, at which point the cycle is then complete and will typically restart.

[0061] Typically a Rankine cycle employs a turbine configured to expand the working fluid during the stage 48-4. In such cases, a practical Rankine cycle additionally requires a superheat boiler to take the working fluid into superheated range in order to remove or evaporate all liquid therefrom. Such an additional superheating process is generally required so that any liquid remaining within the working fluid will not collect at the turbine causing corrosion, pitting, and eventual failure of the turbine blades. As shown, the ORC of Figure 13 is characterized by the absence of such a superheat boiler and the attendant superheating process needed to evaporate all liquid from the working fluid. The preceding omission is permitted by the fact that the expander 20 is configured as a twin interleafed rotor device which is not detrimentally impacted by the presence of a liquid in the working fluid 12. Furthermore, the expander 20 benefits from the presence of such a liquid, primarily because the remaining liquid tends to enhance the operational efficiency of the expander by sealing clearances between the first and second rotors 30, 32, and between the rotors and the housing 22. Accordingly, when useful work is generated by the expander 20 in the system 100, the working fluid 12 within the expander is present in two phases, i.e., as a liquid-vapor, such that conversion efficiency of the ORC is increased. However, it is to be understood that the recovery device 20 can be used in configurations involving a superheated gas.

[0062] Additionally, a smaller size expander may be used in the system 100 to achieve the required work output. The efficiency will never be above the Carnot efficiency of 63% because that is the maximum Caarnot efficiency eff= 1-Tcold/ Thot. The working fluid will likely be ethanol which has a max temp of 350c before it starts to break down. The expander efficiency will be less than the peak efficiency of a turbo but the efficiency islands are considerably larger over a greater flow range then than the turbo expander so an overall efficiency for a cycle is larger.

Claims

1. A method for generating mechanical work via a closed-loop Rankine cycle, the method comprising:

passing a working fluid through a heat exchanging device (18) to increase the temperature of the working fluid;
passing the working fluid through a first volumetric fluid expansion stage (20-1) to decrease the temperature and pressure of the working fluid and to create a third mechanical work;
passing the working fluid through a second volumetric fluid expansion stage (20-2) to decrease the temperature and pressure of the working fluid and to create a first mechanical work;
passing the working fluid through a third volumetric fluid expansion stage (20-3) to decrease the temperature and pressure of the working fluid and to create a second mechanical work;
condensing the working fluid; and
returning the working fluid to the first volumetric fluid expansion stage (20-1);
characterized in that each of the first, second, and third volumetric fluid expansion stages (20-1, 20-2, 20-3) comprises:

a housing (22) with a fluid inlet (24) and a fluid outlet (26);
first and second interleaved counter-rotating non-contacting rotors (30, 32) disposed in a cavity (28) of the housing (22), each of the rotors (30, 32) having lobes that are straight, twisted or helically disposed along the length of the rotors, each of the rotors (30, 32) having the same number of lobes; and
an output shaft (38) driven by said first and second rotors (30, 32);
wherein the working fluid stream is admitted at the fluid inlet (24) at a first pressure and is discharged from the outlet port (26) at a second pressure lower than the first pressure, wherein the flow of the working fluid stream through the housing (22) provides for rotation of the rotors (30, 32).

2. The method of claim 1, wherein the step of passing the working fluid through the heat exchanging device comprises:

receiving, by the heat exchanging device (18), a heat stream from a power plant; and
transferring, by the heat exchanging device (18), heat from the heat stream to the working fluid.

3. The method of claim 1, wherein the step of passing the working fluid through the heat exchanging device comprises providing a first heat exchanger (18-1) arranged between the first volumetric fluid expansion stage (20-1) and the second volumetric fluid expansion stage (20-2),
the method further comprising:

> passing the working fluid through the first heat exchanger (18-1) to increase the temperature of the working fluid, wherein the first heat exchanger is configured to receive a heat stream from a power plant and transfer heat from the heat stream to the working fluid.

4. The method of claim 3, further comprising, after condensing the working fluid, passing the working fluid through a second heat exchanger (18-2) to increase the temperature of the working fluid.

5. The method of claim 4, wherein the step of passing the working fluid through the heat exchanging device comprises providing a third heat exchanger (18-3) arranged downstream of the second heat exchanger (18-2) to receive the working fluid from the second heat exchanger,
the method further comprising:

> passing the working fluid through the third heat exchanger (18-3) to increase the temperature of the working fluid, wherein the third heat exchanger is configured to receive a heat stream from a power plant and transfer heat from the heat stream to the working fluid.

6. The method of claim 4, wherein the step of passing the working fluid through the heat exchanging device comprises providing a third heat exchanger (18-3) arranged downstream of the second heat exchanger (18-2) to receive the working fluid from the second heat exchanger,
the method further comprising:

> passing the working fluid through the third heat exchanger (18-3) to increase the temperature of the working fluid, wherein the third heat exchanger is configured to receive the heat stream from the first heat exchanger (18-1) and transfer heat from the heat stream to the working fluid.

7. The method of claim 5, wherein the step of passing the working fluid through the heat exchanging device comprises providing a fourth heat exchanger (18-4) arranged downstream of the third heat exchanger (18-3) to receive the working fluid from the third heat exchanger,
the method further comprising:

> passing the working fluid through the fourth heat exchanger (18-4) to increase the temperature of the working fluid, wherein the fourth heat exchanger is configured to receive a heat stream from a power plant and transfer heat from the heat stream to the working fluid.

8. A system used to generate mechanical work via a closed-loop Rankine cycle, the system comprising:

> a power plant producing a heat stream and having a heat outlet through which the heat stream exits;
> a heat exchanging device (18) configured to transfer heat from the heat stream to a working fluid steam;
> a first volumetric fluid expansion stage (20-1) configured to receive the working fluid stream from the heat exchanging device (18);
> a second volumetric fluid expansion stage (20-2) configured to receive the working fluid stream from the first volumetric fluid expansion stage (20-1); and
> a third volumetric fluid expansion stage (20-3) configured to receive the working fluid stream from the second volumetric fluid expansion stage (20-2);
> wherein each of the first, second, and third volumetric fluid expansion stages (20-1, 20-2, 20-3) is configured to generate mechanical work from the working fluid stream;
> **characterized in that** each of the first, second, and third volumetric fluid expansion stages (20-1, 20-2, 20-3) comprises:
>
> > a housing (22) with a fluid inlet (24) and a fluid outlet (26);
> > first and second interleaved counter-rotating non-contacting rotors (30, 32) disposed in a cavity (28) of the housing (22), each of the rotors (30, 32) having lobes that are straight, twisted or helically disposed along the length of the rotors, each of the rotors (30, 32) having the same number of lobes; and
> > an output shaft (38) driven by said first and second rotors (30, 32);
> > wherein the working fluid stream is admitted at the fluid inlet (24) at a first pressure and is discharged from the outlet port (26) at a second pressure lower than the first pressure, wherein the flow of the working fluid stream through the housing (22) provides for rotation of the rotors (30, 32).

9. The system of claim 8, further comprising a condenser (25) configured to receive the working fluid from the third volumetric fluid expansion stage (20-3) and condense the working fluid.

10. The system of claim 9, further comprising a pump (16) configured to receive the working fluid from the condenser (25) and pump the working fluid in the cycle.

11. The system of claim 9, wherein the heat exchanging device (18) includes a first heat exchanger (18-1) configured to receive the heat stream from the power plant, receive the working fluid from the first volumetric fluid expansion stage (20-1), transfer heat from the heat stream to the working fluid steam, and provide the working fluid stream to the second volumetric fluid expansion stage (20-2).

12. The system of claim 9, wherein the heat exchanging device (18) includes a second heat exchanger (18-2) configured to receive the working fluid discharged from the second volumetric fluid expansion stage (20-2), wherein the working fluid exiting the second heat exchanger flows into the condenser (25), the second heat exchanger further configured to receive the working fluid discharged from the condenser and transfer heat from the working fluid discharged from the third volumetric fluid expansion stage (20-3) to the working fluid discharged from the condenser.

13. The system of claim 12, wherein the heat exchanging device (18) includes a third heat exchanger (18-3) configured to receive the heat stream from the first heat exchanger (18-1) and the working fluid from the second heat exchanger (18-2), the third heat exchanger configured to transfer heat from the heat stream to the working fluid discharged from the second heat exchanger.

14. The system of claim 13, wherein the heat exchanging device (18) includes a fourth heat exchanger (18-4) configured to receive the heat stream from the power plant and the working fluid from the third heat exchanger (18-3), the fourth heat exchanger configured to transfer heat from the heat stream to the working fluid discharged from the third heat exchanger.

15. The system of claim 14, wherein the first volumetric fluid expansion stage (20-1) is arranged between the fourth heat exchanger (18-4) and the first heat exchanger (18-1) and configured to receive the working fluid discharged from the fourth heat exchanger and discharge the working fluid to the first heat exchanger.

Patentansprüche

1. Verfahren zum Erzeugen von mechanischer Arbeit mittels eines Rankine-Regelkreises, wobei im Zuge des Verfahrens:

ein Arbeitsfluid durch eine Wärmetauschervorrichtung (18) geleitet wird, um die Temperatur des Arbeitsfluids zu erhöhen,
das Arbeitsfluid durch eine erste volumetrische Fluidexpansionsstufe (20-1) geleitet wird, um die Temperatur und den Druck des Arbeitsfluids zu senken und eine dritte mechanische Arbeit zu erzeugen;
das Arbeitsfluid durch eine zweite volumetrische Fluidexpansionsstufe (20-2) geleitet wird, um die Temperatur und den Druck des Arbeitsfluids zu senken und eine erste mechanische Arbeit zu erzeugen;
das Arbeitsfluid durch eine dritte volumetrische Fluidexpansionsstufe (20-3) geleitet wird, um die Temperatur und den Druck des Arbeitsfluids zu senken und eine zweite mechanische Arbeit zu erzeugen;
das Arbeitsfluid kondensiert wird; und
das Arbeitsfluid zu der ersten volumetrischen Fluidexpansionsstufe (20-1) zurückgeleitet wird;
dadurch gekennzeichnet, dass jede der ersten, zweiten, und dritten volumetrischen Fluidexpansionsstufen (20-1, 20-2, 20-3) versehen ist mit:

einem Gehäuse (22) mit einem Fluideinlass (24) und einem Fluidauslass (26)
ersten und zweiten ineinander verschachtelten, gegenläufigen, sich nicht berührenden Rotoren (30, 32), die in einem Hohlraum (28) des Gehäuses (22) angeordnet sind, wobei jeder der Rotoren (30, 32) Flügel aufweist, die gerade, gewunden oder wendelförmig entlang der Länge der Rotoren angeordnet sind, wobei jeder der Rotoren (30, 32) die gleiche Anzahl von Flügeln aufweist; und
einer Abtriebswelle (38), die durch die ersten und zweiten Rotoren (30, 32) angetrieben wird;
wobei der Arbeitsfluidstrom an dem Fluideinlass (24) mit einem ersten Druck anliegen kann, und von dem Auslassanschluss (26) bei einem zweiten Druck abgegeben wird, der niedriger als der erste Druck ist, wobei der Durchfluss des Arbeitsfluidstroms durch das Gehäuse (22) für eine Rotation der Rotoren (30, 32) sorgt.

