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(54) **CASCADED ORGANIC RANKINE CYCLE (ORC) SYSTEM USING WASTE HEAT FROM A RECIPROCATING ENGINE**

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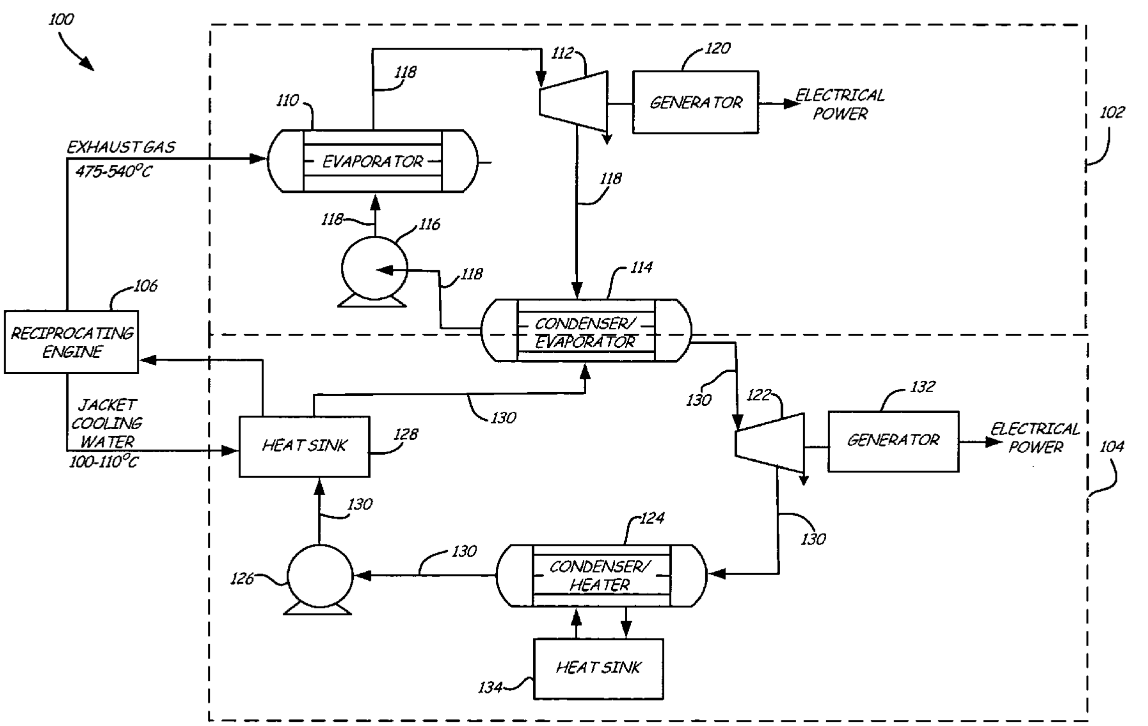
(57) **ABSTRACT**

A method and system for operating a cascaded organic Rankine cycle (ORC) system (**100**) utilizes two waste heat sources from a positive-displacement engine (**106**), resulting in increased efficiency of the engine (**106**) and the cascaded ORC system (**100**). A high temperature waste heat source from the positive-displacement engine (**106**) is used in a first ORC system (**102**) to vaporize a first working fluid (**118**). A low temperature waste heat source from the positive-displacement engine (**106**) is used in a second ORC system (**104**) to heat a second working fluid (**130**) to a temperature less than the vaporization temperature. The second working fluid (**130**) is then vaporized using heat from the first working fluid (**118**). In an exemplary embodiment, the positive-displacement engine (**106**) is a reciprocating engine. The high temperature waste heat source may be exhaust gas and the low temperature waste heat source may be jacket cooling water.



