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(54) **Rankine Cycle System**

(57) The rankine cycle system (10) includes an evaporator (12) coupled to a heat source (14) and configured to circulate a working fluid in heat exchange relationship with a hot fluid from the heat source (14) so as to heat the working fluid and vaporize the working fluid. An expander (16) is coupled to the evaporator (12) and configured to expand the vaporized working fluid from the

evaporator (12). The exemplary expander (16) is operable at variable speed. A condenser (20) is coupled to the expander (16) and configured to condense the vaporized working fluid from the expander (16). A pump (22) is coupled to the condenser (20) and configured to feed the condensed working fluid from the condenser (20) to the evaporator (12).

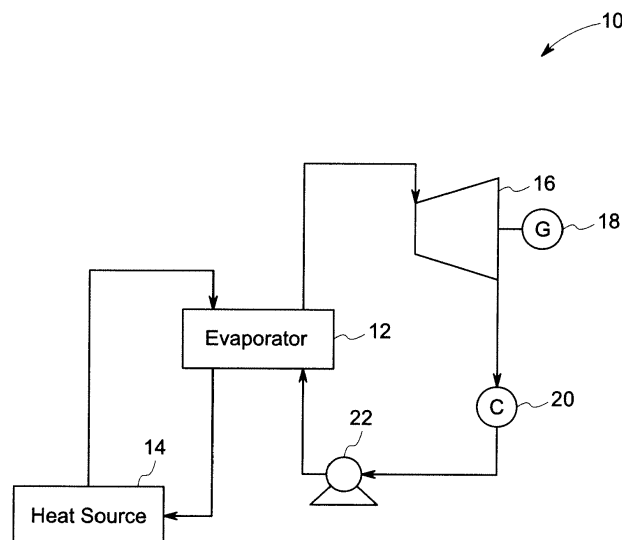


FIG. 1

Description

[0001] The invention relates generally to rankine cycle system, and more particularly to a rankine cycle system having a variable speed expander.

[0002] Enormous amounts of waste heat are generated by a wide variety of industrial and commercial processes and operations. Example sources of waste heat include heat from space heating assemblies, steam boilers, engines, and cooling systems. When waste heat is low grade, such as waste heat having a temperature of heat below 840 degrees Fahrenheit, for example, conventional heat recovery systems do not operate with sufficient efficiency to make recovery of energy cost-effective. The net result is that vast quantities of waste heat are simply dumped into the atmosphere, ground, or water.

[0003] Some power generation systems provide better reliability and off-grid operation with alternate fuels such as biogas or landfill gas, with examples being gas turbines and combustion engines such as microturbines and reciprocating engines. Combustion engines may be used to generate electricity using fuels such as gasoline, natural gas, biogas, plant oil, and diesel fuel. However, atmospheric emissions such as nitrogen oxides and particulates may be emitted.

[0004] One method to generate electricity from the waste heat of a combustion engine without increasing the output of emissions is to apply a bottoming rankine cycle. A fundamental rankine cycle typically includes a turbo generator, an evaporator/boiler, a condenser, and a liquid pump. The turbo generator of conventional rankine cycle is operated at fixed speed. Hence conventional rankine cycle has constraints that it can operate only at design state points (pressures, mass flows and temperatures). During partial load conditions or off design operating conditions, the rankine cycle can only be operated at a limited range of state points. As a result, the cycle efficiency is lowered and component operation limits are exceeded.

[0005] It is desirable to have a rankine cycle system that can be operated at higher cycle efficiency without exceeding component operation limits.

[0006] In accordance with one exemplary embodiment of the present invention, a rankine cycle system is disclosed. The rankine cycle system includes an evaporator coupled to a heat source and configured to circulate a working fluid in heat exchange relationship with a hot fluid from the heat source so as to heat the working fluid and vaporize the working fluid. An expander is coupled to the evaporator and configured to expand the vaporized working fluid from the evaporator. The exemplary expander is operable at variable speed. A condenser is coupled to the expander and configured to condense the vaporized working fluid from the expander. A pump is coupled to the condenser and configured to feed the condensed working fluid from the condenser to the evaporator.

