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(54) **HIGH PRESSURE OXY-FIRED COMBUSTION SYSTEM**

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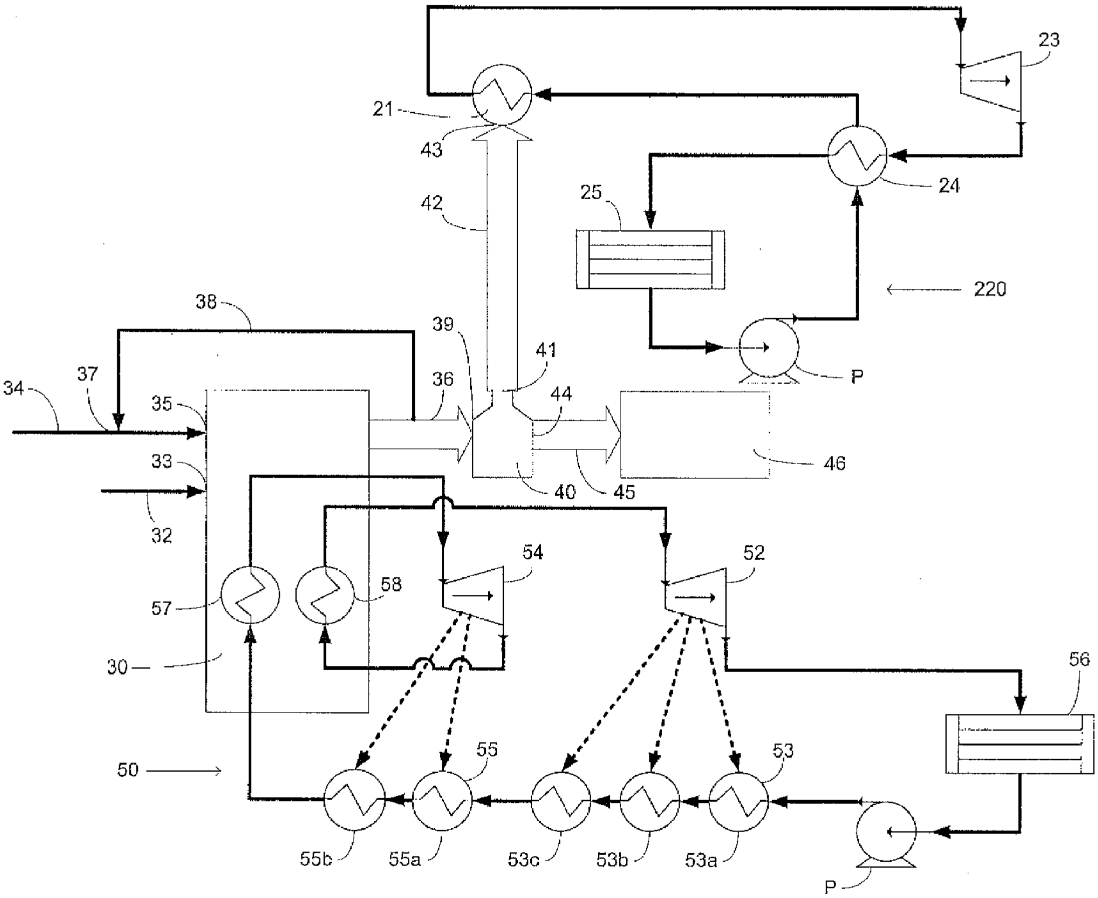
(57) **ABSTRACT**

A combustion system, and method. A combustor oxy-fired at high pressure delivers flue gas at pressure to a condensing means, such as a condensing heat exchanger, to produce a high temperature condensate for delivering thermal energy to an industrial process system, particularly for power generation, including a Brayton cycle, a Rankine cycle, or a binary fluid cycle system such as a Kalina cycle, and in particular as a bottoming cycle for an organic Rankine cycle. The combustor can concurrently provide direct heat to a secondary system, including a Brayton cycle system, a Rankine cycle system, and a binary fluid cycle system such as a Kalina cycle, without requiring significant modifications to the secondary system. The system and method provide for efficient and advantageous use of the higher temperature condensate produced.



