(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
4 October 2012 (04.10.2012)

WIPO | PCT

(10) **International Publication Number**
WO 2012/130421 A2

(51) **International Patent Classification**:
F01K 13/00 (2006.01) ***F01K 25/10*** (2006.01)
F01K 25/00 (2006.01)

(21) **International Application Number**:
PCT/EP2012/001291

(22) **International Filing Date**:
23 March 2012 (23.03.2012)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
11159901.5 25 March 2011 (25.03.2011) EP

(71) **Applicant** *(for all designated States except US)*: **CATERPILLAR MOTOREN GMBH & CO. KG** [DE/DE]; Falckensteiner Strasse 2, 24159 Kiel (DE).

(72) **Inventor; and**
(75) **Inventor/Applicant** *(for US only)*: **REEH, Jens-Uwe** [DE/DE]; Butenschönsredder 42, 24220 Flintbek (DE).

(74) **Agent**: **KRAMER - BARSKE - SCHMIDTCHEN**; Landsberger Strasse 300, 80687 München (DE).

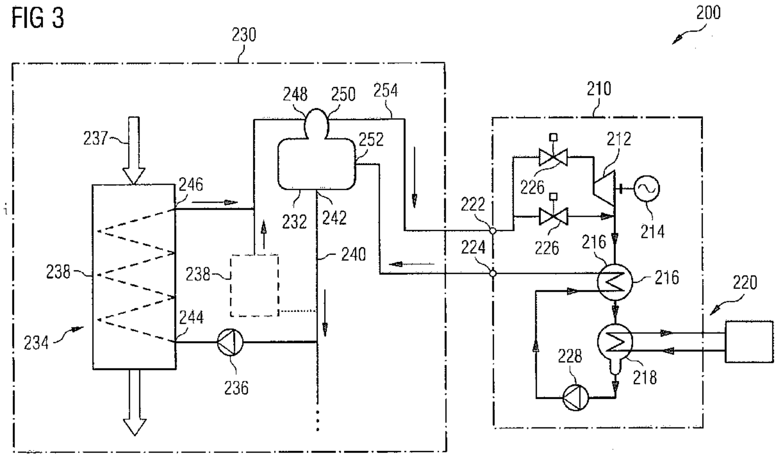
(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title**: DIRECT ORGANIC RANKINE CYCLE SYSTEM, BIOMASS COMBINED CYCLE POWER GENERATING SYSTEM, AND METHOD FOR OPERATING A DIRECT ORGANIC RANKINE CYCLE

FIG 3



(57) **Abstract**: According to an aspect of the present disclosure, a direct organic Rankine cycle system for generating power using a working medium may comprise a boiler subsystem comprising a pump and a boiler, the pump configured to pump the working medium through the boiler, a vapor separator connected to a working medium outlet of the boiler and configured for separating a gaseous phase of the working medium, an organic Rankine turbine module fluidly connected to the vapor separator for refilling the vapor separator with the working medium haven been used in the organic Rankine turbine module, the organic Rankine turbine module comprising a turbine driven by the separated working medium gaseous phase, and a control system configured to control the pump for adjust the circulation speed of the working medium through the boiler such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the boiler.

WO 2012/130421 A2

Description

DIRECT ORGANIC RANKINE CYCLE SYSTEM, BIOMASS COMBINED CYCLE POWER GENERATING SYSTEM, AND METHOD FOR OPERATING A DIRECT ORGANIC RANKINE CYCLE

Technical Field

[01] The present disclosure generally refers to power generation from waste heat and more particularly to using an organic Rankine cycle (ORC) for converting waste heat of multiple waste heat sources to electric power.

Background

[02] The efficiency of generating power with, e.g., a combustion engine can be increased, for example, by additionally generating power from waste heat of the combustion engine, such as the heat of exhaust gas. Similarly, the generation of power from waste heat is used in combined cycle power generation, which combines the generation of power from steam or combustion turbines with at least one additional stage deriving power from waste heat of the steam or combustion turbine using, e.g. an ORC.

[03] Herein the term "combined cycle" is to be understood to include the combination of an ORC with combustion based power generating systems, such as combustion engines, e.g. gas or liquid fuel genset, as well as the combination of an ORC with steam or combustion turbine based power generating systems.

[04] To efficiently generate energy from low-temperature waste heat, ORC technology has been developed. ORC uses a working medium that changes into gas phase at the available temperature of the waste heat and is used to drive an ORC turbine. In general, there are two types of ORC:

[05] Indirect ORC uses an intermediate liquid cycle to transfer the waste heat to the working medium, whereby the working medium circulates in a closed cycle of an ORC unit. These types of system are referred to as closed loop ORC systems.

[06] In contrast, direct ORC (also referred to as open loop ORC) heats the working medium directly with the waste heat. Direct ORC systems are disclosed, for example, in US 2007/0240420 A1 and US 2008/0289313 A1.

[07] A multi-component working-fluid system for low temperature direct Rankine cycles is disclosed, for example, in US 2011/0011089 A1.

[08] The present disclosure is directed, at least in part, to improving or overcoming one or more aspects of prior systems.

Summary of the Disclosure

According to an aspect of the present disclosure, a direct organic Rankine cycle system for generating power using a working medium may comprise a boiler sub-system comprising a pump and a boiler, the pump configured to pump the working medium through the boiler, a vapor separator connected to a working medium outlet of the boiler and configured for separating a gaseous phase of the working medium, an organic Rankine turbine module fluidly connected to the vapor separator for refilling the vapor separator with the working medium haven been used in the organic Rankine turbine module, the organic Rankine turbine module comprising a turbine driven by the separated working medium gaseous phase, and a control system configured to control the pump for adjust the circulation speed of the working medium through the boiler such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the boiler.

[09] According to another aspect, a direct organic Rankine cycle system for generating power using a working medium may comprise a boiler sub-system comprising a pump and a boiler, the pump configured to pump the working medium through the boiler; a vapor separator connected to a working

medium outlet of the boiler and configured for separating a gaseous phase of the working medium; an organic Rankine turbine module fluidly connected to the vapor separator, the organic Rankine turbine module comprising a turbine driven by the separated working medium gaseous phase; a control system configured to control the pump for adjust the circulation speed of the working medium through the boiler such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the boiler.

[10] According to another aspect of the present disclosure, a biomass combined cycle power generating system may comprise a pyrolysis reactor generating pyrolysis oil and pyrolysis gas from biomass; a pyrolysis oil engine for generating power from the pyrolysis oil, thereby producing waste heat; a pyrolysis gas engine for generating power from the pyrolysis gas, thereby producing waste heat; and a direct organic rankine cycle system (e.g. as indicated above) comprising two boiler sub-systems for generating power from the waste heat of the pyrolysis oil engine and the pyrolysis gas engine, wherein the waste heat is supplied to a respective boiler of the boiler sub-systems.

[11] According to an aspect of the present disclosure, a method for operating a direct Rankine cycle may comprise circulating an organic working medium through a boiler at a circulation speed such that at least 15%, 20 %, 30 %, 40 %, or 50% of the organic working medium are maintained in the liquid phase when exiting the boiler.

[12] In some embodiments, the control system may be connected with a temperature sensor for receiving temperature data of the working medium and configured for receiving a load parameter of a genset, which provides waste heat to the boiler sub-system, and wherein the control system may be further configured for deriving a pump speed control parameter for controlling the speed of the pump from the load parameter and the temperature parameter, in particular using a load/temperature depending flow curve tables associated with the boiler sub-system.

[13] In some embodiments, a boiler may be configured for heating the working medium with waste heat of exhaust gas of a combustion and/or waste heat of a high temperature cooling cycle of a combustion engine. The boiler may be operable as a Lamont boiler. The boiler may comprise a super-heating system connected with a gaseous phase outlet of the vapor separator. The super-heating system may be configured for super-heating the separated working medium gaseous phase and providing the super-heated separated working medium gaseous phase to the organic Rankine turbine module.

[14] In some embodiments, the working medium may be selected from the group of organic working media comprising saturated and unsaturated hydrocarbons, fluorated hydrocarbons, silicon oils such as siloxane, ammonia, and ammonia-water mixture.

