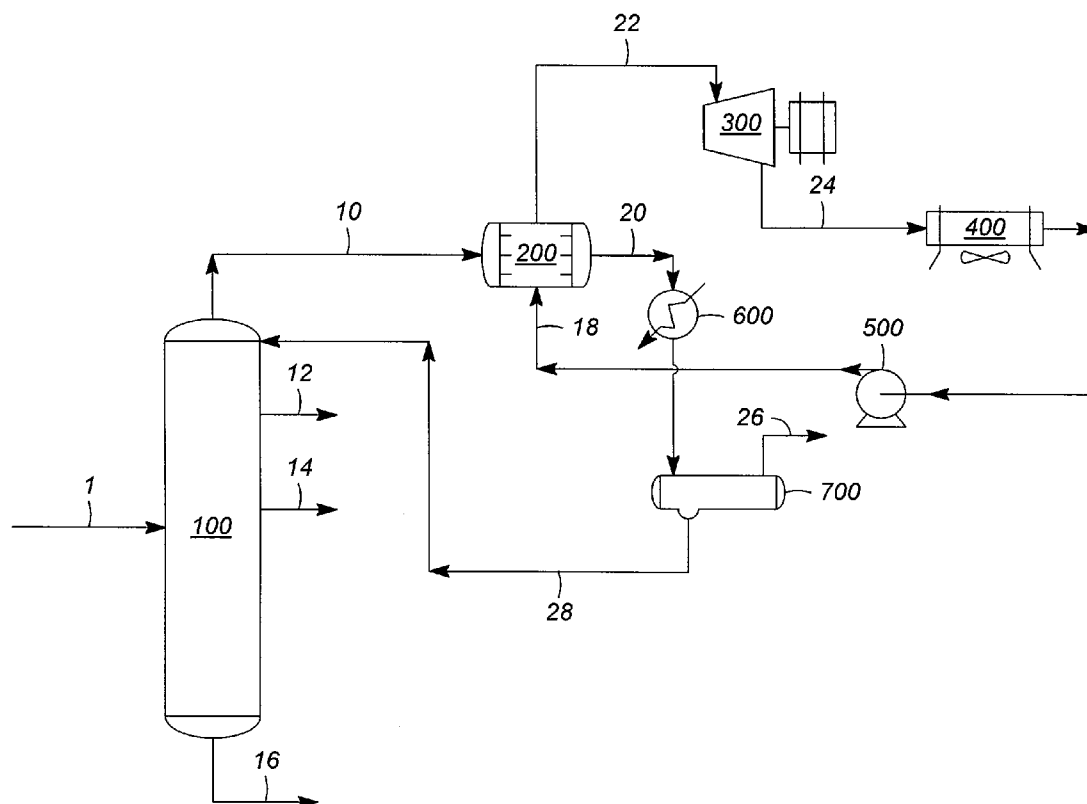




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ULAS ACIKGOZ et al.(10) **Pub. No.: US 2012/0031096 A1**(43) **Pub. Date: Feb. 9, 2012**(54) **LOW GRADE HEAT RECOVERY FROM
PROCESS STREAMS FOR POWER
GENERATION****Publication Classification**(51) **Int. Cl.**
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F01K 9/00 (2006.01)
(52) **U.S. Cl.** **60/651; 60/692; 60/671**(57) **ABSTRACT**

Methods are described for generating electrical power from low grade heat sources from refining and petrochemical processes, including overhead vapors from vapor-liquid contacting apparatuses such as distillation columns, absorbers, strippers, quenching towers, scrubbers, etc. In many cases, these overhead vapors exit the apparatuses at a temperature from about 90° C. (194° F.) to about 175° C. (347° F.). Rather than rejecting the low temperature heat contained in these vapors to cooling air and/or cooling water, the vapors may instead be used to evaporate an organic working fluid. The vapors of the working fluid may then be sent to a turbine to drive a generator or other load.

