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(54) ENERGY CONVERSION USING RANKINE CYCLE SYSTEM

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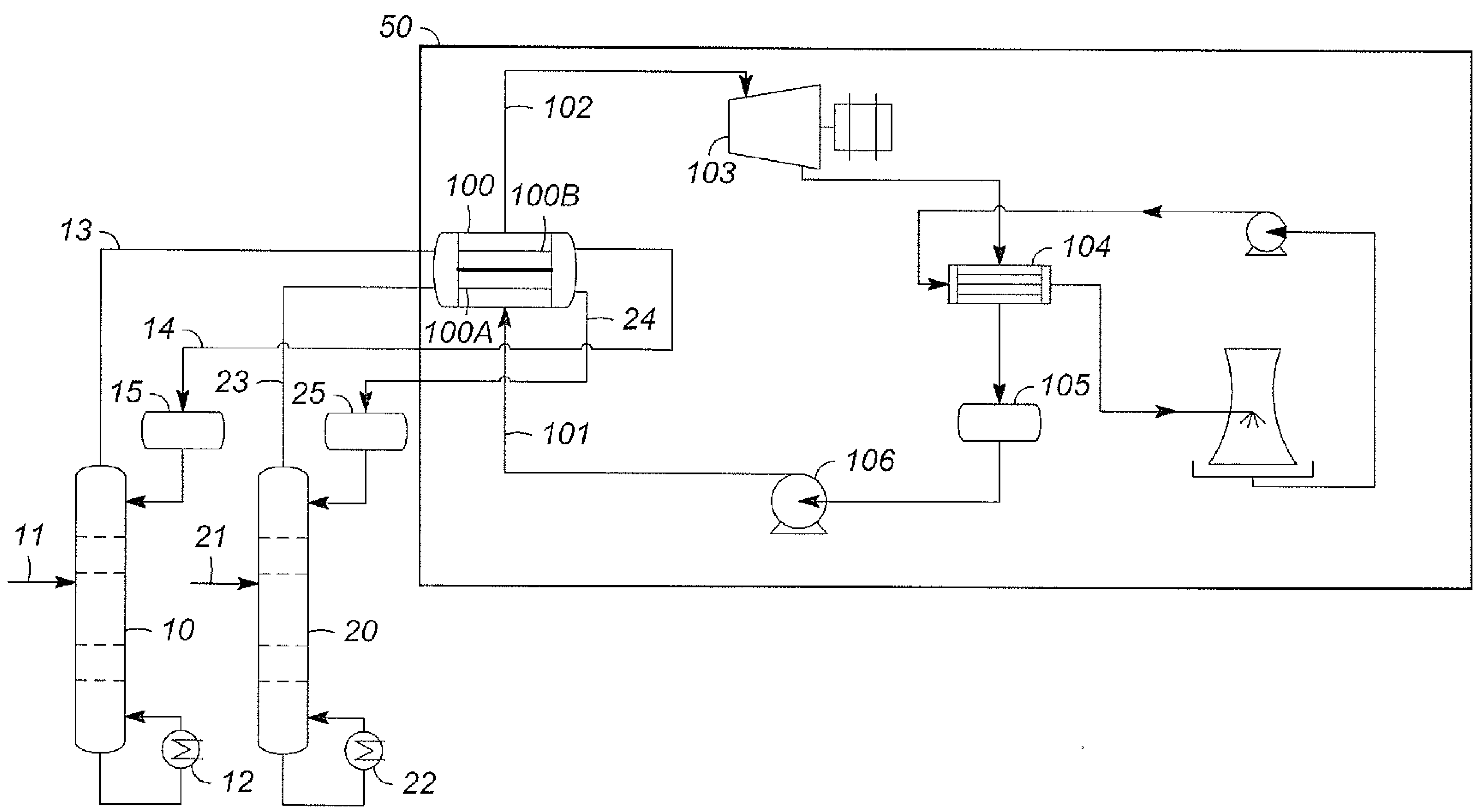
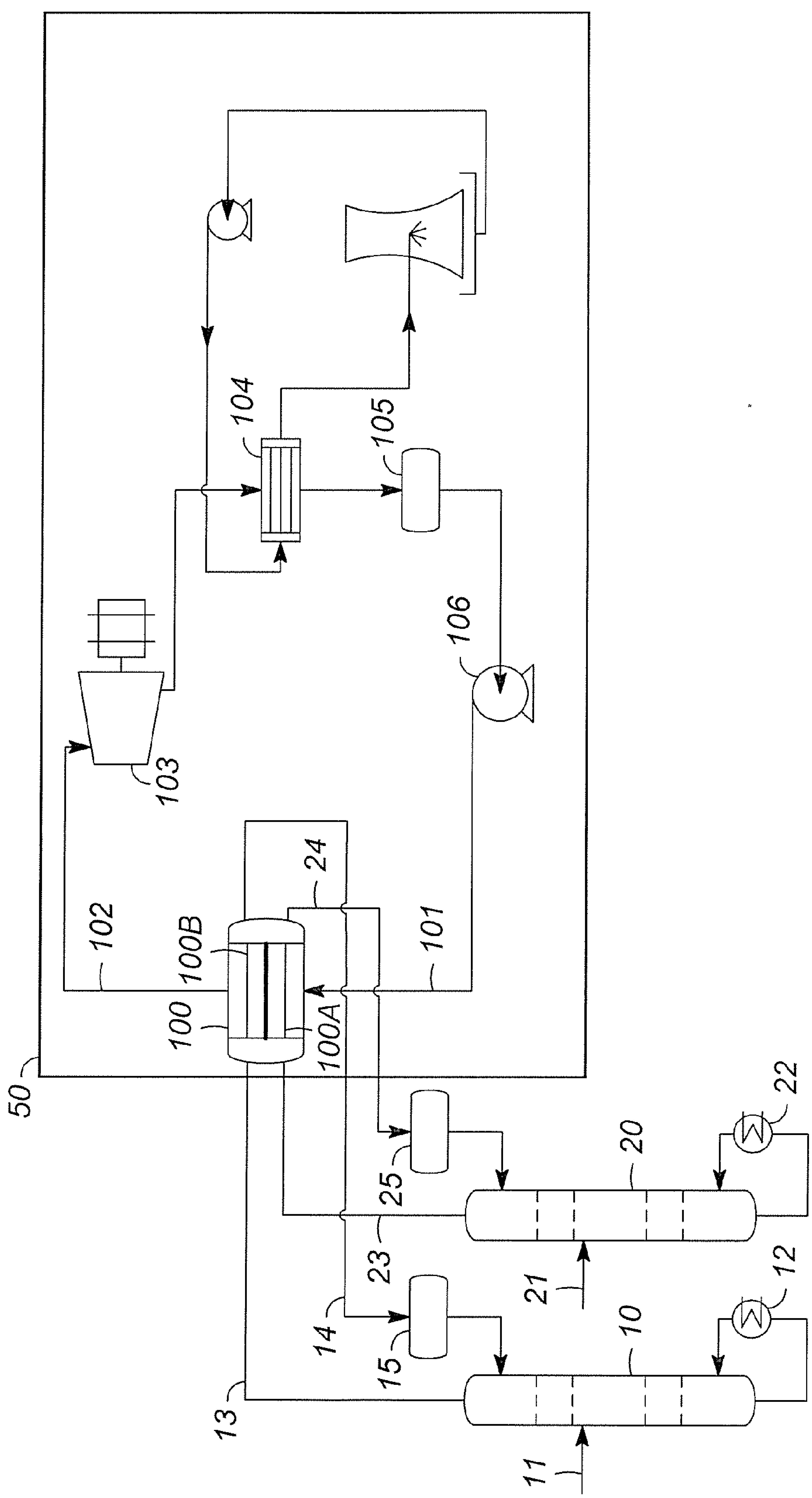
(57) **ABSTRACT**

