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(54) Conversion system for converting waste heat to shaft power

(57) The present invention relates to the conversion of industrial waste heat, and particularly to a conversion system (30) for converting waste heat from an industrial waste heat source (7) to shaft power. A conversion system (30) for converting waste heat from an industrial waste heat source (7) to shaft power is provided, the conversion system (30) having a closed Organic Rankine Cycle (ORC) system (16), comprising an evaporator (1) for evaporating an ORC working fluid and heated by the waste heat, a turbine (2) driven by the evaporated ORC working fluid and connected to a shaft (3), and a condenser (5), fluidly interconnected between the turbine (2) and the evaporator (1), wherein the ORC working fluid is organic, non-toxic, and non-fluorinated.

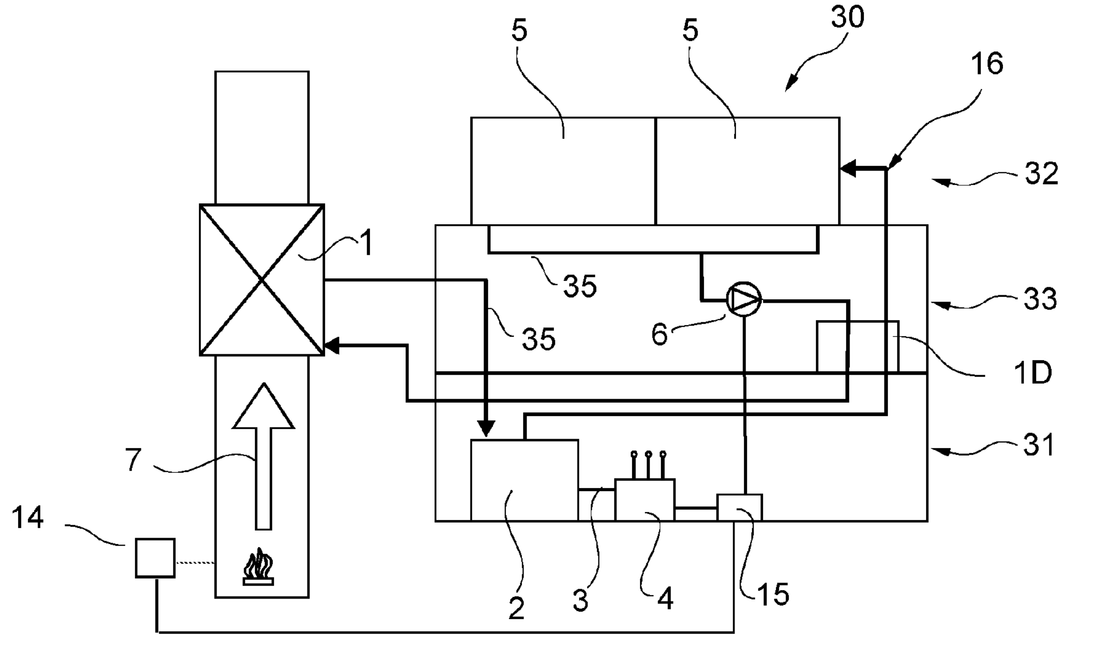

Fig. 3

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Description

FIELD OF THE INVENTION

[0001] The invention relates to the field of waste heat recovery, and is particularly concerned with conversion of waste heat from an industrial waste heat source to shaft power.

BACKGROUND OF THE INVENTION

[0002] Industrial processes generally produce waste heat, e.g. by gas condensation or cooling fluids, or comprised in exhaust gases or cooling air from cement, chemical, glass, paper or steel production processes, from waste incineration processes, or from fuel combustion in internal combustion engines such as gas turbines or reciprocating engines. Such waste heat is commonly discharged to the atmosphere. However, in order to improve the overall efficiency of the industrial processes without increasing the output of emissions, a bottoming cycle for recovering the waste heat is commonly used. Bottoming cycles usually require high exhaust temperatures, yet an example of a bottoming cycle which requires lower exhaust temperatures is the Organic Rankine Cycle (ORC). ORC produces shaft power from lower temperature waste heat sources by using an organic working fluid with a boiling temperature suited to the heat source.