2. Verfahren gemäß Anspruch 1, bei welchem im Zuge des Schrittes des Durchleitens des Arbeitsfluids durch die Wärmetauschervorrichtung:

ein Wärmestrom von einer Energieversorgungsanlage durch die Wärmetauschervorrichtung (18) erhalten wird; und
Wärme von dem Wärmestrom mittels der Wärmetauschervorrichtung (18) auf das Arbeitsfluid übertragen wird.

3. Verfahren gemäß Anspruch 1, bei welchem im Zuge des Schrittes des Durchleitens des Arbeitsfluids durch die Wärmetauschervorrichtung ein erster Wärmetauscher (18-1) bereitgestellt wird, der zwischen der ersten volumetrischen Fluidexpansionsstufe (20-1) und der zweiten volumetrischen Fluidexpansionsstufe (20-2) angeordnet ist,
wobei im Zuge des Verfahrens ferner:

das Arbeitsfluid durch den ersten Wärmetauscher (18-1) geleitet wird, um die Temperatur des Arbeitsfluids anzuheben, wobei der erste Wärmetauscher ausgelegt ist, einen Wärmestrom von einer Energieversorgungsanlage aufzunehmen und Wärme von dem Wärmestrom auf das Arbeitsfluid zu übertragen.

4. Verfahren gemäß Anspruch 3, bei welchem ferner, nach dem Kondensieren des Arbeitsfluids, das Arbeitsfluid durch einen zweiten Wärmetauscher (18-2) geleitet wird, um die Temperatur des Arbeitsfluids anzuheben.

5. Verfahren gemäß Anspruch 4, bei welchem im Zuge des Schrittes des Durchleitens des Arbeitsfluids durch die Wärmetauschervorrichtung ein dritter Wärmetauscher (18-3) bereitgestellt wird, der stromab des zweiten Wärmetauschers (18-2) angeordnet ist, um das Arbeitsfluid von dem zweiten Wärmetauscher zu erhalten;
wobei im Zuge des Verfahrens ferner:

das Arbeitsfluid durch den dritten Wärmetauscher (18-3) geleitet wird, um die Temperatur des Arbeitsfluids anzuheben, wobei der dritte Wärmetauscher ausgelegt ist, einen Wärmestrom von einer Energieversorgungsanlage zu erhalten und Wärme von dem Wärmestrom auf das Arbeitsfluid zu übertragen.

6. Verfahren gemäß Anspruch 4, bei welchem der Schritt des Durchleitens des Arbeitsfluids durch die Wärmetauschervorrichtung das Bereitstellen eines dritten Wärmetauschers (18-3) umfasst, der stromab von dem zweiten Wärmetauscher (18-2) angeordnet ist, um das Arbeitsfluid von dem zweiten Wärmetauscher zu erhalten,
wobei im Zuge des Verfahrens ferner
das Arbeitsfluid durch den dritten Wärmetauscher (18-3) geleitet wird, um die Temperatur des Arbeitsfluids anzuheben, wobei der dritte Wärmetauscher ausgelegt ist, den Wärmestrom von dem ersten Wärmetauscher (18-1) zu erhalten und Wärme von dem Wärmestrom auf das Arbeitsfluid zu übertragen.

7. Verfahren gemäß Anspruch 5, bei welchem der Schritt des Durchleitens des Arbeitsfluids durch die Wärmetauschervorrichtung das Bereitstellen eines vierten Wärmetauschers (18-4) umfasst, der stromab von dem dritten Wärmetauscher (18-3) angeordnet ist, um das Arbeitsfluid von dem dritten Wärmetauscher zu erhalten,
wobei im Zuge des Verfahrens ferner:

das Arbeitsfluid durch den vierten Wärmetauscher (18-4) geleitet wird, um die Temperatur des Arbeitsfluids anzuheben, wobei der vierte Wärmetauscher ausgelegt ist, einen Wärmestrom von einer Energieversorgungsanlage zu erhalten und Wärme von dem Wärmestrom auf das Arbeitsfluid zu übertragen.

8. System zur Verwendung beim Erzeugen von mechanischer Arbeit mittels eines Rankine-Regelkreises, wobei das System versehen ist mit:

einer Energieerzeugungsanlage, die einen Wärmestrom erzeugt und die einen Wärmeauslass aufweist, durch welchen die Wärmeströme austreten;
einer Wärmetauschervorrichtung (18), die ausgelegt ist, Wärme von dem Wärmestrom auf einen Arbeitsfluidstrom zu übertragen;
einer ersten volumetrischen Fluidexpansionsstufe (20-1), die ausgelegt ist, den Arbeitsfluidstrom von der Wärmetauschervorrichtung (18) zu erhalten;
einer zweiten volumetrischen Fluidexpansionsstufe (20-2), die ausgelegt ist, den Arbeitsfluidstrom von der ersten volumetrischen Fluidexpansionsstufe (20-1) zu erhalten; und
einer dritten volumetrischen Fluidexpansionsstufe (20-3), die ausgelegt ist, den Arbeitsfluidstrom von der zweiten volumetrischen Fluidexpansionsstufe (20-2) zu erhalten;
wobei jede der ersten, zweiten, und dritten volumetrischen Fluidexpansionsstufen (20-1, 20-2, 20-3) ausgelegt ist, mechanische Arbeit aus dem Arbeitsfluidstrom zu erzeugen;
dadurch gekennzeichnet, dass jede der ersten, zweiten, und dritten volumetrischen Fluidexpansionsstufen (20-1, 20-2, 20-3) versehen ist mit:

einem Gehäuse (22) mit einem Fluideinlass (24) und einem Fluidauslass (26);
ersten und zweiten ineinander verschachtelten, gegenläufigen, sich nicht berührenden Rotoren (30, 32), die in einem Hohl-

raum (28) des Gehäuses (22) angeordnet sind, wobei jeder der Rotoren (30, 32) Flügel aufweist, die gerade, gewunden oder wendelförmig entlang der Länge der Rotoren angeordnet sind, wobei jeder der Rotoren (30, 32) die gleiche Anzahl von Flügeln aufweist; und
einer Abtriebswelle (38), die durch die ersten und zweiten Rotoren (30, 32) angetrieben wird;
wobei der Arbeitsfluidstrom an dem Fluideinlass (24) mit einem ersten Druck anliegen kann, und von dem Auslassanschluss (26) bei einem zweiten Druck abgegeben wird, der niedriger als der erste Druck ist, wobei der Durchfluss des Arbeitsfluidstroms durch das Gehäuse (22) für eine Rotation der Rotoren (30, 32) sorgt.

9. System gemäß Anspruch 8, ferner versehen mit einem Kondensator (25), der ausgelegt ist, das Arbeitsfluid von der dritten volumetrischen Fluidexpansionsstufe (20-3) zu erhalten und das Arbeitsfluid zu kondensieren.

10. System gemäß Anspruch 9, ferner versehen mit einer Pumpe (16), die ausgelegt ist, das Arbeitsfluid von den Kondensator (25) zu erhalten und das Arbeitsfluid in dem Kreis zu pumpen.

11. System gemäß Anspruch neun, bei welchem die Wärmetauschervorrichtung (18) einen ersten Wärmetauscher (18-1) aufweist, der ausgelegt ist, den Wärmestrom von der Energieversorgungsanlage zu erhalten, das Arbeitsfluid von der ersten volumetrischen Fluidexpansionsstufe (20-1) zu erhalten, Wärme von dem Wärmestrom auf den Arbeitsfluidstrom zu übertragen, und den Arbeitsfluidstrom zu der zweiten volumetrischen Fluidexpansionsstufe (20-2) zu liefern.

12. System gemäß Anspruch 9, wobei die Wärmetauschervorrichtung (18) einen zweiten Wärmetauscher (18-2) umfasst, der ausgelegt ist, das Arbeitsfluid, welches von der zweiten volumetrischen Fluidexpansionsstufe (20-2) abgegeben wird, zu erhalten, wobei das Arbeitsfluid, welches den zweiten Wärmetauscher verlässt, in den Kondensator (25) fließt, wobei der zweite Wärmetauscher ferner ausgelegt ist, das Arbeitsfluid zu erhalten, welches von dem Kondensator abgegeben wird und Wärme von dem Arbeitsfluid, welches von der dritten volumetrischen Fluidexpansionsstufe (20-3) abgegeben wird, zu dem von dem Kondensator abgegebenen Arbeitsfluid zu übertragen.

13. System gemäß Anspruch 12, bei welchem die Wärmetauschervorrichtung (18) einen dritten Wärmetauscher (18-3) umfasst, der ausgelegt ist, den Wärmestrom von dem ersten Wärmetauscher (18-1) zu erhalten und das Arbeitsfluid von dem zweiten Wärmetauscher (18-2) zu erhalten, wobei der dritte Wärmetauscher ausgelegt ist, Wärme von dem Wärmestrom auf das von dem zweiten Wärmetauscher abgegebene Arbeitsfluid zu übertragen.