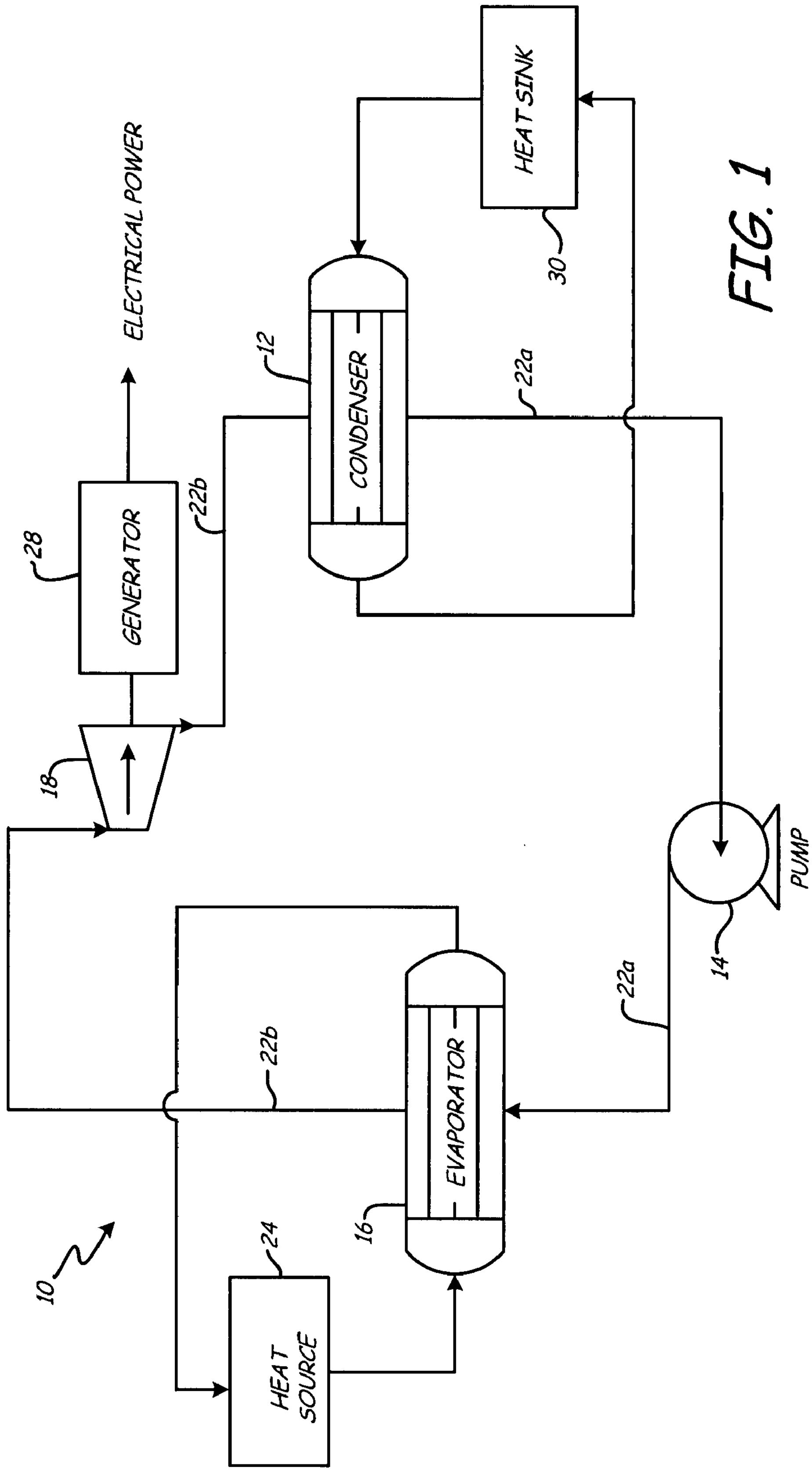

ELECTRICAL POWER
HEAT SINK
30
GENERATOR
28
22b
12
CONDENSER
22a
18
PUMP
14
22a
22b