[0007] In accordance with another exemplary embodiment of the present invention, a waste heat recovery system including at least two integrated rankine cycle systems having an expander operable at variable speed is disclosed.

[0008] Various features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a diagrammatical representation of a rankine cycle system having a variable speed expander in accordance with an exemplary embodiment of the present invention,

FIG. 2 is a diagrammatical representation of a cascaded rankine cycle system having at least one variable speed expander in accordance with an exemplary embodiment of the present invention,

FIG. 3 is a diagrammatical representation of an expander system in accordance with an exemplary embodiment of the present invention,

FIG. 4 is a diagrammatical representation of an expander system in accordance with an exemplary embodiment of the present invention, and

FIG. 5 is a diagrammatical representation of an expander system in accordance with an exemplary embodiment of the present invention.

[0009] In accordance with exemplary embodiments of the present invention, a rankine cycle system is disclosed. The rankine cycle system includes an evaporator coupled to a heat source and configured to circulate a working fluid in heat exchange relationship with a hot fluid from the heat source so as to heat the working fluid and vaporize the working fluid. An expander is coupled to the evaporator and configured to expand the vaporized working fluid from the evaporator. The exemplary expander is operable at variable speed. A condenser is coupled to the expander and configured to condense the vaporized working fluid from the expander. A pump is coupled to the condenser and configured to feed the condensed working fluid from the condenser to the evaporator. In accordance with a specific embodiment of the present invention, a waste heat recovery system including at least two integrated rankine cycle systems having an expander operable at variable speed is disclosed.

[0010] Referring to FIG. 1, a rankine cycle system 10 is illustrated in accordance with an exemplary embodiment of the present invention. A working fluid is circulated through the rankine cycle system 10. In one embodiment, the working fluid may be an organic working fluid and may include cyclohexane, cyclopentane, thiophene, ke-

tones, aromatics, propane, butane, pentafluoro-propane, pentafluoro-butane, pentafluoro-polyether, or combinations thereof. It should be noted herein that list of working fluids are not inclusive and other working fluids applicable to rankine cycles are also envisaged. The rankine cycle system 10 includes an evaporator 12 coupled to a heat source 14, for example an exhaust unit of a heat generation system (for example, an engine). The evaporator 12 receives heat from a hot fluid generated from the heat source 14 and generates a working fluid vapor. The vaporized working fluid is passed through an expander 16 to drive a generator 18 configured to generate power. The expander 16 may be at least one radial type expander, axial type expander, high temperature screw type or impulse type expander, positive displacement type expander. After expanding through the first expander 16, the working fluid vapor at a relatively lower pressure and lower temperature is passed through a condenser 20. The working fluid vapor is condensed into a liquid, which is then pumped via a pump 22 to the evaporator 12. The cycle may then be repeated.

[0011] In the illustrated embodiment, the expander 16 is directly coupled to the generator 18 configured to generate power. The speed of the expander 16 is operable at variable speed. The exemplary generator 18 is an asynchronous generator. In such generators, if the revolutions per minute are held constant, the frequency varies depending on the power level. The peaks of the sinusoidal waveform have no fixed relationship with a rotor position. The magnetic field of a rotor is generated via a stator through electromagnetic induction.

[0012] The exemplary rankine cycle system 10 does not have constraints that it can operate only at design state points (pressures, mass flows and temperatures). The expander 16 and the generator 18 are operable at variable speeds during partial load conditions or off design operating conditions. Hence the rankine cycle system 10 can be operated at a wide range of state points. As a result, the cycle efficiency is increased and component operation limits are not exceeded.