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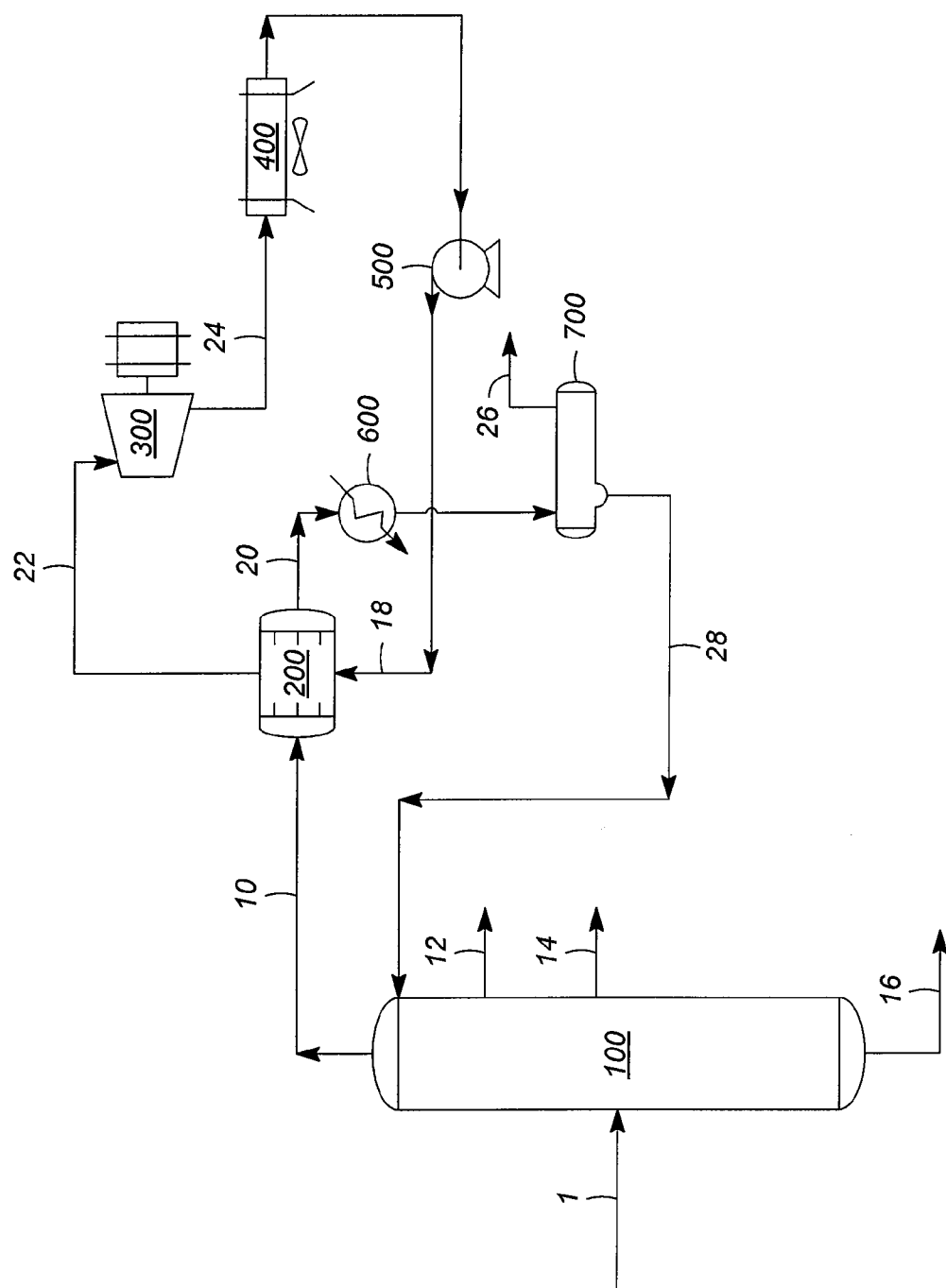
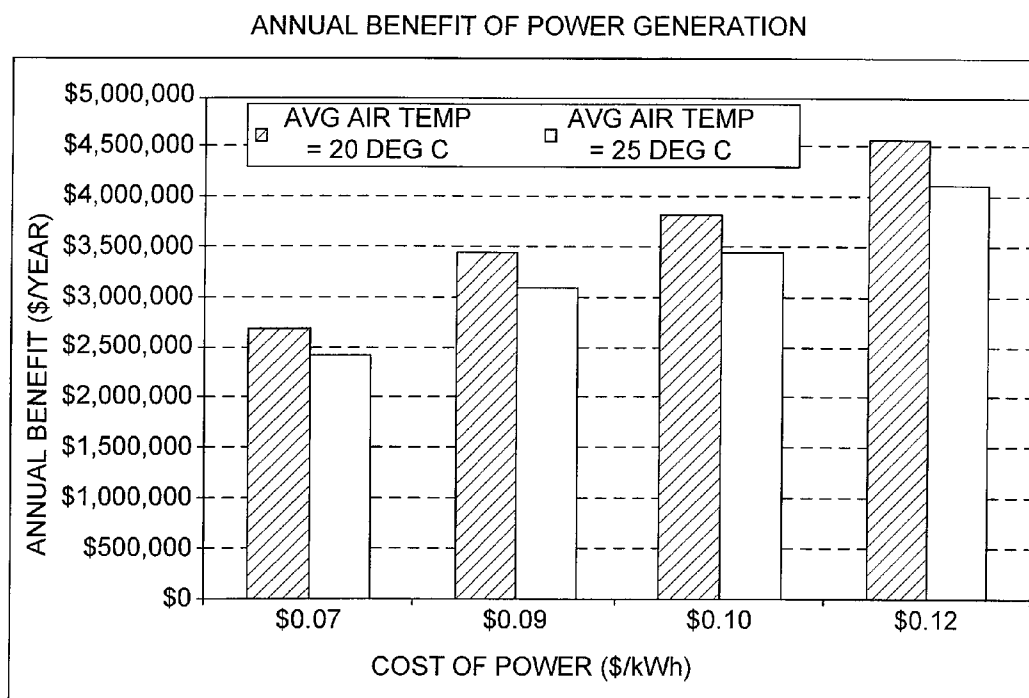
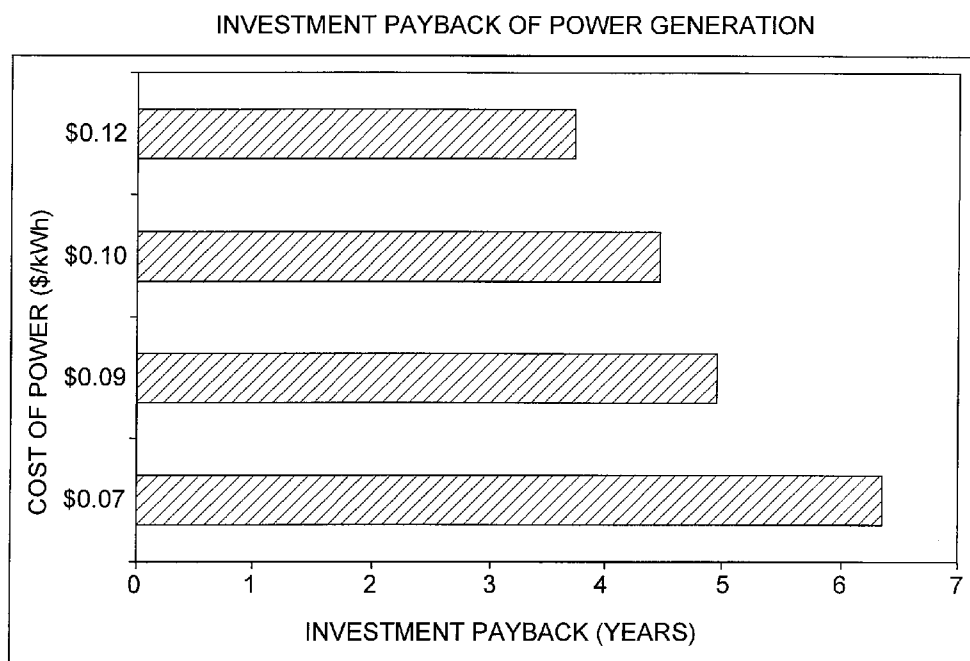


FIG. 1

**FIG. 2**

**FIG. 3**

LOW GRADE HEAT RECOVERY FROM PROCESS STREAMS FOR POWER GENERATION

FIELD OF THE INVENTION

[0001] The invention relates to apparatuses and methods for generating power from low grade heat sources including refinery and petrochemical process streams. A representative stream is an overhead vapor from a distillation column, such as a product fractionation column of a hydrocracking process.

DESCRIPTION OF RELATED ART

[0002] Sources of low grade heat are prevalent in refining, petrochemical, and other industrial applications. For example, low grade heat is estimated to account for 20-30% of the overall energy in a refinery. Low grade heat is normally considered waste heat and treated accordingly. This is due to the relatively low (although often well above ambient) temperatures of low grade heat sources that render them unsuitable for feed preheating, generation of pressurized steam, distillation column reboiling, and generally any other practical use involving heat exchange. As a result, the heat content of such low grade heat sources, though significant, is rejected, for example to the atmosphere using air cooling.

