

Description**BACKGROUND OF THE INVENTION**

[0001] The present invention relates to Rankine cycle systems and, in particular, to a non-azeotropic working fluid mixture that may circulate through an organic Rankine cycle system to generate power.

[0002] An organic Rankine cycle (ORC) system may be used for generating electrical power within, for example, a geothermal power generation system. A typical organic Rankine cycle system may include an organic working fluid that is circulated through a pump, an evaporator, a turbine generator and a condenser. A recuperator may be also used if the technical and economical merits warrant. During operation, the evaporator transfers thermal energy from a relatively warm thermal source fluid into the working fluid in order to form working fluid vapor, which drives the turbine generator as the vapor expands. The condenser transfers thermal (e.g., heat) energy from the expanded working fluid vapor into a relatively cool thermal sink fluid in order to condense the working fluid vapor before it is resupplied to the evaporator through the pump.

[0003] A typical organic working fluid may include a single (pure) chemical component, or an azeotropic mixture of different chemical components. Pinch points associated with single component organic working fluids in heat exchangers, however, typically reduce overall efficiencies of the organic Rankine cycle systems in which they are implemented. The term "pinch point" may describe a point in a working fluid temperature profile where a minimum (smallest) temperature difference exists between the temperature of the working fluid and that of the thermal source or sink fluid.

SUMMARY OF THE DISCLOSURE

[0004] According to a first aspect of the invention, a power generation system includes a non-azeotropic working fluid mixture and a Rankine cycle system. The Rankine cycle system includes a turbine generator that is driven by vapor of the working fluid mixture, and a condenser that exchanges thermal energy between the vapor received from the turbine generator and a cooling medium. The working fluid mixture exhibits a condenser temperature glide between approximately five degrees and thirty degrees Kelvin, a condensing pressure between approximately one tenth of one percent and eleven percent of a critical pressure of the working fluid mixture, and a condenser bubble point temperature between approximately one degree and nine degrees Kelvin greater than a temperature at which the cooling medium is received by the condenser.

[0005] According to a second aspect of the invention, a power generation system includes an intermediate heat exchanger, a first Rankine cycle system and a second Rankine cycle system. The heat exchanger includes a condenser passage that receives a first working fluid, and an evaporator passage that receives an organic, non-azeotropic second working fluid mixture. The heat exchanger transfers thermal energy from the first working fluid to the second working fluid mixture. The first Rankine cycle system includes a first pump that directs the first working fluid through an evaporator and the condenser passage. The second Rankine cycle system includes a second pump that directs the second working fluid mixture through the evaporator passage, a turbine generator that is driven by vapor of the second working fluid mixture, and a condenser that exchanges thermal energy between the vapor received from the turbine generator and a cooling medium. The second working fluid mixture is characterized by a condenser temperature glide between approximately five degrees and thirty degrees Kelvin, a condensing pressure between approximately one tenth of one percent and eleven percent of a critical pressure of the second working fluid mixture, and a condenser bubble point temperature between approximately one degree and nine degrees Kelvin greater than a temperature at which the cooling medium is received by the condenser.

[0006] The foregoing features and the operation of the invention will become more apparent in light of the following description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS**[0007]**

FIG. 1 is a schematic illustration of a power generation system that includes a Rankine cycle system;
 FIG. 2 is a temperature-entropy phase diagram for an organic, non-azeotropic working fluid mixture circulating through the Rankine cycle system illustrated in FIG. 1; and
 FIG. 3 is a schematic illustration of an alternate embodiment power generation system that includes a plurality of Rankine cycle systems.
 FIG. 4 is a temperature-entropy phase diagram of working fluid mixtures during operation of a power generation system.
 FIG. 5 is another temperature-entropy phase diagram of working fluids during operation of a power generation system.

DETAILED DESCRIPTION OF THE INVENTION

[0008] FIG. 1 is a schematic illustration of a power generation system 10 that includes a working fluid mixture (e.g., an organic, non-azeotropic working fluid mixture) that circulates through a Rankine cycle system 12 (e.g., an organic Rankine cycle system). The Rankine cycle system 12 may include a turbine generator 14, a condenser 16 (e.g., a counterflow heat exchanger), a pump 18 and an evaporator 20 (e.g., a counterflow heat exchanger). The condenser 16 may include a first heat exchange passage 22 and a second heat exchange passage 24. The evaporator 20 may include a first heat exchange passage 26 and a second heat exchange passage 28.

[0009] During operation, the working fluid mixture may circulate sequentially through the turbine generator 14, the first heat exchange passage 22 of the condenser, the pump 18 and the second heat exchange passage 28 of the evaporator, which may be connected together in a closed loop circuit. In some embodiments, the power generation system 10 may also include a liquid receiver/accumulator connected, for example, between the first heat exchange passage 22 and the pump 18. A cooling medium (e.g. water, seawater, air), may be directed through the second heat exchange passage 24 of the condenser. A thermal source fluid may be directed through the first heat exchange passage 26 of the evaporator.

