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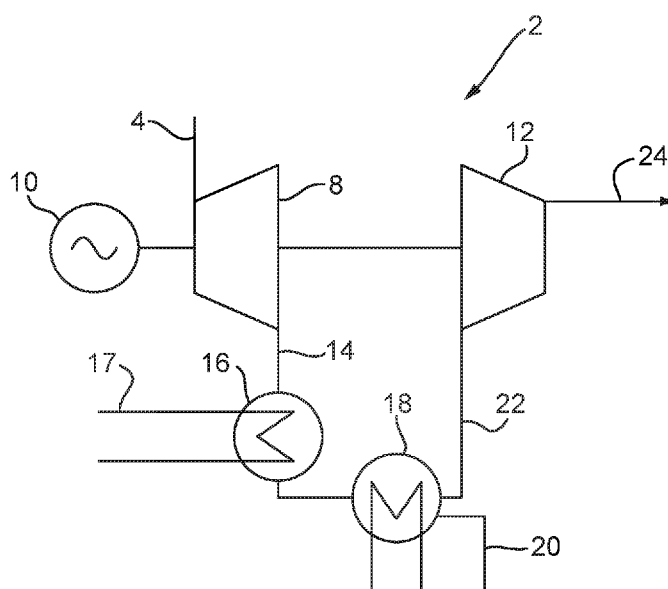
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Fig. 1



(57) Abstract: A system (2) for extracting power and water from the exhaust gas (4) of an engine 6 comprises a turbine 8 for reducing the pressure of the exhaust gas 4, a condenser (18) for cooling the reduced-pressure exhaust gas (14) below its water dew point and separating condensed water (20) from the exhaust gas (14), and a compressor (12) for compressing the dried exhaust gas (22). Optionally, the water (20) may be vaporised in a boiler (16) by heat exchange with the exhaust gas (14) upstream of the condenser (18). The water (20) may be used to improve efficiency of the engine (6) by injection into a compressor (26) or combustor (28) of the engine (6), or to improve the efficiency of the power and water extraction system (2) by injection into the compressor (8) or turbine (12) of the system (2).

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## EXHAUST GAS POWER AND WATER RECOVERY

The present invention relates to the processing of exhaust gas from an engine, and particularly to the recovery of energy and/or water from the exhaust gas.

A gas turbine engine is a type of internal combustion engine. It comprises an upstream rotating compressor coupled to a downstream turbine, with a combustion chamber or combustor located in between the compressor and turbine. In the ideal model of a gas turbine, known as the Brayton cycle, gases undergo four thermodynamic processes: isentropic compression, isobaric combustion, isentropic expansion, and heat rejection.

In practice, fresh atmospheric air flows into the compressor where it is brought to a high pressure. Energy is added by spraying fuel into the compressed air and igniting it so as to generate a high-temperature flow. This high-temperature, high-pressure gas enters the turbine, where it expands back down to atmospheric pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. However, not all of the energy from the combustion can be extracted as shaft work and so the exhaust gases leaving the gas turbine engine are still at a high temperature, often in the region of 500°C.

Often, the exhaust gas from the gas turbine engine is simply vented to atmosphere. However, the present invention seeks to provide improved processing of the exhaust gas to provide useful outputs.

Viewed from a first aspect, the present invention provides a method of processing exhaust gas from an engine, comprising: reducing the pressure of the exhaust gas; cooling the reduced-pressure exhaust gas; separating condensed water from the cooled exhaust gas to produce a water stream and a dried exhaust gas; and compressing the dried exhaust gas.

By expanding the exhaust gas, cooling it, and re-compressing it, this method permits extraction of further energy from the gases because more energy is extracted from expansion of the hot gas than is required to compress the gas once cooled. This processing extracts energy from the gas using the same effect as is applied in the gas turbine engine (where gas is compressed, heated and then expanded) but in reverse. Thus, an additional Brayton cycle is added to the normal cycle of the engine. For example, in the case of a gas turbine engine, the present

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invention effectively extends the range of the Brayton cycle of the gas turbine engine by expanding the gases to below the exhaust pressure before performing at least part of the heat rejection stage. Thus, more energy is extracted from the exhaust gas, thereby increasing the fuel efficiency of the gas turbine engine.