[0003] Low grade heat often results, for example, from the generation of overhead vapors in vapor-liquid contacting apparatuses such as distillation columns, in which upwardly moving vapor and downwardly moving liquid fractions contact each other for heat and mass exchange, with the contacting normally aided by the use of vapor-liquid contacting devices such as trays or packing materials. Often, a single feed (e.g., containing predominantly hydrocarbons) enters the distillation column and an overhead vapor, enriched in one or more components of relatively higher volatility, as well as a liquid bottoms, enriched in one or more components of relatively lower volatility, exit the distillation column. Distillation can also involve the use of two or more feeds that enter a distillation column at differing axial heights, corresponding to different contacting stages of the column. Whether a single feed or multiple feeds are used, in many cases other product fractions may be desired, in addition to the overhead vapor and liquid bottoms, with each product fraction containing components (e.g., hydrocarbons) having boiling points within different ranges. In addition to distillation columns, examples of vapor-liquid contacting apparatuses include columns used for the contacting of, and exchange of components between, at least two streams fed to the column, for example liquid and vapor streams that are fed in a countercurrent manner. Absorption, quenching, scrubbing, stripping, etc. are representative of operations that occur in such columns.

[0004] Generally, overhead product such as overhead vapors from distillation columns or other types of vapor-liquid contacting apparatuses are cooled by indirect heat exchange with air (e.g., using an air cooled exchanger) and/or cooling water (e.g., using a trim condenser), since the residual heat in the overhead streams is not considered of sufficient value for recovery of energy in an economical manner.

[0005] A Rankine cycle is useful for generating power from a low or medium temperature heat source. A working fluid is evaporated, for example in an evaporator or boiler, upon exchanging heat with the source, and the vaporized fluid is then used in a turbine that drives an electrical generator or other load. Exhaust vapors from the turbine are condensed,

and the resulting fluid may be recycled for heat exchange. An Organic Rankine Cycle (ORC) uses an organic fluid as a working fluid. Known applications of ORC systems include generating power from geothermal heat sources, as described in U.S. Pat. No. 5,497,624 and U.S. Pat. No. 6,539,718. The use of an ORC in combination with fuel cell products and other forms of waste heat is described in US 2006/0010872, WO 2006/104490, and WO 2006/014609. Applications of an ORC involving solar energy and biomass are described in CN11055121, JP2003227315A2, INTERNATIONAL JOURNAL OF ENERGY RESEARCH, 28(11): 1003-1021 (2004), and ENERGY, 32(4): 371-377 (2007). The use of an ORC is also taught in U.S. Pat. No. 7,049,465, for improving energy recovery from exothermic reactions and particularly the liquid phase oxidation of paraxylene to terephthalic acid.

[0006] There is an ongoing need in the art for methods for recovering energy such as electricity from sources providing low grade heat that is otherwise wasted, especially those sources resulting from refinery and petrochemical plant operations. This need is particularly significant in view of the large quantities of low grade heat generated in these operations and the high energy and cost savings potentially realized from recovering even a fraction of this heat. The net generation of electricity is of significant benefit to refiners and petrochemical producers, due to reduced emissions of the combustion product CO₂ from materials (e.g., coal) used as a raw material in power plants.

SUMMARY OF THE INVENTION

[0007] Aspects of the present invention are associated with the discovery of methods for generating electrical power from low grade heat sources from refining and petrochemical processes, including overhead products such as vapors from vapor-liquid contacting apparatuses. These apparatuses include distillation columns, absorbers, strippers, quenching towers, scrubbers, etc., from which the overhead product exits, in many cases, at a temperature from about 90° C. (194° F.) to about 150° C. (302° F.). Rather than rejecting the low temperature heat contained in these overhead products to cooling air and/or cooling water, the products may instead be used, in an evaporator, to evaporate an organic working fluid. The vapors of the working fluid may then be sent to a turbine to drive a generator or other load. Exhaust vapors from the turbine may be condensed and recycled via a pump to the evaporator. The power generated using such an Organic Rankine Cycle (ORC) can be used within the process to supply at least a portion of its power requirement (e.g., to operate pumps and/or compressors) or otherwise sent to a central power station.

[0008] The methods described herein are therefore suitable for power recovery from overhead products, and especially overhead vapors, generated in vapor-liquid contacting operations and particularly those associated with oil refining and petrochemical production. The temperature of the overhead product, although characteristic of a low grade heat source, is nevertheless sufficient to vaporize the organic working fluid used in the ORC. Suitable working fluids therefore include non-flammable, low toxicity chemical compounds having a boiling point that is typically from about 5° C. to about 14° C. (about 10° F. to about 25° F.) lower than the temperature of an overhead product used in a particular ORC application.

[0009] Also, if two or more sources of low grade heat are available (e.g., from different vapor-liquid contacting apparatuses, from heat exchangers operating in series or in paral-

lel, or from other processing equipment), their low grade heat may be consolidated by transfer to a common, intermediate heat transfer medium (e.g., water). The intermediate heat transfer medium may then be used to evaporate the working fluid of the ORC to generate power, for example, from a single turbine. In this manner of consolidating sources of low grade heat, the ORC can be sized to realize greater efficiencies and economies of scale. Moreover, such a consolidated operation improves flexibility in design and plot space planning, since the requirement for close proximity of the turbine to the low grade heat source(s) is relaxed.

[0010] Embodiments of the invention are therefore directed to methods for generating electrical power from a low grade heat source (e.g., a refining or petrochemical process stream having a temperature from about 90° C. (194° F.) to about 175° C. (347° F.)). Representative methods comprise passing a hydrocarbon containing feed (e.g., comprising at least a portion of a refining process reactor effluent) to a vapor-liquid contacting apparatus, such as a distillation column, to provide an overhead product (e.g., an overhead vapor), as well as a bottoms liquid. The methods also comprise indirectly exchanging heat between the overhead product and an organic fluid (e.g., a working fluid as described above) to provide a cooled and/or condensed overhead product and a vapor-enriched fluid, as a result of the indirect heat exchange. The methods further comprise passing the vapor-enriched fluid to a turbine to generate electricity. In order to complete the ORC, methods described herein may further comprise condensing (e.g., using an air cooled exchanger) the vapor-enriched fluid to regenerate the organic fluid and then pumping this fluid to an evaporator for re-use in indirect heat exchange with the overhead product.