[15] In some embodiments, the boiler sub-system and the vapor separator may be part of a modular heat rejection system of the direct organic Rankine cycle system, and the modular heat rejection system may comprise a plurality of boiler sub-systems and the pumps of the boiler sub-systems are controlled by the control system such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the respective boiler.

[16] In some embodiments of the biomass combined cycle power generating system, the waste heat may include at least one of heat of exhaust gas and heat of a coolant system of the pyrolysis oil engine and at least one of heat of exhaust gas and heat of a coolant system of the pyrolysis gas engine.

[17] In some embodiments of the method for operating a direct Rankine cycle, the method may comprise circulating an organic working medium through a boiler at a circulation speed such that at least 15%, 20 %, 30 %, 40 %, or 50% of the organic working medium are maintained in the liquid phase when exiting the boiler.

[18] In some embodiments, the method may further comprise heating the working medium in the boiler using waste heat such as heat of an exhaust gas or a cooling circuit of an combustion engine; separating a working medium gas phase and a working medium liquid phase from the heated working medium, eventually additionally super-heating the separated working medium gas phase; deriving power from the separated working medium gas phase; regenerating a working medium liquid phase of the working medium after power generation; and returning a mix of the regenerated working medium liquid phase and the separated working medium liquid phase to the boiler.

[19] In some embodiments, the method may further comprise receiving information on a load parameter of a genset, which provides waste heat to the boiler sub-system; receiving temperature data of the working medium; and deriving a pump speed control parameter from the load parameter and the temperature parameter for controlling the circulation speed.

[20] In general, using direct ORC systems as disclosed herein, which are based on, e.g., heat from the exhaust gas or a charge air cooling system of a combustion engine, may result in a gain in efficiency of, e.g., about 10% in addition to the efficiency of the conventional combustion engine(s) generated power.

[21] In view of the large expense of an ORC system, combining several heat sources within a modular concept for the heat rejection cycle of the working medium may reduce the cost for implementing ORC based generation of power from waste heat.

[22] In addition, various types of heat sources such as high temperature charge air cooling systems can alternatively or additionally be used to preheat the working medium.

[23] In view of the fact that heating an organic working medium directly has to be performed in a manner that does not affect the working medium itself, e.g. causes polymerization, a control concept is disclosed herein for

controlling direct ORC. The control concept may avoid or at least reduce the amount of overheating of the working medium and, thereby, provide long term use of the working medium.

[24] Other features and aspects of this disclosure will be apparent from the following description and the accompanying drawings.

Brief Description of the Drawings

[25] Fig. 1 is a schematic overview of a combined system including a direct ORC system using the waste heat of three gensets;

[26] Fig. 2 is a schematic overview of a combined system for a pyrolysis-based power plant including a direct ORC system using waste heat from a gas genset and a liquid genset;

[27] Fig. 3 is a schematic illustration of a direct ORC system with a modular heat rejection system and an ORC turbine module;

[28] Fig. 4 is a schematic diagram illustrating a direct ORC system with a modular heat rejection system comprising three heat rejection modules;

[29] Fig. 5 is a schematic illustration of a direct ORC system including a super-heating zone;

[30] Fig. 6 is a schematic illustration of a direct ORC system including pre-heating of a working medium before being supplied to the modular heat rejection system and a super-heating zone; and

[31] Fig. 7 is a schematic illustration of an air system and a cooling system of a genset.

Detailed Description

[32] The following is a detailed description of exemplary embodiments of the present disclosure. The exemplary embodiments described therein and illustrated in the drawings are intended to teach the principles of the present disclosure, enabling those of ordinary skill in the art to implement and use the present disclosure in many different environments and for many different

applications. Therefore, the exemplary embodiments are not intended to be, and should not be considered as, a limiting description of the scope of patent protection. Rather, the scope of patent protection shall be defined by the appended claims.

[33] The present disclosure may be based in part on the realization that to increase the efficiency of a power plant, e.g. a biomass based power plant, the waste heat of various gensets or various types of waste heat of one or more genset may be turned into electric power via a common organic Rankine cycle.

[34] Combining multiple waste heat sources via a modular heat rejection cycle as disclosed herein may be based on a common vapor separator and a common ORC turbine module with a turbine and a regenerator.

[35] The common vapor separator may be connectable to the common ORC turbine module to provide the gas phase of the working medium to the turbine and to receive the working medium after regeneration of the working medium with the regenerator of the ORC turbine module. In a combined cycle power generating system, the common vapor separator may be configured as an interface between the ORC turbine module and the modular heat rejection cycles. Moreover, configuring the common vapor separator as an interface that receives the working medium from the ORC turbine module and then distributes the working medium to the various heat rejection cycles may allow a simple control concept of an ORC.

[36] In some embodiments and/or under specific operation conditions, the common vapor separator may be configured to provide the working medium at a common preset temperature prior supplying the working medium to the various heat rejection cycles.

[37] In some embodiments, the common vapor separator may receive the working medium preheated, for example, using a cooling system of the engine and a low temperature region of a boiler. The preheating using the engine cooling system may be performed prior a working medium regeneration unit

while the preheating using the low temperature region of the boiler may be performed after the working medium regeneration unit but prior supplying the working medium to the common vapor separator.

[38] In some embodiments, waste heat at different temperature levels may be used during different stages of the working medium cycle. For example, a low temperature waste heat source such as coolant of the low and/or high temperature cooling circuit of an engine may be used for preheating the working medium following the condensation to supporting the regeneration with the preheated working medium. With respect to high temperature waste heat sources such as exhaust gas, a highest temperature zone within a boiler (superheating zone) may be used for superheating the gaseous phase of the working medium prior being supplied to the turbine. In a medium temperature zone (vaporizing zone), the main energy transfer may take place and initiate the liquid – gaseous phase transition of the working medium. A lowest temperature zone (preheating zone) of a boiler may be used for (additionally) preheating the working medium prior being supplied into a vapor separator and being mixed therein with the liquid phase generated in the vapor separated. In some embodiments, the superheating zone, the vaporizing zone, and the preheating zone of the boiler may be arranged in flow direction of the high temperature waste heat source.

[39] To allow using heat of a plurality of waste heat sources, the common vapor separator may be configured such that a plurality of parallel heat rejection cycles share the common vapor separator. For example, each heat rejection cycle may comprise its own pump and boiler and provide a heating cycle that begins and ends at the common vapor separator. As each heat rejection cycle may have its own pump, the flow within the heat rejection cycles may be adjusted as described herein for protecting the working medium.

[40] For example, to avoid overheating and, thereby, decomposing of the organic working medium, a control concept as described herein may adjust the circulation rate within the heat rejection cycle to a value of 1.3 to 1.5.

Thereby, a value of 1.0 is defined as a circulation rate that results in heating the working medium such that 100% of the working medium changes into the gas phase, i.e. the complete amount of working medium that passes through a boiler is evaporated. Accordingly, a value above 1.0 indicates that more working medium is circulated. As an example, for a value of 1.30, 130 % of the amount of working medium, which correspond to the value of 1.00, are circulated. This corresponds to operating the heat rejection cycles under the Lamont principle. For example, the boiler may be considered to be operated as a Lamont boiler.

[41] As an example, the control strategy as described herein may operate the heat rejection cycles under the condition that at least 30% of the working medium that passes through a boiler is maintained in the liquid phase. Then, an energy buffer may be provided in form of the not yet evaporated working medium such that in case the temperature is further increased the liquid phase can receive that energy.

[42] Specifically, the control concept may control the pump speed within the heat rejection cycles to a value that may provide a time of the working medium within the heat rejection cycle that results in a preset ratio of the fluid and gas phase of the working medium at the exit of the boiler.

[43] In the following and with reference to Figs. 1 to 7, various embodiments of direct ORC systems and their implementation in combined power generating systems are disclosed.

[44] As illustrated in Fig. 1, multiple gensets 10 may provide waste heat to a direct ORC system 20. Specifically, a single genset 10 may provide different types of waste heat to direct ORC system 20 such as heat of exhaust gas, heat of a coolant of a charge-air cooling system, e.g. a high-temperature charge-air coolant cycle and/or a low-temperature charge-air coolant cycle, and heat of jacket water.