EVAPORATOR
16
24
HEAT SOURCE
10

FIG. 1

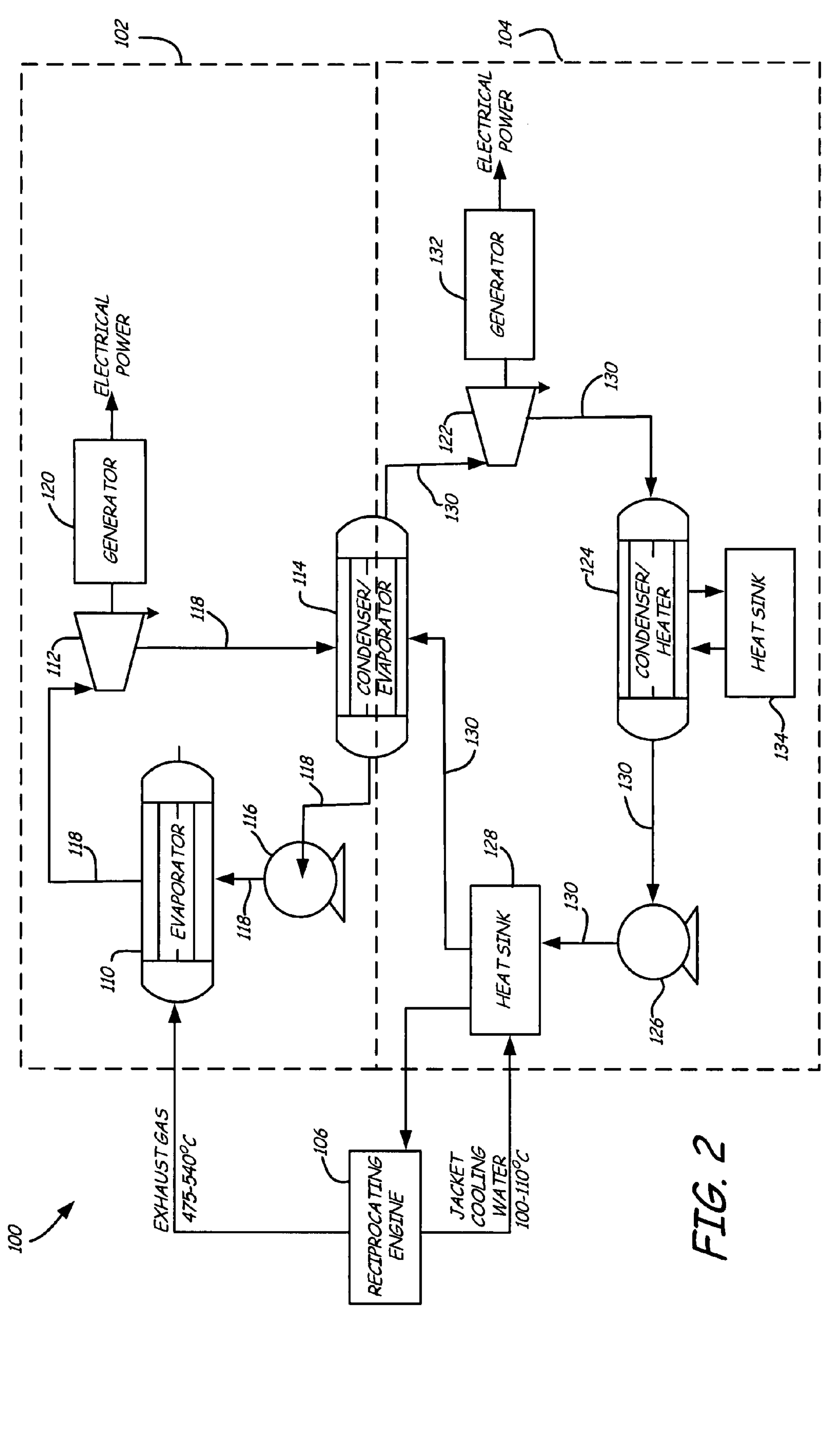
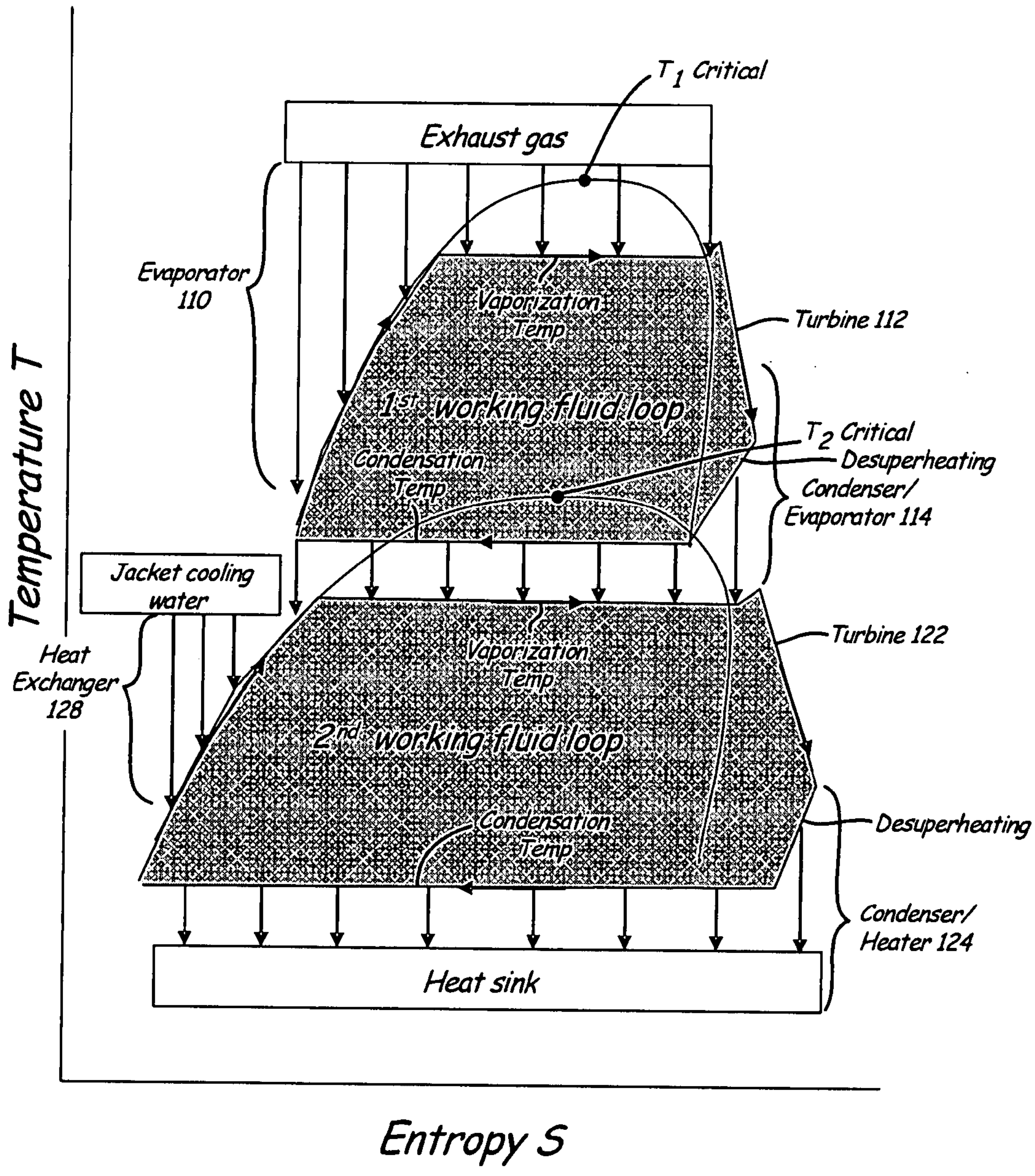