[0010] FIG. 2 is a temperature-entropy phase diagram of the working fluid mixture during operation of the Rankine cycle system 12. The phase diagram illustrates a first curve 30 for the organic non-azeotropic working fluid mixture, a second curve 32 for the cooling medium, and a third curve 34 for the thermal source fluid. Referring to FIGS. 1 and 2, superheated vapor of the working fluid mixture is directed into the turbine generator 14 at point 200. The vapor expands and mechanically drives the turbine generator 14 between the point 200 and point 204, which may thereby generate power (e.g., electricity). The vapor is directed from the turbine generator 14 into the first heat exchange passage 22 at point 204. Thermal energy is transferred from the working fluid mixture into the cooling medium through the condenser 16 between the point 204 and point 206, which may cause the working fluid mixture to undergo a phase change from vapor to liquid. The vapor may be, for example, de-superheated within the first heat exchange passage 22 between the point 204 and point 208, and condensed into liquid between the point 208 and point 210. The liquid may also be sub-cooled within the first heat exchange passage 22 between the points 210 and 206. The liquid is directed from the first heat exchange passage 22 into the pump 18 between the point 206 and point 212. The liquid is pressurized within the pump 18 between the point 212 and point 214, and is directed into the second heat transfer passage 28 at point 216. Thermal energy is transferred from the thermal source fluid into the working fluid mixture through the evaporator 20 between the point 216 and point 200, which may cause the working fluid mixture to undergo another phase change from the liquid to the vapor. The liquid may be, for example, preheated within the second heat exchange passage 28 between the point 216 and point 220, and evaporated into vapor between the points 220 and 218. The vapor may also be, for example, superheated beyond point 218 to point 200 to minimize risk of condensation of the mixture vapor in the turbine generator 14. The vapor is then directed from the second heat exchange passage 28 into the turbine generator 14 at point 200.

[0011] The working fluid mixture may exhibit certain properties such as temperature glide during phase change, pressure, bubble point temperature in both the condenser passage 22 and the evaporator passage 28, and a mixture critical pressure that increases (e.g., maximizes) the power generation potential and cycle thermal efficiency during the afore-described Rankine cycle. The term "temperature glide" describes the temperature difference between the saturated vapor temperature and the saturated liquid temperature of a working fluid mixture. The term "saturated vapor temperature" describes a dew point temperature of the working fluid mixture; e.g., the temperature at the point 208 during condensation, and the temperature at the point 218 during evaporation. The term "saturated liquid temperature" describes a bubble point temperature of the working fluid mixture; e.g., the temperature at the point 210 during condensation, and the temperature at the point 220 during evaporation. The condenser temperature glide may be, for example, between about five and thirty degrees Kelvin (e.g., between about 6-8°K and 20-25°K). The condenser pressure may be, for example, between about one tenth of one percent (0.1 %) and eleven percent of the critical pressure (e.g., between about 1-2.5% and 7.5-8% of the critical pressure) of the working fluid mixture. The condenser bubble point temperature at the point 210 may be, for example, between about one and nine degrees Kelvin (e.g., between about 1°K and 5°K) greater than temperature T_5 (e.g., T_5 is between about 280 °K and 308°K) at which the cooling medium is received by the second heat exchange passage 24. The critical pressure may be, for example, between about 2 MPa and 6.5 MPa.

[0012] The working fluid mixture may also exhibit other characteristics during the Rankine cycle such as, for example, low global warming potential (GWP), low flammability, low ozone depletion potential, low toxicity, etc. The term "global warming potential" is a relative measure of how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide for the atmospheric lifetime of the species. The global warming potential of carbon dioxide is standardized to 1. The global warming potential of the working fluid mixture may be, for example, less than about 675 (e.g., less than about 150-250), and the working fluid mixture may be, for example, non-flammable.

[0013] Some non-azeotropic mixtures may exhibit a lower condensation heat transfer coefficient due to a reduced interfacial temperature between the liquid and vapor phases. This reduced interfacial temperature gives rise to heat and mass transfer resistances. In order to avoid such implications, the working fluid mixture may be selected such that the

condensing heat transfer coefficient of the mixture is greater than the (e.g., smallest) condensing heat transfer coefficient of the components. The least volatile component refers to the component with the lowest boiling point at a given temperature.

[0014] The working fluid mixture may be manufactured by mixing together a plurality of different chemical components (e.g., organic chemical components). The working fluid mixture may include, for example, a plurality of the chemical components listed in Table 1 below.

TABLE 1	
Chemical Group	Representative Chemical Components (CAS Registry Number)
Hydrocarbon	Propane (74-98-6), butane (106-97-8), pentane (109-66-0), hexane (110-54-3), heptanes (142-82-5), octane (111-65-9), nonane (111-84-2), decane (124-18-5), ethylene (74-85-1), propylene (115-07-1), propyne (74-99-7), isobutene (75-28-5), isobutene (115-11-7), 1 butene (106-98-9), c2butene (590-18-1), cyclopentane (287-92-3), isopentane (78-78-4), neopentane (463-82-1), isohexane (107-83-5), cyclohexane (110-82-7)
Fluorocarbon	R14 (75-73-0), R218 (76-19-7)
Ether	RE170 (dimethyl ether 115-10-6)
Hydrochlorofluorocarbon	R21 (75-43-4), R22 (75-45-6), R30 (75-09-2), R32 (75-10-5), R41 (593-53-3), R123 (306-83-2), R124 (2837-89-0)
Hydrofluorocarbon	R134a (811-97-2), R143a (420-46-2), R152a (75-37-6), R161 (353-36-6), R23 (75-46-7), R227ea (431-89-0), R236ea (431-63-0), R236fa (690-39-1), R245ca (679-86-7), R245fa (460-73-1), R365mfc (406-58-6), R338mccq (662-35-1)
Fluorinated Ketone	1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone (e.g., Novec®649) (756-13-8), C7FK (C7 fluoroketone)
Hydrofluoro ether	RE125 (3822-68-2), RE134, RE143a (421-14-7) RE236fa, RE245cb2 (22410-44-2), RE245fa2 (1885-48-9), HFE-7000 (C3F7OCH3), HFE-7100 (C4F9OCH3), HFE-7200 (C4F9OC2H5)
Hydrochlorofluoro olefin	R1233zd (102687-65-0), 2-chloro-3,3,3-trifluoropropene
Bromofluoro olefin	C5F9Cl
Fluoro olefin	R1216 (116-15-4)
Hydrofluoro olefin	R1234yf (754-12-1), R1234ze (1645-83-6), R1243zf (677-21-4), R1225ye (5595-10-8)
Cyclic siloxane	D2 (7782-39-0), D4 (556-76-2), D5 (541-02-6), D6 (540-97-6)
Linear siloxane	MM (107-46-0), MDM (107-51-7), MD2M (141-62-8), MD3M (141-63-9), MD4M (00107-52-8)