5           The described method also further permits extraction of water from the exhaust gas. As will be appreciated, combustion produces significant quantities of water (as steam due to the temperature). However, this steam is often simply vented to atmosphere because it is not worthwhile to extract it from the exhaust gas. In accordance with the present technique, the exhaust gases are first cooled  
10 by expansion and then further cooled by the cooling stage. This combined cooling effect is sufficient to condense a significant quantity of the steam from the exhaust gas, which may then be separated from the exhaust gas to be used elsewhere in the turbine system or for external use.

          Preferably, the engine is a gas turbine engine. Whilst it will be appreciated  
15 that the described technique is applicable to other types of engines, gas turbine engines in particular produce very hot exhaust gas that is well suited to generation of additional power in the described manner.

          In one embodiment, the pressure of the gas is reduced using a turbine. Preferably, the turbine is arranged to drive a power shaft. The power shaft may be  
20 coupled to a generator and/or coupled to a power shaft of the engine. Hence, power is extracted from the expansion of the exhaust gas.

          Preferably the pressure of the exhaust gas is reduced by at least 30%, and preferably between 50% and 70%. For example, the pressure of the exhaust gas may be reduced from approximately atmospheric pressure (e.g. an absolute  
25 pressure of 0.8 bar to 1.2 bar) and/or may be reduced to an absolute pressure of below 0.7 bar, and preferably to an absolute pressure of below 0.5 bar and/or above 0.3 bar.

          Preferably the dried exhaust gas is compressed using a compressor. The compressor may be driven by the power extracted by the turbine. For example the  
30 turbine may be coupled to the compressor. In one embodiment, the turbine and/or compressor may be arranged on the same shaft as the host engine to even further simplify the system.

          The exhaust gas may be cooled using an energy recovery system arranged to extract power from the residual heat of the exhaust gas. Thus, in addition to the  
35 energy extracted by the turbine during the expansion phase, energy may also be

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extracted during the cooling phase. For example, the energy recovery system may be a heat recovery steam generator or a thermoelectric generator.

In other embodiment, the exhaust gas may be cooled by heat exchange with an ambient fluid, such as ambient air or sea water. In yet further embodiment, the exhaust gas may be cooled using a refrigeration system or the like.

In some embodiments, the exhaust gas may be used before the cooling to heat at least part of the water stream. Optionally, heating the water stream may cause the water stream to vaporise to produce steam. Thus, the cooled water may be used to partially cool the gas stream. This may be advantageous where the temperature of the water does not affect its subsequent use and/or where steam is required.

Preferably the exhaust gas is cooled to a temperature below a water dew point of the gas (e.g. below about 75°C at 0.4 bar), and more preferably below about 50°C. In some embodiments, the exhaust gas may be cooled to a temperature between 15° and 35°C, and preferably between 20°C and 30°C. Preferably the temperature is not reduced below 0°C so as to prevent the water from freezing.

In one embodiment, the separating may comprise centrifugally separating the water from the exhaust gas. This is can be beneficial in terms of space/weight savings. However, it will be appreciated that other forms of separation may be used as appropriate. The separation may separate only relatively large droplets and may allow relatively small droplets to be carried through the compressor. This will advantageously reduce the compression power required because, although a higher pressure drop results in smaller droplets, it will also require more pumping power.

Optionally, after separation, the water may be subject to one or more water treatment processes, e.g. to remove impurities. For example, the one or more water treatment processes may include one or more of aeration, coagulation, sedimentation, filtration, desalination and acidity regulation.

After separation, the water stream may be used for various purposes within the engine system or externally of the system. Optionally, the respective part of the water stream may be pressurised as required for the respective purpose.

In one embodiment, at least part of the water stream may be supplied to a combustion chamber of the engine generating the exhaust gas. Optionally the part of the water stream may be vaporised to steam before supply to the combustor, as

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discussed above. It is known that injecting a small quantity of steam into the combustion chamber of an engine can improve the fuel efficiency of the engine and reduced the NOx emissions of the engine. This technique therefore provides a ready supply of water for this application.

5           In one embodiment, at least part of the water stream may be mixed with the exhaust gas before reducing its pressure. Optionally the part of the water stream may be vaporised to steam before mixing with the exhaust gas, as discussed above, such that the exhaust gas does not need to vaporise the water. The injected steam can be expanded together with the exhaust gas to increase the  
10           efficiency of the energy extraction.