100
102
104
106
RECIPROCATING ENGINE
EXHAUST GAS 475-540°C
JACKET COOLING WATER 100-110°C
110
EVAPORATOR
112
114
CONDENSER/ EVAPORATOR
116
118
120
GENERATOR
ELECTRICAL POWER
122
124
CONDENSER/ HEATER
126
128
HEAT SINK
130
132
GENERATOR
ELECTRICAL POWER
134
HEAT SINK

FIG. 2



T1 Critical
Exhaust gas
Evaporator 110
Vaporization Temp
Turbine 112
1st working fluid loop
T2 Critical
Desuperheating
Condensation Temp
Condenser/ Evaporator 114
Jacket cooling water
Heat Exchanger 128
Vaporization Temp
Turbine 122
2nd working fluid loop
Desuperheating
Condensation Temp
Condenser/ Heater 124
Heat sink
Temperature T
Entropy S

FIG. 3

CASCADED ORGANIC RANKINE CYCLE (ORC) SYSTEM USING WASTE HEAT FROM A RECIPROCATING ENGINE

BACKGROUND

[0001] The present disclosure relates to an organic Rankine cycle (ORC) system. More particularly, the present disclosure relates to operating a cascaded ORC system using two waste heat sources from a reciprocating engine.

[0002] Rankine cycle systems are commonly used for generating electrical power. The Rankine cycle system includes an evaporator or a boiler for evaporation of a motive fluid, a turbine that receives the vapor from the evaporator to drive a generator, a condenser for condensing the vapor, and a pump or other means for recycling the condensed fluid to the evaporator. The motive fluid in Rankine cycle systems is often water, and the turbine is thus driven by steam. An organic Rankine cycle (ORC) system operates similarly to a traditional Rankine cycle, except that an ORC system uses an organic fluid, instead of water, as the motive fluid.

[0003] The ORC system uses a waste heat source to provide heat to vaporize the organic fluid in the evaporator. A reciprocating engine is a common source of waste heat for an ORC system. Usable waste heat from the reciprocating engine may include exhaust gas at temperatures near approximately 540 degrees Celsius (approximately 1000 degrees Fahrenheit), as well as cooling water at approximately 105 degrees Celsius (approximately 220 degrees Fahrenheit). Challenges arise in trying to use both of the waste heat sources from the reciprocating engine, particularly given the temperature difference between them. As such, the exhaust gas is typically preferred over the cooling water, given the potential for greater heat transfer.

[0004] To effectively utilize the high-temperature exhaust heat from the reciprocating engine, the ORC system typically uses an organic fluid with a high critical temperature, allowing boiling at elevated temperatures. However, expanding an organic fluid with a single turbine over a large pressure ratio causes the vapor exiting the turbine to be more superheated, thus limiting the amount of power captured by the turbine. The highly superheated fluid exiting the turbine may also require special condensation equipment.