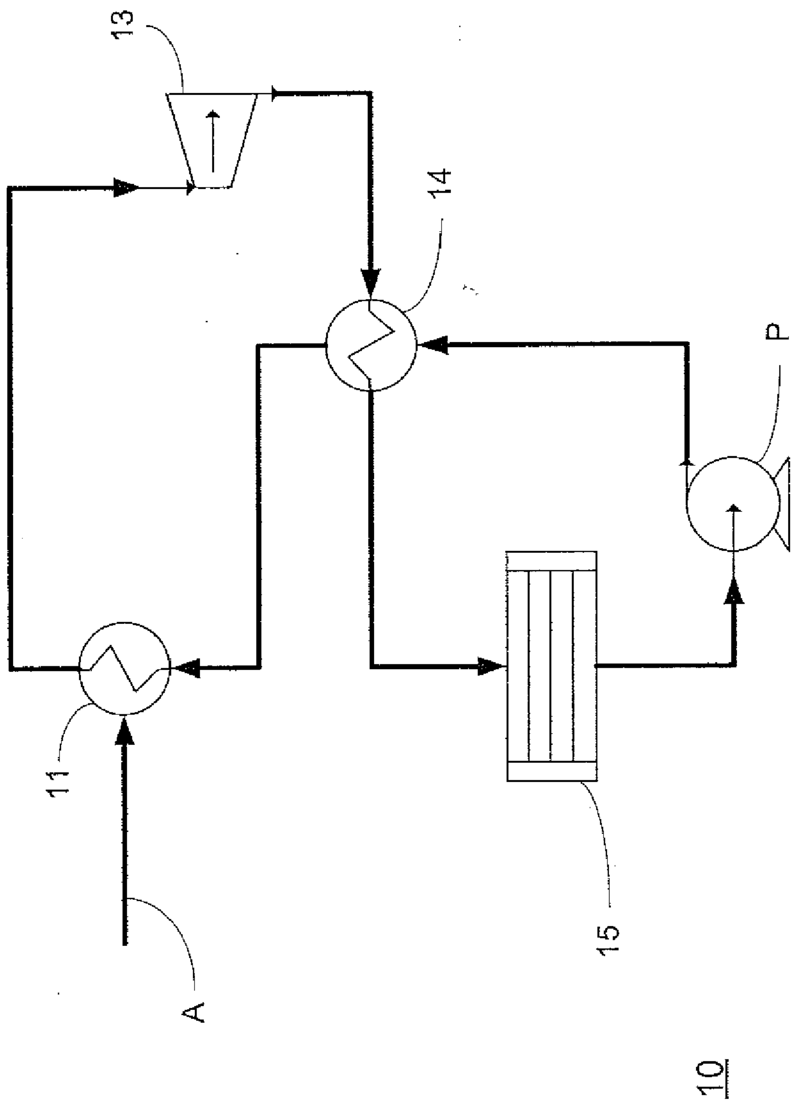


Figure 1

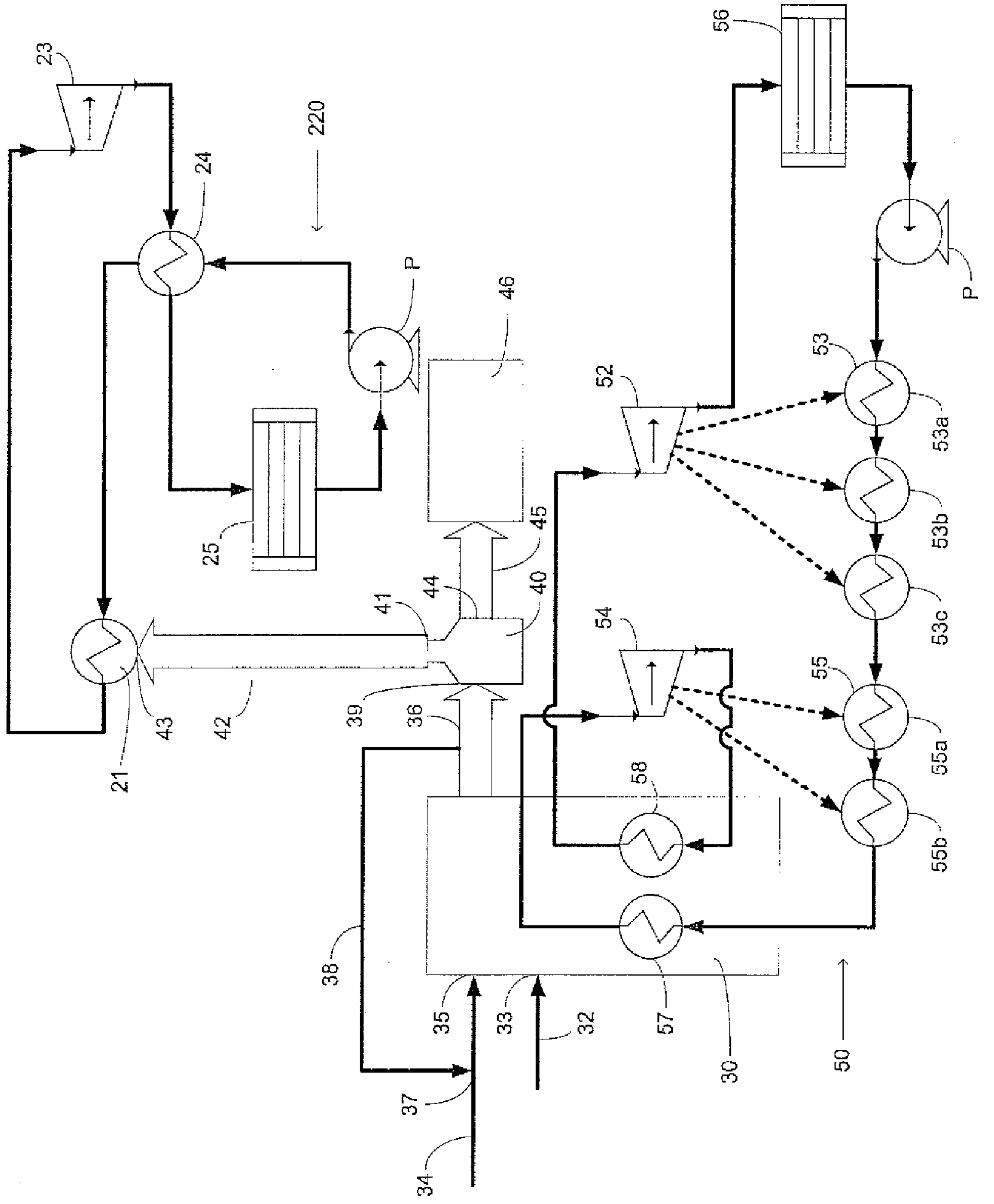
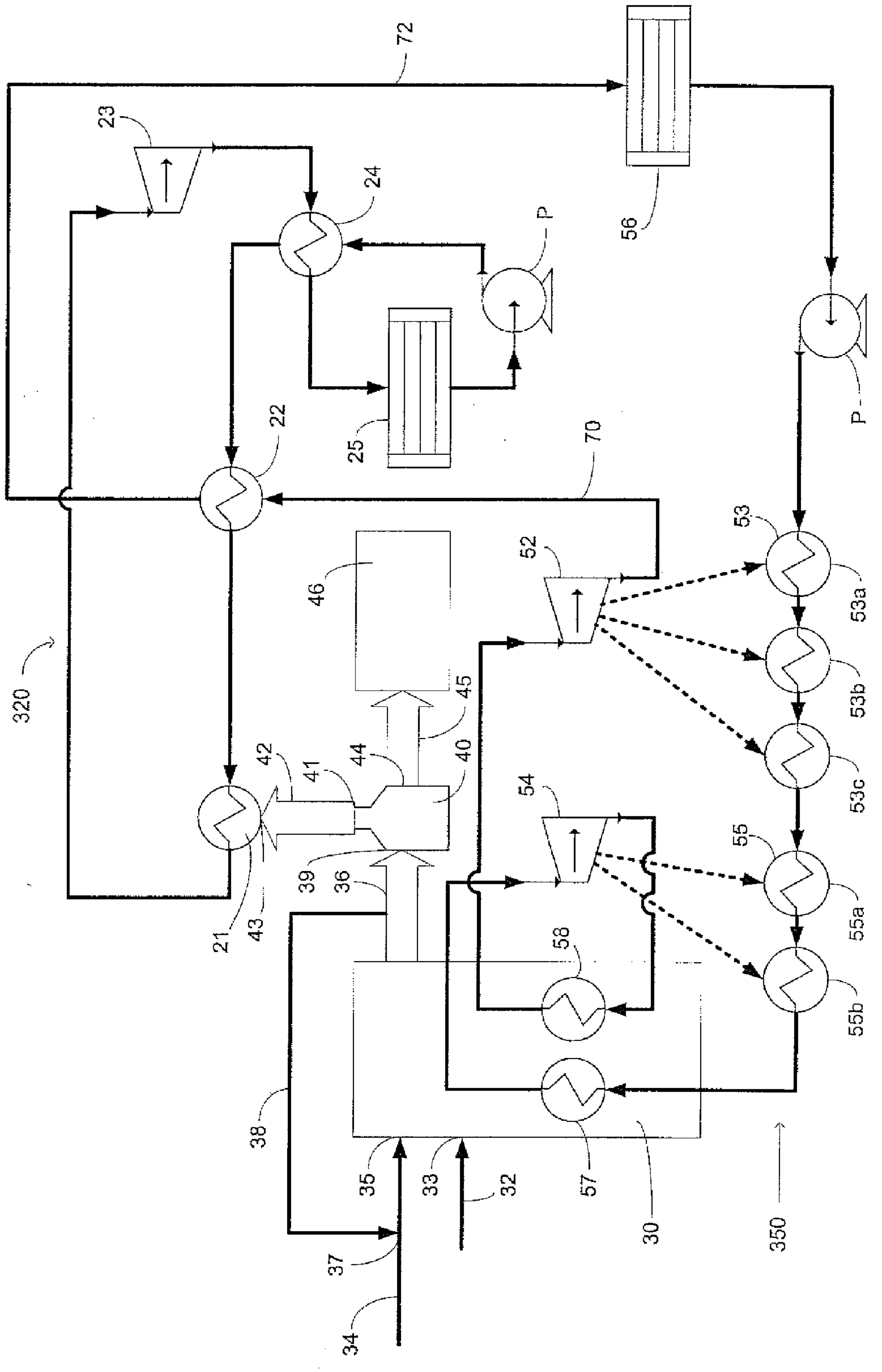

23
220
24
P
46
56
25
45
44
40
41
21
43
42
39
36
52
53
53a
53b
53c
54
55
55a
55b
58
57
38
35
33
32
30
50
37
34
P

Figure 2


72
23
24
P
56
22
25
70
320
46
52
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53a
53b
53c
42
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44
45
40
54
55
55a
55b
39
36
21
43
58
38
57
35
33
32
30
37
34
350
P