[0003] The closed rankine cycle comprises an evaporator or boiler for the evaporation of a working fluid, a turbine fed with vapour from the evaporator to drive a generator or other load, a condenser for condensing the exhaust vapour from the turbine and means, such as a pump, for recycling the condensed working fluid to the evaporator. Such rankine cycle systems are used for the purpose of generating electrical power. By way of example, the patent US 6,880,344 describes a closed rankine cycle that can efficiently use waste heat from several sources in a reciprocating or gas turbine engine system.

[0004] WO 2008/074637 discloses a system for converting waste heat from a waste heat source into shaft power, comprising a closed rankine cycle system including an evaporator for evaporating a working fluid and heated by the waste heat, a turbine driven by the evaporated working fluid and connected to a shaft, and a condenser fluidly interconnected between the turbine and the evaporator. The waste heat temperature at the evaporator is below 350°C, and the pressure of the evaporated working fluid does not exceed 8 bar. The working fluid, e.g. known as R-245fa, adapted to these conditions is organic, non-toxic and fluorinated. As a consequence, fluorinated fluid may escape. The fluid is chemically stable and is a green house gas, i.e. it contributes to climate change, and thus might be subject to environmental regulations. Ultimately specific and costly measures may be required on the system to avoid working fluid residues to escape to the atmosphere.

SUMMARY OF THE INVENTION

[0005] It may be seen as an object of the invention to reduce an environmental impact of a waste heat conversion system based on an Organic Rankine Cycle ORC. This object is achieved by a conversion system for converting waste heat from a waste heat source to shaft power, as well as an industrial plant according to the independent claims. Further embodiments are evident from the dependent claims.

[0006] According to one embodiment of the invention, a conversion system for converting waste heat from an industrial waste heat source to shaft power is provided, the conversion system having a closed rankine cycle system, comprising an evaporator heated by the waste heat, a turbine connected to a shaft and driven by an ORC working fluid evaporated in the evaporator, and a condenser fluidly interconnected between the turbine and the evaporator, wherein the ORC working fluid is organic, non-toxic, and non-fluorinated. Reverting to an ORC working fluid without fluorine reduces environmental concerns without requiring dedicated leakage prevention, and thus contributes to the public acceptance of the waste heat conversion system.

[0007] Preferably, the ORC working fluid consists of pure hydrocarbon compounds such as isobutane (C_4H_{10}) and pentane (C_5H_{12}), or a combination thereof. Such ORC working fluids circulate in the rankine cycle at a pressure above ambient pressure, both in the gaseous and in the liquefied phase. This improves the black-start capabilities, as no vacuum has to be produced after the turbine to start up the system.

[0008] In the context of the present invention, the term industrial waste heat source refers to industrial plants having a primary goal other than producing or exploiting the waste heat. This in particular excludes geothermal heat sources and renewable-based heat sources such as wood chips fired boilers.

[0009] Exemplary waste heat sources include exhaust gas from fuel combustion in internal combustion engines such as gas turbines or reciprocating engines; stack gas or waste gas from e.g. waste incineration processes and expelled through a chimney; cooling air from cement, chemical, glass, paper, or steel production processes; or cooling water from industrial processes or combustion engines. Specifically, clinker cooler air of a cement plant and waste gas of a pre-heater tower of a same cement plant may be considered. Of course, availability of the waste heat of an industrial plant for producing shaft power has to be balanced against other possible uses of the same waste heat, both plant-internal, e.g. for drying, or plant-external, e.g. for district heating.

[0010] In an advantageous embodiment, the system comprises an intermediate circuit for transferring waste heat to the evaporator. The intermediate circuit comprises a heat exchanger for heating, by the waste heat, of an intermediate circuit working fluid such as pressurized water. The heated intermediate circuit working fluid is then circulated to the evaporator, where the waste heat is further transferred to the ORC working fluid. The intermediate circuit is particularly preferred in case of high dust load in the heat source such as in cement plants.

[0011] In a preferred embodiment, the working fluid of the intermediate circuit is pressurized water. Hence, no evaporation occurs in the heat exchanger, and the surfaces of the latter may remain comparatively small.

[0012] The intermediate circuit provides for increased flexibility, and in particular allows connecting a plurality of heat sources to one single rankine cycle evaporator. Specifically, distinct heat sources such as clinker cooler air or waste gas of a pre-heater tower of a same cement plant may be series or parallel connected in the intermediate circuit.