[0013] Referring to FIG. 2, a waste heat recovery system 24 is illustrated in accordance with an exemplary embodiment of the present invention. The illustrated waste heat recovery system 24 includes a first organic rankine cycle system 26 (top cycle) and a second organic rankine cycle system 28 (bottom cycle). A first organic working fluid is circulated through the first organic rankine cycle system 26. The first organic working fluid may include cyclohexane, cyclopentane, thiophene, ketones, aromatics, or combinations thereof. The first organic rankine cycle system 26 includes an evaporator 30 coupled to a first heat source 32, for example an exhaust unit of a heat generation system 34 (for example, an engine). The evaporator 30 receives heat from the exhaust gas generated from the first heat source 32 and generates a first organic working fluid vapor. The first organic working fluid vapor is passed through a first expander 36 to drive a first generator 38. The first expander may be

radial type expander, axial type expander, impulse type expander, or high temperature screw type expander, positive displacement type expander. After passing through the first expander 36, the first organic working fluid vapor at a relatively lower pressure and lower temperature is passed through a cascaded heat exchange unit 40. The first organic working fluid vapor is condensed into a liquid, which is then pumped via a pump 42 to the evaporator 30. The cycle may then be repeated.

[0014] The cascaded heat exchange unit 40 is used both as a condenser for the first organic rankine cycle system 26 and as evaporator for the second organic rankine cycle system 28. A second organic working fluid is circulated through the second organic rankine cycle system 28. The second organic working fluid may include propane, butane, pentafluoro-propane, pentafluoro-butane, pentafluoro-polyether, oil, or combinations thereof. It should be noted herein that list of first and second organic working fluids are not inclusive and other organic working fluids applicable to organic rankine cycles are also envisaged. Cascaded heat exchange unit 40 may be coupled to any one or more of a plurality of second heat sources such as an intercooler 44, an oil heat exchanger 46, and a cooling water jacket heat exchanger 48. Such second heat sources are also typically coupled to the engine. It should be noted herein that the second heat source includes a lower temperature heat source than the first heat source. It should be noted that in other exemplary embodiments, first and second heat sources may include other multiple low-grade heat sources such as gas turbines with intercoolers. The cascaded heat exchange unit 40 receives heat from the first organic working fluid and generates a second organic working fluid vapor. The second organic working fluid vapor is passed through a second expander 50 to drive a second generator 52. In certain other exemplary embodiments, the second expander 50 may be a radial type expander, an axial type expander, high temperature screw type or an impulse type expander, positive displacement type expander.

[0015] In an exemplary embodiment, neither of the first and second organic working fluids are expanded below the atmospheric pressure, and the boiling point temperature of the first organic working fluid is below the average temperature of the second heat source. After passing through the second expander 50, the second organic working fluid vapor at lower pressure and lower temperature is passed through a condenser 54. The second organic working fluid vapor is condensed into a liquid, which is then pumped via a pump 56 to the second heat sources. The cycle may then be repeated. It should be noted herein that the number of second heat sources such as intercoolers, oil heat exchangers, jacket heat exchangers, evaporators and their relative positions explained in greater detail in U.S. Patent Application 11/770,895 is incorporated herein by reference.

[0016] In the illustrated embodiment, the expanders 38, 52 are coupled to the generators 38, 52 respectively

configured to generate power. The speed of the expanders 38, 52 are operable at variable speed. The exemplary generators 38, 52 are asynchronous generators.

[0017] Referring to FIG. 3, an exemplary expander system 58 for a rankine cycle system is disclosed. In the illustrated embodiment, the system 58 includes a multi-stage expander 60 having an expander first stage 62 and an expander second stage 64. In certain other embodiments, the multi-stage expander may include more than two stages. In a more specific embodiment, the expander 60 is a multi-screw expander. The expander first stage 62 and the expander second stage 64 are coupled to a generator 66 via a gearbox 68. The generator 66 is an asynchronous generator. In a specific embodiment, a gear ratio of the gearbox 68 may be varied to vary the speed of the expander 60. In the illustrated embodiment, the vaporized working fluid is passed through the expander first stage 62 and then through the expander second stage 64 to drive the generator 66 configured to generate power. In other words, the vaporized working fluid is expanded successively through the stages 62, 64. After expanding through the stages 62, 64, the working fluid vapor at a relatively lower pressure and lower temperature is passed through a condenser.