Figure 3

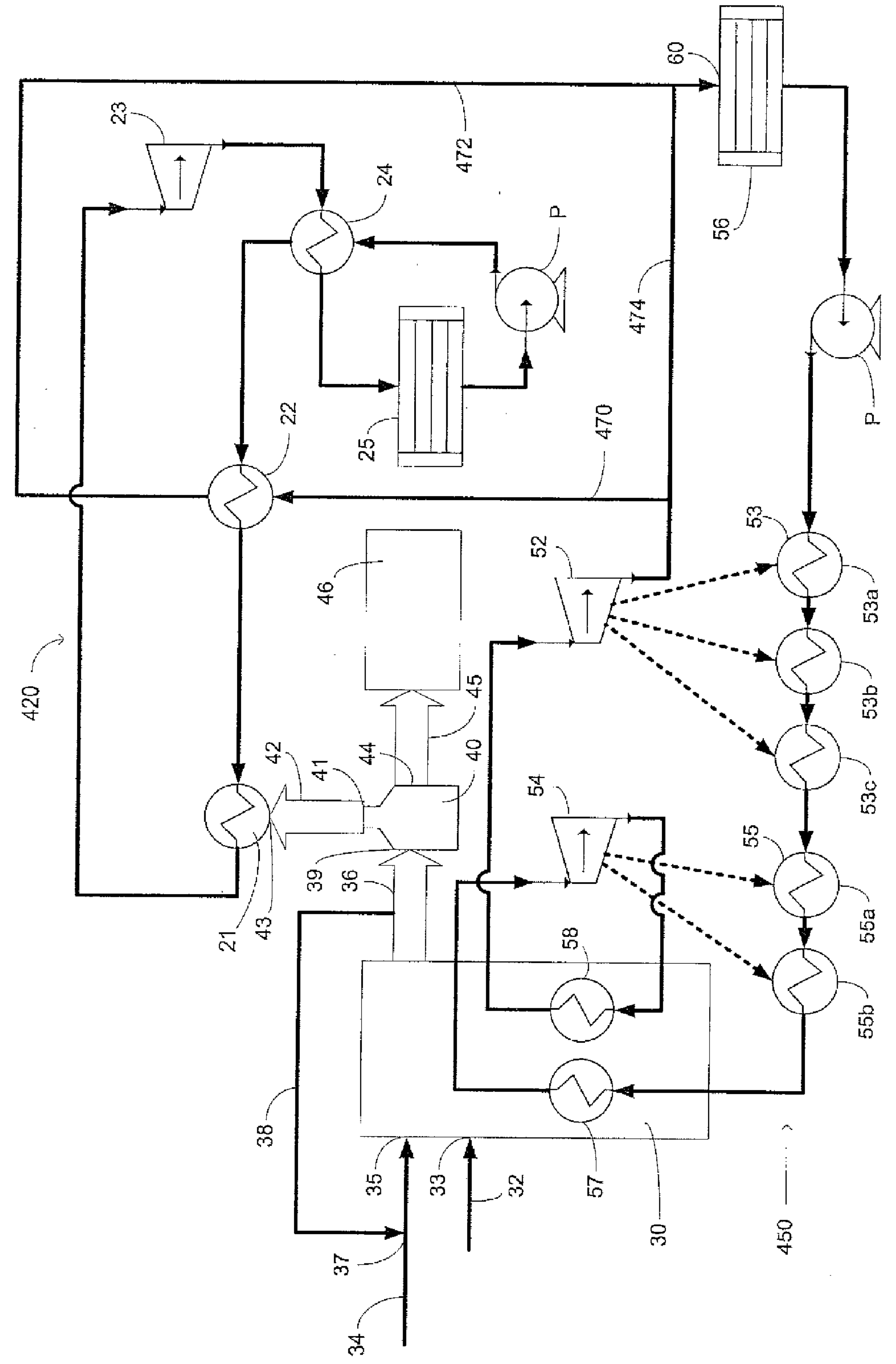
60
472
23
24
P
56
474
P
22
25
470
420
52
53
46
53a
53b
42
41
44
45
40
53c
54
55
39
36
21
43
58
55a
55b
38
57
35
33
32
30
450
37
34

Figure 4

HIGH PRESSURE OXY-FIRED COMBUSTION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] None.

STATEMENT OF FEDERALLY FUNDED RESEARCH

[0002] None.

INCORPORATION-BY-REFERENCE OF MATERIALS FILED ON COMPACT DISC

[0003] None.

FIELD OF THE INVENTION

[0004] This invention relates to combustion systems for industrial processes, including but not limited to electric power generation. More particularly, the invention relates to a high pressure oxy-fuel system, and the delivery of thermal energy from condensation from the flue gas of the high pressure oxy-fuel system to an organic Rankine cycle system. Concurrently, direct thermal energy from the combustion in the system of the invention can be provided to a Rankine cycle or a wide variety of other systems.

BACKGROUND OF THE INVENTION

[0005] In the ongoing aim to reduce the emission of greenhouse gases in industrial processes which generate carbon dioxide, but while continuing to use fossil fuels which are generally otherwise preferable over other fuels for practical and economic reasons, attempts have been made to simplify the isolation of the carbon dioxide so that it can be removed from the processes for sequestration or other containment or use. In particular, it has been found that the replacement of ambient air by concentrated oxygen in what are known as oxy-fuelled or oxy-fired combustion processes is advantageous in that the absence of the high levels of nitrogen and other constituents in air, thus avoiding the need to separate either the nitrogen or other constituents. Further, the absence of nitrogen avoids the formation of NOx and other problematic compounds, and the high costs in situations where these are required to be separated. Oxy-fuel systems thus result in a flue gas which has a high purity level of carbon dioxide and requires minimal or no further separation treatment before being prepared, for example by pressurization, for sequestration or use.