14. System gemäß Anspruch 13, bei welchem die Wärmetauschervorrichtung (18) einen vierten Wärmetauscher (18-4) umfasst, der ausgelegt ist, den Wärmestrom von der Energieerzeugungsanlage zu erhalten und das Arbeitsfluid von dem dritten Wärmetauscher (18-3) zu erhalten, wobei der vierte Wärmetauscher ausgelegt ist, Wärme von dem Wärmestrom auf das von dem dritten Wärmetauscher abgegebene Arbeitsfluid zu übertragen.

15. System gemäß Anspruch 14, bei welchem die erste volumetrische Fluidexpansionsstufe (20-1) zwischen dem vierten Wärmetauscher (18-4) und dem ersten Wärmetauscher (18-1) angeordnet ist und ausgelegt ist, dass von dem vierten Wärmetauscher abgegebene Arbeitsfluid zu erhalten und das Arbeitsfluid zu dem ersten Wärmetauscher abzugeben.

Revendications

1. Procédé pour générer une énergie mécanique via un cycle de Rankine à boucle fermée, le procédé comprenant les étapes consistant à :

faire passer un fluide de travail par un dispositif d’échange de chaleur (18) pour augmenter la température du fluide de travail ;
faire passer le fluide de travail par un premier étage de détente de fluide volumétrique (20-1) pour diminuer une température et la pression du fluide de travail et pour créer une troisième énergie mécanique ;
faire passer le fluide de travail par un deuxième étage de détente de fluide volumétrique (20-2) pour diminuer la température et la pression du fluide de travail et pour créer une première énergie mécanique ;
faire passer le fluide de travail par un troisième étage de détente de fluide volumétrique (20-3) pour diminuer la température et la pression du fluide de travail et pour créer une deuxième énergie mécanique ;
condenser le fluide de travail ; et
ramener le fluide de travail au premier étage de détente de fluide volumétrique (20-1) ;
caractérisé en ce que chacun des premier, deuxième et troisième étages de détente de fluide volumétrique (20-1, 20-2, 20-3) comprend :

un boîtier (22) avec une entrée de fluide (24) et une sortie de fluide (26) ;
des premier et second rotors intercalés sans contact à rotation inverse (30, 32) disposés dans une cavité (28) du boîtier (22), chacun des rotors (30, 32) ayant des lobes qui sont droits, torsadés ou disposés de manière hélicoïdale le long de la longueur des rotors, chacun des rotors (30, 32) ayant le même nombre de lobes ; et
un arbre de sortie (38) entraîné par lesdits premier et second rotors (30, 32) ;
dans lequel le flux de fluide de travail est admis au niveau de l'entrée de fluide (24) à une première pression et est déchargé par l'orifice de sortie (26) à une seconde pression inférieure à la première pression, dans lequel l'écoulement du flux de fluide de travail à travers le boîtier (22) fournit la rotation des rotors (30, 32).

2. Procédé selon la revendication 1, dans lequel l'étape consistant à faire passer le fluide de travail par le dispositif d'échange de chaleur comprend les étapes consistant à :

recevoir, par le dispositif d'échange de chaleur (18), un flux de chaleur d'une installation électrique ; et
transférer, par le dispositif d'échange de chaleur (18), la chaleur du flux de chaleur au fluide de travail.

3. Procédé selon la revendication 1, dans lequel l'étape consistant à faire passer le fluide de travail par le dispositif d'échange de chaleur comprend l'étape consistant à prévoir un premier échangeur de chaleur (18-1) agencé entre le premier étage de détente de fluide volumétrique (20-1) et le deuxième étage de détente de fluide volumétrique (20-2),
le procédé comprenant en outre l'étape consistant à :

faire passer le fluide de travail par le premier échangeur de chaleur (18-1) pour augmenter la température du fluide de travail, dans lequel le premier échangeur de chaleur est configuré pour recevoir un flux de chaleur d'une installation électrique et transférer la chaleur du flux de chaleur au fluide de travail.

4. Procédé selon la revendication 3, comprenant en outre, après avoir condensé le fluide de travail, l'étape consistant à faire passer le fluide de travail par un deuxième échangeur de chaleur (18-2) pour augmenter la température du fluide de travail.

5. Procédé selon la revendication 4, dans lequel l'étape consistant à faire passer le fluide de travail par le dispositif d'échange de chaleur comprend l'étape consistant à prévoir un troisième échangeur de chaleur (18-3) agencé en aval du deuxième échangeur de chaleur (18-2) pour recevoir le fluide de travail du deuxième échangeur de chaleur,
le procédé comprenant en outre l'étape consistant à :

faire passer le fluide de travail par le troisième échangeur de chaleur (18-3) pour augmenter la température du fluide de travail, dans lequel le troisième échangeur de chaleur est configuré pour recevoir un flux de chaleur d'une installation électrique et transférer la chaleur du flux de chaleur au fluide de travail.

6. Procédé selon la revendication 4, dans lequel l'étape consistant à faire passer le fluide de travail par le dispositif d'échange de chaleur comprend l'étape consistant à prévoir un troisième échangeur de chaleur (18-3) agencé en aval du deuxième échangeur de chaleur (18-2) pour recevoir le fluide de travail du deuxième échangeur de chaleur,
le procédé comprenant en outre l'étape consistant à :

faire passer le fluide de travail par le troisième échangeur de chaleur (18-3) pour augmenter la température du fluide de travail, dans lequel le troisième échangeur de chaleur est configuré pour recevoir le flux de chaleur du premier échangeur de chaleur (18-1) et transférer la chaleur du flux de chaleur au fluide de travail.

7. Procédé selon la revendication 5, dans lequel l'étape consistant à faire passer le fluide de travail par le dispositif d'échange de chaleur comprend l'étape consistant à prévoir un quatrième échangeur de chaleur (18-4) agencé en aval du troisième échangeur de chaleur (18-3) pour recevoir le fluide de travail du troisième échangeur de chaleur,
le procédé comprenant en outre l'étape consistant à :

faire passer le fluide de travail par le quatrième échangeur de chaleur (18-4) pour augmenter la température du fluide de travail, dans lequel le quatrième échangeur de chaleur est configuré pour recevoir un flux de chaleur provenant d'une installation électrique et transférer la chaleur du flux de chaleur au fluide de travail.

8. Système utilisé pour générer de l'énergie mécanique via un cycle de Rankine à boucle fermée, le système comprenant :

une installation électrique produisant un flux de

chaleur et ayant une sortie de chaleur par laquelle le flux de chaleur sort ;
un dispositif d'échange de chaleur (18) configuré pour transférer la chaleur du flux de chaleur à une vapeur de fluide de travail ;
un premier étage de détente de fluide volumétrique (20-1) configuré pour recevoir le flux de fluide de travail du dispositif d'échange de chaleur (18) ;
un deuxième étage de détente de fluide volumétrique (20-2) configuré pour recevoir le flux de fluide de travail du premier étage de détente de fluide volumétrique (20-1) ; et
un troisième étage de détente de fluide volumétrique (20-3) configuré pour recevoir le flux de fluide de travail du deuxième étage de détente de fluide volumétrique (20-2) ;
dans lequel chacun parmi les premier, deuxième et troisième étages de détente de fluide volumétrique (20-1, 20-2, 20-3) est configuré pour générer de l'énergie mécanique à partir du flux de fluide de travail ;
caractérisé en ce que chacun des premier, deuxième et troisième étages de détente de fluide volumétrique (20-1, 20-2, 20-3) comprend :

un boîtier (22) avec une entrée de fluide (24) et une sortie de fluide (26) ;
des premier et second rotors entrelacés sans contact à rotation inverse (30, 32) disposés dans une cavité (28) du boîtier (22), chacun des rotors (30, 32) ayant des lobes qui sont droits, torsadés ou disposés de manière hélicoïdale le long de la longueur des rotors, chacun des rotors (30, 32) ayant le même nombre de lobes ; et
un arbre de sortie (38) entraîné par lesdits premier et second rotors (30, 32) ;
dans lequel le flux de fluide de travail est admis au niveau de l'entrée de fluide (24) à une première pression et est déchargé de l'orifice de sortie (26) à une seconde pression inférieure à la première pression, dans lequel l'écoulement du flux de fluide de travail par le boîtier (22) fournit la rotation des rotors (30, 32).

9. Système selon la revendication 8, comprenant en outre un condenseur (25) configuré pour recevoir le fluide de travail du troisième étage de détente de fluide volumétrique (20-3) et pour condenser le fluide de travail.

10. Système selon la revendication 9, comprenant en outre une pompe (16) configurée pour recevoir le fluide de travail du condenseur (25) et pour pomper le fluide de travail dans le cycle.

11. Système selon la revendication 9, dans lequel le dispositif d'échange de chaleur (18) comprend un premier échangeur de chaleur (18-1) configuré pour recevoir le flux de chaleur de l'installation électrique, recevoir le fluide de travail du premier étage de détente de fluide volumétrique (20-1), transférer la chaleur du flux de chaleur à la vapeur de fluide de travail, et amener le flux de fluide de travail au deuxième étage de détente de fluide volumétrique (20-2).