[0011] According to other embodiments for generating electrical power from a low grade heat source, liquid and vapor feeds (i.e., feeds that are predominantly in the liquid and vapor phases, respectively) are passed to respective upper and lower sections of a vapor-liquid contacting apparatus to provide an overhead product (e.g., overhead vapor) and a bottoms liquid, having compositions that differ from those of the vapor and liquid feeds, respectively, as a result of contacting. The methods further comprise indirectly exchanging heat between the overhead product and an organic fluid to provide a cooled or condensed overhead product and a vapor-enriched fluid, and passing the vapor-enriched fluid to a turbine to generate electricity.

[0012] In any of the methods described herein, a net benefit of electricity generated from passing the vapor-enriched fluid to the turbine is generally from about 0.005 to about 0.05, and often from about 0.01 to about 0.03, watts per BTU/hr of waste heat in the low grade heat source (e.g., an overhead vapor of a vapor-liquid contacting apparatus). The latter range corresponds to a cycle efficiency of the ORC from about 3% to about 10%.

[0013] Further embodiments of the invention are directed to apparatuses for generating electrical power from at least one low grade heat source. Representative apparatuses comprise an evaporator for indirectly exchanging heat between the low grade heat source and an organic fluid; a turbine in communication with a vapor-enriched fluid conduit from the evaporator; and a condenser in communication with an exhaust conduit from the turbine. According to more specific embodiments, the evaporator and/or condenser may be tubular heat exchangers. To improve the heat transfer coefficient

and reduce exchanger area, the external surfaces of the tubes may have surface enhancements such as fins and/or recessions.

[0014] These and other aspects and embodiments associated with the present invention are apparent from the following Detailed Description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 depicts a representative refining process in which an upgraded hydrocarbon product, such as a product obtained from a hydrocracking reaction zone, is passed to a distillation column to provide an overhead product as a low grade heat source, from which electricity is generated.

[0016] FIG. 1 is not necessarily drawn to scale and should be understood to present an illustration of the invention and/or principles involved. Some features depicted have been enlarged or distorted relative to others, in order to facilitate explanation and understanding. As is readily apparent to one of skill in the art having knowledge of the present disclosure, methods for generating electrical power from low grade heat sources, according to various other embodiments of the invention, will have configurations and components determined, in part, by their specific use.

[0017] FIG. 2 is a bar graph illustrating the estimated annual benefit of generating electricity, using an Organic Rankine Cycle (ORC), from low grade heat that is normally rejected from a main fractionation column overhead product of a commercial hydrocracking process. Estimates are shown at varying electrical power costs and using two average air inlet temperatures to the condenser, namely 20° C. (68° F.) and 25° C. (77° F.).

[0018] FIG. 3 is a bar graph illustrating the investment payback, at varying electrical power costs, associated with generating electricity from the overhead product as described with respect to FIG. 2

DETAILED DESCRIPTION

[0019] The invention is associated with methods for generating electrical power from sources of low grade heat, particularly refining and petrochemical process streams, through the use of an Organic Rankine Cycle (ORC). Sources of low grade heat can include any process stream from which recovery of at least part of its heat content in the form of electricity is desired. These streams are often conventionally subjected to cooling with air and/or water, since they are not at a sufficiently high temperature for economically useful heat integration applications (e.g., preheating, medium- or high-pressure steam generation, or distillation column reboiling). The temperature of these sources of low grade heat is generally from about 75° C. (167° F.) to about 180° C. (356° F.) and often from about 90° C. (194° F.) to about 175° C. (347° F.). Representative streams as sources of low grade heat include refining and petrochemical process streams having temperatures within these ranges, with particular examples being overhead vapors, and more generally overhead products, from vapor-liquid contacting apparatuses such as distillation columns and other columns (e.g., absorbers, strippers, quenching towers, scrubbers, etc) as described above.

[0020] Distillation columns refer to those used in separation processes based on differences in the relative volatility of components present in an impure mixture. Distillation involves the purification of components having differing relative volatilities by achieving multiple theoretical stages of

vapor-liquid equilibrium along the length of a vertical column. Rising vapor, enriched in a lower boiling component relative to the liquid from which it is vaporized in a lower stage in the column, is contacted with falling liquid, enriched in a higher boiling component relative to the vapor from which it is condensed in a higher stage in the column.

[0021] Distillation columns, which also include fractionation columns that provide number of product fractions, each having components within certain boiling point ranges, are widely used, for example, in separating effluents of reaction zones. Reaction zones generally comprise one or more reactors that are used to convert (e.g., catalytically) a feedstock to the more valuable reactor effluent, containing the product fractions that are subsequently resolved through fractionation. In refining, representative hydrocarbon conversions occurring in catalytic reaction zones include hydrocracking, fluid catalytic cracking (FCC), catalytic reforming, isomerization, dehydrogenation, alkylation, disproportionation, and others. Hydrocarbon-containing feeds to vapor-liquid contacting apparatuses such as distillation columns therefore include reactor effluents or otherwise upgraded hydrocarbon products comprising at least a portion of a reactor effluent, optionally after initial treatments or separations (e.g., in single stage high-, medium-, and/or low-pressure separators to remove hydrogen and/or light hydrocarbons such as methane). These hydrocarbon-containing feeds generally comprise at least about 80% by weight, and often comprise at least about 90% by weight, hydrocarbons.

[0022] In the case of a catalytic hydrocracking process, for example, the feedstock to the reaction zone is generally a distillate hydrocarbon, namely a distillable petroleum derived fraction having a boiling point range which is above that of naphtha. Suitable distillate feedstocks that may be obtained from refinery fractionation and conversion operations include middle distillate hydrocarbon streams, such as highly aromatic hydrocarbon streams. Distillate feedstocks include distillate hydrocarbons boiling at a temperature greater than about 149° C. (300° F.), typically boiling in the range from about 149° C. (300° F.) to about 399° C. (750° F.), and often boiling in the range from about 204° C. (400° F.) to about 371° C. (700° F.).

[0023] Representative distillate feedstocks to hydrocracking processes can therefore include various hydrocarbon mixtures, such as straight-run fractions, or blends of fractions, recovered by fractional distillation of crude petroleum. Such fractions produced in refineries include coker gas oil and other coker distillates, straight run gas oil, deasphalted gas oil, and vacuum gas oil. These fractions or blends of fractions can be a mixture of hydrocarbons boiling in range from about 343° C. (650° F.) about 566° C. (1050° F.), with boiling end points in other embodiments being below about 538° C. (1000° F.) and below about 482° C. (900° F.). Thus, distillate feedstocks are often recovered from crude oil fractionation or distillation operations, and optionally following one or more hydrocarbon conversion reactions. However, distillate feedstocks may be utilized from any convenient source such as tar sand extract (bitumen) and gas to liquids conversion products, as well as synthetic hydrocarbon mixtures such as recovered from shale oil or coal. Suitable conditions and catalysts for hydrocracking distillate feedstocks are described, for example, in co-pending U.S. application Ser. No. 12/268,048, hereby incorporated by reference with respect to its description of hydrocracking feedstocks, process conditions, and catalysts.