A process for recovering waste heat in an organic Rankine cycle system which comprises passing a liquid phase working fluid through heat exchange in successive communication with two or more process streams which thus heat the working fluid, removing a vapor phase working fluid from the heat exchanger, passing the vapor phase working fluid to an expander wherein the waste heat is converted into mechanical energy, and passing the vapor phase working fluid from the expander to a condenser wherein the vapor phase working fluid is condensed into the liquid phase working fluid.

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ENERGY CONVERSION USING RANKINE CYCLE SYSTEM

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention generally relates to energy conservation in the cooling or condensing of process streams. Waste heat from process streams may be converted in organic Rankine cycle systems into mechanical energy to generate electric power.

[0003] 2. Discussion of the Background Art

[0004] Rankine cycle systems are known to be a simple and reliable means to convert heat energy into mechanical shaft power. Organic working fluids are useful in place of water/steam when low-grade thermal energy is encountered. Water/steam systems operating with low-grade thermal energy (typically 275° C. and lower) will have associated high volumes and low pressures. Thus, a steam Rankine cycle using low-pressure steam as the working fluid results in a large-sized steam turbine with low power-generation efficiency. To keep system size small and efficiency high, organic working fluids with boiling points near room temperature are employed. Such fluids would have higher gas densities lending to higher capacity and favorable transport and heat transfer properties lending to higher efficiency as compared to water at low operating temperatures. In industrial settings there are more opportunities to use flammable working fluids such as toluene and pentane, particularly when the industrial setting has large quantities of flammables already on site in processes or storage. However, the ideal organic working fluid should be environmentally acceptable, non-flammable, of a low order of toxicity, and operate at positive pressures. Such fluids are disclosed in U.S. Pat. No. 7,428,816 B2, incorporated herein by reference thereto.

[0005] Organic Rankine cycle ("ORC") systems are often used to recover waste heat from industrial processes. These systems are particularly appropriate when the potential thermal output is variable and direct load matching becomes difficult, confounding efficient operation of the combined heat and power system. In such an instance, it is useful to convert the waste heat to shaft power by using an organic Rankine cycle system. The shaft power can be used to operate pumps, for example, or it may be used to generate electricity. By using this approach, the overall process efficiency is higher and fuel utilization is decreased. Air emissions from energy production can be decreased since a higher proportion of demand for electric power is provided by the waste heat.

SUMMARY OF THE INVENTION

[0006] A broad embodiment of the invention is apparatus for generating power from two or more process streams having different temperatures in an organic Rankine cycle system, comprising one or more lower-temperature exchangers for exchanging heat between at least one lower-temperature process stream and a liquid Rankine-cycle working fluid to obtain a heated working fluid; one or more higher-temperature exchangers for exchanging heat between at least one higher-temperature process stream and the heated working fluid to obtain a vaporized working fluid; an expander driven by the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid; a working-fluid condenser for reducing the temperature of the reduced-pressure working fluid to obtain a liquid working fluid; a pump to circulate the liquid working fluid in the cycle system; conduits connecting the one or more lower-temperature exchangers, higher-temperature exchangers, expander, condenser, pump, and working-stream bypasses around one or both of the exchangers; and, a controller for monitoring flow rates, temperatures and pressures of the two or more process streams and working fluid and for providing control signals to the pump and expander.

[0007] A more specific embodiment is an apparatus for generating power from two or more process streams having different temperatures in an organic Rankine cycle system, comprising: a lower-temperature condenser for condensing at least one lower-temperature process stream by heating a liquid Rankine-cycle working fluid to obtain a heated working fluid; a higher-temperature condenser for condensing at least one higher-temperature process stream by heating the heated working fluid to obtain a vaporized working fluid; an expander driven by the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid; a working-fluid condenser for reducing the temperature of the reduced-pressure working fluid to obtain a liquid working fluid; a pump to circulate the liquid working fluid in the cycle system; conduits connecting the lower-temperature condenser, higher-temperature condenser, expander, condenser, pump, and working-stream bypasses around one or both of the condenser; and, a controller for monitoring flow rates, temperatures and pressures of the two or more process streams and working fluid and for providing control signals to the pump and expander.