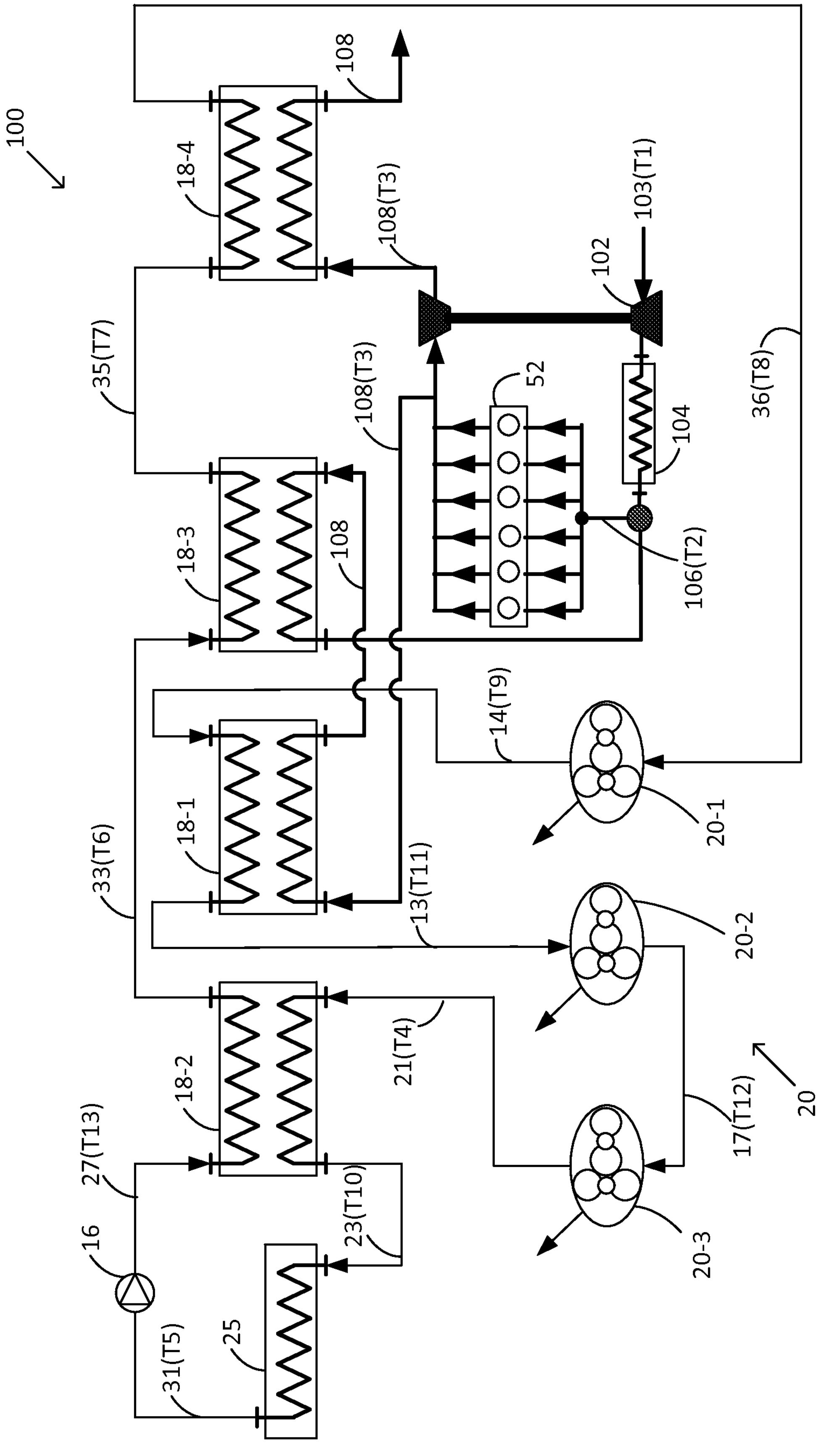
12. Système selon la revendication 9, dans lequel le dispositif d'échange de chaleur (18) comprend un deuxième échangeur de chaleur (18-2) configuré pour recevoir le fluide de travail déchargé du deuxième étage de détente de fluide volumétrique (20-2), dans lequel le fluide de travail sortant du deuxième échangeur de chaleur s'écoule dans le condenseur (25), le deuxième échangeur de chaleur étant en outre configuré pour recevoir le fluide de travail déchargé du condenseur et pour transférer la chaleur du fluide de travail déchargé du troisième étage de détente de fluide volumétrique (20-3) au fluide de travail déchargé du condenseur.

13. Système selon la revendication 12, dans lequel le dispositif d'échange de chaleur (18) comprend un troisième échangeur de chaleur (18-3) configuré pour recevoir le flux de chaleur du premier échangeur de chaleur (18-1) et le fluide de travail du deuxième échangeur de chaleur (18-2), le troisième échangeur de chaleur étant configuré pour transférer la chaleur du flux de chaleur au fluide de travail déchargé du deuxième échangeur de chaleur.

14. Système selon la revendication 13, dans lequel le dispositif d'échange de chaleur (18) comprend un quatrième échangeur de chaleur (18-4) configuré pour recevoir le flux de chaleur de l'installation électrique et le fluide de travail du troisième échangeur de chaleur (18-3), le quatrième échangeur de chaleur étant configuré pour transférer la chaleur du flux de chaleur au fluide de travail déchargé du troisième échangeur de chaleur.

15. Système selon la revendication 14, dans lequel le premier étage de détente de fluide volumétrique (20-1) est agencé entre le quatrième échangeur de chaleur (18-4) et le premier échangeur de chaleur (18-1) et configuré pour recevoir le fluide de travail déchargé du quatrième échangeur de chaleur et décharger le fluide de travail dans le premier échangeur de chaleur.

FIG. 1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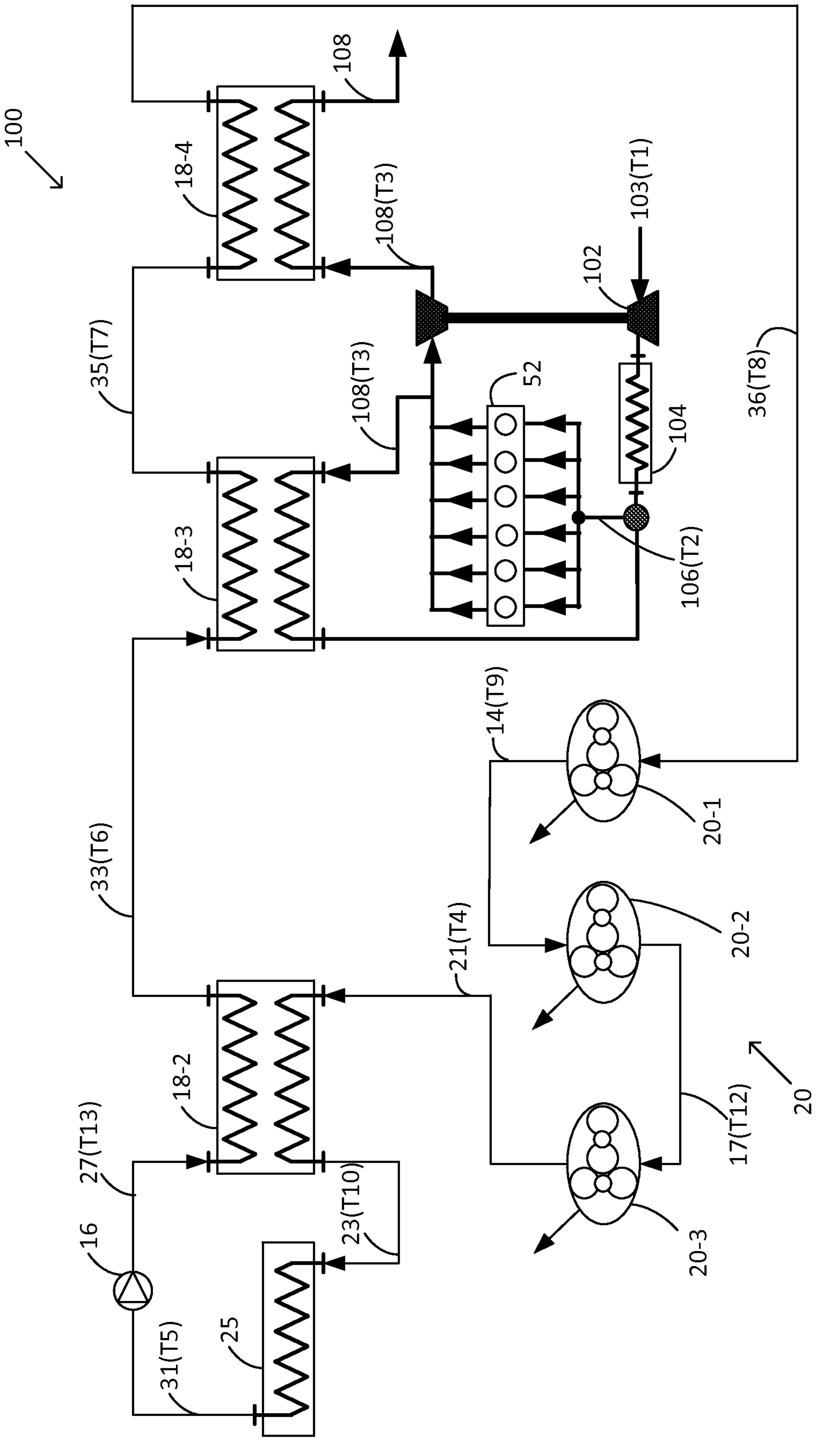
18-4
108
108(T3)
103(T1)
102
35(T7)
52
108(T3)
104
36(T8)
18-3
108
106(T2)
14(T9)
18-1
20-1
33(T6)
13(T11)
20-2
18-2
21(T4)
27(T13)
17(T12)
20
16
23(T10)
20-3
25
31(T5)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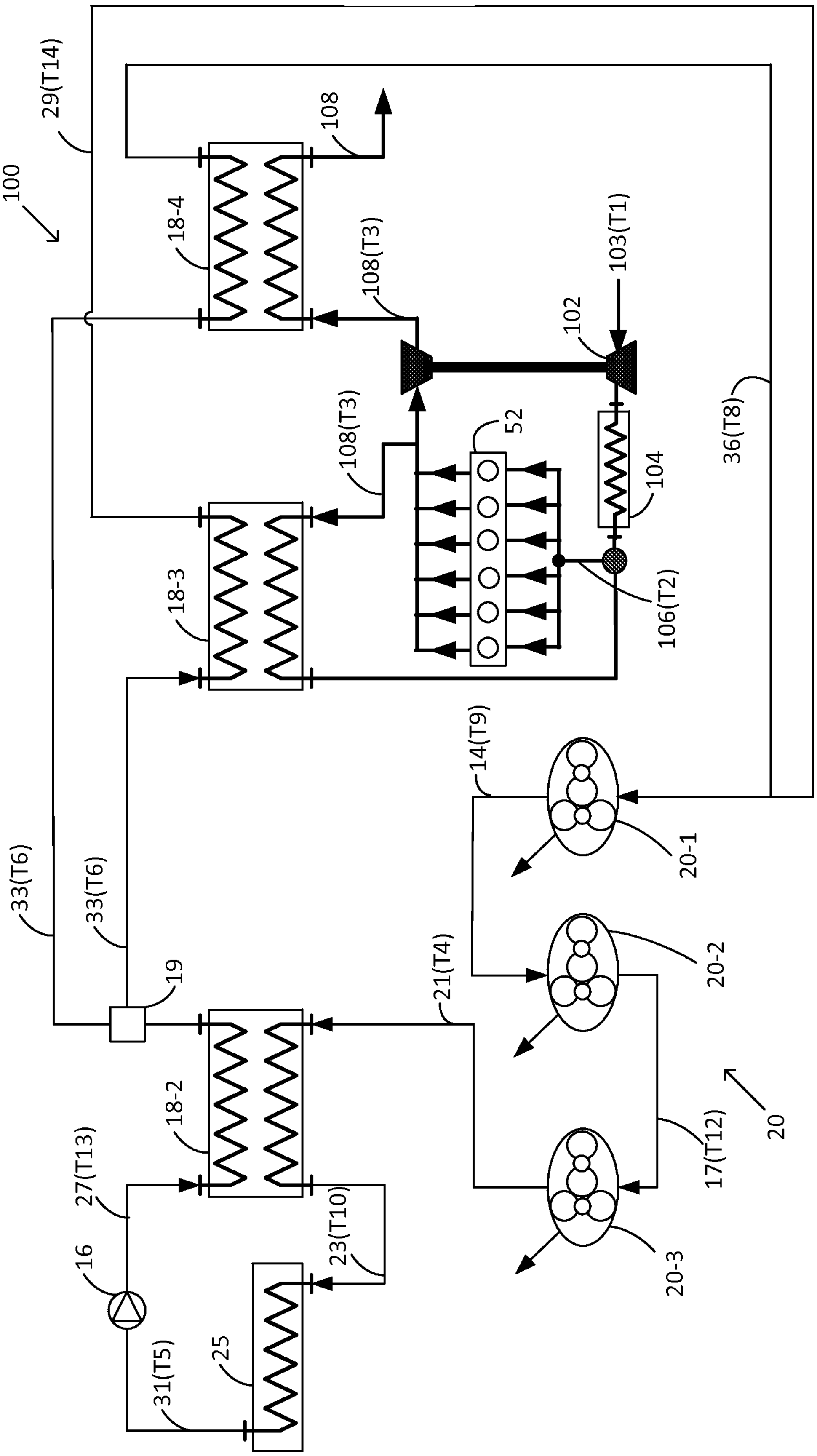
16
23(T10)
20-3
25
31(T5)