[0013] In a further preferred embodiment, a plate-and-shell type heat exchanger with optimized surface to volume ratio is used in the evaporator in connection with the intermediate circuit. Exemplary plate-and-shell heat exchangers which due to an innovative welding process as e.g. described in WO2009068119 are well suited to withstand pressures in the ORC cycle in excess of 40 bar are available from GESMEX GmbH, Schwerin, Germany.

[0014] Advantageously, the conversion system comprises a control unit for controlling all aspects of the waste heat conversion process, including the supply of electrical power from the generator to an electrical grid. The control unit is connected to sensors as well as actuators in order to adapt the operation of the conversion system to meet the operating conditions of the industrial plant and/or the abundance of the waste heat. Exemplary actuators include variable speed drive fluid pumps arranged in the working fluid circuits, condenser fans, a trip valve for tripping the turbine, and variable inlet guide vanes enabling the turbine to operate in a broader load range. In addition, the control unit may even interact with the waste heat generating process, in order to optimize the waste heat conversion within the limits imposed by the operating conditions of the industrial plant.

[0015] In an alternative exemplary embodiment, a conversion system for converting waste heat from an industrial waste heat source to shaft power is provided, the conversion system having an intermediate circuit with an intermediate circuit working fluid heated by the waste haste and a closed rankine cycle system with any suitable organic working fluid and comprising a plate-and-shell type heat exchanger for evaporating the organic working fluid by the heated intermediate circuit working fluid. The closed rankine cycle system further comprises a turbine driven by the organic working fluid evaporated in the plate/shell heat exchanger and a condenser fluidly interconnected between the turbine and the plate/shell heat exchanger. The preferred intermediate circuit working fluid is water, whereas the organic working fluid of the closed rankine cycle may be a toxic or non-toxic, fluorinated or non-fluorinated working fluid. This alternative exemplary embodiment may be combined independently with any of the advantageous variants or embodiments mentioned in this specification.

[0016] In summary, the invention allows exploiting, in an environmental friendly way, waste heat sources of comparatively low quality, which so far have been disregarded mainly for economical reasons as well as for a lack of suitable equipment. A closed rankine cycle system is powered with waste heat that is provided e.g. in the form of a hot cooling fluid or a flow of residual heat gas having a temperature of less than 400°C, eventually less than 250°C and in some circumstances even less than 200°C. In an evaporator in heat exchange relationship with the waste heat, a suitable working fluid is evaporated and heated to a temperature of less than about 170°C at a pressure of less than 40 bar, and eventually even less than 8 bar, and subsequently fed to a turbine for producing shaft power that in turn may drive a compressor or generator.

[0017] These and other aspects of the present invention will become apparent from and be elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The subject-matter of the invention will be explained in more detail in the following text with reference to exemplary embodiments which are illustrated in detailed schematic drawings.

Fig. 1 schematically shows a conversion system according to an embodiment of the invention.

Fig. 2 schematically shows a conversion system with an intermediate circuit according to another embodiment of the invention.

Fig. 3 schematically shows a conversion system with a bottom, middle, and top floor module according to another embodiment of the invention.

Fig. 4 schematically shows the conversion system of Fig. 3 with an intermediate circuit according to another embodiment of the invention.

[0019] The reference symbols used in the drawings, and their meanings, are listed in summary form and a list of reference symbols. In principle, identical parts are provided with the same reference symbols in the figures.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0020] Fig.1 shows a schematic illustration of a conversion system 30 with a closed organic rankine cycle (ORC) 16 comprising, in a clockwise flow direction of an ORC working fluid as indicated by the arrows, an evaporator 1 or boiler for the evaporation of the ORC working fluid, a turbine 2 fed with vapour from the evaporator to drive, via a common shaft 3, a generator 4 connected to an electric power network or any other load, a condenser 5 for condensing the exhaust ORC vapours from the turbine and means, such as a pump 6, for recycling the condensed ORC working fluid to the evaporator 1. A control unit 15 for controlling the conversion of waste heat is connected to generator 4 and to sensor 14 monitoring the heat generation process, as well as to pump 6 as exemplary actuator. Optionally, the system may further comprise an internal heat recovery system for cooling the vapour after the turbine and preheating the condensed working fluid.