[0006] Oxy-fuel systems are advantageous in that they provide relatively simple solutions which are applicable to new systems or the retrofit of existing systems. However, such systems when operated at ambient pressure suffer from disadvantages of inefficiency, as well as the higher costs arising from the need for an air separation unit for provision of the oxygen, and the costs of the carbon dioxide product recovery train.

[0007] Oxy-fuel systems operate at significantly higher temperatures than air-fired systems, and thus require temperature control. There are various known methods of temperature moderation, including staging, the use of fluid beds, or the recirculation of a portion of the flue gas back to the combustor.

[0008] It has therefore been proposed to use high pressure for oxy-fuel systems, to address at least some of the above disadvantages, and to allow for a significant reduction in size for the structures used. For example, U.S. Pat. No. 6,196,000 (Fassbender) proposes a pressurized Rankine cycle oxy-fuel system, allowing for reduced equipment size, and for condensing the carbon dioxide at ambient heat-sink temperatures, thus minimizing the need for multi-stage compression and refrigeration; and for increased efficiency from the use of waste heat to replace regenerative extraction from the turbine. However, the proposed system suffers from various disadvantages, some of which apply to oxy-fuel systems in general, including increased costs for high pressure oxygen feed, and difficulty in achieving temperature moderation using flue gas as recirculation. The proposed system included the variation in the conventional configurations of feedwater heaters, by removing some of them and instead using heat from condensed moisture in the flue gas. However, conventional feedwater heater arrangements are highly developed and efficient, and any changes in those result in the need to adjust various other aspects of the system, including to address the effects of altering the regenerative extraction from the turbine; problems in making such adjustments present a significant disadvantage of the proposed system.

[0009] One advantage of high pressure operation is that it changes the temperature condition at which the gas to liquid phase change occurs for the flue gas, which thus allows for water vapour in the flue gas to be condensed at much higher temperatures than in air-fired systems. For example, moisture in the flue gas condenses in the range of 150° C. to 200° C. at 80 bar, as compared with 50° C. to 55° C. in ambient pressure oxy-fuel systems.

[0010] It has now been found that this, and other advantages, makes the condensate from the flue gas of a pressurized oxy-fuel system a suitable heat source for use in various processes, including but not limited to power generation systems and similar systems, including Brayton cycles, Rankine cycles and binary fluid cycles, and it is particularly advantageous to use such flue gas condensate to provide heat to organic Rankine cycles. It has further been found advantageous to use the direct heat of the combustor of the system and the method of the invention to provide a direct heat energy source for various secondary systems, including but not limited to Brayton cycles, Rankine cycles and binary fluid cycles. Further, it has been found to be particularly advantageous to provide the heat of the condensate as a bottoming cycle to an organic Rankine cycle system, and to provide the direct heat of the combustion within a secondary Rankine cycle system, without making any modification to the conventional feedwater heater arrangements.

SUMMARY OF THE INVENTION

[0011] The invention therefore seeks to provide a combustion system for operational connection to an industrial process system, the combustion system comprising

(a) a combustor constructed and arranged to be selectively operable at a selected operational pressure exceeding atmospheric pressure, and comprising

[0012] (i) a combustor wall comprising a combustion chamber;

[0013] (ii) a burner;

[0014] (iii) at least a first fuel inlet constructed and arranged to deliver a first fuel to the burner at a delivery pressure exceeding the selected operational pressure;

[0015] (iv) at least one oxidant inlet constructed and arranged to deliver a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;

[0016] (v) an outlet region having a flue gas outlet;

(b) a flue gas delivery means, constructed and arranged to be operatively connected to the flue gas outlet, to receive a supply of flue gas therefrom at a pressure exceeding atmospheric pressure and to deliver at least part of the supply of flue gas to a heat removal means comprising

[0017] (i) at least one condensing means to produce condensate from the supply of flue gas; and

[0018] (ii) a heat delivery means to deliver heat from the condensate to the industrial process system.

[0019] Preferably, the condensing means and the heat delivery means comprise at least one condensing heat exchanger.

[0020] Preferably, the first fuel inlet is constructed and arranged to deliver a first fuel selected from at least one of a solid fuel, a liquid fuel, a gaseous fuel, and combinations thereof.

[0021] Preferably, the at least one oxidant inlet is constructed and arranged to deliver a supply of oxygen having a purity of at least 80%, more preferably at least 95%.

[0022] Optionally, the flue gas delivery means comprises a flue gas recirculation outlet and the combustor further comprises at least one flue gas recirculation inlet, and the flue gas recirculation outlet is constructed and arranged to selectively deliver a supply of part of the flue gas to selective ones of the at least one flue gas recirculation inlet.

[0023] The industrial process system can be a power generation system, for example an electric power generation system. Alternatively, the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to a low temperature power cycle system.

[0024] In some embodiments, the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to a system selected from a Brayton cycle system, a Rankine cycle system, and a binary fluid cycle system. Preferably, the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to an organic Rankine cycle system.

[0025] Where the combustion system is constructed and arranged to be operationally connected to a binary fluid cycle system, preferably that system is a Kalina cycle.