FIG. 2

FIG. 3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18-4
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108(T3)
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33(T6)
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20-1
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27(T13)
16
23(T10)
17(T12)
20
25
31(T5)
20-3

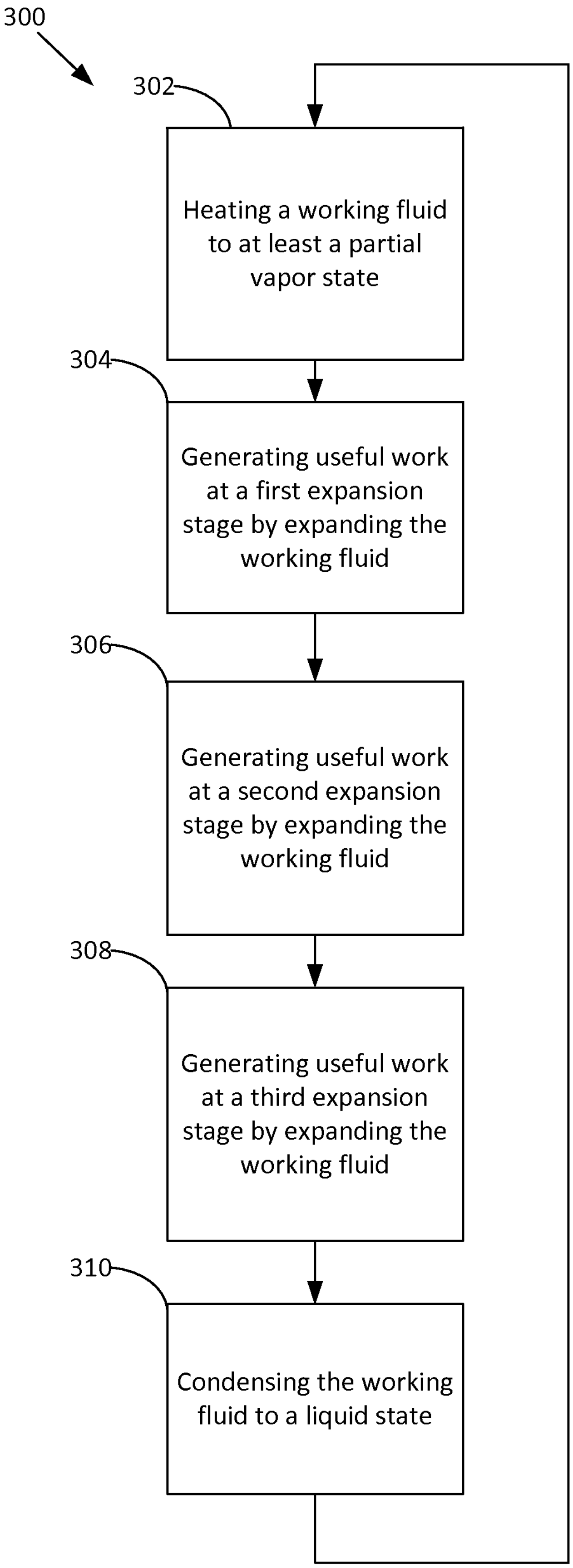

300
302
Heating a working fluid to at least a partial vapor state
304
Generating useful work at a first expansion stage by expanding the working fluid
306
Generating useful work at a second expansion stage by expanding the working fluid
308
Generating useful work at a third expansion stage by expanding the working fluid
310
Condensing the working fluid to a liquid state

FIG. 4

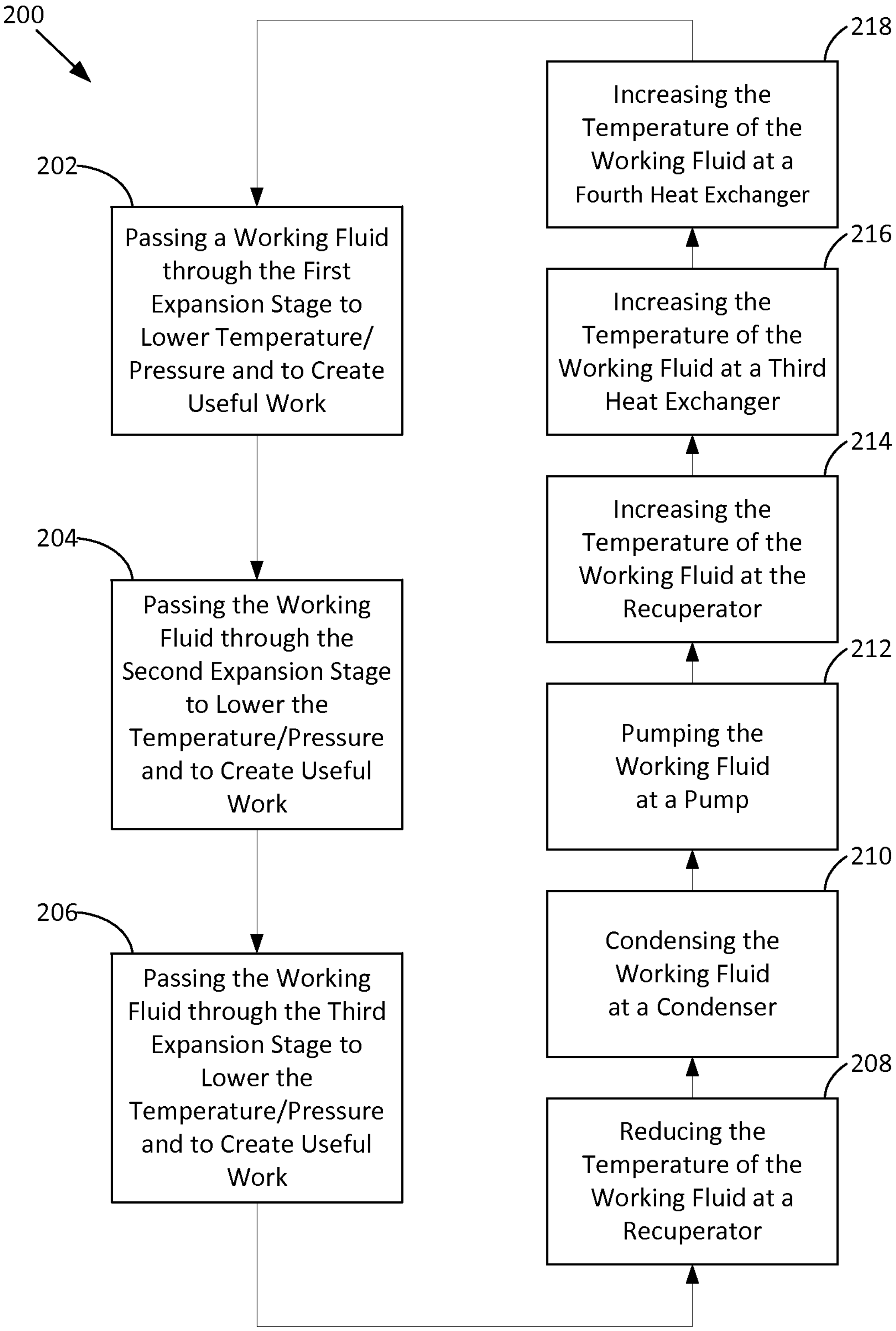

200
202
Passing a Working Fluid through the First Expansion Stage to Lower Temperature/ Pressure and to Create Useful Work
204
Passing the Working Fluid through the Second Expansion Stage to Lower the Temperature/Pressure and to Create Useful Work
206
Passing the Working Fluid through the Third Expansion Stage to Lower the Temperature/Pressure and to Create Useful Work
208
Reducing the Temperature of the Working Fluid at a Recuperator
210
Condensing the Working Fluid at a Condenser
212
Pumping the Working Fluid at a Pump
214
Increasing the Temperature of the Working Fluid at the Recuperator
216
Increasing the Temperature of the Working Fluid at a Third Heat Exchanger
218
Increasing the Temperature of the Working Fluid at a Fourth Heat Exchanger