          In one embodiment, at least part of the water stream may be reintroduced into the exhaust gas before or during compression. For example, the water may be used to perform water washing of the exhaust gas to reduce compressor fouling. Preferably the part of the water stream has been processed as discussed above,  
15           thereby reducing impurities in the water.

          In one embodiment, at least part of the water stream may be injected into upstream or into a compressor of the engine. For example, the water may be used to perform water washing of the inlet gas to reduce compressor fouling. Preferably the part of the water stream has been processed as discussed above, thereby  
20           reducing impurities in the water.

          In one embodiment, at least part of the water may be supplied to a separate system, for example an adjacent engine.

          It will be appreciated that any two or more or all of the above uses for the water and/or steam may be used in combination with one another as desired.

25           Viewed from a second aspect, the present invention provides a system, comprising: an engine that produces exhaust gas; a turbine for expanding the exhaust gas; at least one cooler for cooling the expanded exhaust gas; a separator for separating condensed liquid from the cooled exhaust gas; and a compressor for compressing the dried exhaust gas.

30           Preferably, the engine is a gas turbine engine.

          The turbine is preferably arranged to drive a power shaft. The power shaft may be coupled to a power shaft of the engine. Alternatively or additionally, the system may comprise a generator, wherein the power shaft is coupled to the generator.

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The turbine is preferably arranged to reduce the pressure of the exhaust gas by at least 30%, and preferably between 50% and 70%. For example, the turbine may reduce the pressure of exhaust gas at approximately atmospheric pressure (e.g. an absolute pressure of 0.8 bar to 1.2 bar) to an intermediate pressure of  
5 below 0.7 bar, and preferably to an intermediate pressure of between 0.5 bar and 0.3 bar.

The compressor is preferably configured to be driven by the power extracted by the turbine. For example the turbine may be coupled to the compressor.

At least one of the at least one cooler may be coupled to an energy recovery  
10 system arranged to extract power from the residual heat of the exhaust gas. The energy recovery system may be a heat recovery steam generator or a thermoelectric generator.

The at least one cooler may comprise a heat exchanger for heat exchange with an ambient fluid, such as ambient air or sea water. The heat exchanger may  
15 be a direct contact heat exchanger. That is to say, the cooling fluid may be sprayed directly into the exhaust gas. In one embodiment, the cooling fluid may be cooling water and the cooling water may be separated from the cooled exhaust gas at the same time as the condensed water.

The system may comprise a refrigeration system coupled to the heat  
20 exchanger.

The at least one cooler may comprise a water heater upstream of the at least one cooler. The water heater may be configured to heat at least part of the water stream by heat exchange with the exhaust gas. Optionally, the heat  
25 exchange with the water stream may cause the water stream to vaporise to produce steam.

The at least one cooler is preferably sized so as to permit the exhaust gas to be cooled to a temperature below its water dew point, more preferably below about 50°C. In some embodiments, the exhaust gas may be cooled to a temperature between 15° and 35°C, and preferably between 20°C and 30°C.

30 In one embodiment, the separator may comprise a centrifugal separator. The separator may optionally be integrated with at least one of the at least one cooler.

The system may comprise one or more water treatment processing stages for processing the water stream from the separator, e.g. to remove impurities. For  
35 example, the one or more water treatment processing stages may be arranged to

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perform one or more of aeration, coagulation, sedimentation, filtration, desalination and acidity regulation.

The system may be arranged to supply the water stream for various purposes within the system or externally of the system. Optionally, the system may include one more pump arranged to pressurise the respective part of the water stream as required for the respective purpose.

In one embodiment, the system may be arranged to supply at least part of the water stream to a combustion chamber of the engine. Optionally the part of the water stream may be vaporised to steam before supply to the combustor.

In one embodiment, the system may be arranged to supply at least part of the water stream to be mixed with the exhaust gas upstream of the turbine. Optionally the part of the water stream may be vaporised to steam before mixing with the exhaust gas, as discussed above, such that the exhaust gas does not need to vaporise the water.

In one embodiment, the system may be arranged to reintroduce at least part of the water stream into the exhaust gas upstream of the compressor and/or inside the compressor. Preferably the part of the water stream has been processed as discussed above, thereby reducing impurities in the water.

In one embodiment, the system may be arranged to supply at least part of the water to a separate system, for example an adjacent engine.