[0005] There is a need for an improved method and system of recovering waste heat from a reciprocating engine in order to increase efficiency of the reciprocating engine and the ORC system.

SUMMARY

[0006] A method and system for operating a cascaded organic Rankine cycle (ORC) system utilizes two waste heat sources from a positive-displacement engine, resulting in increased efficiency of the engine and the cascaded ORC system. A high temperature waste heat source from the positive-displacement engine is used in a first ORC system to vaporize a first working fluid. A low temperature waste heat source from the positive-displacement engine is used in a second ORC system to heat a second working fluid to a temperature less than the vaporization temperature. The second working fluid is then vaporized using heat from the first working fluid. The first working fluid has a higher critical temperature than the second working fluid. In an exemplary embodiment, the positive-displacement engine is a reciprocating engine and the waste heat sources are exhaust gas and jacket cooling water.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a schematic of an organic Rankine cycle (ORC) system designed to produce electrical power using waste heat.

[0008] FIG. **2** is a schematic of a cascaded ORC system with a first ORC system and a second ORC system, designed to utilize two waste heat sources from a reciprocating engine.

[0009] FIG. **3** is a T-s diagram for the cascaded ORC system of FIG. **2**.

DETAILED DESCRIPTION

[0010] A waste heat recovery system, such as an organic Rankine cycle (ORC) system, may be used to capture heat from a prime mover, such as a reciprocating engine. The ORC system may then be used to generate electrical power. A reciprocating engine has two sources of waste heat that may be recoverable by the ORC system—exhaust gas (high temperature) and cooling water (low temperature). However, given the large temperature difference between the waste heat sources, it is difficult to effectively utilize both of these waste heat sources in a single ORC system. As described herein, in a cascaded ORC system, a first ORC system utilizes a high temperature working fluid to power a generator and a second ORC system utilizes a low temperature working fluid to power a second generator. The first ORC system recovers heat from the exhaust gas of the reciprocating engine. The second ORC system recovers heat from the cooling water of the reciprocating engine, as well as the heat of condensation from the high temperature working fluid of the first ORC system. The cascaded ORC system and method described herein utilizes more of the waste heat from the reciprocating engine, and thus generates a greater amount of power per unit of waste heat from the reciprocating engine.

[0011] FIG. **1** is a schematic of a single ORC system **10**, which includes condenser **12**, pump **14**, evaporator **16**, and turbine **18**. Working fluid **22** circulates through system **10** and is used to generate electrical power. Liquid working fluid **22*a*** from condenser **12** passes through pump **14**, resulting in an increase in pressure. High pressure liquid fluid **22*a*** enters evaporator **16**, which utilizes heat source **24** to vaporize fluid **22**. Heat source **24** may include, but is not limited to, any type of waste heat resource, including reciprocating engines, fuel cells, and microturbines, and other types of heat sources such as solar, geothermal or waste gas. Working fluid **22** exits evaporator **16** as a vapor (**22*b***), at which point it passes into turbine **18**. Vaporized working fluid **22*b*** is used to drive turbine **18**, which in turn powers generator **28** such that generator **28** produces electrical power. Vaporized working fluid **22*b*** exiting turbine **18** is returned to condenser **12**, where it is condensed back to liquid **22*a***. Heat sink **30** is used to provide cooling to condenser **12**.

[0012] In those cases in which heat source **24** is a high temperature heat source, working fluid **22** is preferably a high temperature fluid having a high critical temperature. In that case, heat source **24** is able to transfer sufficient heat to the working fluid, while maintaining the working fluid below the critical temperature in evaporator **16**. A disadvantage of such a high temperature working fluid, however, is that when it exits turbine **18**, it is highly superheated. At least a portion of the heat from the superheated vapor is not converted into power, and thus turbine **18** has a low efficiency. Moreover, the high temperature working fluid requires additional cooling in condenser **12**, resulting in expensive equipment and typically a large amount of unrecoverable waste heat from the working fluid.

[0013] In contrast, if heat source **24** is a low temperature heat source, a low temperature working fluid may be used within system **10**. However, there is a reduced efficiency in power output, as compared to when system **10** recovers heat from a high temperature heat source.

[0014] In the scenario in which heat source **24** is waste heat from a reciprocating engine, ORC system **10** typically uses either the exhaust gas (i.e. high temperature waste heat) or the jacket cooling water (i.e. low temperature waste heat), since it is difficult to use both. As such, some of the waste heat from the reciprocating engine is unrecoverable by ORC system **10**.