[0015] The aforesaid chemical components may be selected, for example, in order to tailor the heat exchanger temperature glide, the heat exchange pressure, the bubble point temperature and/or other characteristics (e.g., the GWP, the flammability, etc.) of the working fluid mixture to a particular Rankine cycle system design and application. The chemical components may also be selected, for example, to shift the pinch point in order to reduce a temperature T_6 at which the thermal source fluid exits the heat exchange passage 26 of the evaporator, which may thereby increase Rankine cycle efficiency by increasing the amount of power generated per unit of resource flow. The working fluid mixture included in the power generation system 10 in FIG. 1, for example, may include a first chemical component and a second chemical component. Examples of first and second chemical component combinations are listed below in Table 2.

EP 2 613 026 A2

TABLE 2						
	Representative Chemical Components (A + B)	Concentration (% by mass)		Temp. Glide Range (°K)		Bubble Point Temp. (°K)
		A	B	Min.	Max.	
5	C2butene + hexane	5-90	95-10	10-17	25-31.2	3.1-4.1
10	Cyclopentane + Octane	55-95	45-5	9-15.4	27.6-36.2	3.6-4.4
	Isohexane + t2butene	15-95	85-5	10.5	23.8-27.2	3.1-3.9
15	Cyclohexane + isopentane	10-95	90-5	7.5	21.5	3.4-4.1
	Pentane + propyne	10-95	90-5	5.9	22.2-31.7	3.5-5.6
20	Pentane + R245fa	30-95	70-5	4.8	8.2	3.4-4.1
	Octane + R30	5-25	95-75	13.8	27.6-35.4	4.8-5.8
	Heptane + R30	5-95	95-5	5.6-9.7	13.2-24.6	2.8-5.8
25	Isobutane + Pentane	5-90	95-10	5.3	17.7	3.4-3.8
	Cyclohexane + R245ca	10-95	90-5	8.9-9.3	19.1-28.9	4.1-4.7
	Hexane + R245fa	30-95	70-5	8.2	17.8-27	3.1-3.85
30	Isohexane + R245fa	30-95	70-5	6.5	18.2-21.9	3.1-3.9
	Cyclopentane + R236ea	45-90	55-10	6.5-9	19.2	4.5-4.65
35	Cyclopentane + R152a	10-30	90-70	14.7	21.2-34.4	4.6-4.8
	Heptane + R365mfc	25-80	75-20	13.7	17.7-23.1	2.7-3.1
40	Pentane + 1 butene	15-95	85-5	5.2-7.4	14.8	3.5-4.0
	Hexane + R1233zd	5-90	95-10	5.5-7.8	18.4	3.0-3.6
45	R245fa + R1234ze	25-70	75-30	5.2	11	3.7-3.9
	Isopentane + R1234ze	5-85	95-15	6.2	16.4-18	3.3-3.6
50	Pentane + R1234ze	5-90	95-10	6.6	16.4-23.9	3.3-3.6
	Cyclopentane + R245fa	30-90	70-10	5.1	14.1	4.5-4.75
55	Cyclohexane + HFE-7000	5-80	95-20	5.7-8.5	16.1	2.7-4.0
	R152a + R245fa	35-75	65-25	6.7	12.8	4.1-4.5

(continued)

TABLE 2						
Representative Chemical Components (A + B)	Concentration (% by mass)		Temp. Glide Range (°K)		Crit. Pressure (MPa)	Bubble Point Temp. (°K)
	A	B	Min.	Max.		
R30 + R152a	5-95	95-5	5.6-10.9	22.6-33.8	4.6-6.0	289-291
R236ea + R161	25-55	75-45	5.5-9.9	11.9	4.4-4.9	289-291
R30 + R1234ze	5-90	95-10	8.9	22.5-27.2	3.7-5.85	289-291
Pentane + MM	5-90	95-10	7.2	20.9-31	2.0-3.3	289-291
C7FK + R245fa	30-90	70-10	10.2	19.1-29.8	2.8-3.4	289-291
R30 + MM	5-90	95-10	6.4-9.1	22.3-28	2.1-5.6	289-291
Novec®649 + isobutene	25-95	75-5	8.8	15.4-26.1	2.9-4.0	289-291
Novec®649 + R245fa	45-95	55-5	5.2	12.6	2.0-3.2	289-291
Novec®649 + R236ea	45-65	55-35	10.6	16.1	2.7-3.1	289-291
R245ca + MM	65-90	35-10	11.2	23.3-34.4	3.4-3.9	289-291
R365mfc + MM	10-75	90-25	13.3	23.1-25.1	2.0-3.0	289-291
HFE-7000 + R1234ze	10-95	90-5	6.5	16-23.8	2.6-3.6	289-291
R30 + R245fa	30-45	70-55	5.1	5.8	4.4-4.9	289-291
Isobutane + r365mfc	25-85	75-15	5.8-9.5	17-20.7	3.3-3.6	289-291
R152a + R365mfc	30-90	70-10	6.7-9.8	20.0-32.8	3.9-4.5	289-291
R245fa + CF3I	25-65	75-35	5.6-10.3	16.4-17.8	4.3-4.55	289-291
HFE-7000 + R1243zf	10-40	90-60	6.2-11.7	20.8	3.2-3.5	289-291
R236ea + HFE-7000	15-35	85-65	5	7.4	2.6-2.85	289-291