It will be appreciated that any two or more or all of the above uses for the water and/or steam may be used in combination with one another as desired.

Certain preferred embodiments of the present invention will now be described in greater detail, by way of example only and with reference to the accompanying drawings, in which.

Figure 1 illustrates a system for extracting power and water from the exhaust gas of a gas turbine; and

Figure 2 illustrates the system in combination with the gas turbine.

Figure 1 illustrates a system 2 for extracting power and water from the exhaust gas 4 of a gas turbine 6.

The exhaust gas 4 is received from the gas turbine engine 6 at approximately atmospheric pressure and a temperature of about 540°C.

The exhaust gas 4 is then supplied to a turbine 8, which extracts energy from the exhaust gas by expanding it. The turbine 8 has an output shaft that is coupled to a generator 10, which converts the kinetic energy of the turbine 8 into

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electrical energy. However, it will be appreciated that the energy of the turbine 8 may be used in other ways. For example, the output shaft of the turbine 8 could be coupled to the shaft of the gas turbine engine 6, directly or via a gearing arrangement. Alternatively, the output shaft may be connected to a gearbox to drive other components of the system.

The turbine 8 is also coupled to a compressor 12, as will be described in more detail later.

The turbine 8 expands the exhaust gas 4 from approximately atmospheric pressure to provide a reduced-pressure exhaust gas 14 a pressure of between about 0.3 bar and about 0.5 bar, such as about 0.4 bar. The reduced-pressure exhaust gas 14 has a temperature of about 380°C. However, it will be appreciated that the cycle intermediate pressure can be anywhere between vacuum and gas turbine exhaust pressure, which can be above atmospheric pressure.

An optional steam boiler 16 may be used to vaporise water using the heat from the reduced-pressure exhaust gas 14 to produce steam 17. This may slightly cool the reduced pressure exhaust gas 14, but does not significantly reduce the temperature of the exhaust gas 14. In other embodiments, the steam boiler 16 may be used to vaporise water to drive a heat recovery steam generator (not shown) in which the steam drives a turbine to extract energy from the heat of the reduced pressure exhaust gas 14.

Next, the reduced-pressure exhaust gas 14 is supplied to a condenser 18. The condenser 18 may for example use sea water at a temperature of about 10 degrees to cool the reduced pressure exhaust gas 14. For maximum weight and space reduction, the condenser 18 may be wholly or partly a direct contact type using water spray nozzles. The condenser 18 in this embodiment cools the reduced pressure exhaust gas 14 to a temperature of about 30°C.

As the reduced-pressure exhaust gas is cooled by the condenser 18, water generated in the combustion process will condense. This condenser 18 is configured to incorporate or act as a separator and comprises a drain to extract the liquid phase water 20, resulting in a dried reduced-pressure exhaust gas 22 having a temperature of about 30°C and a reduced water content. For maximum weight and space reduction, the water/exhaust gas separator may be of centrifugal type, either static or rotating.

The dried reduced-pressure exhaust gas 22 is finally supplied to the compressor 12, which compresses the dried reduced-pressure exhaust gas 22

back to atmospheric pressure. The atmospheric-pressure dried exhaust gas 24 is then vented from the system 2, for example to atmosphere. The compression increases the temperature of the exhaust gas such that the atmospheric-pressure dried exhaust gas 24 is vented from the system 2 at a temperature of about 100°C.

5 As discussed above, the compressor 12 is driven by the turbine 8. When operating under the described conditions, the compressor consumes approximately 55% of the power extracted by the turbine 8, whilst the remaining power can be converted to useful electric power by the generator 10. The power output may be further increased if a heat recovery steam generator is used as discussed above.

10 In one embodiment, the system 2 can extract around 4 MW power from the exhaust of a General Electric ® LM2500 base engine (22 MW) when the system 2 operates at an intermediate pressure of around 0.4 bar. With addition of steam injection in the host gas turbine 6, an additional 2 MW can be extracted without adding extra fuel. If additional power is not required in the gas turbine, the steam  
15 injected can reduce fuel consumption accordingly.

The proposed system 2 thus takes exhaust gas 4 from the gas turbine engine 6 (or another combustion engine) at close to atmospheric pressure, expands it to a pressure level below atmospheric, cools it and then recompresses to atmospheric pressure for disposal to surrounding air. This part of the cycle is a  
20 variant of the commonly used Brayton cycle.