[45] While in principle for a fuel combustion engine, as an example of gensets 10, about 50% of the energy input in form of fuel may be transferred into

mechanical output, using waste heat, e.g., of the exhaust gas and/or the charge-air coolant system for a secondary power generation based on an ORC system may result in an increase of e.g. additional 10% of the engine generated power, i.e. in this example additional 5 % of the energy input may be transferred into electricity.

[46] The general concept of applying ORC to multiple gensets 10 is described in the following in connection with Fig.2.

[47] Fig. 2 shows a flow chart for a pyrolysis-based power plant 100 as an example of a power system using biomass integrated liquidation. Pyrolysis-based power plant 100 may be adapted to include an ORC system using waste heat.

[48] Pyrolysis-based power plant 100 may include a pyrolysis reactor 110 that is provided with biomass 111 such as wood or agricultural waste (e.g. stalks of wheat or corn, grass, wood, wood shavings, grapes, and sugar cane). Using, for example, flash-pyrolysis, pyrolysis reactor 110 may generate pyrolysis gas 112A, pyrolysis oil 112B, and char 114. Flash-pyrolysis is a specific type of conventional slow pyrolysis that is performed with the task to maximize te liquid fraction (here pyrolysis oil).

[49] Pyrolysis gas 112A and pyrolysis oil 112B may be provided to conditioning units 120A, 120B. The PCT application PCT/EP2010/002114 of Caterpillar Motoren GmbH & Co. KG filed on 1. April 2010 and published as WO 2011/120542 A1 discloses an exemplary method for preparing (conditioning) pyrolysis oil for an internal combustion engine. The conditioning of the pyrolysis gas may include, for example, cleaning, cooling, and compressing the pyrolysis gas.

[50] Conditioned pyrolysis gas 112A and conditioned pyrolysis oil 112B may be used as fuel for a gas genset 130A and a liquid genset 130B, respectively.

[51] Gensets 130A and 130B may each provide an electricity output 132A, 132B, respectively. Gas genset 130A may be, for example, a conventional gas engine adapted to run with pyrolysis gas. Liquid genset 130B may be, for example, a conventional diesel engine adapted to run with pyrolysis oil.

[52] In addition, gas genset 130A and liquid genset 130B may generate one or more types of waste heat outputs 134A and 134B, respectively. Waste heat outputs 134A and 134B may be provided to an organic Rankine system 140 that uses the waste heat outputs 134A and 134B to additionally provide an electricity output 142.

[53] Organic Rankine system 140 may be based on a direct ORC system, examples of which are described in the following in connection with Figs. 3 to 6. Specifically, direct ORC systems may be based on a modular concept.

[54] Referring to Fig. 3, an exemplary direct ORC system 200 of a modular concept may include an ORC turbine module 210 and a modular heat rejection system 230.

[55] Direct ORC system 200 may be configured such that in a closed cycle, a working medium passes through ORC turbine module 210 and modular heat rejection system 230. Accordingly, the heating of the working medium is performed directly within modular heat rejection system 230 from one ore more waste heat types of one or more gensets (see also Fig. 7). Depending on the energy content and temperature, some types of waste heat may be used to preheat the working medium within ORC turbine module 210 (for example, low temperature and high temperature engine cooling circles) or in-between ORC turbine module 210 and modular heat rejection system 230 (for example, preheating zone of an exhaust gas boiler). Waste heat sources having a large energy content and temperature may be used for vaporizing the working medium within the modular heat rejection system 230 (for example, the higher temperature zones of an exhaust gas boiler).

[56] The ORC working medium is of organic nature instead of water (water steam). Examples of the organic working medium include saturated and unsaturated hydrocarbons, fluorated hydrocarbons, silicon oils such as siloxane, ammonia, and ammonia-water mixture. The type of working medium defines inter alia the temperature range in which the ORC may be performed. Silicone base fluids may, for example, be applied with pyrolysis-based power plant 100.

[57] Referring again to Fig. 3, ORC turbine module 210 may include a turbine 212 for driving a generator 214. ORC turbine module 210 may further include a regeneration unit 216 and a condenser unit 218.

[58] Regeneration unit 216 may transfer heat of the working medium being still in the gaseous phase after having driven turbine 212 to regenerated working medium in the liquid phase.

[59] Condenser unit 218 may be connected to a water cycle 220 and further cool down and condense the working medium until it is in the liquid phase again.

[60] ORC turbine module 210 may further include one or more control valves 226 and one or more pumps 228.

[61] ORC turbine module 210 may further include a working medium inlet 222 and a working medium outlet 224 for a fluid connection between a working medium cycle section within in ORC turbine module 210 and a working medium cycle section within modular heat rejection system 230.

[62] Modular heat rejection system 230 may include a common vapor separator 232 with an inlet 252 and a plurality of boiler sub-systems 234.

[63] For connecting the working medium cycle section within in ORC turbine module 210 and the working medium cycle section within modular heat rejection system 230, working medium outlet 224 of ORC turbine module 210 may be fluidly connected to inlet 252 of vapor separator 232. Accordingly, the working medium may directly flow from in particular regeneration unit 216 into vapor separator 232. In some embodiments, preheating of the working medium

pior being supplied to vapor separator 232 may be performed within the working medium cycle section within in ORC turbine module 210 or in-between ORC turbine module 210 and modular heat rejection system 230, specifically prior being supplied to vapor separator 232. Preheating is described , for example, in connection with Fig. 6 and 7.

[64] Vapor separator 232 may be configured for separating a gaseous phase from a liquid phase of working medium that was heated in boiler sub-systems 234.

[65] Before being supplied to boiler sub-systems 234, the working medium returned from ORC turbine module 210 may be mixed in vapor separator 232 with the separated liquid working medium having passed boiler sub-systems 234, resulting in a further heating of the working medium returned from ORC turbine module 210. The vapor separator (232) may comprise a section for deriving the working medium liquid phase and the working medium gaseous phase and a section for mixing the derived working medium liquid phase and the working medium received from the organic rankine turbine module (210, 410). The mixing within vapor separator 232 may have the further advantage of a simple piping configuration and symmetric conditions when supplying various boiler sub-systems 234 within a combined cycle power generating system.

[66] Each boiler sub-system 234 may include a pump 236 and a boiler 238. Boiler 238 may be configured for transferring heat of a waste heat output of a genset such as exhaust gas 237 or cooling water of an increased temperature onto the working medium. One or more boiler sub-system 234 may be operated according to the Lamont principle. Then, boiler 238 of boiler sub-systems 234 may be considered a Lamont boiler.

[67] Operating boiler sub-systems 234 according to the Lamont principle may provide a fast response time with respect to changes in the heat transfer conditions within respective boiler sub-systems 234. This may be based on a low pipe wall temperature and good alpha-values associated with the heat

transfer. Lamont boiler may further be based on small size pipes, which may also positively affect the response time. These advantages may in particular apply to the concept of adjusting the circulation rate within the heat rejection cycle to a value of 1.3 to 1.5.

[68] In the exemplary embodiment shown in Fig. 3, multiple boiler sub-systems 234 may be fluidly connected to vapor separator 232 via one or more boiler sub-system connection lines 240.

[69] Referring exemplarily to boiler sub-systems 234 shown in detail in Fig. 3, a separator outlet 242 of vapor separator 232 may be connected to a pump 236 of boiler sub-systems 234 via boiler sub-system connection line 240. For boiler sub-system 234, pump 236 may be connected to a boiler inlet 244 of respective boiler 238. A boiler outlet 246 of boiler 238 may be connected to a separator inlet 248 of vapor separator 232. A vaporizing pipe system (schematically indicated by dashed lines) may be integrated into boiler 238. The vaporizing pipe system may be configured to transfer heat of the high temperature waste heat source (e.g. exhaust gas) to the working medium.

[70] A gas phase outlet 250 of vapor separator 232 may be connected via a connection line 254 to working medium inlet 222 of ORC turbine module 210 such that the gaseous phase working medium may be provided to turbine 212 for driving generator 214, thereby closing the working medium cycle. Super heating of the gas phase may additionally be performed between the gas phase outlet 250 and working medium inlet 222 of ORC turbine module as described below in connection with Fig. 5.