[0018] Referring to FIG. 4, an exemplary expander system 70 for a rankine cycle system is disclosed. In the illustrated embodiment, the system 70 includes a multi-stage expander 72 having an expander first stage 74 and an expander second stage 76. In one embodiment, the expander 72 is a multi-screw expander. The expander first stage 74 and the expander second stage 76 are coupled directly to a generator 78. The generator 78 is an asynchronous generator. In the illustrated embodiment, the vaporized working fluid is passed through the expander first stage 74 and then through the expander second stage 76 to drive the generator 78 configured to generate power. After expanding through the stages 74, 76, the working fluid vapor at a relatively lower pressure and lower temperature is passed through a condenser.

[0019] In the illustrated embodiment, the asynchronous generator 78 is operable at variable speed so as to control the speed of the expander 72. The exemplary generator 78 is coupled to a frequency inverter 80 configured to vary the speed of the generator 78. The frequency inverter 80 controls the rotational speed of the generator 78 by controlling the frequency of the electrical power of the generator 78.

[0020] Referring to FIG. 5, an exemplary expander system 82 for a rankine cycle system is disclosed. In the illustrated embodiment, the system 82 includes a multi-stage expander 84 having an expander first stage 86 and an expander second stage 88. In one embodiment, the expander 84 is a multi-screw expander. The expander first stage 86 and the expander second stage 88 are coupled respectively to generators 90, 92. The generators 90, 92 are asynchronous generators. In the illustrated embodiment, the vaporized working fluid is passed through the expander first stage 86 and then through the

expander second stage 88 to drive the generators 90, 92 configured to generate power. After expanding through the stages 86, 88 the working fluid vapor at a relatively lower pressure and lower temperature is passed through a condenser. Similar to the previous embodiments, the expander 84 is operable at variable speed.

[0021] The exemplary expander discussed above with reference to FIGS. 1-5, are adaptable to full and partial load conditions of organic rankine cycles. Further the exemplary expander is also robust to changes in inlet and outlet flow conditions of organic rankine cycles. It should be noted herein that embodiments discussed with reference to FIGS. 3-5 is applicable to the rankine cycle system 10 of FIG. 1, the first organic rankine cycle system 26 (top cycle), or a second organic rankine cycle system 28 (bottom cycle), or combinations thereof of FIG. 2. All such permutations and combinations are envisaged.

[0022] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

[0023] Various aspects and embodiments of the present invention are defined by the following numbered clauses:

1. A rankine cycle system, comprising:

an evaporator coupled to a heat source and configured to circulate a working fluid in heat exchange relationship with a hot fluid from the heat source so as to heat the working fluid and vaporize the working fluid;

an expander coupled to the evaporator and configured to expand the vaporized working fluid from the evaporator; wherein the expander is operable at variable speed;

a condenser coupled to the expander and configured to condense the vaporized working fluid from the expander;

a pump coupled to the condenser and configured to feed the condensed working fluid from the condenser to the evaporator.

2. The system of clause 1, wherein the working fluid comprises cyclohexane, cyclopentane, thiophene, ketones, aromatics, propane, butane, pentafluoropropane, pentafluorobutane, pentafluoropolyether, or combinations thereof.

3. The system of any preceding clause, wherein the expander comprises at least one radial type expander, axial type expander, high temperature screw type or impulse type expander, positive displacement

type expander.

4. The system of any preceding clause, wherein the expander comprises a multi-stage screw expander.

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5. The system of any preceding clause, wherein the expander is a multi-screw expander.

6. The system of any preceding clause, wherein the expander is directly coupled to at least one asynchronous generator configured to generate power.

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7. The system of any preceding clause, wherein the asynchronous generator is operable at variable speed to vary the speed of the expander.

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8. The system of any preceding clause, further comprising a frequency inverter configured to vary the speed of the asynchronous generator.

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9. The system of any preceding clause, wherein the expander is coupled via a gearbox to at least one asynchronous generator configured to generate power.

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10. The system of any preceding clause, wherein a gear ratio of the gearbox is variable to vary the speed of the expander.