[0024] The effluent from the hydrocracking reaction zone, usually configured with one or more hydrocracking reactors in series, has a higher value relative to the distillate feedstock, due to the overall decrease in the average molecular weight of the products of hydrocracking. For example, the effluent often comprises a significant proportion of hydrocarbons suitable for blending into either gasoline or diesel fuel. Fractionation of the hydrocracking reaction zone effluent, or at least a portion of this effluent such as an upgraded hydrocarbon product obtained after separation of hydrogen for recycle and possibly after other stages of light ends or heavy ends removal, therefore desirably yields naphtha and diesel product fractions. These product fractions are typically obtained from a main fractionation section or main fractionation column used to distill a large proportion of the hydrocracking zone reactor effluent.

[0025] The overhead product of this fractionation column generally comprises C₄ (e.g., butane and butenes) and lighter hydrocarbons (e.g., propane, propylene, ethane, and ethylene) and can also contain H₂S and NH₃, which are the hydrogenation reaction products of sulfur- and nitrogen-containing components in the feedstock to the hydrocracking reaction zone. Generally, this overhead product is removed from the column completely or substantially in the vapor phase, at a temperature from about 90° C. (194° F.) to about 150° C. (302° F.), prior to being cooled via indirect heat exchange with an air (e.g., using an air cooled exchanger) and/or a water (e.g., using a trim condenser). This overhead product of the main fractionation column of the hydrocracking process therefore serves as a favorable low grade heat source for electricity generation according to methods described herein.

[0026] Other product fractions may similarly be used for electricity generation, although these are typically removed from the main fractionation column of a hydrocracking process at higher temperatures that are more suitable for conventional heat integration in a refinery. Product fractions typically recovered from this column of a hydrocracking process include light naphtha having a distillation end point temperature of about 149° C. (300° F.) (e.g., from about 138° C. (280° F.) to about 160° C. (320° F.)) and heavy naphtha having a distillation end point temperature of about 204° C. (400° F.) (e.g., from about 193° C. (380° F.) to about 216° C. (420° F.)). Otherwise, the naphtha in the upgraded hydrocarbon product of the hydrocracking reaction zone may be fractionated into light naphtha, gasoline, and heavy naphtha, with representative distillation end points being in the ranges from about 138° C. (280° F.) to about 160° C. (320° F.), from about 168° C. (335° F.) to about 191° C. (375° F.), and from about 193° C. (380° F.) to about 216° C. (420° F.), respectively. In any naphtha or naphtha fraction characterized as discussed above with respect to its distillation end point temperature, a representative "front end" or initial boiling point temperature is about 85° C. (185° F.) (e.g., from about 70° C. (158° F.) to about 100° C. (212° F.)).

[0027] Methods for generating electrical power, according to representative embodiments of the invention, are illustrated in the FIG. 1. As shown, fractionation column **100** fractionates hydrocarbon feed **1**, which may, for example, be an upgraded hydrocarbon product from the reaction zone of a refining or petrochemical process (e.g., a portion of a hydrocracking reaction zone effluent after removal of hydrogen and light ends). Fractionation column **100**, in addition to providing other product fractions **12**, **14**, **16** for example light naphtha, heavy naphtha, and relatively unconverted bottoms liquid

(all or a portion of which may be recycled to a hydrocracking reaction zone), respectively, also provides overhead product **10**, for example comprising predominantly (e.g., greater than about 50% by volume) C_4 and heavier hydrocarbons. As discussed above, overhead product **10**, which may be completely or substantially in the vapor phase, is generally removed from fractionation column **100** at a temperature that renders it a low grade heat source suitable for power generation according to methods described herein. Overhead product **10** may also be cooled somewhat, after exiting fractionation column **100**, to a suitable temperature for this application. Overhead product **10** may be all or a portion of the net overhead withdrawn from fractionation column **100**.

[0028] According to the embodiment shown in the FIG. 1, overhead product **10** is passed to evaporator **200** for indirect heat exchange with organic fluid **18**, generally having a boiling point that is from about 5°C . to about 14°C . (about 10°F . to about 25°F .) lower than the temperature of an overhead product **10**. Suitable organic fluids include fluorocarbons and chlorofluorocarbons (CFCs) that are used commercially as refrigerants. Representative fluorocarbons include 1,1,1,3,3-pentafluoropropane (HFC-245fa), 1,1,1,2-tetrafluoroethane (HFC-134a), 1,1,2,2-tetrafluoroethane (HFC-134), 1,1,1,3,3-pentafluorobutane (HFC-365mfc), 1,1,1,2,3,3,3-heptafluoropropane (HFC-227ea), and mixtures thereof. Representative CFCs include CFC-113 (1,1,2-trichloro-1,2,2-trifluoroethane), CFC-11 (trichlorofluoromethane), CFC-12 (dichlorodifluoromethane), CFC-22 (chlorodifluoromethane), and mixtures thereof. Mixtures of fluorocarbons and chlorofluorocarbons may also be used in an organic fluid.

[0029] Indirect heat exchange, in evaporator **200**, between overhead product **10** and organic fluid **18**, provides cooled overhead product **20**, having a temperature that is generally from about 15°C . (27°F .) to about 75°C . (135°F .) less than that of overhead product **10** immediately prior to the heat exchange. In representative embodiments, cooled overhead product **20** has a temperature generally from about 50°C . (122°F .) to about 125°C . (257°F .), and often from about 65°C . (149°F .) to about 100°C . (212°F .), immediately after exchanging heat. Some or all of the heat removed from overhead product **20**, as a result of indirect heat exchange, may be latent heat that causes condensation of at least a portion of cooled overhead product **20** (and an overall increased liquid fraction of this product), as opposed to sensible heat that causes a temperature decrease of this product.

[0030] Also exiting evaporator **200**, as a result of indirect heat exchange, is vapor-enriched fluid **22**, having an increased vapor fraction relative to organic fluid **18**. Preferably, vapor-enriched fluid **22** is completely in the vapor phase after exiting evaporator **200**. Vapor-enriched fluid **22** is then utilized in turbine **300** to drive an electrical generator (for electricity generation) or other type of load. To establish a complete ORC, turbine exhaust **24** from turbine **300** may be condensed, for example using air cooled exchanger **400**, to regenerate organic fluid **18**, which is generally completely in the liquid phase. Organic fluid **18** may then be pumped via pump **500** for indirect heat exchange, as discussed above, in evaporator **200**.