[0021] The evaporator 1 recovers heat from a waste heat source 7 such as a stream of residual heat gas or hot exhaust gas entering the evaporator 1 at a temperature below 400°C at ambient pressure, and being released to the ambient via chimney 8. Typically, in the evaporator 1, the ORC working fluid is heated up to 170°C at a pressure of less than 40 bar, and expanded in the turbine 2 to a pressure where it is still gaseous, at a temperature close to ambient temperature.

[0022] Fig.2 depicts a system with an intermediate circuit 17 (dashed line). A first heat exchanger 9 is placed in the exhaust gas stream in chimney 8 where water as the working fluid of the intermediate circuit is being heated up a first time. The heated water is then circulated to a second heat exchanger 9B that is e.g. arranged in a residual heat gas stream constituting a second waste heat source of generally higher temperature than the exhaust gas stream in chimney 8, and heated up a second time. The hot water is conducted to evaporator 1 and then cycled back to the first heat exchanger 9 by means of a water pump 10. The turbine 2 is connected, via shaft 3, to a compressor 12 instead of a generator, and the shaft power is used to generate pressurized gases.

[0023] The evaporator 1 depicted in Fig. 2 consists of a serial arrangement of distinct stages, i.e. a liquid-liquid pre-heater stage 1A for pre-heating the liquid ORC working fluid, an evaporator stage 1B for evaporating the ORC working fluid, and a liquid-vapour superheater stage 1C for superheating the evaporated ORC working fluid. The liquid intermediate circuit 17 working fluid and the ORC working fluid traverse this arrangement in opposite directions.

[0024] Fig.3 schematically depicts details of a preferred geometrical arrangement of the elements of the conversion system 30 for converting waste heat from a waste heat source 7 to shaft power. The elements of the system are assigned to, and mounted within, a bottom floor module 31 (turbine 2, generator 4), a top floor module 32 (condenser 5) being arranged above the bottom floor module 31, and a middle floor module 33 (pump 6, internal heat recovery heat exchanger 1D, exemplary piping 35) being arranged between the bottom floor module 31 and the top floor module 32. In the direct evaporating system depicted, the evaporator 1 is placed in a waste gas stream at a distance from the remaining components. The working fluid passes directly from the evaporator 1 to the turbine 2, from there via the vapour-liquid type internal heat recovery heat exchanger 1D to the condensers 5, and back via the pump 6 to the internal heat exchanger 1D and then to the evaporator 1.

[0025] Fig.4 schematically depicts a similar geometrical arrangement of the elements of a conversion system 30 with an intermediate water circuit 17. A heat exchanger 9 is placed in the exhaust gas stream in chimney 8 where water is being heated up by heat from the residual gas. The water is conducted to a super-heater 1C, an evaporator 1B, and a pre-heater 1A, which are all assigned to the middle floor module 33. The working fluid is preheated, evaporated, and superheated before it is transferred to the turbine 2. The water of the intermediate water circuit 17 is cycled back to the water heat exchanger 9 by means of a water pump 10 likewise mounted on the middle floor module 33.

[0026] The three aforementioned modules each include a steel frame of standard container size, onto which the assigned elements are mounted. These modules may be pre-fabricated and tested at factory site, and comprise standardized connections or flanges for interconnecting corresponding piping sections of the respective modules.

[0027] The mutual arrangement of the elements or components of the system within one of the aforementioned modules in turn is likewise based on a modular concept. Specific elements, such as the turbine, are selected according to the specification of the conversion system in a particular industrial plant. The elements are then mounted, and/or later exchanged if needed, via standardized connections such as a locking snap connection, a clamping connection, a screw-thread connection. When selecting the elements in order to satisfy the specification, a plurality of identical elements with smaller individual ratings may be preferable over a single large element. For instance, the condenser is advantageously composed of a number of standardized units that matches the system's power rating.

[0028] While the invention has been illustrated and described in detail in the drawings and the foregone description, such illustrations and descriptions are to be considered illustrative or exemplary and non restrictive; the invention is not limited to the disclosed embodiments.

[0029] Other variation of the disclosed embodiments may be understood and effected by those skilled in the art and practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims.