[0016] The thermodynamic and transport properties for the refrigerant mixtures provided in Table 2 were generated using the National Institute of Standards and Technology's REFPROP 8.0 database. The equations of state for these refrigerant mixtures are generated using empirical estimation schemes (e.g. mixing rules) contained within the database. The present invention, however, is not limited to the aforesaid mixing rules.

[0017] The working fluid mixture may also include one or more additional chemical components and/or compounds selected to, for example, enhance system performance, enhance heat transfer between the Rankine cycle fluids, enhance diagnostics, provide fire suppression, provide lubrication, provide fluid stabilization, provide corrosion resistance, etc. The working fluid mixture may include, for example, flammability inhibitors, oils, lubricants, heat transfer enhancement agents, tracers, etc.

[0018] The cooling medium may be water, air or a combination thereof. The water may be received from an underground reservoir, a lake, a stream or the sea. The cooling medium may also be a process stream that may condense the working fluid mixture. The cooling medium may be received from a heat sink having a sink temperature between, for example, about 280°K and 308°K. In other embodiments, the cooling medium may be a working fluid mixture received from another Rankine cycle system, which will be discussed below in further detail.

[0019] The thermal source fluid may be, for example, liquid and/or gas received from a geothermal reservoir, a combustion engine (e.g., a gas turbine engine, an internal combustion engine, etc.), a solar-thermal system, an incinerator

or other waste to energy devices, or an industrial system or process. The thermal source fluid may be received from a heat source having a source temperature between, for example, about 360°K and 623°K. In other embodiments, the thermal source fluid may be a working fluid mixture received from another Rankine cycle system, which will be discussed below in further detail. Alternatively, the thermal source fluid may be omitted from the power generation system 10 where, for example, the evaporator 20 is configured as a solar-thermal heating system (e.g., a system that heats the working fluid mixture directly via solar energy).

[0020] In some embodiments, the turbine generator 14 may be one of a plurality of turbine generators that are, for example, connected in series or parallel together in the Rankine cycle system. In other embodiments, the evaporator 20 may be one of a plurality of evaporators that are, for example, connected in series or parallel together in the Rankine cycle system. In still other embodiments, the condenser 16 may be one of a plurality of condensers that are, for example, connected in series or parallel together in the Rankine cycle system.

[0021] According to another aspect of the invention, a power generation system may include an intermediate heat exchanger, a topping cycle (e.g., a first Rankine cycle system that operates at a relatively high temperature), and a bottoming cycle (e.g., a second Rankine cycle system that operates at a relatively low temperature). The intermediate heat exchanger may include a condenser passage that receives a first organic working fluid mixture from the topping cycle, and an evaporator passage that receives a second working fluid from the bottoming cycle. The intermediate heat exchanger transfers thermal energy from the first working fluid to the second working fluid. In this cascaded ORC arrangement, the topping cycle (e.g., the high temperature ORC system) may extract heat, either sensible such as from a hot gas or hot liquid, or latent such as from a condensing fluid such as steam in a refrigerant boiler/evaporator, and create a high temperature and a high pressure vapor. The bottoming cycle (e.g., the low cost/ low temperature ORC system) may be used efficiently and cost effectively to convert the lower temperature thermal energy to power.

[0022] FIG. 3 is a schematic illustration of a power generation system 36. The power generation system 36 includes an intermediate heat exchanger 38 (e.g., a counterflow heat exchanger), a first working fluid (e.g., an organic, non-azeotropic working fluid mixture) that circulates through a topping cycle 40 (e.g., an organic Rankine cycle system), and a second working fluid (e.g., an organic, non-azeotropic working fluid mixture) that circulates through a bottoming cycle 42 (e.g., an organic Rankine cycle system). The intermediate heat exchanger 38 includes a first heat exchange passage 44 and a second heat exchange passage 46. The first heat exchange passage 44 forms a condenser passage 48 where the first working fluid is condensed. The second heat exchange passage 46 forms an evaporator passage 50 where the second working fluid is evaporated. The topping cycle 40 may include a first turbine generator 52, the condenser passage 48, a first pump 56, an evaporator 58 (e.g., a counterflow evaporator), and a liquid receiver/accumulator 54. The evaporator 58 may include a first heat exchange passage 60 and a second heat exchange passage 62. The bottoming cycle 42 may include a second turbine generator 64, a condenser 68 (e.g., a counterflow condenser), a second liquid receiver/accumulator 66, a second pump 70 and the evaporator passage 50. The condenser 68 may include a first heat exchange passage 72 and a second heat exchange passage 74.