11. A waste heat recovery system including at least two integrated rankine cycle systems, the recovery system comprising:

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a heat generation system comprising at least two separate heat sources having different temperatures;

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a first rankine cycle system comprising a first expander, wherein the first rankine cycle system is coupled to a first heat source among the at least two separate heat sources and configured to circulate a first working fluid; wherein the first rankine system is configured to remove heat from the first heat source; wherein the first expander is operable at variable speed;

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a second rankine cycle system comprising a second expander; wherein the second rankine cycle system is coupled to at least one second heat source among the at least two separate heat sources and configured to circulate a second working fluid, the at least one second heat source comprising a lower temperature heat source than the first heat source, wherein the second rankine cycle system is configured to remove heat from the at least one second heat source; wherein the second expander is operable at variable speed; and

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a cascaded heat exchange unit, wherein the first and second working fluids are circutable in heat exchange relationship through the cascaded heat exchange unit for condensation of the first working fluid in the first rankine cycle system and evaporation of the second working fluid in the second rankine cycle system.

12. The system of any preceding clause, wherein the first working fluid comprises cyclohexane, cyclopentane, thiophene, ketones, aromatics, or combinations thereof.

13. The system of any preceding clause, wherein the first expander comprises at least one radial type expander, axial type expander, high temperature screw type or impulse type expander, positive displacement type expander.

14. The system of any preceding clause, wherein the first expander comprises a multi-stage screw expander.

15. The system of any preceding clause, wherein the first expander is a multi-screw expander.

16. The system of any preceding clause, wherein the first expander is directly coupled to at least one asynchronous generator configured to generate power.

17. The system of any preceding clause, further comprising a frequency inverter configured to vary the speed of the asynchronous generator.

18. The system of any preceding clause, wherein the expander is coupled via a gearbox to at least one asynchronous generator configured to generate power.

19. The system of any preceding clause, wherein a gear ratio of the gearbox is variable to vary the speed of the expander.

20. The system of any preceding clause, wherein the second organic working fluid comprises propane, butane, pentafluoro-propane, pentafluoro-butane, pentafluoro-polyether, oil, or combinations thereof.

21. The system of any preceding clause, wherein the second expander comprises at least one radial type expander, axial type expander, high temperature screw type or impulse type expander, positive displacement type expander.

22. The system of any preceding clause, wherein the second expander comprises a multi-stage screw expander.

23. The system of any preceding clause, wherein the second expander is directly coupled to at least one asynchronous generator configured to generate power.

24. The system of any preceding clause, further comprising a frequency inverter configured to vary the speed of the asynchronous generator.

25. The system of any preceding clause, wherein the second expander is coupled via a gearbox to at least one asynchronous generator configured to generate power.

26. The system of any preceding clause, wherein a gear ratio of the gearbox is variable to vary the speed of the expander.

Claims

1. A rankine cycle system (10), comprising:

an evaporator (12) coupled to a heat source (14) and configured to circulate a working fluid in heat exchange relationship with a hot fluid from the heat source (14) so as to heat the working fluid and vaporize the working fluid;

an expander (16) coupled to the evaporator (12) and configured to expand the vaporized working fluid from the evaporator (12); wherein the expander (16) is operable at variable speed;

a condenser (54) coupled to the expander (16) and configured to condense the vaporized working fluid from the expander (16);

a pump (22) coupled to the condenser (54) and configured to feed the condensed working fluid from the condenser (54) to the evaporator (12).

2. The system (10) of claim 1, wherein the expander (16) comprises at least one radial type expander, axial type expander, high temperature screw type or impulse type expander, positive displacement type expander.

3. The system (10) of any preceding claim, wherein the expander (16) comprises a multi-stage screw expander.

4. The system (10) of any preceding claim, wherein the expander (16) is a multi-screw expander.

5. The system (10) of any preceding claim, wherein the expander (16) is directly coupled to at least one asynchronous generator (78) configured to generate power.

6. The system (10) of any preceding claim, wherein the

asynchronous generator (78) is operable at variable speed to vary the speed of the expander (16).