FIG. 5

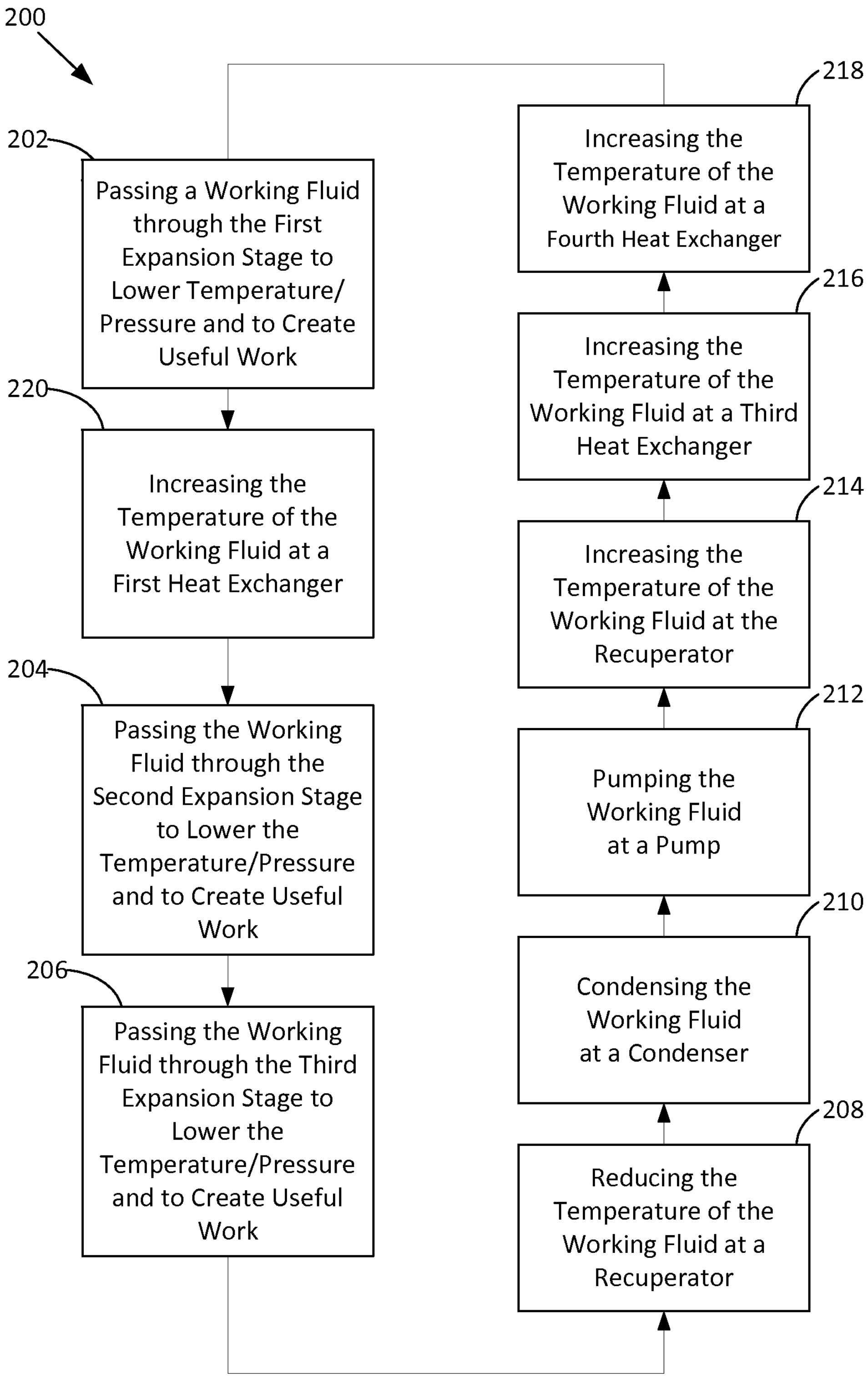

200
202
Passing a Working Fluid through the First Expansion Stage to Lower Temperature/ Pressure and to Create Useful Work
220
Increasing the Temperature of the Working Fluid at a First Heat Exchanger
204
Passing the Working Fluid through the Second Expansion Stage to Lower the Temperature/Pressure and to Create Useful Work
206
Passing the Working Fluid through the Third Expansion Stage to Lower the Temperature/Pressure and to Create Useful Work
208
Reducing the Temperature of the Working Fluid at a Recuperator
210
Condensing the Working Fluid at a Condenser
212
Pumping the Working Fluid at a Pump
214
Increasing the Temperature of the Working Fluid at the Recuperator
216
Increasing the Temperature of the Working Fluid at a Third Heat Exchanger
218
Increasing the Temperature of the Working Fluid at a Fourth Heat Exchanger