[0023] During operation, the first working fluid may circulate sequentially through the first turbine generator 52, the first heat exchange passage 44 (i.e., the condenser passage 48 of heat exchanger 38), the first liquid receiver/accumulator 54, the first pump 56 and the second heat exchange passage 62, which may be connected together in a closed loop circuit. The second working fluid may circulate sequentially through the second turbine generator 64, the first heat exchange passage 72 (i.e. the condenser 68), the second liquid receiver/accumulator 66, the second pump 70 and the second heat exchange passage 46 (i.e., the evaporator passage 50 of heat exchanger 38), which may be connected together in a closed loop circuit. A heat source fluid may be received from a heat source 76, and directed through the first heat exchange passage 60 (i.e., the evaporator 58). A cooling medium may be received from a heat sink 78, and directed through the second heat exchange passage 74 (i.e., the condenser 68).

[0024] In some embodiments, the working fluids (e.g., the non-azeotropic working fluid mixtures) for the topping and bottoming cycles may be selected such that the condensation temperature of the first, higher temperature, cycle is useable for evaporation of the second, lower temperature, cycle. In this way, the thermal efficiencies of the organic Rankine cycle may be increased through increased utilization of the available thermal energy.

[0025] In some embodiments, a relatively high temperature non-azeotropic mixture may be directed through the topping cycle and a relatively low temperature non-azeotropic mixture may be directed through the bottoming cycle. The use of the non-azeotropic mixture in the topping cycle may enable increased utilization of the thermal source fluid through glide matching. The use of a non-azeotropic mixture in the bottoming cycle may reduce (e.g., minimize) irreversibilities realized in the intermediate heat exchanger where the fluid's evaporating glide is equal to the condensing glide of the topping cycle's working fluid mixture. FIG. 4 illustrates a temperature-entropy (T-s) phase diagram of the aforesaid working fluid mixtures during operation of such a power generation system. The phase diagram illustrates a first curve 400 for the non-azeotropic mixture directed through the topping cycle, and a second curve 402 for the non-azeotropic mixture directed through the bottoming cycle.

[0026] The difference of working temperature between the components of the working fluid mixture may become greater as the temperature glide increases. This difference may increase the thermal cycle efficiency of the system.

However, high temperature glide working fluid mixtures may require condensers that include a relatively large surface area to provide the desired heat transfer necessary to condense the vapor into liquid. In some embodiments, therefore, one or more of the heat exchangers (e.g., the condenser and the evaporator) may be configured as a plate-frame counter-flow heat exchanger, a one pass direct expansion shell and tube counter-flow heat exchanger, or a plate-shell counter-flow heat exchanger.

[0027] In some embodiments, a non-azeotropic first working fluid mixture may be directed through the topping cycle and a second working fluid that exhibits relatively no temperature glide may be directed through the bottoming cycle. The working fluid in the bottoming cycle may include a pure substance or an azeotropic mixture of one or more known substances (i.e., chemical components). The non-azeotropic mixture in the topping cycle may enable increased utilization of the thermal source fluid through glide matching. Although the use of an azeotropic fluid or pure substance in the bottoming cycle may increase the irreversibilities in the intermediate heat exchanger, the negative impact associated with glide in the bottoming cycle's condenser are reduced (e.g., minimized). FIG. 5 illustrates a temperature-entropy (T-s) phase diagram of the aforesaid working fluids during operation of such a power generation system. The phase diagram illustrates a first curve 500 for the non-azeotropic first working fluid mixture directed through the topping cycle, and a second curve 502 for the second working fluid directed through the bottoming cycle. Alternatively, in other embodiments, a first working fluid that exhibits relatively no temperature glide may be directed through the topping cycle, and a non-azeotropic second working fluid mixture may be directed through the bottoming cycle.

[0028] While various embodiments of the present invention have been disclosed, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible within the scope of the invention. The chemical components included in the organic, non-azeotropic working fluid mixture, for example, are not intended to be limited to the chemical groups and components listed in Tables 1 and 2. Accordingly, the present invention is not to be restricted except in light of the attached claims.

Claims

1. A power generation system (10), comprising:

a non-azeotropic working fluid mixture; and

a Rankine cycle system (12) comprising a turbine generator (14) that is driven by vapor of the working fluid mixture, and a condenser (16) that exchanges thermal energy between the vapor received from the turbine generator (14) and a cooling medium, wherein the working fluid mixture exhibits a condenser temperature glide during phase change between approximately five degrees and thirty degrees Kelvin, a condensing pressure between approximately one tenth of one percent and eleven percent of a critical pressure of the working fluid mixture, and a condenser bubble point temperature between approximately one degree and nine degrees Kelvin greater than a temperature at which the cooling medium is received by the condenser (16).

2. The system (10) of claim 1, wherein the working fluid mixture comprises a first chemical component and a second chemical component, and the first chemical component and the second chemical component each comprise at least one of a hydrocarbon, a fluorocarbon, an ether, a hydrochlorofluorocarbon, a hydrofluorocarbon, a fluorinated ketone, a hydrofluoro ether, a hydrochlorofluoro olefin, a bromofluoro olefin, a fluoro olefin, a hydrofluoro olefin, a cyclic siloxane and a linear siloxane.

3. The system (10) of claim 2, wherein the first chemical component comprises at least one of R134a, R245fa, R236ea, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, HFE-7000, R1234ze, R1234yf, R1233zd and R1243zf,

4. The system (10) of claim 2 or 3, wherein the second chemical component comprises at least one of pentane, hexane, isohexane, cyclopentane, cyclohexane, R245fa, R1234ze, isopentane, R161, R30, R134a, R1233zd, C7FK, isobutene, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, R236ea, HFE-7000, CF3I and R1243zf.