7. The system (10) of claim 5 or claim 6, further comprising a frequency inverter (80) configured to vary the speed of the asynchronous generator (78).

8. The system (10) of any preceding claim, wherein the expander (16) is coupled via a gearbox (68) to at least one asynchronous generator (78) configured to generate power.

9. The system (10) of claim 8, wherein a gear ratio of the gearbox (68) is variable to vary the speed of the expander (16).

10. A waste heat recovery system (24) including at least two integrated rankine cycle systems (26, 28), the recovery system (24) comprising:

a heat generation system (34) comprising at least two separate heat sources (32, 44, 46, 48) having different temperatures;

a first rankine cycle system (26) comprising a first expander (36), wherein the first rankine cycle system (26) is coupled to a first heat source (32) among the at least two separate heat sources (32, 44, 46, 48) and configured to circulate a first working fluid; wherein the first rankine system (26) is configured to remove heat from the first heat source (32); wherein the first expander (36) is operable at variable speed;

a second rankine cycle system (28) comprising a second expander (50); wherein the second rankine cycle system (28) is coupled to at least one second heat source (44, 46, 48) among the at least two separate heat sources (32, 44, 46, 48) and configured to circulate a second working fluid, the at least one second heat source (44, 46, 48) comprising a lower temperature heat source than the first heat source (32), wherein the second rankine cycle system (28) is configured to remove heat from the at least one second heat source (32, 44, 46, 48); wherein the second expander (50) is operable at variable speed; and a cascaded heat exchange unit (40), wherein the first and second working fluids are circutable in heat exchange relationship through the cascaded heat exchange unit (40) for condensation of the first working fluid in the first rankine cycle system (26) and evaporation of the second working fluid in the second rankine cycle system (28).