[71] During operation, exhaust gas at a temperature of e.g. 310°C and a mass of e.g. 75000-112000 kg/h may be supplied through boiler 238. Pump 236 may pump the working medium through boiler 238 such that the working medium partially changes into the gas phase and a mixture of working medium in the gaseous phase and the liquid phase is generated. The exhaust gas may exit boiler 238 at a temperature of about 180°C.

[72] As an example of the temperature development of the working medium, the working medium may exit ORC turbine module 210 at a temperature of about 170°C and may be heated in boiler 238 to a temperature of about 250°C in a mixed state of the working medium being partially in a gaseous phase and partially in a liquid phase. After the separation in vapor separator 232, the gaseous working medium enters the ORC turbine module 210 at a temperature of about 250°C.

[73] The mixture of gas phase and liquid phase of the heated working medium may be supplied to and separated in vapor separator 232 so that only the gas phase may be provided to ORC turbine module 210.

[74] During operation of ORC turbine module 210, turbine 212 may drive generator 214 by the gaseous working medium, which thereby expands and decreases in temperature. Downstream of turbine 212, working medium may pass regeneration unit 216, in which heat of the still gaseous working medium may be transferred to the liquid working medium, which has been generated in condenser 218 from the gaseous phase of the working medium using water cycle 220.

[75] The separation of gas phase and liquid phase of the heated working medium in vapor separator 232 and the supplying of the gas phase to turbine 212 results in liquid working medium at (referring to the above example) 250 °C that than may be mixed in vapor separator 232 with (potentially preheated) working medium being received from ORC turbine module 210 (in the embodiment shown in Fig. 3 being received from regeneration unit 216).

[76] As indicated in Fig. 3, additional boiler sub-systems 234 may be fluidly connected to vapor separator 232. Specifically, distributing the working medium to additional boiler sub-systems 234 may be performed via boiler sub-system connection line 240 (see also Fig. 4).

[77] For a direct ORC system with three boiler sub-systems 234, Fig. 4 illustrates the flow of the working medium within boiler sub-systems 234. Moreover, Fig. 4 illustrates the control of pumps 236 of boiler sub-systems 234.

[78] Specifically, beginning at outlet 224 of ORC turbine module 210, regenerated working medium may be provided to vapor separator 232, specifically through inlet 252, and mixed in vapor separator 232 with the working medium originating from the separation process of vapor separator 232. Alternatively, or in addition, the regenerated working medium and the separated working medium may be mixed external to vapor separator 232.

[79] Referring again to Fig. 4, at outlet 242, working medium may exit vapor separator 232 along boiler sub-system connection line 240, which may distribute the working medium to three boiler sub-systems 234, each including at least one pump 236 and at least one boiler 238.

[80] Pumps 236 may be controlled via a control unit 305 to adjust the circulation speed of the working medium through boilers 238 such that at least 15%, 20%, 30%, 40%, or 50% of the working medium are maintained in the liquid phase when exiting respective boilers 238. For that purpose, control unit 305 may receive information of physical parameters (such as temperature and pressure) of the working medium after the heating process in boilers 238. For example, respective sensors may be provided at or downstream of outlets 246. Alternatively or in addition, control unit may receive information on the current performance and/or future performance of the gensets.

[81] As an example, in some embodiments, a load /temperature depending flow curve table may be provided in control unit 305. The load refers to the load of the genset of which the waste heat is used in the respective boiler sub-system. The temperature refers to the temperature of the working medium measured within the working medium loop of that respective boiler sub-system. Fig. 4 shows schematically a temperature measurement line 307 connecting control unit 305 with a temperature sensor 308 installed downstream of boiler 238. In Fig. 4, only one temperature measurement line 307 is shown exemplarily. In general, temperature measurement lines may be provided for one or more boiler sub-systems.

[82] The load /temperature depending flow curve may be used to control the speed of respective pump 236 within a predefined range of throughput through boiler 238. Accordingly, control unit 305 may assess the parameter load of the genset and temperature of the working medium and derive there from a control parameter for controlling the pump speed. The control output parameter may be limited such that the speed of pump 236 may only be adjustable within a range of, e.g., 70-100%.

[83] Control unit 305 may comprise a memory unit for providing load /temperature depending flow curve tables for each of the boiler sub-systems. Control system may further be connected via control lines 306 to pumps 236 of each of the boiler sub-systems.

[84] In general, control unit 305 may allow adjusting individually the circulation speed for each boiler and associated waste heat source such that the organic working medium is protected, e.g., from thermal decomposition.

[85] For example, increases the temperature of the working medium towards a preset temperature limit, the pump speed may be increased as well. Similarly, is the load of the genset increased, an increase of, e.g., the exhaust gas temperature may be expected and, accordingly, the pump speed can be increased to avoid, to limit or at least to slow down the increase of temperature and phase transition of the working medium. In some embodiments, by-pass lines may be provided that allow the waste heat carrying medium to by-pass respective boiler(s) such that also by controlling the flow of the waste heat carrying medium the temperature and phase transition of the working medium may be ensured to be within acceptable limits.

[86] Referring again to Fig. 4, waste heat from, for example, three gensets such as combustion engines, e.g. diesel or gas engines, may be transferred onto the working medium in boilers 238. The heated working medium may then be combined and provided to inlet 248 of vapor separator 232.

[87] Vapor separator 232 may separate the gaseous phase of the working medium from the liquid phase and provide the gaseous phase via outlet 250 and line 254 to inlet 222 of ORC turbine module 210.

[88] An embodiment of a boiler for modular heat rejection system 230 is described in connection with Fig. 5. Specifically, heat rejection system 230 may include a boiler 438 that includes a superheating zone 460.

[89] In the embodiment shown in Fig. 5, ORC turbine module 210 as well as the heat transfer in boiler sub-systems 234 onto the liquid phase working medium may work essentially as described in connection with Figs. 3 and 4.

[90] The embodiment shown in Fig. 5 distinguishes from the system shown in Fig. 3 downstream of gaseous phase outlet 250 of vapor separator 232. Instead of being directly connected to ORC turbine module 210, gaseous phase outlet 250 may be connected to an inlet 462 of a superheating pipe system (schematically indicated by dashed lines) within superheating zone 460 of boiler 438. The superheating pipe system may be configured to transfer heat of the high temperature waste heat source (e.g. exhaust gas) to the gaseous phase of the working medium

[91] In Fig. 5, several reference signs for features, which essentially maintain unchanged with respect to the embodiment of Fig. 3, were nor reproduced to increase clarity of the illustration.

[92] In superheating zone 460, the gaseous phase working medium is superheated by the waste heat of e.g. exhaust gas 237 entering boiler 438. Superheated gaseous phase working medium may exit superheating zone 460 at outlet 464, which may then be fluidly connected to inlet 222 of ORC turbine module 210, such that the gaseous phase working medium may be provided at a higher temperature to increase the efficiency of turbine 212.

[93] As indicated in Fig. 5, additional boiler sub-systems 234 may include boilers 438 with superheating zones 460. Accordingly, gaseous phase may be distributed to additional superheating zones as indicated by line 466. In

that case, superheated gaseous phase working medium exiting additional superheating zones 460 at outlet 464 may be combined with superheated working medium from other superheating zones as indicated by line 468. In some boiler sub-systems 234 may not have a superheating zone and mixtures of superheated and not superheated gas phases may be supplied to ORC turbine module 210.

[94] Similarly, as indicated in Figs. 3 and 4, additional boiler sub-systems 234 may be provided such that heated working medium from a plurality of boiler sub-systems 234 is combined before entering vapor separator 232 at inlet 248.

[95] An embodiment of a direct ORC system using intensified preheating of the working medium is described in connection with Fig. 6. In Fig. 6, several reference signs for features, which essentially maintain unchanged with respect to the embodiment of Figs. 3 and 4, were nor reproduced to increase clarity of the illustration.

[96] Fig. 6 shows a direct ORC system that includes an ORC turbine module 510 and a boiler sub-system 534 including a superheating zone 460 as described in connection with Fig. 5.