[0015] FIG. **2** is a schematic of cascaded ORC system **100** having first ORC system **102** and second ORC system **104**, both of which recover waste heat from reciprocating engine **106**. First ORC system **102** is similar to ORC system **10** of FIG. **1** and includes evaporator **110**, turbine **112**, condenser **114**, and pump **116**. First working fluid **118** is circulated through system **102** and used to drive turbine **112**, which enables generator **120** to produce electrical power. Second ORC system **104** includes turbine **122**, condenser **124**, pump **126**, heat exchanger **128**, and evaporator **114**. Second working fluid **130** is used in second ORC system **104** to drive turbine **122**, which powers generator **132**. Condenser **124** of second ORC system **104** uses heat sink **134** to provide cooling and condense vaporized working fluid **130** from turbine **122**. Heat sink **134** may be water or air, and in some cases, heat sink **134** may be used to provide useful heating to an external source, as discussed further below. First working fluid **118** and second working fluid **130** are organic working fluids, examples of which are provided below.

[0016] Condenser **114** of first ORC system **102** also functions as the evaporator of second ORC system **104**. As described further below, first working fluid **118** is a high temperature working fluid and second working fluid **130** is a low temperature working fluid. As such, evaporator/condenser **114** is configured such that vaporized working fluid **118** from turbine **112** is condensed, thereby transferring heat to vaporize second working fluid **130**.

[0017] Reciprocating engine **106** has two sources of waste heat recoverable by system **100**. The first source is exhaust gas ranging in temperature from approximately 475 to 540 degrees Celsius (approximately 885 to 1005 degrees Fahrenheit). The second source is jacket cooling water with a temperature range of approximately 100 to 110 degrees Celsius (approximately 212 to 230 degrees Fahrenheit). Heat from the exhaust gas is used by first ORC system **102**. More specifically, exhaust gas is used by evaporator **110** to vaporize working fluid **118**.

[0018] Second ORC system **104** receives heat from the jacket cooling water. Heat exchanger **128** of system **104** is located between pump **126** and evaporator **114**, and is designed to transfer heat from the jacket cooling water to liquid working fluid **130**. Because jacket cooling water is a lower temperature waste heat source, as compared to the exhaust gas, the jacket cooling water is used to heat working fluid **130** to a temperature that is less than its vaporization temperature. Thus, working fluid **130** has a higher temperature at an outlet of heat exchanger **128** compared to its temperature at an inlet of heat exchanger **128**. The jacket cooling water may be recycled back to reciprocating engine **106** after exiting heat exchanger **128**.

[0019] After passing through heat exchanger **128**, second working fluid **130** passes through condenser/evaporator **114**, which is designed to transfer heat between first working fluid **118** and second working fluid **130**, such that first working fluid **118** condenses to a liquid and second working fluid **130** is vaporized. First working fluid **118** preferably has a condensation temperature that is suitable to boil second working fluid **130**.

[0020] Second working fluid **130** passes from evaporator **114** to turbine **122**, and then to condenser **124**, which may be a water-cooled condenser or an air-cooled condenser (i.e. heat sink **134** is water or air). In some embodiments, after water in heat sink **134** exits condenser **124**, the heated water may be used to provide heating to a source external to cascaded ORC system **100**. For example, heat sink **134** may be used to heat district heating water and/or provide environmental heating, for example, to agricultural crops or greenhouses.

[0021] Using cascaded ORC system **100**, it is possible to utilize essentially all of the waste heat from reciprocating engine **106**. The high temperature waste heat source (the exhaust gas) is recovered by ORC system **102** which utilizes a high temperature working fluid. The low temperature waste heat source (the jacket cooling water) is recovered by ORC system **104**, which utilizes a low temperature working fluid. Moreover, the design of cascaded ORC system **100** results in greater efficiency overall since the heat from first working fluid **118** exiting turbine **112** may be transferred to second working fluid **130**. An efficiency of second ORC system **104** is increased by preheating second working fluid **130** in heat exchanger **128**. Moreover, the heat utilization efficiency of ORC system **100** may be further increased by using heat sink **134** to heat a source external to cascaded ORC system **100**.

[0022] First working fluid **118** has a higher critical temperature than second working fluid **130**. Because exhaust gas from reciprocating engine **106** is used in evaporator **110** to vaporize first working fluid **118**, working fluid **118** preferably has a high critical temperature such that it is able to boil at a high temperature inside evaporator **110**. Operating with the working fluid in the supercritical phase presents technical challenges that are preferably avoided by remaining below the critical temperature.