[0008] An alternative embodiment is a process for generating power from two process streams having different temperatures in an organic Rankine cycle system, comprising cooling a lower-temperature process stream by heating a liquid Rankine-cycle working fluid to obtain a heated working fluid; cooling a higher-temperature process stream by heating the heated working fluid to obtain a vaporized working fluid; expanding the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid; and, condensing the reduced-pressure working fluid to obtain the liquid Rankine-cycle working fluid.

[0009] Additional objects, embodiments and details of this invention can be obtained and inferred from the following detailed description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The FIGURE is a simplified process flow diagram showing heat recovery from two distillation columns using ORC.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0011] To better understand how organic Rankine cycle equipment can be configured to utilize waste heat from distillation columns, a diagram of a basic equipment configuration is provided in the FIGURE. High-temperature column **10** effects separation of two or more components from feed **11** by distillation, employing reboiler **12** to provide heat to the column. Overhead vapor in conduit **13** passes through section **100**B of Rankine cycle exchanger **100** where it is condensed at least partially to liquid and routed via conduit **14** to receiver **15**. In parallel, low-temperature column **20** effects separation of two or more components from feed **21** by distillation, employing reboiler **22** to provide heat to the column. Overhead vapor in conduit **23** passes through section **100**A of Rankine cycle exchanger **100** where it is condensed at least partially to liquid and routed via conduit **24** to receiver **25**. The low-temperature column overhead transfers heat to the Rankine fluid entering the exchanger via conduit **101** before the high-temperature column overhead transfers heat to the Rankine fluid, as this staged transfer is more effective in increasing the temperature of the heated Rankine fluid **102**. The temperature difference between the two process streams leaving the exchanger, **24** and **14**, preferably is at least about 10° C. although this is not intended to limit the invention thereby.

[0012] The Rankine cycle system embodied in box **50** is not limited to condensing vapor streams such as **13** and **23**. Any process streams exchanging heat with Rankine-cycle working fluid in two or more sections of exchanger **100**, such as mixed-phase or liquid streams being cooled, are within the invention. The invention is most effective in condensing services because the temperature ranges are smaller between the inlet and outlet of process streams. Individual exchangers may be applied to the two or more services shown in exchanger **100** rather than sections of the same exchanger, i.e., exchangers **100**A and **100**B may be two separate exchangers in series in the ORC circuit.

[0013] The Rankine cycle system working fluid circulates through the heat-recovery heat exchangers **100** wherein it increases in temperature and converts to vapor. The working fluid vapor is routed via conduit **102** to the expander **103** where the expansion process results in conversion of the heat energy into mechanical shaft power. The shaft power can be used to do any mechanical work by employing conventional arrangements of belts, pulleys, gears, transmissions or similar devices depending on the desired speed and torque required. Importantly, the shaft can be connected to an electric power-generating device such as an induction generator. The electricity produced can be used locally or delivered to the grid. Working fluid that exits the expander continues to the condenser **104** where adequate heat rejection using either water (as shown) or air as a cooling medium causes the fluid to condense to liquid. It is also desirable to have a liquid surge tank **105** located between the condenser and pump to ensure there is always and adequate supply of liquid to the pump suction. The liquid flows to a pump **106** that elevates the pressure of the fluid to that it can be introduced back into the heat recovery heat exchanger thus completing the Rankine cycle loop.

[0014] When the Rankine cycle expander **103** is off-line or during transient conditions, such as start-up and shut-down, heat could be rejected to air or to water in condenser **104** as the working fluid continues to circulate. The energy that would have been recovered in the expander would instead be rejected to the working fluid condenser **104**. The heat exchanger designs can be fin/plate, plate/plate, shell/tube, fin/tube, microchannel, including double-wall or other designs that would be obvious to those skilled in the art.

[0015] Energy recovery according to the present invention, often involving close temperature approaches between process fluids, is improved through the use of exchangers having enhanced nucleate boiling surface. Such enhanced boiling surface can be effected in a variety of ways as described, for example, in U.S. Pat. No. 3,384,154; U.S. Pat. No. 3,821,018; U.S. Pat. No. 4,064,914; U.S. Pat. No. 4,060,125; U.S. Pat. No. 3,906,604; U.S. Pat. No. 4,216,826; U.S. Pat. No. 3,454,081; U.S. Pat. No. 4,769,511 and U.S. Pat. No. 5,091,075; all of which are incorporated herein by reference. Such enhanced tubing is particularly suitable for the exchange of heat to column reboilers and for rejecting heat from column condensers to other reboilers or to steam generators.