[97] In addition to the preheating discussed already in connection with Fig. 3 and regeneration unit 216, the embodiment of Fig. 6 shows two types of preheating of the regenerated working medium: a heat transfer unit 570 interacting with ORC turbine module 510 and a preheating zone 580 of boiler sub-system 534. One or more of those types of preheating may be performed to adapt the temperature of the working medium coming from ORC turbine module 510 to the temperature of the separated liquid phase working medium provided by vapor separator 232.

[98] In the section of the working medium cycle within ORC turbine module 510, preheating with a low temperature heat source such as, for example, a high-temperature or low-temperature cooling circuit of a combustion engine (see also Fig. 7) may be implemented.

[99] Specifically, heat transfer unit 570 may receive heat from a coolant medium 571 of a coolant cycle of a genset, e.g. a combustion engine, and transfer that heat to the regenerated working medium exiting pump 228. For that purpose, heat transfer unit 570 may be fluidly connected with pump 228 and regeneration unit 216.

[100] The working medium exiting condenser 218 at a temperature of, e.g., about 50°C may be heated in heat transfer unit 570 to a temperature of, e.g., about 120°C. As shown by the dotted lines and arrows between pump 228 and heat transfer unit 570 as well as between heat transfer unit 570 and regeneration unit 216, multiple heat transfer units associated with the same or different gensets may be employed, for example, using a parallel arrangement of those heat transfer units. Thereafter, the working medium may be further be heated by regeneration unit 216 to a temperature of, e.g., about 190°C.

[101] In the section of the working medium cycle within boiler sub-systems 534, preheating may be performed using, e.g., the low-temperature section of at least one boiler 538 of boiler sub-systems 524. Specifically, before entering vapor separator 232, the working medium may pass preheating zone 580. E.g., outlet 224 of ORC turbine module 510 may be fluidly connected with inlet 582 of a preheating pipe system of preheating zone 580. The preheating pipe system (schematically indicated by dashed lines) may be configured to transfer heat of the high temperature waste heat source (e.g. exhaust gas) to the, for example preheated, working medium prior being supplied to vapor separator 232.

[102] The preheated working medium may leave preheating zone 580 at outlet 584 at a temperature of, e.g., about 260°C. Also the preheating within preheating zone 580 may be structurally associated with boiler sub-systems 534, in a funktional point of view, vapor separator 232 may be considered as an interface between ORC turbine module 510 and the working medium cycle section within boiler sub-systems 534. In that point of view, preheating within preheating zone 580 may be either considered to belong to the working medium

cycle section of ORC turbine module 510 or to be an inserted additional working medium cycle section.

[103] As shown by the dotted lines and arrows between regeneration unit 216 and inlet 582 as well as between outlet 584 and vapor separator 232, multiple preheating zones of the same or different boilers 538 may be employed, for example, using a parallel arrangement of those preheating zones.

[104] Outlet 584 may be fluidly connected to inlet 252 of vapor separator 232 in which the preheated working medium is mixed with the separated liquid phase working medium being also at a temperature of, e.g, 260°C.

[105] As described in connection with Figs. 3 and 4, boiler 538 may provide a heating cycle of the liquid working medium controlled by pump 236 such that the circulation speed of the working medium may provide the working medium to vapor separator 232 in a gas liquid mixed state.

[106] As described in connection with Fig. 5, the separated gas phase may be provided to superheating zone 460 of boiler 538 to further heat the gaseous phase working medium, for example, to a temperature of, e.g., 270°C before providing the super-heated gaseous phase working medium to turbine 212.

[107] Exemplarily, waste heat sources of a genset for the direct organic Rankine cycle systems disclosed herein are illustrated in Fig. 7 based on a schematic medium-sized diesel or gas engine.

[108] Specifically, Fig. 7 shows an exemplary air system and cooling systems of a conventional combustion engine 700 such as gas engine 130A or liquid fuel engine 130B used in pyrolysis-based power plant 100 described in connection with Fig. 2. In Fig. 7, dual line arrows refer to the air system, e.g. stream of the charge air and exhaust gas, and single line arrows refer to the cooling systems, e.g. the stream of a coolant medium, usually water.

[109] Engine 700 may comprise a turbocharger system 710 (single or double stage), a high temperature cooling circle 720, and a low temperature cooling circle 730.

[110] Assuming an initial temperature of the charge air of 25°C, the compression of the charge air in turbocharger system 710 may increase the temperature of the charge air from 25°C to 225°C. High temperature cooling circle 720 may reduce the temperature of the charge air from 225°C to 90°C and low temperature cooling circle may reduce the temperature of the charge air further from 90°C to 45°C such that engine 700 is charged with air at a temperature of about 45°C.

[111] After the combustion process, exhaust gas at a temperature of several hundred degrees may exit the combustion chamber and may be used to drive turbocharger system 710. After turbocharger system 710, the temperature of the exhaust gas may be reduced to about 310°C.

[112] In general, heat can be recovered from coolant medium 571 of high temperature cooling circle 720 and/or low temperature cooling circle 730 as well as from high temperature exhaust gas 237 before or after turbocharger system 710.

[113] As an example, boiler 238 is indicated to use the waste heat of exhaust gas 237 after turbocharger system 710 (for example, for preheating, evaporating, and superheating of the working medium in respective sections) and heat transfer unit 570 is indicated to use the waste heat of coolant medium 571 of high temperature cooling circle 720 and/or low temperature cooling circle 730 (for example, within the working medium cycle section within the ORC turbine module).

Industrial Applicability

[114] The term "genset" as used herein comprises inter alia internal combustion engines and steam or combustion turbine based power generating systems.

[115] The term "internal combustion engine" as used herein is not specifically restricted and comprises any engine, in which a fuel combustion process is performed. Examples of fuel include gas or liquid fuel such as diesel, marine diesel, and pyrolysis oil. Examples of internal combustion engines for the herein disclosed configuration of a two-stage turbocharged system include medium speed internal combustion diesel engines, like inline and V-type engines of the series M20, M25, M32, M43 manufactured by Caterpillar Motoren GmbH & Co. KG, Kiel, Germany, operated in a range of 500 to 1000 rpm as well as high speed gas engines, e.g. provided by Caterpillar Motoren GmbH & Co. KG, Kiel

[116] The herein disclosed types of preheating and super-heating may be included in an ORC system alone or in combination/sub-combination.

[117] In some embodiments, the section of the vapor separator for mixing the derived working medium liquid phase and the working medium received from the organic rankine turbine module may be a mixing chamber supplied, from the section for deriving the liquid and gaseous phases, with the derived working medium liquid phase and, from the organic rankine turbine module, with the working medium.

[118] The modular ORC systems disclosed herein may allow increasing the over all efficiency (e.g. the generated power) of diesel, gas, biomass power plants as well as reducing the operation costs.

[119] Percentages indicated herein with respect to the working medium being maintained in the liquid phase, e.g. 15%, 20 %, 30 %, 40 %, or 50% being maintained in the liquid phase, relate to volume percentages (% by volume), which in the case of a liquid does essentially not differ from mass percentages. For example, when a pump adjusts the circulation speed of the working medium through the boiler such that at least 15% of the working medium are maintained in the liquid phase when exiting the boiler, the working medium supplied to the boiler is in the liquid phase and represents 100% of the volume. After the boiler,

at least 15% by volume of the working medium is still in the liquid phase and 85% by volume or less of the working medium supplied to the boiler evaporated and are in the gaseous phase.

[120] Although the preferred embodiments of this invention have been described herein, improvements and modifications may be incorporated without departing from the scope of the following claims.

Claims

1. A direct organic Rankine cycle system (200) for generating power using a working medium, the direct organic Rankine cycle system (200) comprising:

a boiler sub-system (234) comprising a pump (236) and a boiler (238), the pump (236) configured to pump the working medium through the boiler (238);

a vapor separator (232) fluidly connected to a working medium outlet (246) of the boiler (238), fluidly connected to the pump (236), and configured for separating a gaseous phase of the working medium;

an organic Rankine turbine module (210, 410) fluidly connected to the vapor separator (232) for providing the vapor separator (232) with the working medium having been used in the organic Rankine turbine module (210, 410) and being in the liquid phase, the organic Rankine turbine module (210, 410) comprising a turbine (212) driven by the separated working medium gaseous phase; and

a control system (305) configured to control the pump (236) for adjust the circulation speed of the working medium through the boiler (238) such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the boiler (238).