FIG. 6

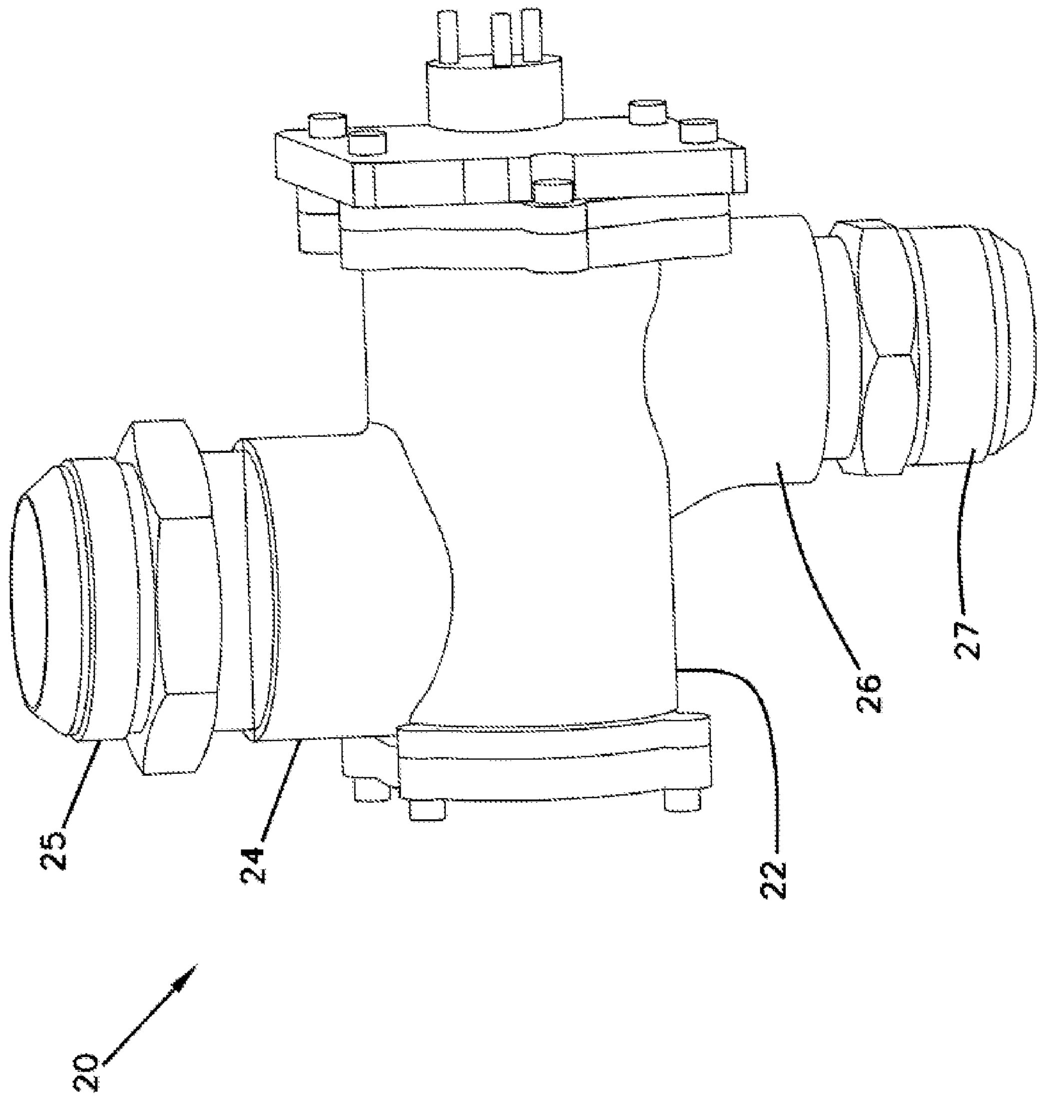


FIG. 7

FIG. 8

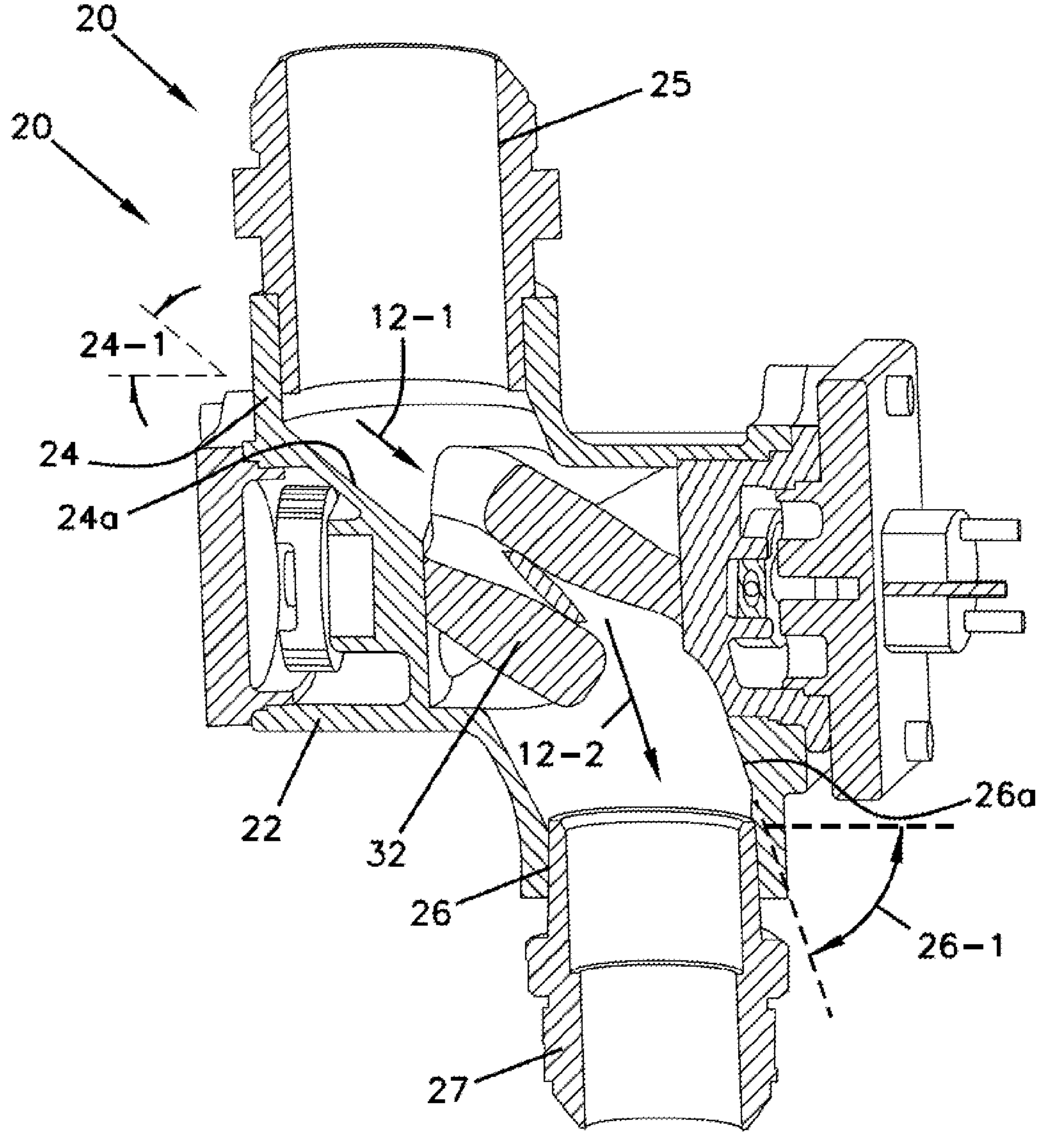


FIG. 9

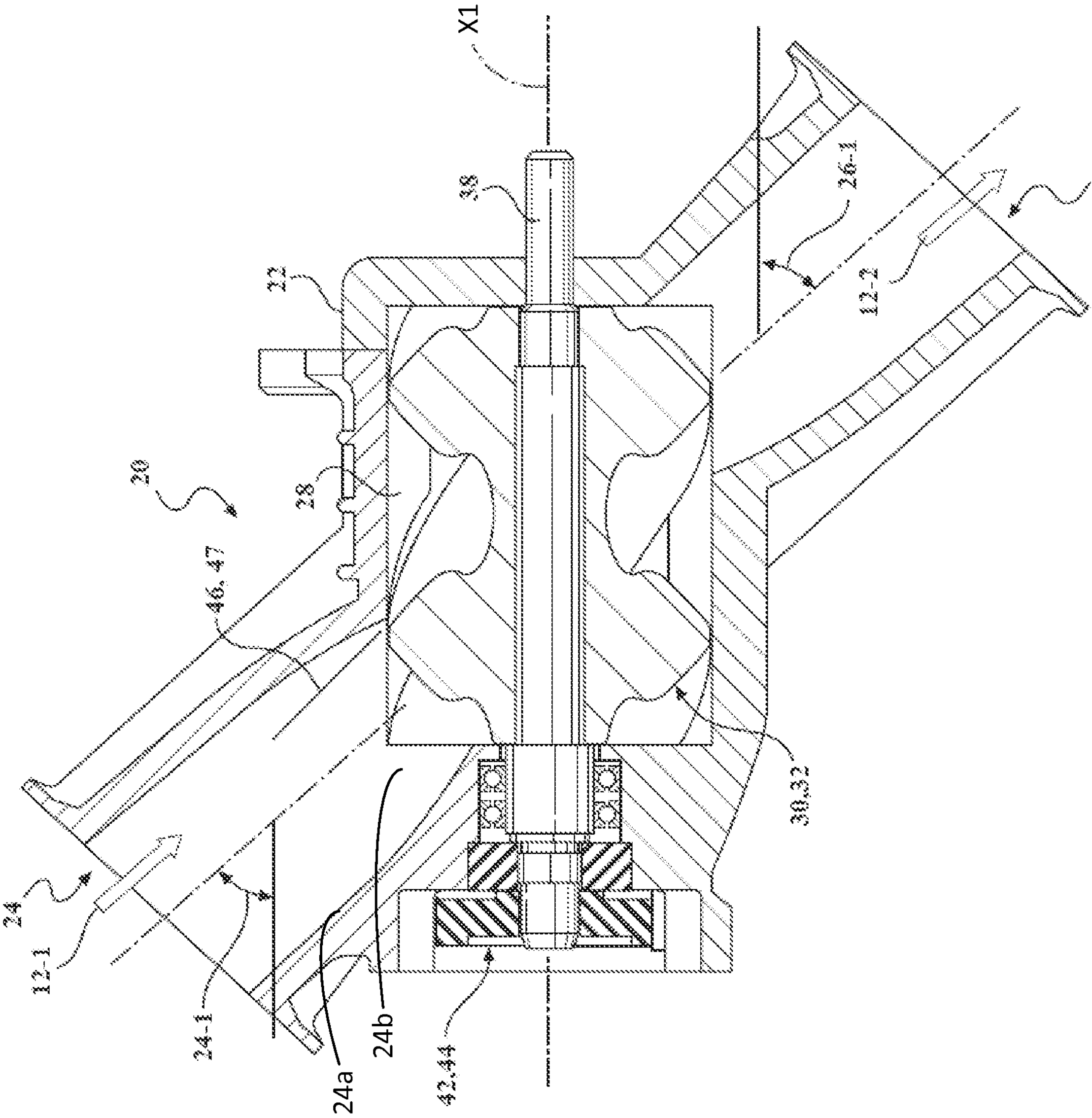
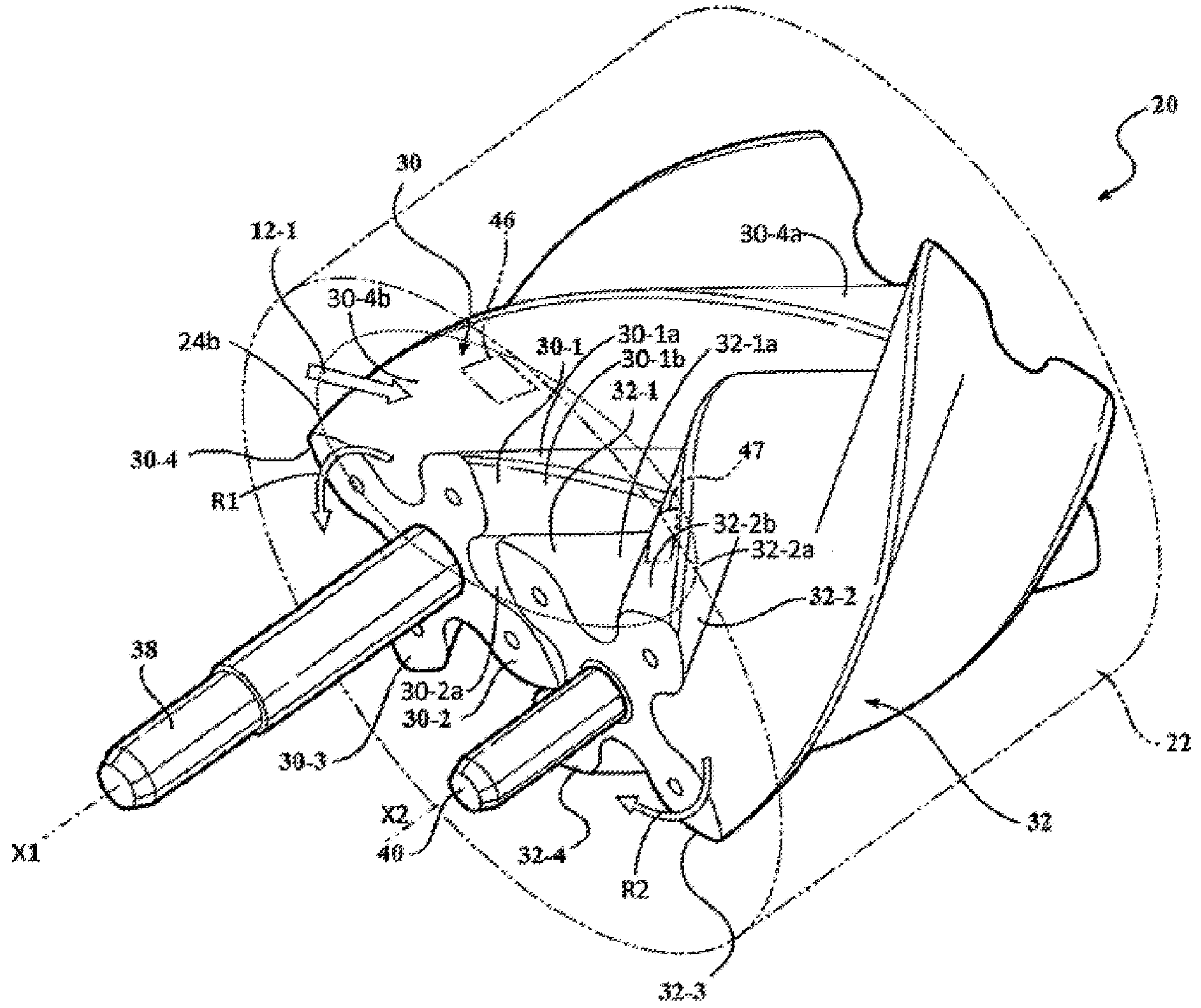


FIG. 10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30
46
30-4a
12-1
30-4b
24b
30-1
30-1a
30-1b
32-1a
32-1
30-4
47
R1
32-2b
32-2a
32-2
38
30-2a
30-2
30-3
X2
40
X1
32-4
R2
32
22
32-3