[0026] Preferably, the combustor is further constructed and arranged to be operationally connected to and deliver direct heat to a secondary system. Such secondary system can be selected from an engine, a secondary industrial process system and a secondary power system; and selected from a Brayton cycle system, a Rankine cycle system, and a binary fluid cycle system. Where the secondary system comprises a binary fluid cycle system, preferably it is a Kalina cycle.

[0027] In some embodiments, the secondary system is a secondary industrial process system comprising a Rankine cycle system having a flow path for a flow of working fluid, the flow path being constructed and arranged to deliver the flow through a low pressure turbine, and thereafter to deliver at least part of the flow selectively to an evaporator in the organic Rankine cycle system.

[0028] The invention therefore further seeks to provide a method of providing heat energy to an industrial process system, the method comprising the steps of

(a) providing a combustion system according to the invention and selecting an operational pressure;

(b) connecting the flue gas delivery means to the heat removal means, and connecting the heat removal means to the industrial process system;

(c) delivering a supply of the first fuel to at least the first fuel inlet at a delivery pressure exceeding the selected operational pressure;

(d) delivering a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;

(e) operating the combustor at the selected operational pressure to generate a supply of flue gas, and delivering at least part of the supply of flue gas to the heat removal means;

(f) producing condensate from the supply of flue gas, and delivering heat from the condensate to the industrial process system.

[0029] Preferably, step (d) comprises delivering a supply of oxygen having a purity of at least 80%, more preferably at least 95%.

[0030] Optionally, step (b) comprises providing the flue gas delivery means with a flue gas recirculation outlet and step (e) further comprises delivering at least a part of the supply of flue gas through the recirculation outlet and into the combustor.

[0031] The invention therefore further seeks to provide a method of providing heat energy to an industrial process system, the method comprising the steps of

(a) providing a combustion system according to the invention and selecting an operational pressure;

(b) connecting the flue gas delivery means to the heat removal means, and connecting the heat removal means to the industrial process system;

(c) connecting the combustor to the secondary system;

(d) delivering a supply of the first fuel to at least the first fuel inlet at a delivery pressure exceeding the selected operational pressure;

(e) delivering a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;

(f) operating the combustor at the selected operational pressure to produce heat energy and generate a supply of flue gas;

(g) delivering heat energy to the secondary system and delivering at least part of the supply of flue gas to the heat removal means;

(h) producing condensate from the supply of flue gas, and delivering heat from the condensate to the industrial process system.

[0032] Preferably, step (e) comprises delivering a supply of oxygen having a purity of at least 80%, more preferably at least 95%.

[0033] Optionally, step (b) comprises providing the flue gas delivery means with a flue gas recirculation outlet and step (g) further comprises delivering at least a part of the supply of flue gas through the recirculation outlet and into the combustor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] The invention will now be described with reference to the drawings, in which

[0035] FIG. **1** is a schematic representation of a conventional layout of a Rankine cycle system of the prior art;

[0036] FIG. **2** is a schematic representation of a combustion system in an embodiment of the invention;

[0037] FIG. **3** is a schematic representation of a combustion system in a second embodiment of the invention; and

[0038] FIG. **4** is a schematic representation of a combustion system in a third embodiment of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

[0039] Referring to FIG. **1**, this is a schematic representation of a conventional layout of a Rankine cycle system **10** of the prior art. Various layouts are known and used, but in accordance with the principles of operation of such cycles, each includes at least the elements shown in FIG. **1**. In sequence, the working fluid (not shown) passes through boiler/evaporator **11**, is expanded in turbine **13**, passes through regenerator (also known as recuperator) **14**, and thence to condenser **15**. From condenser **15**, the working fluid is pumped by pump P, and passed through regenerator **14** for preheating before being returned to boiler/evaporator **11**.

[0040] Referring now to FIG. **2**, an embodiment of the invention is shown in a schematic representation, in which furnace **30** is operationally connected to an organic Rankine cycle **220**, and a secondary Rankine cycle **50**. Organic Rankine cycle **220** comprises high temperature evaporator **21**, turbine **23**, regenerator **24** and condenser **25**, and will have a suitable working fluid selected from those known and permitted to be used pursuant to any applicable regulations.

[0041] Furnace **30** is designed for high pressure oxy-firing, and is fed by fuel supply from line **32** at fuel inlet **33**, and oxygen supply from line **34** at oxygen inlet **35**. Oxygen is supplied at the selected level of purity, by known methods, for example from an air separation unit (not shown). Flue gas generated by the combustion leaves furnace **30** in flue gas line **36**. Optionally, a recirculation stream can be separated from the flue gas stream in flue gas line **36**, to be selectively recirculated back in flue gas recirculation line **38** to be reintroduced to the furnace in a suitable manner, either through a separate inlet (not shown) or by joining the oxygen supply in line **34**. The main flue gas stream is delivered to a condenser **40** at flue gas inlet **39**. Condenser **40** can be of any known construction, and is preferably a condensing heat exchanger.