2. The direct organic Rankine cycle system (200) according to claim 1, wherein the control system (305) is connected with a temperature sensor (308) for receiving temperature data of the working medium and configured for receiving a load parameter of a genset, which provides waste heat to the boiler sub-system (234), and wherein the control system (305) is further configured for deriving a pump speed control parameter for controlling the speed of the pump (236) from the load parameter and the temperature parameter, in

particular using a load/temperature depending flow curve tables associated with the boiler sub-system (234).

3. The direct organic Rankine cycle system (200) according to claim 1 or 2, wherein the boiler (238) is configured for heating the working medium with waste heat of exhaust gas of a combustion engine (130A, 130B) and/or waste heat of a high temperature cooling cycle of a combustion engine (130A, 130B).

4. The direct organic Rankine cycle system (200) according to any one of the preceding claims, wherein the boiler (238) comprises a super-heating piping system connected with a gaseous phase outlet of the vapor separator, the super-heating system (460) configured for super-heating the separated working medium gaseous phase and providing the super-heated separated working medium gaseous phase to the organic Rankine turbine module.

5. The direct organic Rankine cycle system (200) according to any one of the preceding claims, wherein the boiler (238) is operatable as a Lamont boiler.

6. The direct organic Rankin cycle system (200) according to any one of the preceding claims, wherein the working medium is selected from the group of organic working media comprising saturated and unsaturated hydrocarbons, fluorated hydrocarbons, silicon oils such as siloxane, ammonia, and ammonia-water mixture.

7. The direct organic Rankine cycle system (200) according to any one of the preceding claims, wherein the boiler sub-system (234) is one of a plurality of boiler sub-systems each having a boiler, and each boiler is fluidly

connected to the vapor separator (232) and configured for heating the working medium with waste heat.

8. The direct organic Rankine cycle system (200) according to claim 7, wherein the vapor separator (232) comprise an inlet (252) for regenerated working medium provided by the organic Rankine turbine module (210, 410) for mixing the regenerated working medium with the separated liquid working medium and/or wherein a gaseous phase outlet of the vapor separator (232) is configured for providing the separated working medium gaseous phase to the organic Rankine turbine module (210, 410) directly or via a super-heating zone (460).

9. The direct organic rankine cycle system (200) according to any one of the preceding claims, wherein the boiler sub-system (234) and the vapor separator (232) are part of a modular heat rejection system (230) of the direct organic Rankine cycle system (200), and the modular heat rejection system (230) comprises a plurality of boiler sub-systems and the pumps of the boiler sub-systems are controlled by the control system such that at least 15%, 20 %, 30 %, 40 %, or 50% of the working medium are maintained in the liquid phase when exiting the respective boiler.

10. The direct organic rankine cycle system (200) according to any one of the preceding claims, wherein the organic Rankine turbine module (210, 410) further comprises a heating system (570) for heating regenerated working medium in the liquid phase, e.g., by the heat of a charge air coolant system of a combustion engine.

11. A biomass combined cycle power generating system (100) comprising:

a pyrolysis reactor (110) generating pyrolysis oil and pyrolysis gas from biomass;

a pyrolysis oil engine (130B) for generating power from the pyrolysis oil, thereby producing waste heat;

a pyrolysis gas engine (130A) for generating power from the pyrolysis gas, thereby producing waste heat; and

a direct organic rankine cycle system according to any of the preceding claims 1-11 comprising two boiler sub-systems (234) for generating power from the waste heat of the pyrolysis oil engine (130B) and the pyrolysis gas engine (130A), wherein the waste heat is supplied to a respective boiler of the boiler sub-systems.

12. The biomass combined cycle power generating system (100) of claim 11, wherein the waste heat includes at least one of heat of exhaust gas and heat of a coolant system of the pyrolysis oil engine (130B) and at least one of heat of exhaust gas and heat of a coolant system of the pyrolysis gas engine (130A).

13. A method for operating a direct organic Rankine cycle, the method comprising:

circulating an organic working medium through a boiler (238) at a circulation speed such that at least 15%, 20 %, 30 %, 40 %, or 50% of the organic working medium are maintained in the liquid phase when exiting the boiler (238).

14. The method of claim 13, further comprising:

heating the working medium in the boiler (238) using waste heat such as heat of an exhaust gas or a cooling circuit of an combustion engine;

separating a working medium gas phase and a working medium liquid phase from the heated working medium, eventually additionally superheating the separated working medium gas phase;

deriving power from the separated working medium gas phase;

regenerating a working medium liquid phase of the working medium after power generation; and

returning a mix of the regenerated working medium liquid phase and the separated working medium liquid phase to the boiler (238), for example, after mixing the regenerated working medium liquid phase with the separated working medium liquid phase.

15. The method of claim 13 or 14, further comprising:

receiving information on a load parameter of a genset, which provides waste heat to the boiler sub-system (234);

receiving temperature data of the working medium; and

deriving a pump speed control parameter from the load parameter and the temperature parameter for controlling the circulation speed.

FIG 1

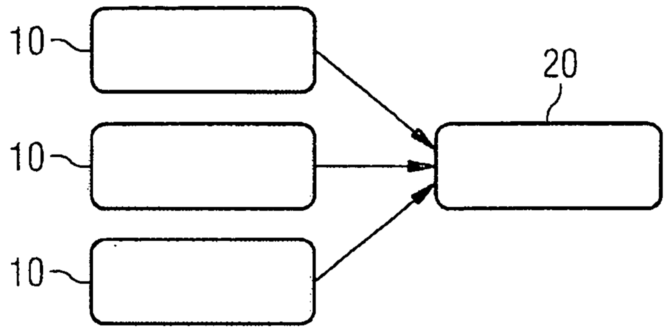
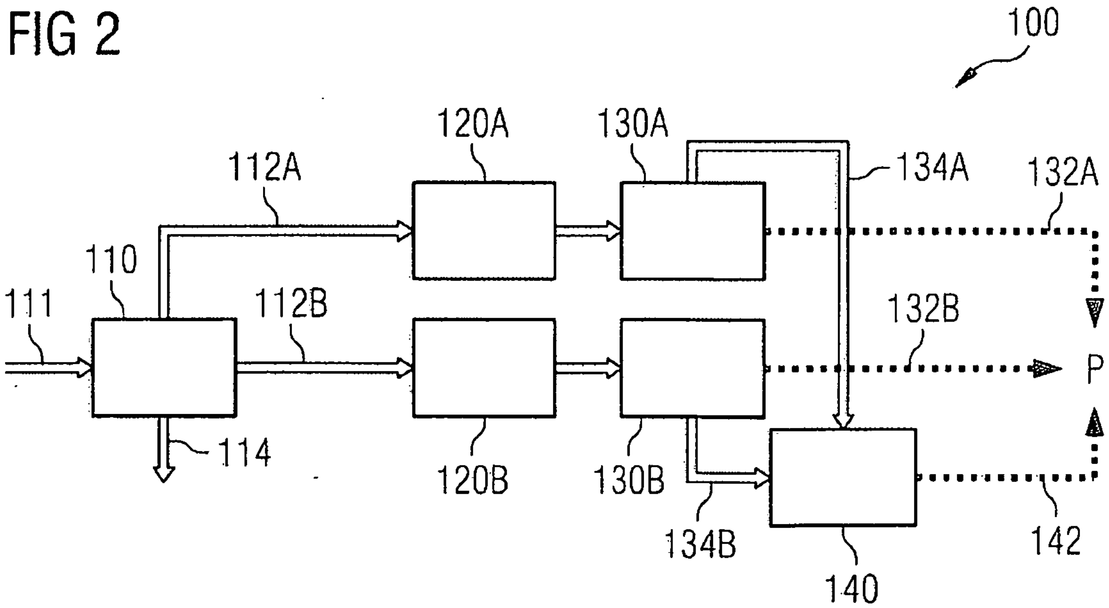