[0016] Typically, these enhanced nucleate boiling surfaces are incorporated on the tubes of a shell-and-tube type heat exchanger. These enhanced tubes are made in a variety of different ways which are well known to those skilled in the art. For example, such tubes may comprise annular or spiral cavities extending along the tube surface made by mechanical working of the tube. Alternately, fins may be provided on the surface. In addition the tubes may be scored to provide ribs, grooves, a porous layer and the like.

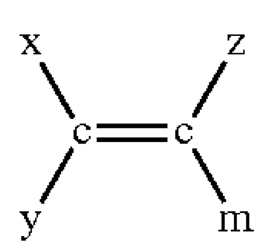
[0017] Generally, the more efficient enhanced tubes are those having a porous layer on the boiling side of the tube. The porous layer can be provided in a number of different ways well known to those skilled in the art. The most efficient of these porous surfaces have what are termed reentrant cavities that trap vapors in cavities of the layer through restricted cavity openings. In one such method, as described in U.S. Pat. No. 4,064,914, the porous boiling layer is bonded to one side of a thermically conductive wall. An essential characteristic of the porous surface layer is the interconnected pores of capillary size, some of which communicate with the outer surface. Liquid to be boiled enters the subsurface cavities through the outer pores and subsurface interconnecting pores, and is heated by the metal forming the walls of the cavities. At least part of the liquid is vaporized within the cavity and resulting bubbles grow against the cavity walls. A part thereof eventually emerges from the cavity through the outer pores and then rises through the liquid film over the porous layer for disengagement into the gas space over the liquid film. Additional liquid flows into the cavity from the interconnecting pores and the mechanism is continuously repeated. Such enhanced tubes containing a porous boiling layer are commercially available under the trade name High Flux Tubing made by UOP, Des Plaines, Ill. To achieve minimum temperature differences across exchanger **100** and thus improve the efficiency of the Rankine cycle, enhanced nucleate boiling surfaces are preferred within the present invention for vaporizing the working fluid in exchanger **100**.

[0018] Enhanced condensing surfaces are also useful for practical heat exchanger designs with small temperature approaches. Enhanced condensing surfaces are preferred within the present invention for either the overhead condensers in **100** or for the working fluid condenser in **105**.

[0019] The apparatus comprises a controller for monitoring flow rates, temperatures and pressures of the two or more process streams and working fluid and for providing control signals to the pump and expander. An electronic controller as known to the skilled routineer is linked to the numerous components of an energy-conversion system to monitor and/or control the operation of the component typically based on set points or operating points in memory or electronically set within the controller. The electronic controller is linked inter alia to the expander, condenser, pump, and working-stream bypasses around one or both of the condensers. Of course, the electronic controller can be implemented using multiple controllers with the important concept being maintenance relatively steady operations even in periods of varying input fluid temperatures or the variance of other operating parameters.

[0020] Organic compounds often have an upper temperature limit above which thermal decomposition will occur. The onset of thermal decomposition relates to the particular structure of the chemical and thus varies for different compounds. In order to access a high-temperature source using direct heat exchange with the working fluid, design considerations for heat flux and mass flow, as mentioned above, can be employed to facilitate heat exchange while maintaining the working fluid below its thermal decomposition onset temperature. Direct heat exchange in such a situation typically requires additional engineering and mechanical features which drive up cost. In such situations, a secondary loop design may facilitate access to the high-temperature heat source by managing temperatures while circumventing the concerns enumerated for the direct heat exchange case. This approach also can provide more freedom to retrofit to future improved working fluids in the Rankine cycle system without having to disturb or alter the process heat rejection package. A cost-risk/benefit analysis is often conducted in order to determine the best approach (direct or indirect heat exchange) for a particular application.