[0031] Often, cooling of overhead product **10** using evaporator **200** replaces at least part of the cooling using conventional air and/or water indirect heat exchangers to reject the low grade heat to the environment. Cooled overhead product **20** may, in some cases depending on its temperature, be further cooled, for example using a cooler **600**, such as a water

cooled exchanger or trim condenser, prior to passing to overhead receiver **700**. In overhead receiver **700**, the vapor phase is removed as net column overhead **26** and the liquid phase is returned as reflux **28** back to fractionator **100**.

[0032] According to other embodiments of the invention, a low grade heat source, other than overhead product **10**, may be an intermediate heat transfer medium (e.g., water) having been initially subjected to heat exchange against overhead product **10**, and optionally at least one additional source of low grade heat. Representative methods according to the invention therefore comprise (i) indirectly exchanging heat between the overhead product, such as an overhead vapor, and an intermediate heat transfer medium and (ii) indirectly exchanging heat between the intermediate heat transfer medium and the organic fluid as discussed above. In embodiments in which at least one additional source of low grade heat is used to provide heat, via indirect heat exchange, to the intermediate heat transfer medium, this additional source may be any refinery or petrochemical process stream having a temperature as discussed above with respect to sources of low grade heat (e.g., generally from about 75°C . (167°F .) to about 180°C . (356°F .) and often from about 90°C . (194°F .) to about 175°C . (347°F)).

[0033] In yet further embodiments, the low grade heat source, rather than overhead product **10** of fractionation column **100**, may be an overhead product, such as an overhead vapor, obtained from a countercurrent vapor-liquid contacting apparatus (e.g., an absorber, stripper, quenching tower, scrubber, etc). Liquid and vapor feeds, which may be predominantly in the liquid and vapor phases, respectively, are generally passed to upper and lower sections, respectively, of such an apparatus to provide the overhead product, in addition to a bottoms liquid. These overhead and bottoms products have compositions that differ from those of the vapor and liquid feeds as a result of the contacting that occurs in the vapor-liquid contacting apparatus. Regardless of whether the vapor-liquid contacting apparatus is a distillation column or any other apparatus as described above, it will generally contain packing material and/or contacting trays, as conventionally used in the art to improve contacting efficiency.

[0034] Still other embodiments of the invention are directed to apparatuses for performing the methods described herein for generating electrical power from one or more low grade heat sources. Representative apparatuses comprise the equipment shown and described with respect to FIG. 1, including an evaporator **200** for indirectly exchanging heat between the low grade heat source(s) and an organic fluid; a turbine **300** in fluid communication with a vapor-enriched fluid conduit from the evaporator **200**; and a condenser **400** (e.g., an air cooled exchanger such as an exchanger referred to in the art as a "fin fan" cooler) in fluid communication with an exhaust conduit from the turbine. To complete an ORC, the apparatuses generally also comprise a pump **500** in fluid communication with both a condensed fluid outlet of the condenser **400** and an inlet for the organic fluid to the evaporator **200**. Additionally, a cooler **600**, such as a water cooled exchanger or trim condenser as discussed above, may be in fluid communication with a low grade heat source outlet (e.g., a cooled overhead product conduit) from the evaporator **200**, and an overhead receiver **700** may be in fluid communication with an outlet of cooler **600**. Otherwise, in embodiments in which cooler **600** is not used, overhead received may be

directly in fluid communication with a low grade heat source outlet (e.g., a cooled overhead product conduit) from the evaporator 200.

[0035] If an air cooled exchanger is used for condenser 400, the ambient air temperature significantly affects the condenser size, or surface area for heat exchange. Directionally, cooler ambient air temperatures result in a smaller condenser requirement. Higher ambient air temperatures and lower prices of cooling water directionally favor the use of cooling water over air as a medium of heat exchange in condenser 400. In many cases, both evaporator 200 and condenser 400 (whether using air or cooling water), or at least one of these, is a tubular heat exchanger with either of the heat exchange medium or the process fluid flowing through a plurality of tubes, having surfaces exposed to the other of the heat exchange medium or the process fluid. To improve the heat transfer coefficient and reduce exchanger area, the external surfaces of the tubes may have surface enhancements such as fins and/or recessions. For example, if tubular exchangers are used, the plurality of tubes of the evaporator 200, condenser 400, or both may have circumferentially extending fins having outer edges that include a plurality of notches. Various surface enhancements of heat exchanger tubes are known for improving heat transfer. For example various enhancements are described in U.S. Pat. No. 4,219,078; U.S. Pat. No. 4,288,897; U.S. Pat. No. 4,191,181; U.S. Pat. No. 4,136,427; U.S. Pat. No. 4,136,428; and U.S. Pat. No. 3,847,212, including features characteristic of tubes referred to in the art as "High Flux" or "High Cond" tubes. Surface enhancements and other features of evaporator and/or condenser tubes may also beneficially reduce the temperature approach to equilibrium of the exchanging streams, increase cycle efficiency of the ORC, and/or reduce plot space.

[0036] Representative surface enhancements include shaped recessions, circumferentially extending fins, axially extending fins, or combinations of these, as described in co-pending U.S. application Ser. No. 12/433,064, hereby incorporated by reference with respect to its description of these surface enhancements and other features of heat exchanger tubes. Circumferentially extending fins may be characteristic of those used for "low finned" tubes, with the fins having a height from about 0.76 mm (0.03 inches) to about 3.8 mm (0.15 inches). Circumferentially extending fins generally refer to a plurality of "plates" that are spaced apart (e.g., uniformly or at regular intervals) along the axial direction of the tube. The plates of circumferentially extending fins, in an alternative embodiment, may be provided by a single, continuously wound, helical spiral rather than discrete extensions. In either case, the plates often each have an outer edge (or outer perimeter), with a single tube extending through central sections of a plurality of plates. The outer edges of the plates may be circular or may have some other geometry, such as rectangular or elliptical. In the case of circumferentially extending fins, further tube surface enhancements can include one or more notches on the outer edges of all or a portion of these fins or plates, where the notches may be spaced apart radially about the edges, for example, in a uniform manner or at a constant radial spacing. In other embodiments, non-uniform radial spacing may be used. Also, it may be desirable to align the notches axially with respect to the immediately adjacent fins. The axial alignment of these notches, such that they may be superimposed when viewed axially, can improve condensate drainage.