10
10
10
20

FIG 2


100
120A
130A
134A
132A
112A
110
111
112B
132B
P
114
120B
130B
134B
140
142

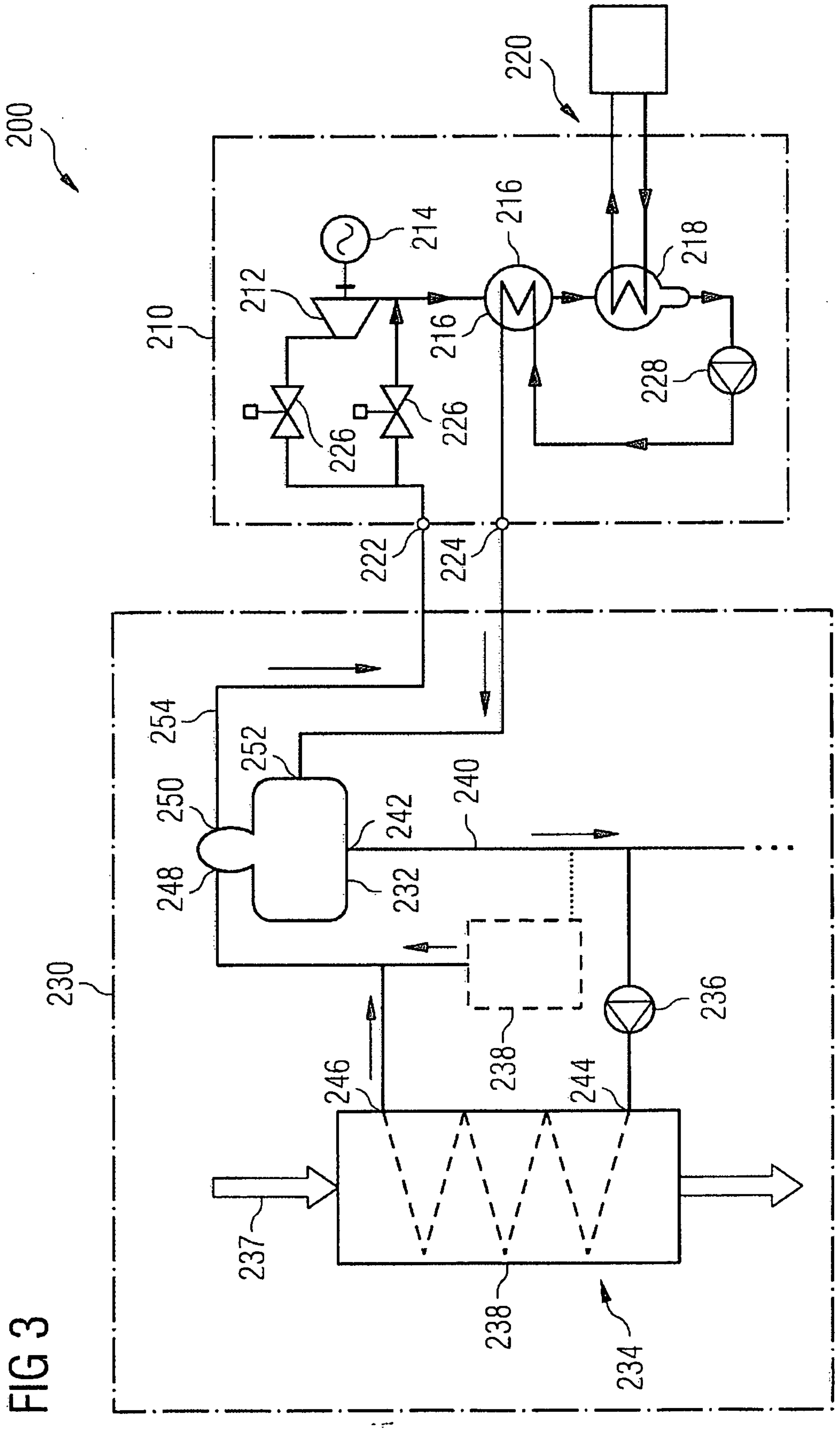

200
210
212
214
216
216
218
220
222
224
226
226
228
230
232
234
236
237
238
238
240
242
244
246
248
250
252
254