[0030] In the claims, the word "comprising" does not exclude other elements or steps, and the independent article "a" or "an" does not exclude a plurality. A single conversion system for converting a waste heat from a waste heat source into shaft power may fulfil the function of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate, that a combination of these measures may not be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

LIST OF DESIGNATIONS

[0031]

1	evaporator
1A	liquid-liquid pre-heater stage
1B	evaporator stage
1C	liquid-vapour superheater stage
1D	internal heat recovery heat exchanger
2	turbine
3	shaft
4	generator
5	condenser
6	pump
7	waste heat source
8	chimney
9	waste heat to water heat exchanger
10	pump
12	compressor
14	sensor, sensors
15	control unit
16	closed rankine cycle
17	intermediate circuit
30	conversion system
31	bottom floor module
32	top floor module
33	middle floor module
35	piping

Claims

1. A conversion system (30) for converting waste heat from an industrial waste heat source (7) to shaft power, the conversion system (30) having a closed Organic Rankine Cycle ORC system (16) comprising:

- an evaporator (1), heated by the waste heat, for evaporating an ORC working fluid,
- a turbine (2) driven by the evaporated ORC working fluid and connected to a shaft (3), and
- a condenser (5) fluidly interconnected between the turbine (2) and the evaporator (1); wherein the ORC working fluid is organic, non-toxic, and non fluorinated.

2. The conversion system (30) according to claim 1, wherein the ORC working fluid is a pure hydrocarbon compound such as isobutane (C_4H_{10}) or pentane (C_5H_{12}).

3. The conversion system (30) according to claim 1 or 2, wherein waste heat from the industrial waste heat source (7) is transferred to the evaporator (1) via an intermediate circuit (17) comprising a heat exchanger (9) for heating, by the waste heat, a working fluid of the intermediate circuit.

4. The conversion system (30) according to claim 3, wherein the working fluid of the intermediate circuit (17) comprises pressurized water with a temperature below 200°C.

5. The conversion system (30) according to claim 3 or 4, wherein the intermediate circuit (17) is connected to a plurality of heat sources (7).

6. The conversion system (30) according to claim 5, wherein the plurality of heat sources (7) comprises clinker cooler air and waste gas of a pre-heater tower of a cement plant.

7. The conversion system (30) according to anyone of claims 3 to 6,
wherein the evaporator (1) comprises a plate-and-shell heat exchanger (1) for transferring waste heat from the heated working fluid of the intermediate circuit (17) to the ORC working fluid.

8. The conversion system (30) according to anyone of the preceding claims, further comprising a control unit (15) adapted to control an operation of the conversion system according to operating conditions of an industrial plant comprising the industrial waste heat source (7).

9. The conversion system (30) according to anyone of the preceding claims, wherein the waste heat temperature is below 400°C and wherein the pressure of the ORC working fluid does not exceed 40 bar.

10. An industrial cement plant with a waste heat source (7) and a conversion system (30) according to anyone of claims 1 to 9.