[0037] In the case of shaped recessions on the tube surface, all or at least a portion of the recessions may extend axially (e.g., in the form of one or more elongated troughs) or otherwise be aligned in one or more axially extending rows (e.g., in the form of a plurality of discrete, smaller recessions). One or more axially extending fins may also be used as a tube surface enhancement to improve the heat transfer coefficient of the tubes. Combinations of any of the surface enhancements described herein are generally all located in the same region of the tubes used for heat transfer, for example a region extending over a section of the length of the evaporator and/or condenser. The surface enhancements may also be combined with other features such as a twisted tube geometry in this region. In a particular embodiment, for example, tubes having a twisted tube geometry may also have circumferential fins as surface enhancements. In a more specific embodiment, these circumferential fins can have outer edges that include a plurality of notches. In yet more specific embodiments, the notches may be aligned axially with respect to adjacent circumferentially extending fins and/or they may be bent at their respective corners outside of the plane of the circumferentially extending fins.

[0038] Alone or in combination with surface enhancements, the tubes themselves, while extending in a generally linear direction, may have, in at least one region of the tubes used for heat transfer as described above, a non-linear central axis, which can provide a non-linear internal flow path for fluid flow through the tubes. For example, the tubes, as well as their internal central axes, may have a wave, jagged, or helical (coiled) shape to increase pressure drop and/or fluid mixing. Otherwise, an overall helical fluid flow path can be provided, for example, in the case of a flattened or eccentric profile tube (e.g., having a rectangular cross-section or otherwise an oval-shaped or elliptical cross section) that has a twisted tube geometry (i.e., such that a major axis of the cross-sectional shape, for example the major axis of an ellipse, rotates clockwise or counterclockwise along the linear direction of the tube). In the case of a twisted tube geometry, the central axis of fluid flow may be linear or non-linear (e.g., helical). Adjacent tubes extending generally linearly, for example in a region of the tubes where heat transfer takes place, but having a wave, jagged, or helical shape or a twisted tube geometry may have a plurality of external contact points with adjacent tubes, with these contact points possibly being evenly spaced apart by regions where the adjacent tubes are not in contact. Such spaced apart contact points with one or more adjacent tubes can physically stabilize the positions of the tubes and even avoid the need for baffles or tube supports.

[0039] Alternatively, an enhanced condensing layer (ECL) may be applied to the outside or external surfaces of the evaporator and/or condenser tubes as another type of surface enhancement. Examples of ECLs include textured surfaces, chemical coatings that improve drop-wise condensation, nano-coatings, etc.

[0040] In addition to their exterior surfaces, the tube internal surfaces may be modified to improve heat transfer capability. For example, all, a majority, or at least a portion of the tubes in a tube bundle may have internal surfaces, at least in a region of the tubes that extends (e.g., vertically or horizontally) over a section of the evaporator and/or condenser, onto which a coating is bonded. If a coating is used, it is generally bonded to at least a region of the tubes (e.g., where condensation occurs on the external tube surfaces) having the surface enhancement(s), as discussed above, on outer or external

surfaces. A representative internal tube surface coating comprises a porous metallic matrix that can improve the internal heat transfer coefficient of the tube and consequently the overall heat exchange capacity of an evaporator and/or condenser using the tubes. Some suitable coatings are referred to as enhanced boiling layers (EBLs), which are known in the art for their applicability to heat transfer surfaces on which boiling occurs, and particularly for their ability to achieve a high degree of heat transfer at relatively low temperature differences. An EBL often has a structure comprising a multitude of pores that provide boiling nucleation sites to facilitate boiling.

[0041] An EBL or other coating may be applied to the inside or internal surfaces of tubular evaporator and/or condenser tubes. A representative metal coating is applied as described, for example, in U.S. Pat. No. 3,384,154. The coated metal is subjected to a reducing atmosphere and heated to a temperature for sufficient time so that the metal particles sinter or braze together and to the base metal surface. An EBL may also have mechanically or chemically formed reentrant grooves as described, for example, in U.S. Pat. No. 3,457,990. Other known methods of applying coatings and EBLs in particular to metal surfaces, such as the internal surfaces of metal tubes, that may be used include those described in GB 2 034 355, U.S. Pat. No. 4,258,783, GB 2 062 207, EP 303 493, U.S. Pat. No. 4,767,497, U.S. Pat. No. 4,846,267, and EP 112 782.

[0042] In addition to EBLs, another internal enhancement for evaporator and/or condenser tubes involves the use of one or a plurality of ridges, which may, for example, be in the form of a spiral or multiple spirals. Such ridges may be used to further improve the transfer of heat, and particularly sensible heat, across the internal tube surface. Internal ridges may be used alone or in combination with other features of evaporator and/or condenser tubes as described herein. Further internal enhancements include twisted tape, wire matrix inserts (e.g., from Cal-Gavin Limited, Warwickshire, UK), and other in-tube heat transfer devices that can enhance the tubeside heat transfer coefficient.

[0043] Overall, aspects of the invention are directed to methods for generating electrical power from low grade heat sources from refining and petrochemical processes, including overhead products such as overhead vapors from vapor-liquid contacting apparatuses, including distillation columns, absorbers, strippers, quenching towers, scrubbers, etc. Rather than rejecting the low temperature heat contained in these vapors to cooling air and/or cooling water, the vapors may instead be used to evaporate an organic working fluid. The vapors of the working fluid may then be sent to a turbine to drive a generator or other load, thereby reducing overall utility requirements and emissions, such as CO₂, otherwise generated in electricity production.

[0044] In view of the present disclosure, it will be seen that several advantages may be achieved and other advantageous results may be obtained. Those having skill in the art will recognize the applicability of the methods disclosed herein to any of a number of refining, petrochemical, and other processes. Those having skill in the art, with the knowledge gained from the present disclosure, will recognize that various changes could be made in the above processes without departing from the scope of the present disclosure. Mechanisms used to explain theoretical or observed phenomena or results, shall be interpreted as illustrative only and not limiting in any way the scope of the appended claims.

[0045] The following example is set forth as representative of the present invention. The example is not to be construed as limiting the scope of the invention as other equivalent embodiments will be apparent in view of the present disclosure and appended claims.

Example 1

[0046] The economics of generating electricity were investigated, using an Organic Rankine Cycle (ORC) and a low grade heat source from a commercial refining process stream. In particular, this stream was the main fractionation column overhead product of a hydrocracking process, exiting the column at a temperature of 126° C. (259° F.). Normally, this stream is cooled using an air cooled exchanger to reject 231 GJ/hr (55.1 Gcal/hr) of low grade heat and achieve a cooler outlet temperature of 91° C. (196° F.).