FIG 3

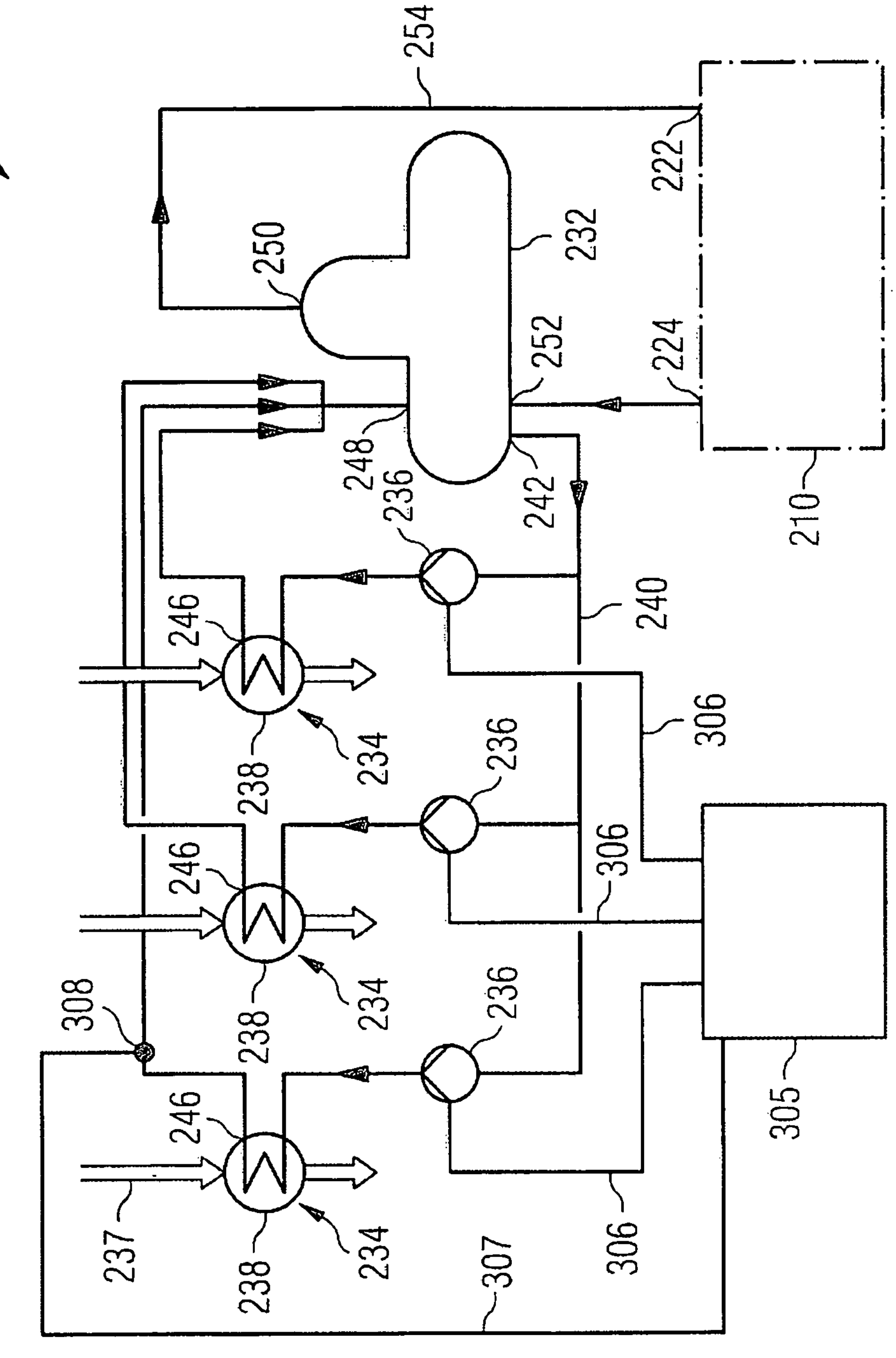

230
254
222
232
250
252
224
248
242
236
210
240
246
306
234
238
308
305
237
307

FIG 4

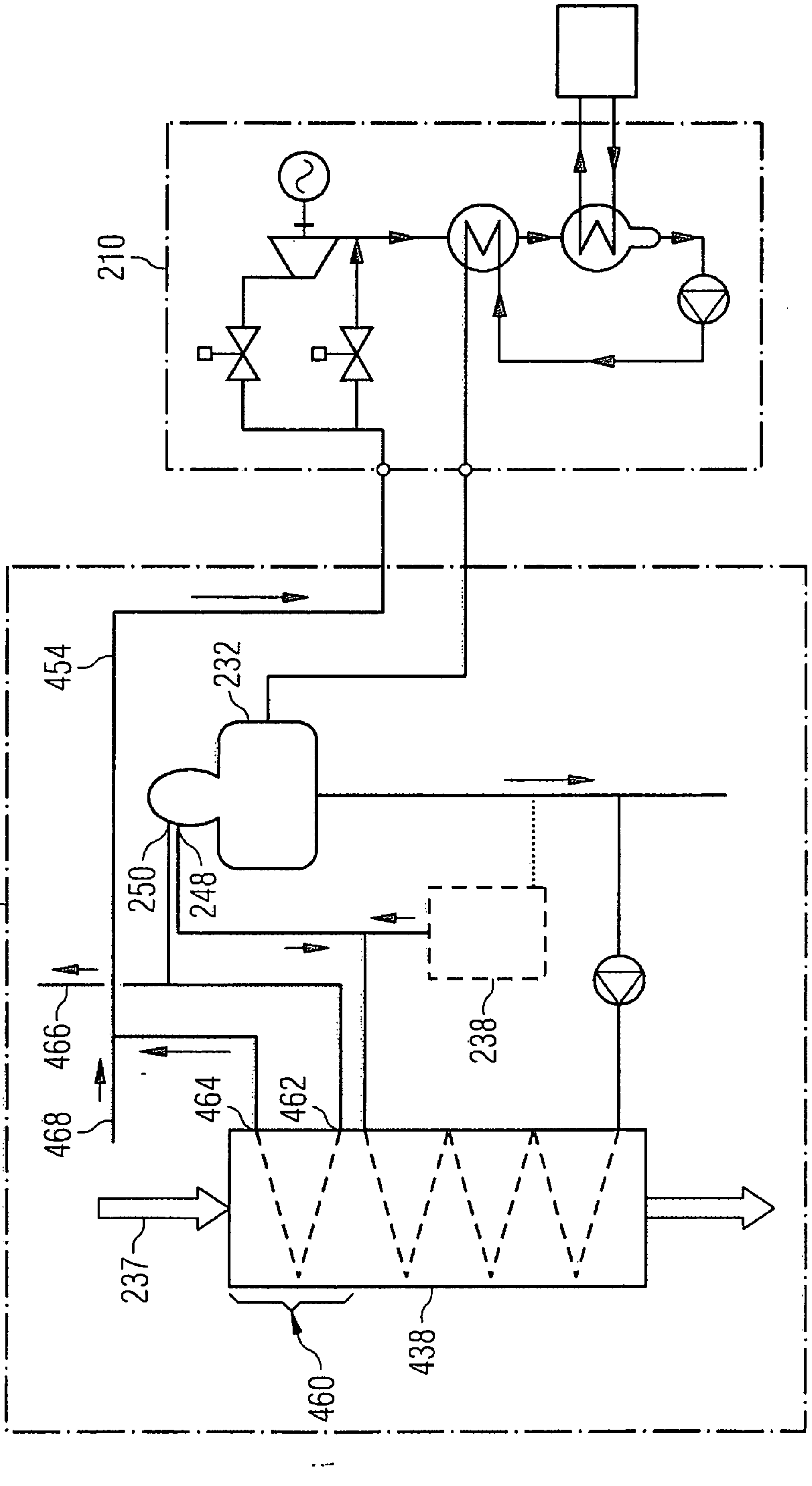


FIG 5

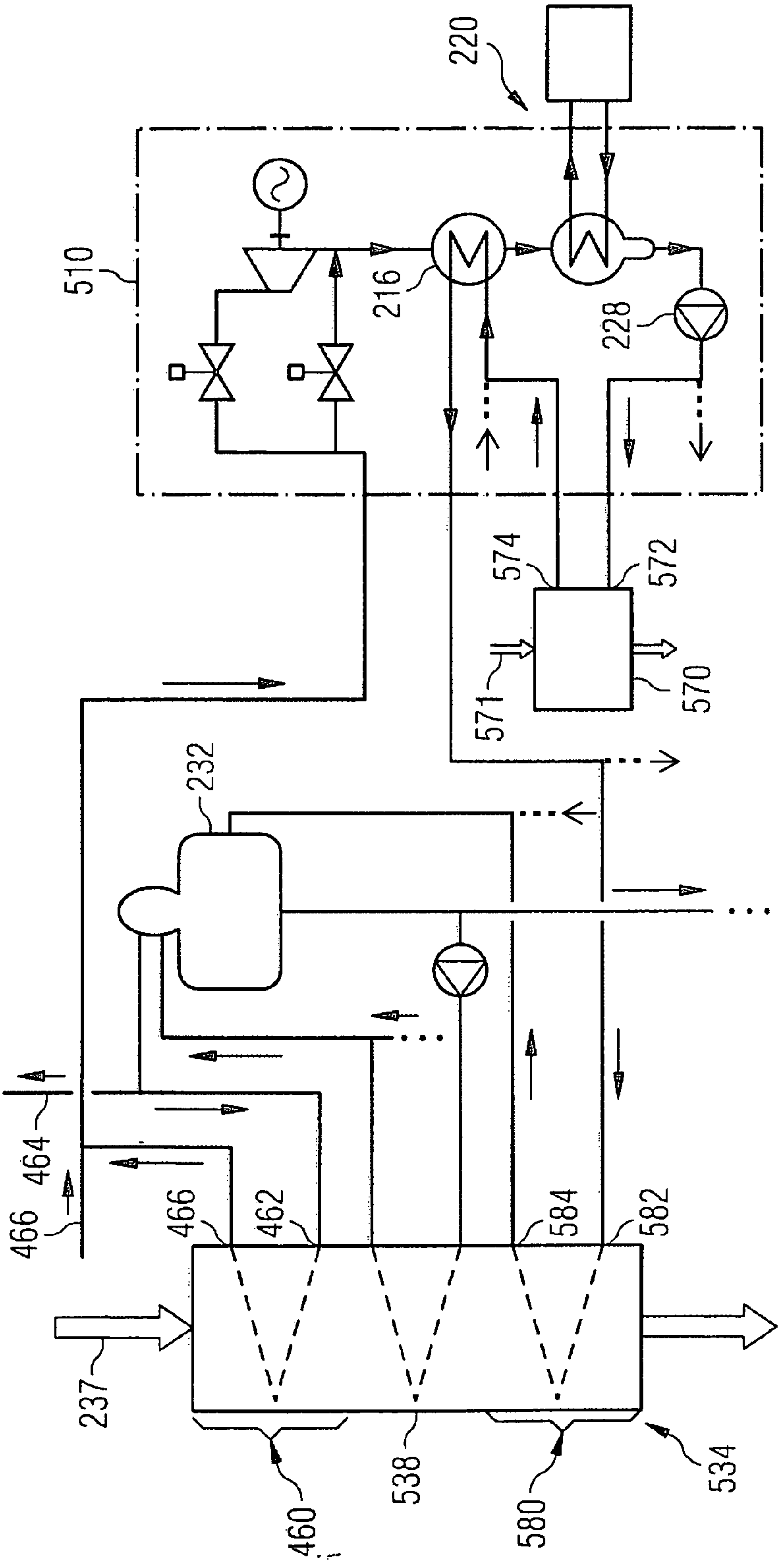

220
510
216
228
574
572
571
570
232
466
464
466
462
584
582
237
538
460
580
534

FIG 6

FIG 7