[0023] On the other hand, since second ORC system **104** uses lower temperature heat sources (i.e. cooling water and lower-temperature condensation heat of working fluid **118**) to vaporize second working fluid **130**, working fluid **130** preferably has a low critical temperature compared to working fluid **118**. If a working fluid with a high critical temperature were used in second ORC system **104**, the pressures inside system **104** may become too low, resulting in low fluid densities and requiring larger equipment.

[0024] First working fluid **118** may include, but is not limited to, siloxanes, toluene, isobutene, isopentane, n-pentane and 4-trifluoromethy1-1,1,1,3,5,5,5-heptafluoro-2-pentene ($(CF_3)_2CHCF{=}CHCF_3$). Examples of siloxanes that are suitable for first working fluid **118** include, but are not limited to, MM hexamethyldisiloxane ($C_6H_{18}OSi_2$), MDM octamethyltrisiloxane ($C_8H_{24}O_2Si_3$), and MD2M decamethyltetrasiloxane ($C_{10}H_{30}O_3Si_4$). In some embodiments, siloxanes may be preferred over toluene, isobutene, isopentane, and n-pentene, which are flammable.

[0025] Second working fluid **130** may include, but is not limited to, R123, R134a, R236fa and R245fa. In preferred embodiments, R134a or R245fa is used in ORC system **104**. If an ambient air temperature is cooler, thereby reducing a temperature of heat sink **34**, then R134 may be preferred; if the ambient air temperature is warmer, then R245fa may be preferred.

[0026] It is recognized that first working fluid **118** and second working fluid **130** may include organic working fluids not listed above. Numerous combinations of first working fluid **118** and second working fluid **130** may be used. As stated above, cascaded ORC system **100** is preferably operated with first working fluid **118** having a higher critical temperature than second working fluid **130**.

[0027] FIG. **3** is a T-s diagram for cascaded ORC system **100** of FIG. **2**. For both first working fluid **118** and second working fluid **130**, temperature T is plotted as a function of entropy S. As described in more detail below, FIG. **3** illustrates the thermal energy transfer from the exhaust gas of reciprocating engine **106** to first working fluid **118**, and from the jacket cooling water of engine **106** to second working fluid **130**. As also shown in FIG. **3**, first working fluid **118** transfers heat to second working fluid **130**, and second working fluid **130** then transfers heat to heat sink **134**.

[0028] Heat from the exhaust gas of reciprocating engine **106** is transferred to first working fluid **118**, which increases a temperature of working fluid **118** until fluid **118** reaches its vaporization temperature, as shown in FIG. **3**. Fluid **118** remains below the critical temperature $T_{1\ critical}$. As vaporized fluid **118** expands in turbine **112**, its temperature decreases, however fluid **118** remains in the vapor phase. In condenser **114**, which also functions as an evaporator for second ORC system **104**, fluid **118** is desuperheated until it reaches its condensation temperature. The heat from fluid **118** is transferred to second working fluid **130** in condenser/evaporator **114**. The temperature of fluid **130** remains below the critical temperature $T_{2\ critical}$.

[0029] Heat from first working fluid **118** is sufficient to vaporize second working fluid **130** inside condenser/evaporator **114**. This is due, in part, to preheating of second working fluid **130** upstream of condenser/evaporator **114**. As shown in FIG. **3**, jacket cooling water from reciprocating engine **106** is used to increase a temperature of working fluid **130** to a temperature below the vaporization temperature.

[0030] As similarly described for fluid **118**, second working fluid **130** shows a decrease in temperature after passing through turbine **122**. At that point, superheated fluid **130** is condensed inside condenser/heater **124** using ambient air or cooling water from heat sink **134**. In other words, heat from second working fluid **130** is transferred to heat sink **34**, as shown in FIG. **3**. As described above, heat sink **34**, in some embodiments, may be used to provide heating to an external source, such as, for example, a greenhouse.

[0031] In the exemplary embodiment of FIG. **2**, cascaded ORC system **100** uses two waste heat sources from a reciprocating engine. The low temperature heat source is jacket cooling water. It is recognized that other types of positive-displacement engines, in addition to reciprocating engines, that require cooling water during engine operation may also be used to supply waste heat to system **100**. This may include, but is not limited to, rotary engines, such as, for example, the Wankel engine.

[0032] The cascaded ORC system described herein uses two distinct waste heat sources from a reciprocating engine. Since two ORC systems are used, the cascaded ORC system generates additional power. Because there is no change in the emission levels of the reciprocating engine, the cascaded ORC system results in a reduction in emissions from the reciprocating engine per unit of power generated. Moreover, the cascaded ORC system described herein reduces any waste heat from the first and second ORC systems. Thus, the method and system described herein results in improved efficiency of the reciprocating engine and each of the ORC systems.