FIG. 11

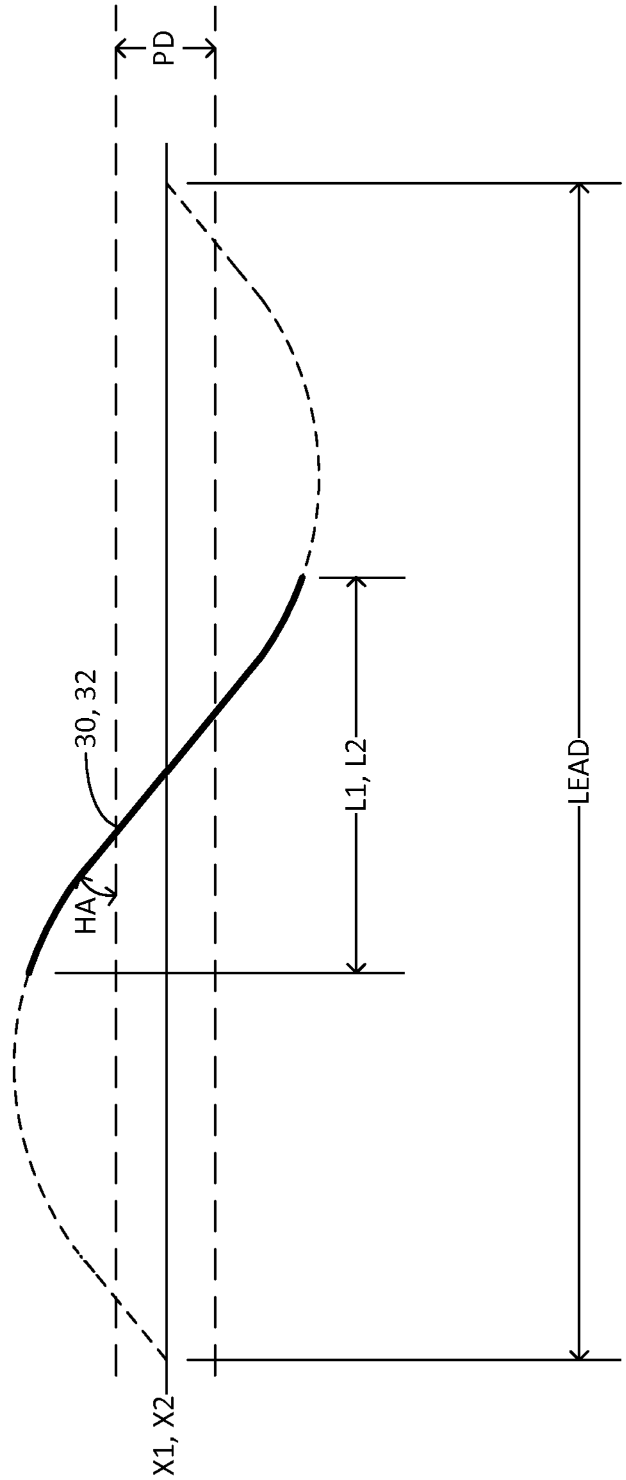


FIG. 12

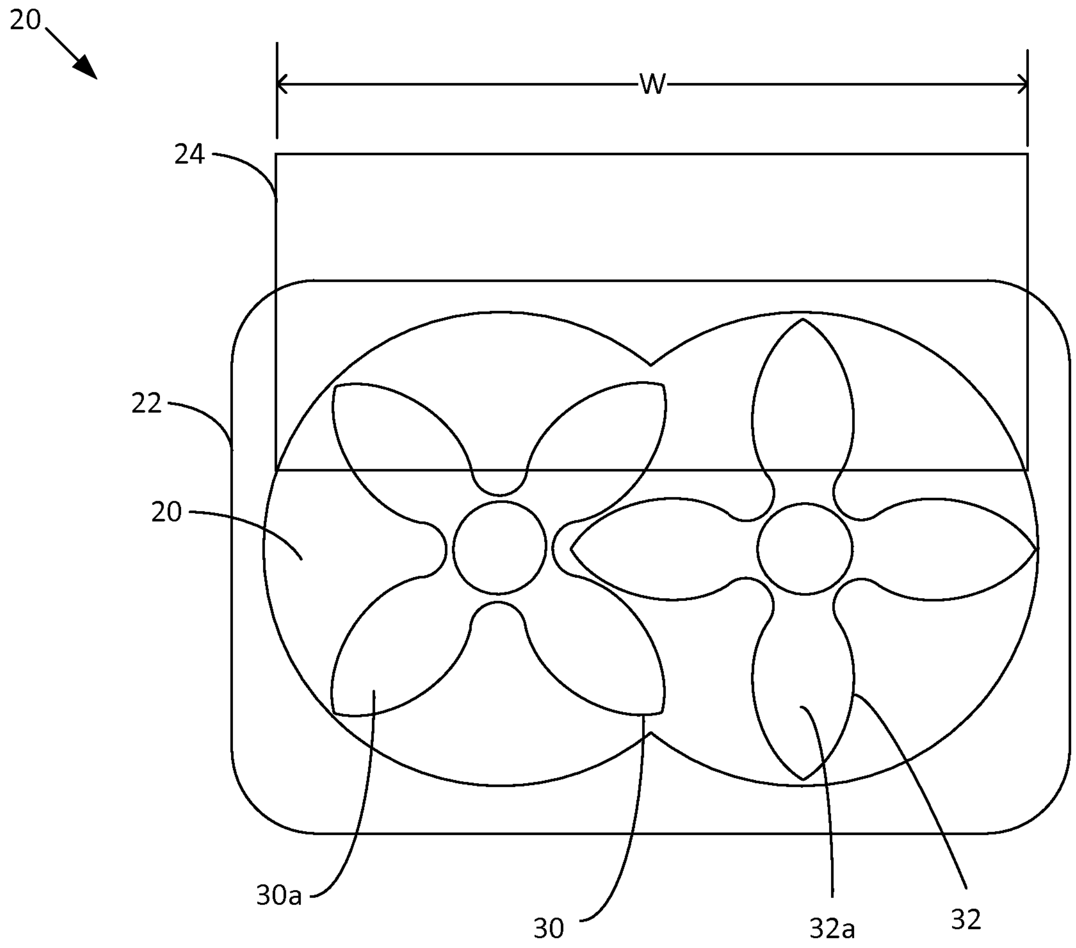
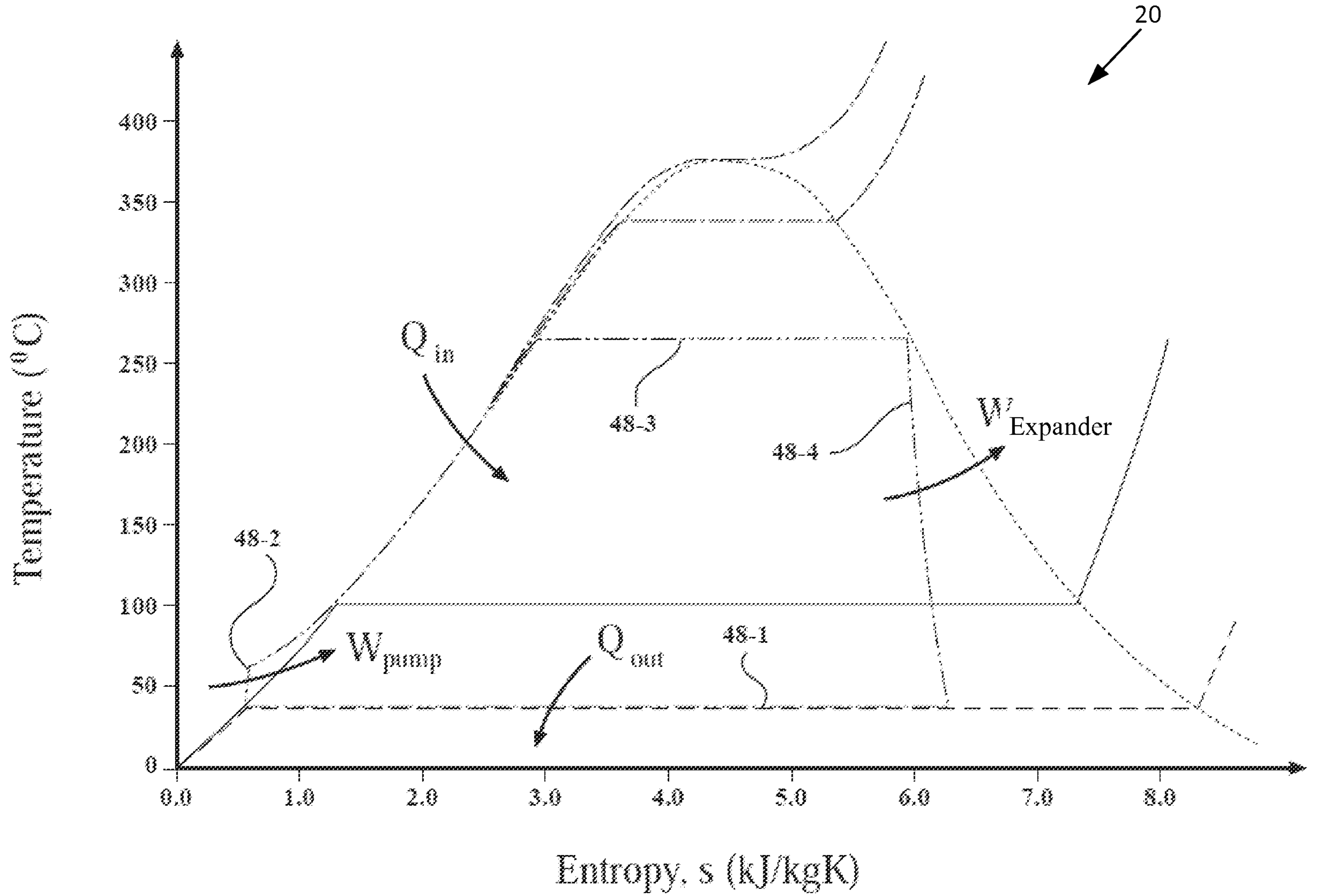


FIG. 13


20
Temperature (^{0}C)
400
350
300
250
200
150
100
50
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Entropy, s (kJ/kgK)
Q_{in}
48-3
48-4
$W'_{Expander}$
48-2
W_{pump}
Q_{out}
48-1

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- DE EE0005650 **[0001]**
- GB 2010974 A **[0007]**