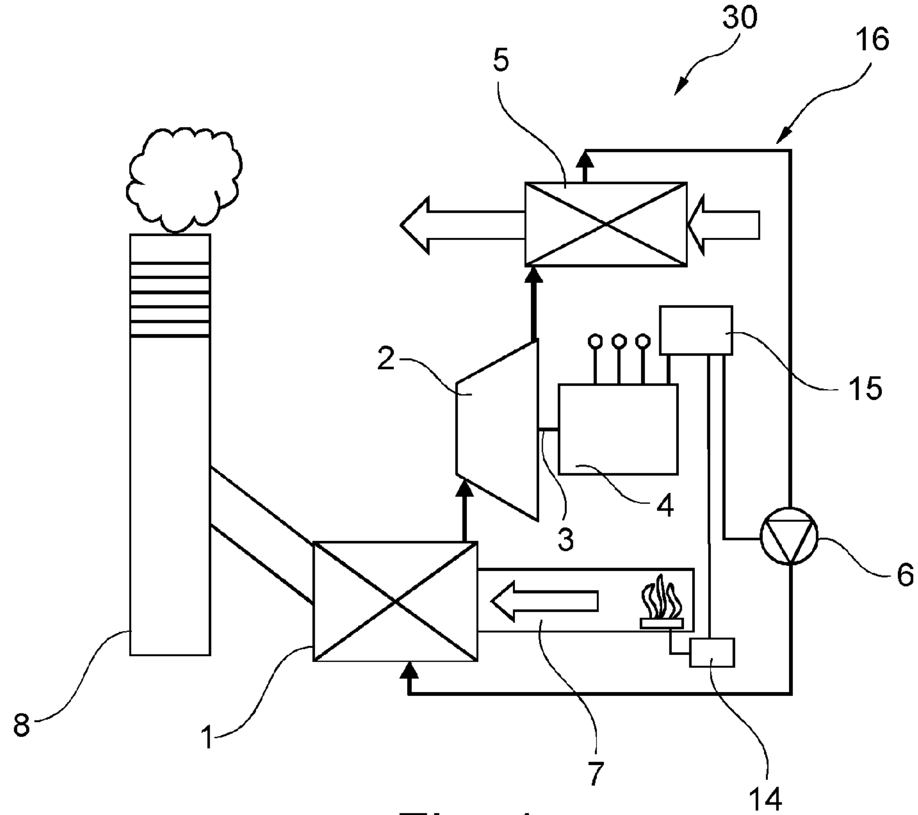

Fig. 1

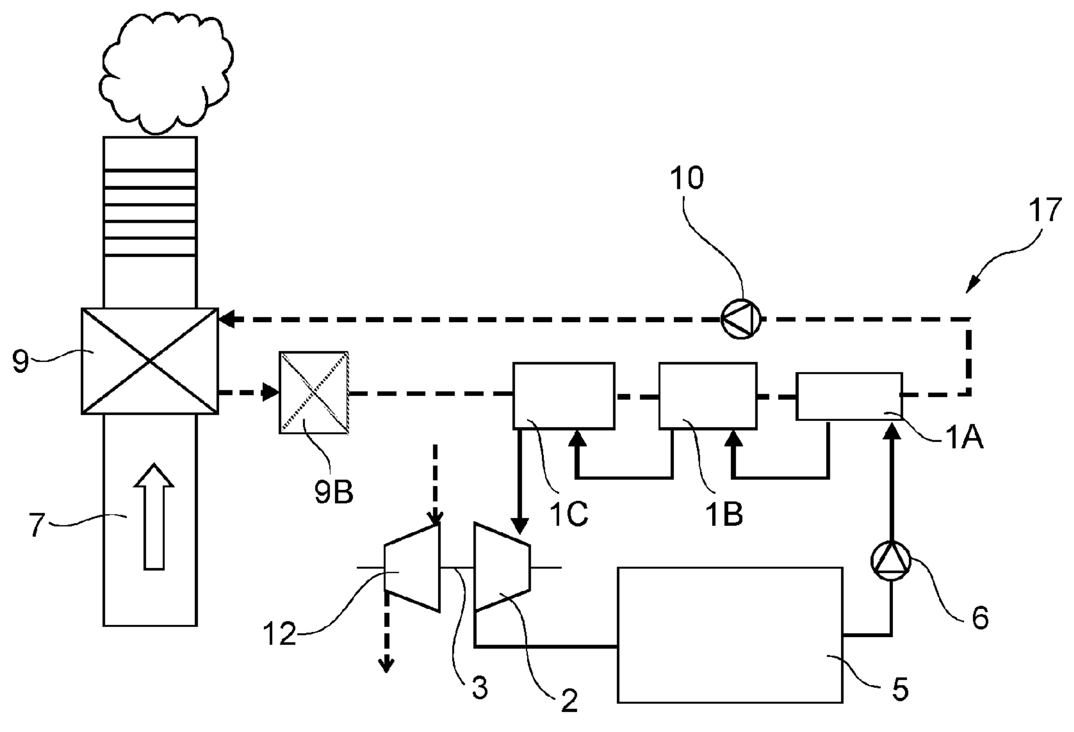

Fig. 2

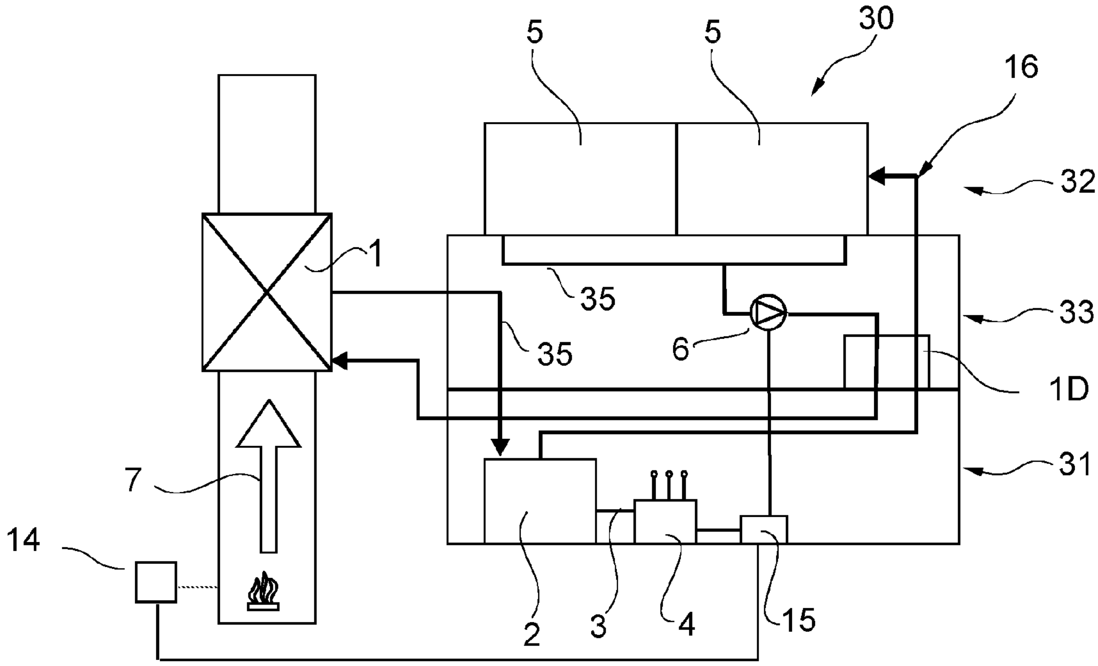
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Fig. 3

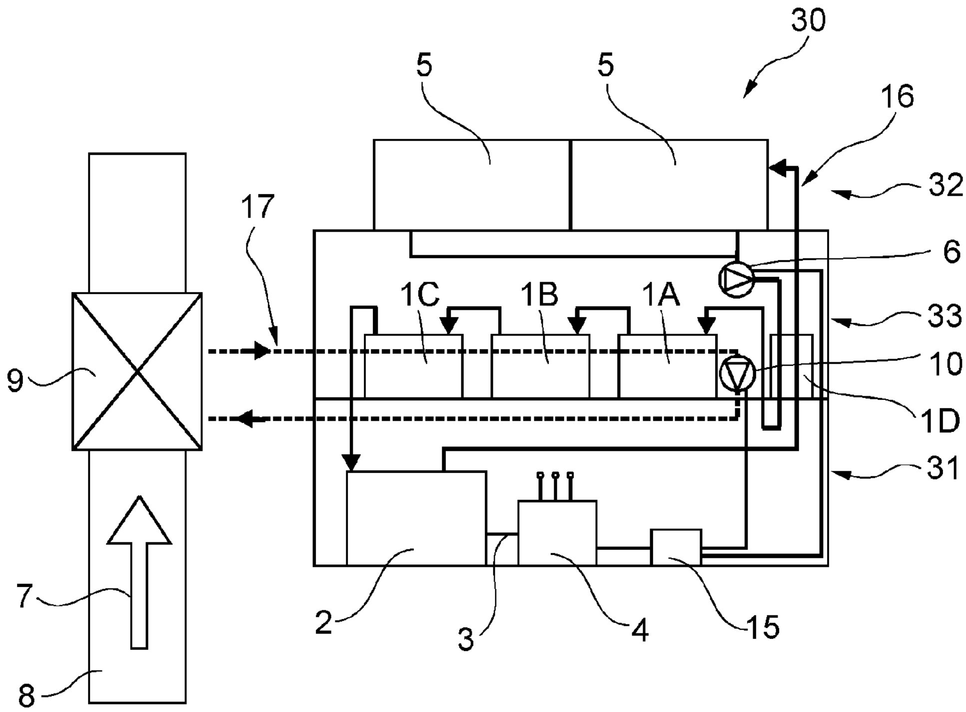
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Fig. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 10 15 9727

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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	16 December 2010	Zerf, Georges

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EUROPEAN SEARCH REPORT

Application Number
EP 10 15 9727

DOCUMENTS CONSIDERED TO BE RELEVANT

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The present search report has been drawn up for all claims

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