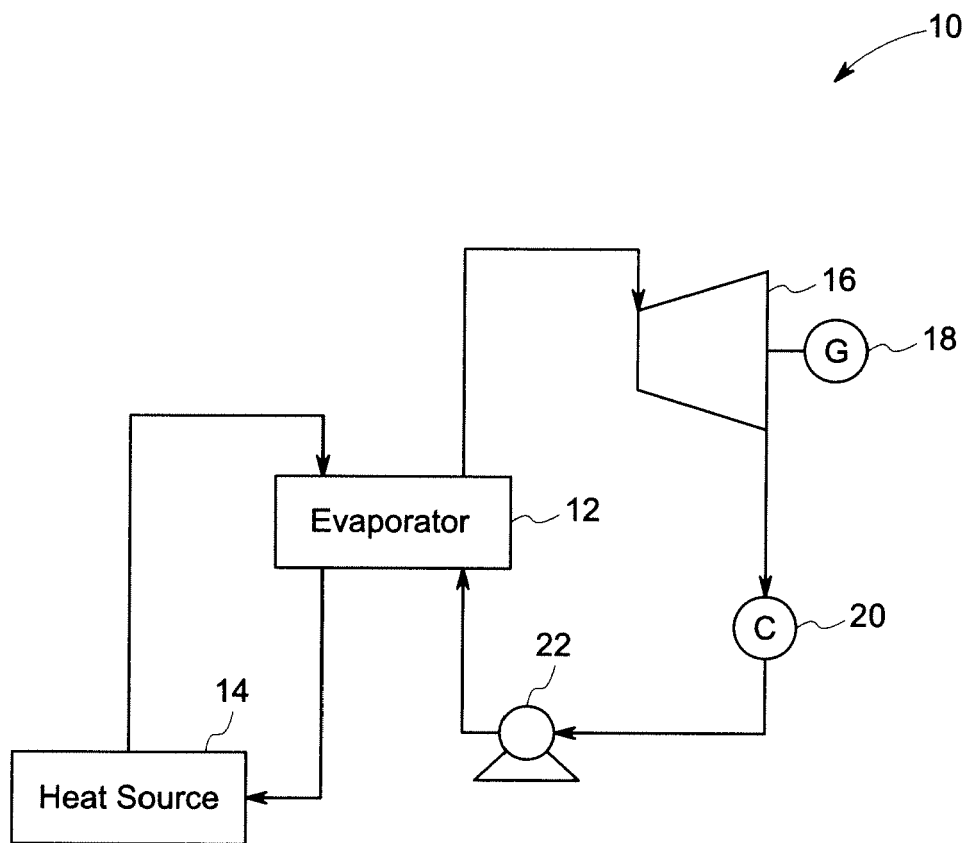


FIG. 1

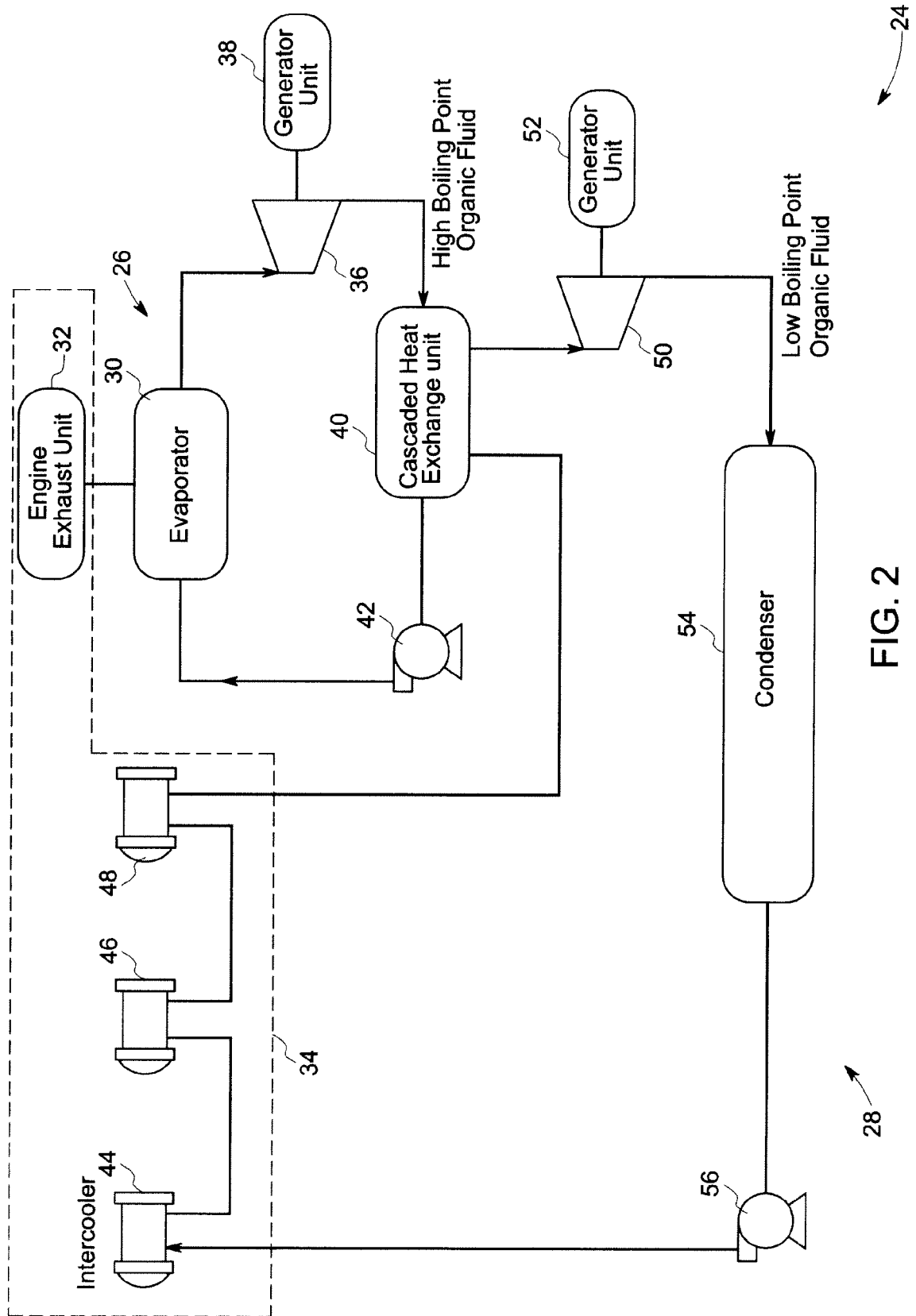


FIG. 2

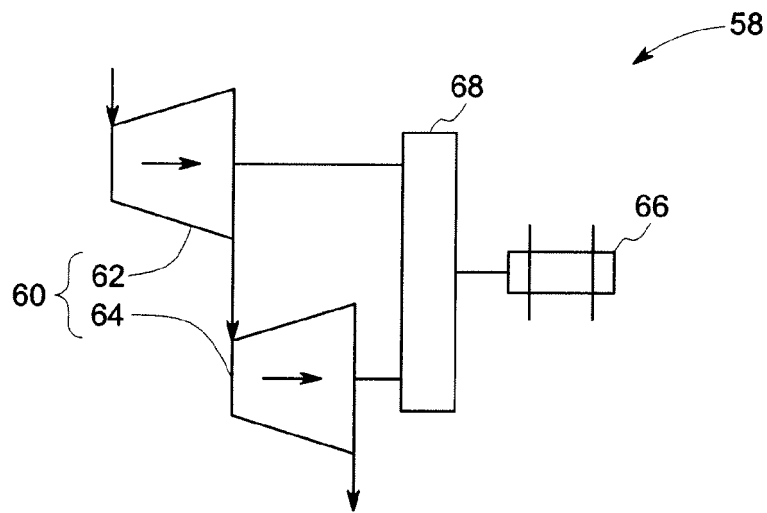


FIG. 3