[0047] Using Unisim® Design Suite R390 (Honeywell International, Inc., Morristown, N.J.) an ORC process was simulated, in which the overhead product was exchanged against the organic fluid 1,1,1,3,3-pentafluoropropane (HFC-245fa) for evaporation of this fluid and utilization of the evaporated fluid in a turbine and generator to obtain electricity. The condensation of this fluid in an air condenser downstream of the turbine and pumping of the condensed fluid back to the evaporator were also included in the simulation, according to the flowscheme shown in FIG. 1.

[0048] Performance was evaluated for two cases, based on air inlet temperatures to the condenser of 20° C. (68° F.) (CASE I) and 25° C. (77° F.) (CASE II). As expected, the simulation results showed that ambient air temperature affects the temperature at the outlet of the turbine, the size of the air condenser, the cycle efficiency, and the overall power recovery. The air condenser sizes and other parameters associated with the air condenser, as estimated for the two average air temperatures, are shown in Table 1 below.

TABLE 1

Comparison of Air Condenser Parameters		
	CASE I	CASE II
Process Inlet Temperature	51° C. (123° F.)	54° C. (129° F.)
Process Outlet Temperature	30° C. (86° F.)	35° C. (95° F.)
Duty	201 GJ/hr (48.1 Gcal/hr)	203 GJ/hr (48.4 Gcal/hr)
Air Inlet Temperature	20° C. (68° F.)	25° C. (77° F.)
Plot Size	1650 m ² (17,800 ft ²)	1730 m ² (18,600 ft ²)
Finned Area	170,000 m ² (1,830,000 ft ²)	178,000 m ² (1,920,000 ft ²)

[0049] The results of the process simulation showed that, using an ORC and the low grade heat contained in the main fractionation column overhead product of the commercial hydrocracking process, 4.0-4.5 megawatts (MW) of electricity could be generated, depending on the average ambient air temperature, which is the air inlet temperature to the condenser. Moreover, since electricity is normally consumed in the air cooled exchanger conventionally used to reject waste heat from the overhead product, the net power benefit of recovering this low grade heat in an ORC increases to 4.3-4.8 MW. This translates to a cost benefit of \$2.5 million-\$4.5 million annually (US dollars), assuming a cost of electrical power of \$0.07-\$0.12 per kilowatt-hour. The relationship between the annual benefit of the electrical power generation

(as determined using CASE I and CASE II simulations) and the cost of power is illustrated in the bar graph of FIG. 2.

[0050] The estimated investment cost for the ORC system evaluated in these simulations is \$18 million-\$20 million. Subtracting the cost of the conventional air cooled exchanger used to reject heat from the main fractionation column overhead product (which is now replaced by the ORC system), the net investment is reduced to \$15 million-\$17 million. The payback period for this investment is estimated to vary between 3.5-6.5 years, based on the cost of electricity, as illustrated in the bar graph of FIG. 3.

1. A method for generating electrical power from a low grade heat source, the method comprising:

- (a) passing a hydrocarbon-containing feed to a vapor-liquid contacting apparatus to provide an overhead product and a bottoms liquid;
- (b) indirectly exchanging heat between the overhead product and an organic fluid to provide a cooled overhead product and a vapor-enriched fluid; and
- (c) passing the vapor-enriched fluid to a turbine to generate electricity and provide a turbine exhaust.

2. The method of claim 1, further comprising,

- (d) condensing the turbine exhaust to regenerate the organic fluid, and
- (e) pumping the organic fluid to an evaporator for indirect heat exchange with the overhead vapor in step (b).

3. The method of claim 1, wherein the hydrocarbon-containing feed stream comprises at least about 90% hydrocarbons by weight.

4. The method of claim 1, wherein the vapor-liquid contacting apparatus is a distillation column.

5. The method of claim 4, wherein the distillation column is a product fractionation column of a hydrocracking process.

6. The method of claim 1, wherein, in step (b), the overhead product has a temperature from about 90° C. (194° F.) to about 150° C. (302° F.) immediately prior to exchanging heat and the cooled overhead product has a temperature from about 65° C. (149° F.) to about 100° C. (212° F.) immediately subsequent to exchanging heat.

7. The method of claim 1, wherein the organic fluid comprises a fluorocarbon or a chlorofluorocarbon.

8. The method of claim 2, wherein step (d) is carried out using an air cooled exchanger.

9. The method of claim 1, wherein indirect heat exchange in step (b) comprises (i) indirectly exchanging heat between the overhead vapor and an intermediate heat transfer medium and (ii) indirectly exchanging heat between the intermediate heat transfer medium and the organic fluid.

10. The method of claim 9, wherein the intermediate heat transfer medium is water.

11. The method of claim 9, wherein, immediately prior to step (b)(ii), the heat transfer medium comprises heat that is transferred from the overhead vapor and from at least one additional source of low grade heat.

12. The method of claim 11, wherein the additional source of low grade heat is a refinery or petrochemical process stream having a temperature from about 90° C. (194° F.) to about 150° C. (302° F.).

13. The method of claim 1, wherein, a net benefit of electricity generated in step (c) is from about 0.005 to about 0.02 watts per BTU/hr of waste heat in the hydrocarbon-containing feed stream.

15. A method for generating electrical power from a low grade heat source, the method comprising:

- (a) passing liquid and vapor feeds to upper and lower sections, respectively, of a vapor-liquid contacting apparatus to provide an overhead vapor and a bottoms liquid;
- (b) indirectly exchanging heat between the overhead vapor and an organic fluid to provide a cooled overhead product and a vapor-enriched fluid; and
- (c) passing the vapor-enriched fluid to a turbine to generate electricity.

16. An apparatus for generating electrical power from a low grade heat source, the apparatus comprising:

- (a) an evaporator for indirectly exchanging heat between the low grade heat source and an organic fluid;
- (b) a turbine in communication with a vapor-enriched fluid conduit from the evaporator;
- (c) a condenser in communication with an exhaust conduit from the turbine; and
- (d) a cooler in communication with a low grade heat source outlet from the evaporator.

17. The apparatus of claim 16, wherein the condenser is an air cooled exchanger.

18. The apparatus of claim 16, wherein both the evaporator and condenser are tubular heat exchangers.

19. The apparatus of claim 18, wherein the evaporator, the condenser, or both have disposed therein a plurality of tubes having fins or recessions on their surfaces.

20. The apparatus of claim 19, wherein the plurality of tubes of the evaporator, the condenser, or both have circumferentially extending fins having outer edges that include a plurality of notches.

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