The new concept further provides water production as a result of cooling the exhaust gas 4 to below its water dewpoint to allow condensing and collecting of the water from the combustion products. This water can be used to further augment the cycle by injecting the water in the host engine 6 and/or to produce steam by a  
25 steam boiler 16 located at the outlet of the turbine 8 (alternatively the steam boiler 16 may use the exhaust gas 4 of the engine 6 or the the dried exhaust gas 24 from the system 2). The produced steam or water can be used for many purposes, as will be described below.

Figure 2 illustrates the energy and water extraction system 2 in combination  
30 with the gas turbine engine 6, including a compression stage 26, a combustion stage 28 and a turbine stage 30. Those of ordinary skill in this field will be well aware of the construction of these components of the gas turbine engine 6 and so they will not be described in detail.

The produced/recovered water 20 can be utilized in the following ways as  
35 illustrated in Figure 2. After being separated in the energy and water extraction

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system 2, the stream of water may be subject to one or more water processing stages 32, 34 and may be pressurised using a pump 36 to provide sufficiently pure water at the required pressure for use within the engine system. The water processing stages 32, 34 and the pump 36 may be used in any order and may optionally provide multiple outputs for different uses, such as having been refined to different standards and/or pressurised to different pressures.

As discussed above, a part of the purified and pressurised water may be supplied to the steam boiler 16 so as to generate steam 17, which may be advantageous for various applications.

Exemplary applications for the water 20 and/or steam 17 include the following.

- I. The steam 17 may be injected in the combustor 28 of the host gas turbine engine 6 to increase cycle efficiency and power output and to reduce NOx emissions.
- II. The steam 17 may be injected into the exhaust gas 4 upstream of the turbine 8 of the energy and water extraction system 2 to increase cycle efficiency and power output of the energy and water extraction system 2.
- III. The steam 17 may be used outside of the combined system, for example by injection in another adjacent engine to increase cycle efficiency and power output and to reduce NOx emissions in that engine.
- IV. The water 20 may be injected into the combustor 28 of the host gas turbine engine 6 to increase cycle efficiency and power output and to reduce NOx emissions.
- V. The water 20 may be used outside of the combined system, for example by injection in another adjacent engine to increase cycle efficiency and power output and to reduce NOx emissions in that engine.
- VI. The water 20 injected into the exhaust gas 4 upstream of the turbine 8 of the energy and water extraction system 2 to increase cycle efficiency and power output of the energy and water extraction system 2.
- VII. The water 20 may be injected into the compressor 12 or upstream of a compressor inlet of the host gas turbine 6 to increase power and cycle

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efficiency. The water can also have an online water washing effect to improve power and efficiency due to reduced compressor fouling.

VIII. The water 20 may be injected into the compressor 26 or upstream of a compressor inlet of the water extraction system 2. to increase power and cycle efficiency. The water can also have an online water washing effect to improve power and efficiency due to reduced compressor fouling.

Options I through VIII can be applied independently or in combination. In addition, surplus fresh water can be drawn from the system 2 for other plant use.

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## CLAIMS

1. A method of processing exhaust gas from an engine, comprising:  
reducing the pressure of the exhaust gas;  
5 cooling the reduced-pressure exhaust gas;  
separating condensed water from the cooled exhaust gas to produce a  
water stream and a dried exhaust gas; and  
compressing the dried exhaust gas.
- 10 2. A method according to claim 1, wherein the engine is a gas turbine engine.
3. A method according to claim 1 or 2, wherein the pressure of the gas is  
reduced using a turbine coupled to a generator and/or a power shaft of the engine.
- 15 4. A method according to claim 3, wherein the dried exhaust gas is  
compressed using a compressor driven by the turbine.
5. A method according to any preceding claim, wherein the exhaust gas is  
cooled using an energy recovery system arranged to extract power from the  
20 residual heat of the exhaust gas.
6. A method according to any preceding claim, wherein the pressure of the  
exhaust gas is reduced to an absolute pressure of between 0.3 bar and 0.5 bar.
- 25 7. A method according to any preceding claim, wherein the exhaust gas is  
cooled to a temperature between 0°C and its water dew point, and preferably  
between 15°C and 35°C.
8. A method according to any preceding claim, wherein before the cooling step  
30 the exhaust gas is used to vaporise at least part of the water stream to produce  
steam.
9. A method according to any preceding claim, wherein at least part of the  
water stream is supplied to a combustion chamber of the engine generating the  
35 exhaust gas.