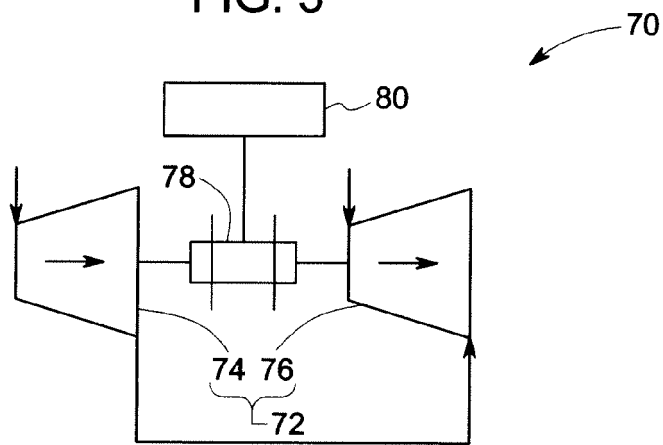


FIG. 4

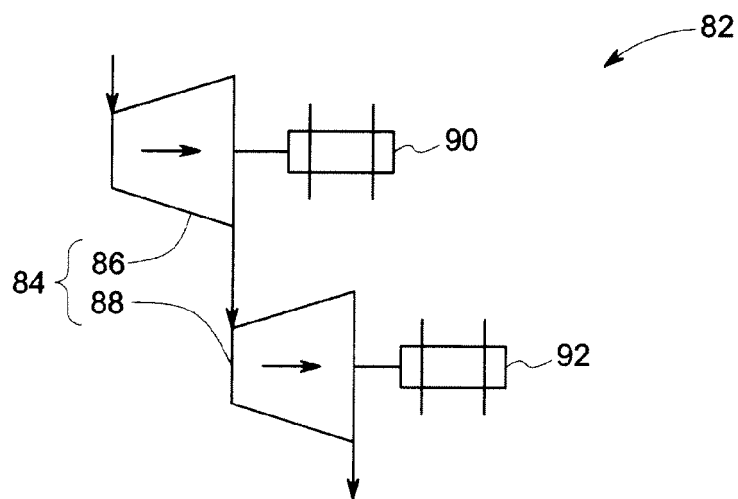


FIG. 5

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 770895 A [0015]