[0042] In condenser **40**, water is condensed from the flue gas stream, the condensate passes through condensate line **42** to be delivered to high temperature evaporator **21** at condensate inlet **43**, and the heat of condensation is provided to high temperature evaporator **21**, to contribute to the heating of the working fluid in organic Rankine cycle **220**. The remaining gaseous portion of the flue gas stream, mostly pressurized carbon dioxide, leaves condenser **40** at outlet **44**, and passes through line **45** to a carbon dioxide capture system **46**, where impurities are removed by known means, and the carbon dioxide product stream is removed for further processing, use or sequestration.

[0043] Concurrently with providing heat of condensation to organic Rankine cycle **220**, furnace **30** can be used to provide direct heat of combustion to various types of system requiring heat energy. In the exemplary embodiment of FIG. **2**, furnace **30** is shown as operationally connected to a Rankine cycle **50** of a conventional configuration and shown here as having water as the working fluid. In Rankine cycle **50**, expanded working fluid leaves intermediate pressure/low pressure turbine **52**, passes through and is condensed in condenser **56**, and passes to a first group of feedwater heaters **53**, shown here as feedwater heaters **53***a*, **53***b* and **53***c*. Extracted heat can be selectively provided to each of feedwater heaters **53***a*, **53***b* and **53***c* from intermediate pressure/low pressure turbine **52**. The working fluid then passes to a second group of feedwater heaters **55**, shown here as feedwater heaters **55***a* and **55***b*. Extracted heat can be selectively provided to each of feedwater heaters **55***a* and **55***b* from high pressure turbine **54**. The working fluid then passes to reheater **57**, which is supplied with heat from furnace **30**, and delivered to and expanded in high pressure turbine **54** to provide energy to the process or system being powered by Rankine cycle **50**. Thereafter, the working fluid is reheated in reheater **58**, which is also supplied with heat from furnace **30**, before passing to and being expanded in intermediate pressure/low pressure turbine **52** to provide energy to the process or system being powered by Rankine cycle **50**, and to complete the cycle.

[0044] In each of FIGS. **2** to **4**, it will be appreciated that various known structural elements will be included in the embodiments of the invention, such as pumps, valves etc. For simplification, these are not included in the figures in general, but some of the pumps are included where this would assist in understanding the invention, and are identified generically as P.

[0045] Referring now to FIG. **3**, a second exemplary embodiment of the invention is shown in a schematic representation. In this embodiment, again furnace **30** supplies the heat of condensation of flue gas to organic Rankine cycle **320**, in the same manner as in the configuration shown in FIG. **2**; and provides direct heat to Rankine cycle **350**, which is shown as having water as the working fluid. However, organic Rankine cycle **320** is provided with a low temperature evaporator **22**, which preheats the working fluid of organic Rankine cycle **320** after the working fluid leaves regenerator **24** and before it enters high temperature evaporator **21**. Working fluid from Rankine cycle **350** leaving intermediate pressure/low pressure turbine **52**, instead of passing directly to steam condenser **56**, passes in line **70** to low temperature evaporator **22**, where it provides heat to the working fluid of organic Rankine cycle **320**. Thereafter the working fluid in Rankine cycle **350** returns in line **72** to steam condenser **56**.

[0046] Referring now to FIG. **4**, a further exemplary embodiment of the invention is shown in a schematic representation. In this embodiment, again furnace **30** supplies the heat of condensation of flue gas to organic Rankine cycle **420**, in the same manner as in the configurations shown in FIGS. **2** and **3**; and provides direct heat to Rankine cycle **450**, which is shown as having water as the working fluid. Further, in the same manner as in the configuration shown in FIG. **3**, organic Rankine cycle **420** is provided with low temperature evaporator **22**, which preheats the working fluid of organic Rankine cycle **420** after the working fluid leaves regenerator **24** and before it enters high temperature evaporator **21**. However, in this embodiment, when the working fluid from Rankine cycle **450** leaves intermediate pressure/low pressure turbine **52**, it is split into two streams, one of which passes in line **470** to low temperature evaporator **22**, where it provides heat to the working fluid of organic Rankine cycle **420**, before returning in line **472** to the input region **60** of steam condenser **56**, where it is joined by the second stream passing directly to steam condenser **56** from intermediate pressure/low pressure turbine **52** in line **474**.

[0047] As noted above, the system and methods of the invention provide an advantageous use for condensate in the flue gas of a pressurized oxy-fuel system, which can be readily connected to many types of conventional systems, without requiring significant modification to those systems, which is of particular significance in relation to (1) delivery of the thermal energy from condensation to all manner of organic Rankine cycles; and (2) connection to Rankine cycles for the provision of direct heat from the combustor, where the connection of the system of the invention to the Rankine cycle can be made without requiring any modification to the highly developed and complex arrangements for the feedwater heaters.

We claim:

1. A combustion system for operational connection to an industrial process system, the combustion system comprising
- (a) a combustor constructed and arranged to be selectively operable at a selected operational pressure exceeding atmospheric pressure, and comprising
  - (i) a combustor wall comprising a combustion chamber;
  - (ii) a burner;
  - (iii) at least a first fuel inlet constructed and arranged to deliver a first fuel to the burner at a delivery pressure exceeding the selected operational pressure;
  - (iv) at least one oxidant inlet constructed and arranged to deliver a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;
  - (v) an outlet region having a flue gas outlet;
- (b) a flue gas delivery means, constructed and arranged to be operatively connected to the flue gas outlet, to receive a supply of flue gas therefrom at a pressure exceeding atmospheric pressure and to deliver at least part of the supply of flue gas to a heat removal means comprising
  - (i) at least one condensing means to produce condensate from the supply of flue gas; and
  - (ii) a heat delivery means to deliver heat from the condensate to the industrial process system.