[0033] Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

1. A method of operating a cascaded organic Rankine cycle (ORC) system, the method comprising:
- vaporizing a first organic working fluid in a first ORC system using a high temperature heat source from a positive-displacement engine;
- heating a second organic working fluid in a second ORC system using a low temperature heat source from the positive-displacement engine; and
- vaporizing the second organic working fluid using heat from the first organic working fluid, wherein the first organic working fluid has a higher critical temperature than the second organic working fluid.

2. The method of claim **1** wherein the positive-displacement engine is a reciprocating engine.

3. The method of claim **1** wherein the high temperature heat source is exhaust gas, and the low temperature heat source is jacket cooling water.

4. The method of claim **1** wherein a temperature of the high temperature heat source is between approximately 475 and 540 degrees Celsius, and a temperature of the low temperature heat source is between approximately 100 and 110 degrees Celsius.

5. The method of claim **1** wherein vaporizing the second organic working fluid is performed by a heat exchanger configured to condense the first organic working fluid and to vaporize the second organic working fluid.

6. The method of claim **1** wherein heating the second organic working fluid in the second ORC system is performed by a heat exchanger configured to extract heat from the low temperature heat source and to preheat the second organic working fluid.

7. The method of claim **1** wherein the first organic working fluid is selected from a group consisting of siloxanes, toluene, isobutene, isopentane, n-pentane and 4-trifluoromethyl-1,1,1,3,5,5,5-heptafluoro-2-pentene ($(CF_3)_2CHCF{=}CHCF_3$).

8. The method of claim **1** wherein the second organic working fluid is selected from a group consisting of R123, R134a, R236fa and R245fa.

9. The method of claim **1** further comprising:
- heating an external source using heat from the second organic working fluid.

10. (canceled)

11. A waste heat recovery system comprising:
- a first organic Rankine cycle (ORC) system configured to vaporize a first organic working fluid using a high temperature waste heat source from a reciprocating engine, and to generate power using the first organic working fluid;

a second organic Rankine cycle (ORC) system configured to receive heat from the first organic working fluid to vaporize a second organic working fluid, and to generate power using the second organic working fluid; and

a heat exchanger configured to increase a temperature of the second organic working fluid using a low temperature waste heat source from the reciprocating engine and prior to vaporizing the second organic working fluid, wherein a critical temperature of the first organic working fluid is greater than a critical temperature of the second organic working fluid.

12. The waste heat recovery system of claim **11** wherein the high temperature waste heat source passes through an evaporator of the first ORC system to vaporize the first organic working fluid.

13. The waste heat recovery system of claim **12** wherein the first organic working fluid passes through a condenser located downstream of the evaporator of the first ORC system to condense the first organic working fluid and vaporize the second organic working fluid.

14. The waste heat recovery system of claim **11** wherein the heat exchanger is located downstream of a condenser of the second ORC system and upstream of an evaporator of the second ORC system.

15. The waste heat recovery system of claim **11** wherein the high temperature waste heat source is exhaust gas from the reciprocating engine, and the low temperature waste heat source is jacket cooling water from the reciprocating engine.

16. (canceled)

17. The waste heat recovery system of claim **11** further comprising:

a heat sink configured to receive heat from the second organic working fluid and to provide heating to an external source.

18. A method of operating a cascaded organic Rankine cycle (ORC) system having a first ORC system configured to circulate a first working fluid and a second ORC system configured to circulate a second working fluid, the method comprising:

vaporizing the first working fluid in an evaporator of the first ORC system using exhaust gas from a reciprocating engine;

heating the second working fluid upstream of an evaporator of the second ORC system using cooling water from the reciprocating engine; and

vaporizing the second working fluid in the evaporator of the second ORC system using heat from the first working fluid of the first ORC system, wherein a critical temperature of the first working fluid is greater than a critical temperature of the second working fluid.

19. The method of claim **18** wherein the evaporator of the second ORC system is configured as a condenser of the first ORC system.

20. The method of claim **18** wherein the first working fluid is selected from a group consisting of siloxanes, toluene, isobutene, isopentane, n-pentane and 4-trifluoromethyl-1,1,1,3,5,5,5-heptafluoro-2-pentene ($(CF_3)_2CHCF{=}CHCF_3$), and the second working fluid is selected from a group consisting of R123, R134a, R236fa and R245fa.

21. The method of claim **18** wherein a temperature of the exhaust gas exiting the reciprocating engine is between approximately 475 and 540 degrees Celsius, and a temperature of the cooling water exiting the reciprocating engine is between approximately 100 and 110 degrees Celsius.

22. The method of claim **18** further comprising:

heating an external source using heat from the second working fluid in the second ORC system.

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