[0021] Fluid selection depends on a variety of factors including temperature match, thermodynamic properties, heat transfer properties, cost, safety concerns, environmental acceptability, and availability. Working fluids that are suitable include water, silicones, aliphatic hydrocarbons, cyclic hydrocarbons, aromatic hydrocarbons, olefins, hydrofluorocarbons (including alkanes and alkenes, cyclic compounds), hydrofluoroethers, perfluoroethers, alcohols, ketones, fluorinated ketones, fluorinated alcohols, esters, phosphate esters. Other fluids that are suitable are described in U.S. Pat. No. 7,428,816 B2 which is incorporated herein by reference. In addition to the fluids mentioned above for use in the processes of this invention, a number of preferred fluids have been identified that are useful in the processes of this invention. Included among the fluids that are useful in the process of the invention are the preferred compounds of the structure.



where x, y, z, and m are each selected from the group consisting of: fluorine, hydrogen, R_f, and R, wherein R and R_f are each an alkyl, aryl, or alkylaryl of 1 to 6 carbon atoms, and wherein R_f is partially or fully fluorinated. Also among the preferred are saturated compounds derived by reacting the aforementioned compounds with HF and those compounds derived by reduction with hydrogen.

[0022] Most preferred are compounds of the formula CxFyHz where x=12−b where b is from 0 to 6, y=2x−z, and for x/2 and 2x/3=integers then z=2x/3; for x/2 and 3x/4=integers then z=3x/4; for x/2.noteq.integer then z=x−2; for x/2 and x/5=integers then z=x−3. Also most preferred are the saturated compounds derived by reacting HF with the aforementioned compounds and those compounds derived by reduction with hydrogen. Genetron 245fa (HFC-245fa) is a particularly favored working fluid.

Example

[0023] The following example illustrates the benefits of the invention using ORC in an aromatics complex producing 900,000 tons/year of para-xylene. Aspects of the aromatics complex are described in U.S. Pat. No. 6,740,788 which is incorporated herein by reference. Columns **10** and **20** as described in the FIGURE of the present application are, respectively, distillation columns in an adsorption separation unit separating C_8-aromatics raffinate from desorbent and para-xylene-rich extract from desorbent. The raffinate column is, relatively, the high-temperature column and the extract column is the low-temperature column. To compare ORC to air cooling and water cooling, the heat duties are as follows:

	Heat Rejected (MW)	T-in (° C.)	T-out (° C.)
Extract Column Overhead	34.0	151.1	128.9
Raffinate Column Overhead	90.6	152.6	140.8
Total	124.6	—	—

[0024] The net power benefit of using ORC relative to air and water condenser cases is calculated using the following equations:

[0025] For Water Cooling:

[0026] Net Power Benefit (MW)=Turbine Power Generation (MW)−Pump Power (MW)−Cooling Water Pump Power (MW)−Cooling Tower Fan Power (MW)+Base Case Air Cooler Fan Power (MW)

[0027] For Air Cooling:

[0028] Net Power Benefit (MW)=Turbine Power Generation (MW)−Pump Power (MW)−Air Cooler Fan Power (MW)+Base Case Air Cooler Fan Power (MW)

	Water Condenser	Air Condenser
Net power benefit (MW)	13.2	12.4
	Annual Benefits ($MM/year)	
Cases	Water Condenser	Air Condenser
Power = $0.07/kWh No CO_2 credits	$7.4 MM	$6.9 MM
Power = $0.10/kWh No CO_2 credits	$10.6 MM	$9.9 MM
Power = $0.07/kWh 30$/MT CO_2 credits	$9.1 MM	$8.4 MM
Power = $0.10/kWh $30/MT CO_2 credits	$12.3 MM	$11.3 MM

Assumptions for Power Generation Calculations	
Turbine/generator efficiency	0.80/0.95
Cooling tower fans	7 kW/1000 gpm
Cooling water pump ΔP	50 psi
Fuel equivalent of power	9,090 Btu/kWh
CO_2 emissions	56.2 kg/GJ

1. An apparatus for generating power from two or more process streams having different temperatures in an organic Rankine cycle system, comprising:

(a) one or more lower-temperature exchangers for exchanging heat between at least one lower-temperature process stream and a liquid Rankine-cycle working fluid to obtain a heated working fluid;