5. The system (10) of any preceding claim, wherein the condenser temperature glide is between approximately six degrees and twenty-five degrees Kelvin, and optionally the condenser temperature glide is between approximately eight degrees and twenty degrees Kelvin.

6. The system (10) of any preceding claim, wherein the condensing pressure is between approximately one percent and eight percent of the critical pressure of the working fluid mixture, and optionally the condensing pressure is between approximately two and one half percent and seven and one half percent of the critical pressure of the

working fluid mixture.

7. The system (10) of any preceding claim, wherein the condenser bubble point temperature is between approximately one degree and five degrees Kelvin greater than the temperature at which the cooling medium is received by the condenser (16).

8. The system of any preceding claim, wherein the working fluid mixture exhibits a global warming potential less than approximately 675, and optionally the global warming potential is less than approximately 150.

9. The system of any preceding claim, wherein the condenser (16) comprises one of a plate-frame counter-flow heat exchanger, a one pass direct expansion shell and tube counter-flow heat exchanger, and a plate-shell counter-flow heat exchanger.

10. A power generation system (36), comprising:

an intermediate heat exchanger (38) comprising a condenser passage (48) that receives a first working fluid, and an evaporator passage (50) that receives an organic, non-azeotropic second working fluid mixture, wherein the intermediate heat exchanger (38) transfers thermal energy from the first working fluid to the second working fluid mixture;

a first Rankine cycle system (40) comprising a first pump (56) that directs the first working fluid through an evaporator (58) and the condenser passage (48); and

a second Rankine cycle system (42) comprising a second pump (70) that directs the second working fluid mixture through the evaporator passage (50), a second turbine generator (64) that is driven by vapor of the second working fluid mixture, and a condenser (68) that exchanges thermal energy between the vapor received from the second turbine generator (64) and a cooling medium, wherein the second working fluid mixture is **characterized by** a condenser temperature glide between approximately five degrees and thirty degrees Kelvin, a condensing pressure between approximately one tenth of one percent and eleven percent of a critical pressure of the second working fluid mixture, and a condenser bubble point temperature between approximately one degree and nine degrees Kelvin greater than a temperature at which the cooling medium is received by the condenser (68).

11. The system (36) of claim 10, wherein the second working fluid mixture comprises a first chemical component and a second chemical component, and the first chemical component and the second chemical component each comprise at least one of a hydrocarbon, a fluorocarbon, an ether, a hydrochlorofluorocarbon, a hydrofluorocarbon, a fluorinated ketone, a hydrofluoro ether, a hydrochlorofluoro olefin, a bromofluoro olefin, a fluoro olefin, a hydrofluoro olefin, a cyclic siloxane and a linear siloxane.

12. The system (36) of claim 11, wherein the first chemical component comprises at least one of R134a, R245fa, R236ea, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, HFE-7000, R1234ze, R1234yf, R1233zd and R1243zf.

13. The system (36) of claim 11 or 12, wherein the second chemical component comprises at least one of pentane, hexane, isohexane, cyclopentane, cyclohexane, R245fa, R1234ze, isopentane, R161, R30, R134a, R1233zd, C7FK, isobutene, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, R236ea, HFE-7000, CF3I and R1243zf.

14. The system (36) of any of claims 10 to 13, wherein the evaporator (58):

transfers thermal energy into the first working fluid from a thermal source fluid received from one of a geothermal reservoir, a combustion engine, a solar-thermal system, an incinerator and an industrial system, and the cooling medium comprises at least one of a liquid and a gas; and/or the evaporator (58) comprises a solar-thermal system.

15. The system (36) of any of claims 10 to 14, wherein the first working fluid comprises a first chemical component and a second chemical component, and the first chemical component and the second chemical component each comprise at least one of a hydrocarbon, a fluorocarbon, an ether, a hydrochlorofluorocarbon, a hydrofluorocarbon, a fluorinated ketone, a hydrofluoro ether, a hydrochlorofluoro olefin, a bromofluoro olefin, a fluoro olefin, a hydrofluoro olefin, a cyclic siloxane and a linear siloxane, and optionally wherein:

EP 2 613 026 A2

the first chemical component comprises at least one of R134a, R245fa, R236ea, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, HFE-7000, R1234ze, R1234yf, R1233zd and R1243zf; and/or
the second chemical component comprises at least one of pentane, hexane, isohexane, cyclopentane, cyclohexane, R245fa, R1234ze, isopentane, R161, R30, R134a, R1233zd, C7FK, isobutene, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, R236ea, HFE-7000, CF3I and R1243zf.