2. A combustion system according to claim **1**, wherein the condensing means and the heat delivery means comprise at least one condensing heat exchanger.

3. A combustion system according to claim **1**, wherein the first fuel inlet is constructed and arranged to deliver a first fuel selected from at least one of a solid fuel, a liquid fuel, a gaseous fuel, and combinations thereof.

4. A combustion system according to claim **1**, wherein the at least one oxidant inlet is constructed and arranged to deliver a supply of oxygen having a purity of at least 80%.

5. A combustion system according to claim **4**, wherein the at least one oxidant inlet is constructed and arranged to deliver a supply of oxygen having a purity of at least 95%.

6. A combustion system according to claim **1**, wherein the flue gas delivery means comprises a flue gas recirculation outlet and the combustor further comprises at least one flue gas recirculation inlet, and the flue gas recirculation outlet is constructed and arranged to selectively deliver a supply of part of the flue gas to selective ones of the at least one flue gas recirculation inlet.

7. A combustion system according to claim **1**, wherein the industrial process system is a power generation system.

8. A combustion system according to claim **7**, wherein the industrial process system is an electric power generation system.

9. A combustion system according to claim **1**, wherein the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to a low temperature power cycle system.

10. A combustion system according to claim **1**, wherein the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to a system selected from a Brayton cycle system, a Rankine cycle system, and a binary fluid cycle system.

11. A combustion system according to claim **10**, wherein the combustion system is constructed and arranged to be operationally connected to and deliver the heat from the condensate to an organic Rankine cycle system.

12. A combustion system according to claim **10**, wherein the combustion system comprises a binary fluid cycle system and is a Kalina cycle.

13. A combustion system according to claim **9**, wherein the combustor is further constructed and arranged to be operationally connected to and deliver direct heat to a secondary system.

14. A combustion system according to claim **13**, wherein the secondary system is selected from an engine, a secondary industrial process system and a secondary power system.

15. A combustion system according to claim **13**, wherein the secondary system is selected from a Brayton cycle system, a Rankine cycle system, and a binary fluid cycle system.

16. A combustion system according to claim **15**, wherein the secondary system comprises a binary fluid cycle system and is a Kalina cycle.

17. A combustion system according to claim **14**, wherein the secondary system is a secondary industrial process system comprising a Rankine cycle system having a flow path for a flow of working fluid, the flow path being constructed and arranged to deliver the flow through a low pressure turbine, and thereafter to deliver at least part of the flow selectively to an evaporator in the organic Rankine cycle system.

18. A method of providing heat energy to an industrial process system, the method comprising the steps of
- (a) providing a combustion system according to claim **1** and selecting an operational pressure;
- (b) connecting the flue gas delivery means to the heat removal means, and connecting the heat removal means to the industrial process system;
- (c) delivering a supply of the first fuel to at least the first fuel inlet at a delivery pressure exceeding the selected operational pressure;
- (d) delivering a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;
- (e) operating the combustor at the selected operational pressure to generate a supply of flue gas, and delivering at least part of the supply of flue gas to the heat removal means;
- (f) producing condensate from the supply of flue gas, and delivering heat from the condensate to the industrial process system.

19. A method according to claim **18**, wherein step (d) comprises delivering a supply of oxygen having a purity of at least 80%.

20. A method according to claim **19**, wherein step (d) comprises delivering a supply of oxygen having a purity of at least 95%.

21. A method according to claim **18**, wherein step (b) comprises providing the flue gas delivery means with a flue gas recirculation outlet and step (e) further comprises delivering at least a part of the supply of flue gas through the recirculation outlet and into the combustor.

22. A method of providing heat energy to an industrial process system, the method comprising the steps of

(a) providing a combustion system according to claim **13** and selecting an operational pressure;

(b) connecting the flue gas delivery means to the heat removal means, and connecting the heat removal means to the industrial process system;

(c) connecting the combustor to the secondary system;

(d) delivering a supply of the first fuel to at least the first fuel inlet at a delivery pressure exceeding the selected operational pressure;

(e) delivering a supply of oxygen having a purity of at least 22% to the burner at a delivery pressure exceeding the selected operational pressure;

(f) operating the combustor at the selected operational pressure to produce heat energy and generate a supply of flue gas;

(g) delivering heat energy to the secondary system and delivering at least part of the supply of flue gas to the heat removal means;

(h) producing condensate from the supply of flue gas, and delivering heat from the condensate to the industrial process system.

23. A method according to claim **22**, wherein step (e) comprises delivering a supply of oxygen having a purity of at least 80%.

24. A method according to claim **23**, wherein step (e) comprises delivering a supply of oxygen having a purity of at least 95%.

25. A method according to claim **22**, wherein step (b) comprises providing the flue gas delivery means with a flue gas recirculation outlet and step (g) further comprises delivering at least a part of the supply of flue gas through the recirculation outlet and into the combustor.

* * * * *