(b) one or more higher-temperature exchangers for exchanging heat between at least one higher-temperature process stream and the heated working fluid to obtain a vaporized working fluid;

(c) an expander driven by the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid;

(d) a working-fluid condenser for reducing the temperature of the reduced-pressure working fluid to obtain a liquid working fluid;

(e) a pump to circulate the liquid working fluid in the cycle system;

(f) conduits connecting the one or more lower-temperature exchangers, higher-temperature exchangers, expander, condenser, pump, and working-stream bypasses around one or both of the exchangers; and,

(g) a controller for monitoring flow rates, temperatures and pressures of the two or more process streams and working fluid and for providing control signals to the pump and expander.

2. The apparatus of claim **1** further comprising a generator to produce electric power connected to the output shaft of the expander.

3. The apparatus of claim **1** wherein one or more of the lower-temperature and higher-temperature exchangers are condensers for condensing at least part of the respective process streams from vapor phase into liquid phase.

4. The apparatus of claim **3** wherein one or more of the condensers are overhead condensers of distillation columns.

5. The apparatus of claim **1** wherein one or more of the lower-temperature and higher-temperature exchangers is a reactor effluent cooler.

6. The apparatus of claim **1** wherein at least one of the lower-temperature exchangers is a product cooler.

7. The apparatus of claim **1** wherein one or more of the exchangers has an enhanced nucleate boiling surface.

8. The apparatus of claim **1** wherein one or more of the condensers has an enhanced condensing surface.

9. The apparatus of claim **1** wherein the working fluid comprises R-245a.

10. The apparatus of claim **1** comprising two or more low-temperature exchangers, each for exchanging heat between at least one lower-temperature process stream and a liquid Rankine-cycle working fluid to obtain a heated working fluid;

11. An apparatus for generating power from two or more process streams having different temperatures in an organic Rankine cycle system, comprising:

(a) a lower-temperature condenser for condensing at least one lower-temperature process stream by heating a liquid Rankine-cycle working fluid to obtain a heated working fluid;

(b) a higher-temperature condenser for condensing at least one higher-temperature process stream by heating the heated working fluid to obtain a vaporized working fluid;

(c) an expander driven by the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid;

(d) a working-fluid condenser for reducing the temperature of the reduced-pressure working fluid to obtain a liquid working fluid;

(e) a pump to circulate the liquid working fluid in the cycle system;

(f) conduits connecting the lower-temperature condenser, higher-temperature condenser, expander, condenser, pump, and working-stream bypasses around one or both of the condenser; and,

(g) a controller for monitoring flow rates, temperatures and pressures of the two or more process streams and working fluid and for providing control signals to the pump and expander.

12. The apparatus of claim **11** wherein one or more of the lower-temperature and higher-temperature exchangers are condensers for condensing at least part of the respective process streams from vapor phase into liquid phase.

13. The apparatus of claim **12** wherein one or more of the condensers are overhead condensers of distillation columns.

14. The apparatus of claim **11** further comprising a generator to produce electric power connected to the output shaft of the expander.

15. The apparatus of claim **11** wherein one or more of the exchangers has an enhanced nucleate boiling surface.

16. The apparatus of claim **11** wherein the working fluid comprises R-245a.

17. A process for generating power from two process streams having different temperatures in an organic Rankine cycle system, comprising:

(a) cooling a lower-temperature process stream by heating a liquid Rankine-cycle working fluid to obtain a heated working fluid;

(b) cooling a higher-temperature process stream by heating the heated working fluid to obtain a vaporized working fluid;

(c) expanding the vaporized working fluid to produce power to an output shaft and a reduced-pressure working fluid; and,

(d) condensing the reduced-pressure working fluid to obtain the liquid Rankine-cycle working fluid.

18. The process of claim **17** further comprising generating power via a generator connected to the output shaft of the expander.

19. The process of claim **17** wherein one or more of the process streams comprise overhead vapors of distillation columns and are condensed at least partially to liquid streams.

20. The process of claim **17** wherein the working fluid comprises R-245a.

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