5

10

15

20

25

30

35

40

45

50

55

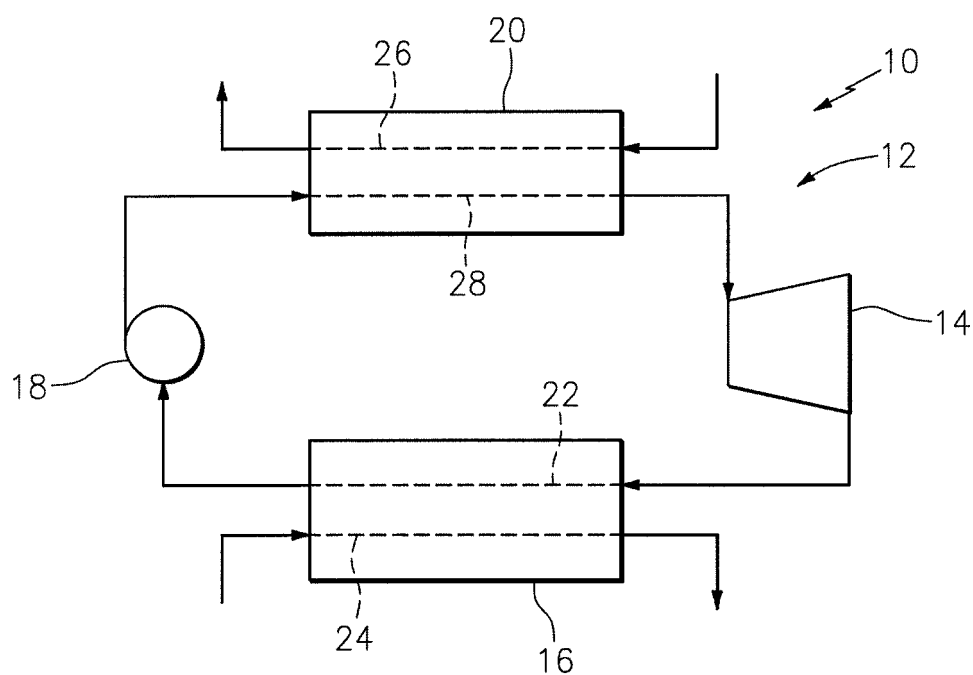


FIG. 1

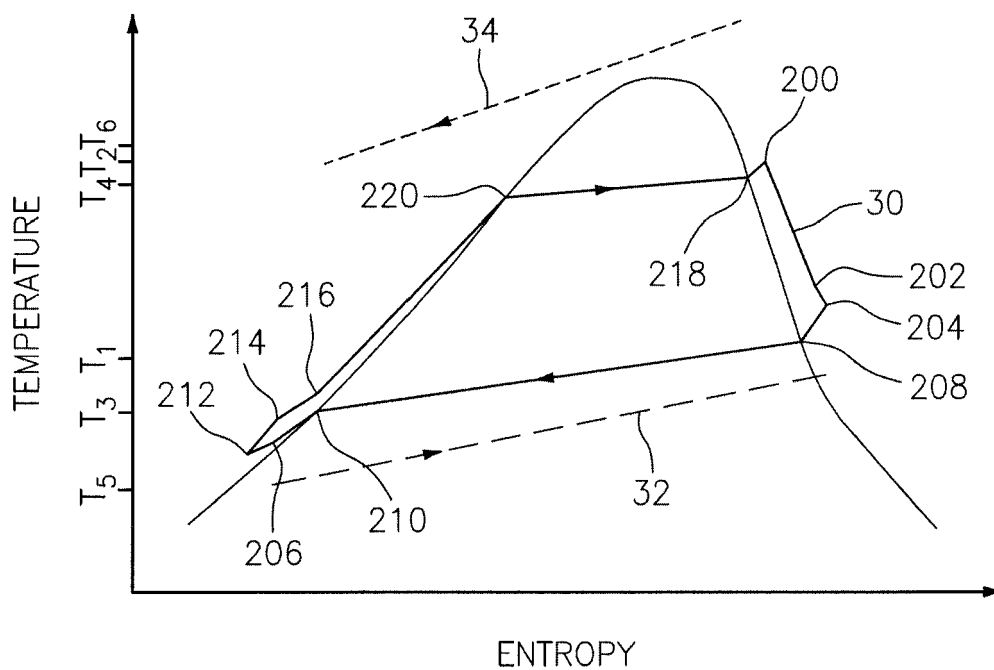


FIG. 2

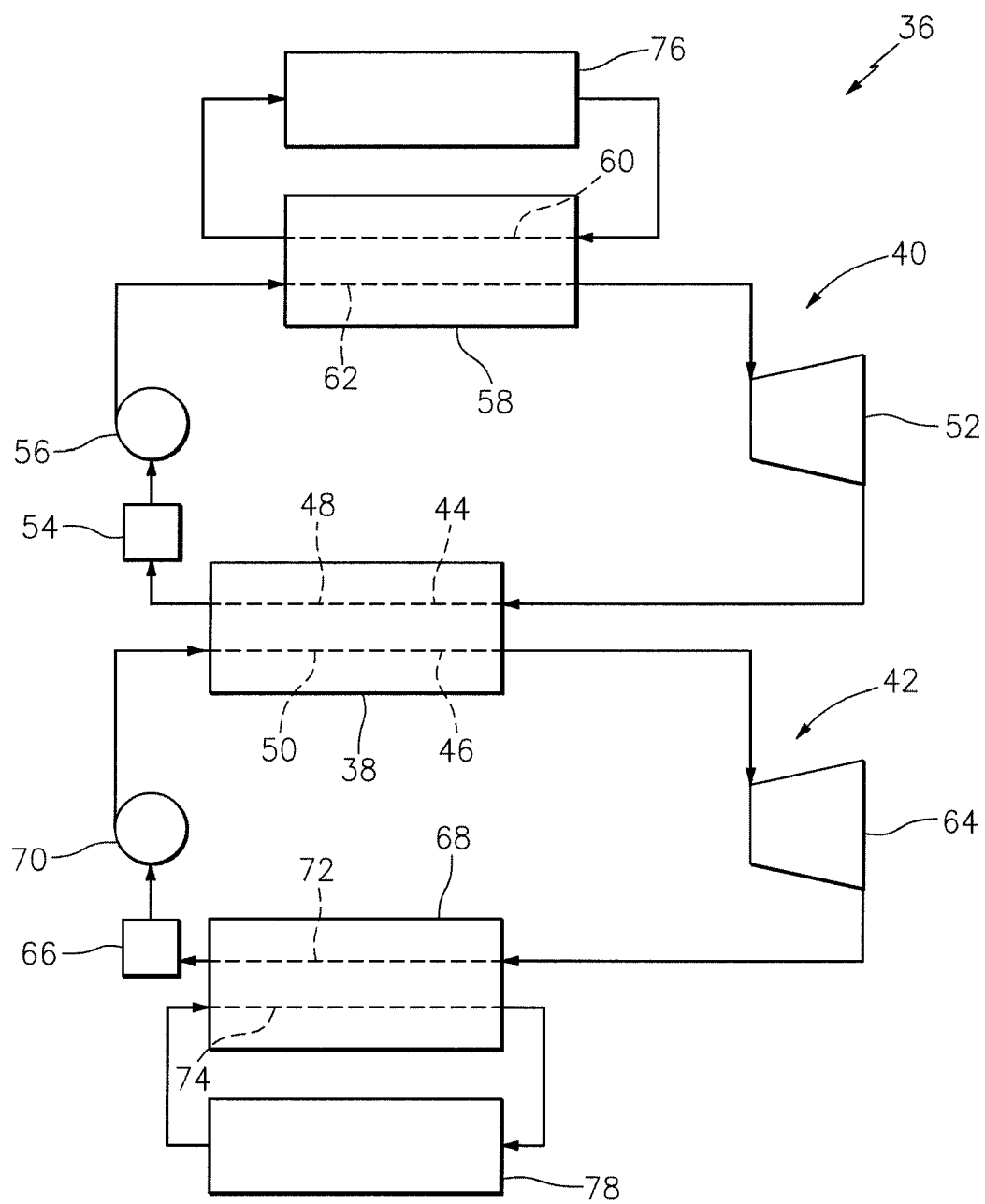


FIG. 3

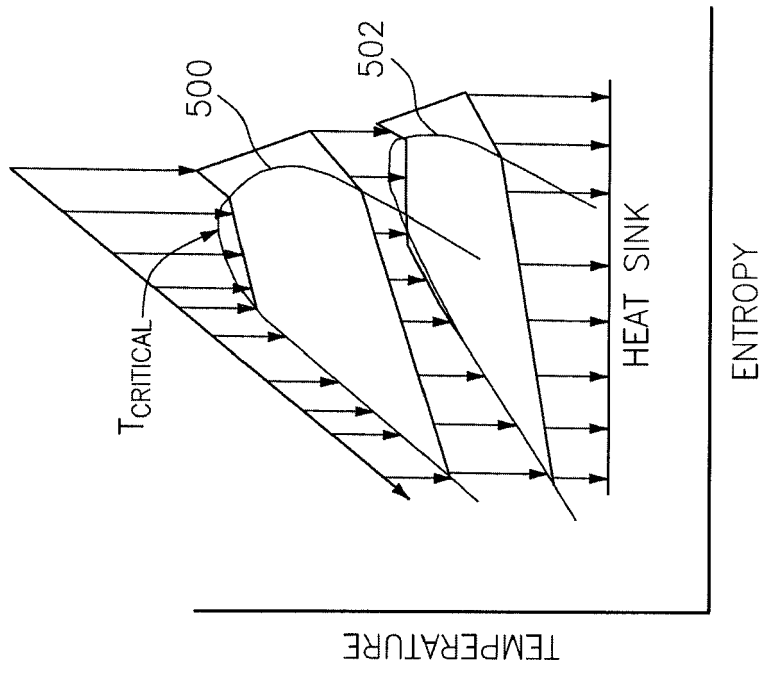


FIG. 4

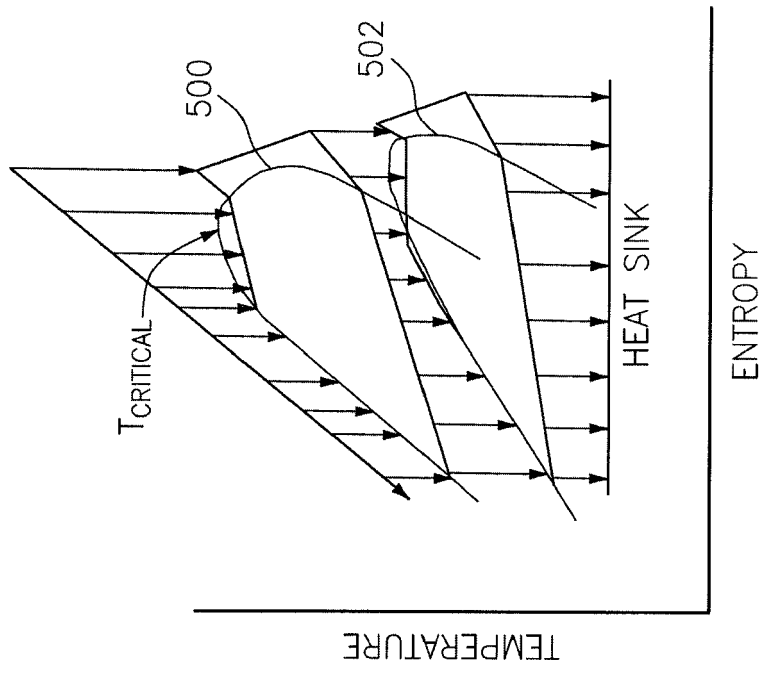


FIG. 5