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10. A method according to any preceding claim, wherein at least part of the water stream is mixed with the exhaust gas before reducing the pressure of the exhaust gas.

5

11. A method according to any preceding claim, wherein at least part of the water stream is reintroduced into the exhaust gas before or during compression.

10

12. A method according to any preceding claim, wherein at least part of the water stream is injected upstream of or into a compressor of the engine.

13. A method according to any preceding claim, wherein at least part of the water stream is supplied to an adjacent engine.

15

14. A system, comprising:  
an engine that produces exhaust gas;  
a turbine for expanding the exhaust gas;  
at least one cooler for cooling the expanded exhaust gas;  
a separator for separating condensed liquid from the cooled exhaust gas;  
and  
a compressor for compressing the dried exhaust gas.

20

15. A system according to claim 14, wherein the engine is a gas turbine engine.

25

16. A system according to claim 14 or 15, comprising a generator, wherein a power shaft of the turbine is coupled to the generator.

17. A system according to claim 14, 15 or 16, wherein the compressor is driven by the turbine.

30

18. A system according to any of claims 14 to 17, wherein the at least one cooler is part of an energy recovery system arranged to extract power from the residual heat of the exhaust gas.

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19. A system according to any of claims 14 to 18, wherein the at least one cooler comprises a water heater to vaporise the water by heat exchange with the exhaust gas upstream of the at least one cooler.

5 20. A system according to any of claims 14 to 19, wherein the system is arranged to supply at least part of the water stream to a combustion chamber of the engine.

10 21. A system according to any of claims 14 to 20, wherein the system is arranged to supply at least part of the water stream to be mixed with the exhaust gas upstream of the turbine.

15 22. A system according to any of claims 14 to 20, wherein the system is arranged to reintroduced at least part of the water stream into the exhaust gas upstream of the compressor and/or inside the compressor.

Fig. 1

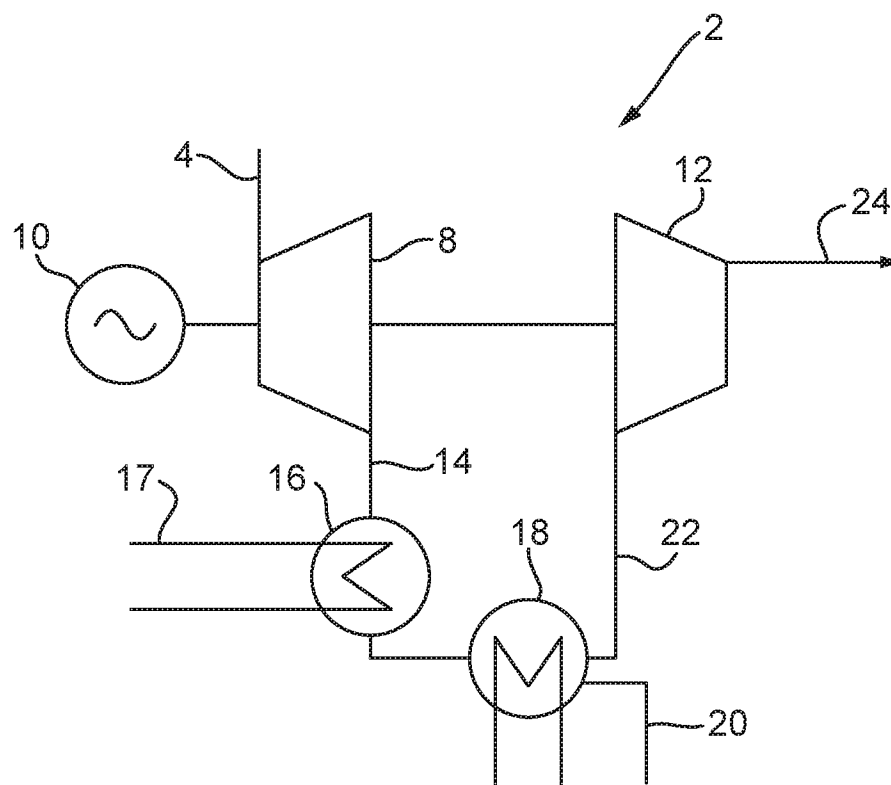
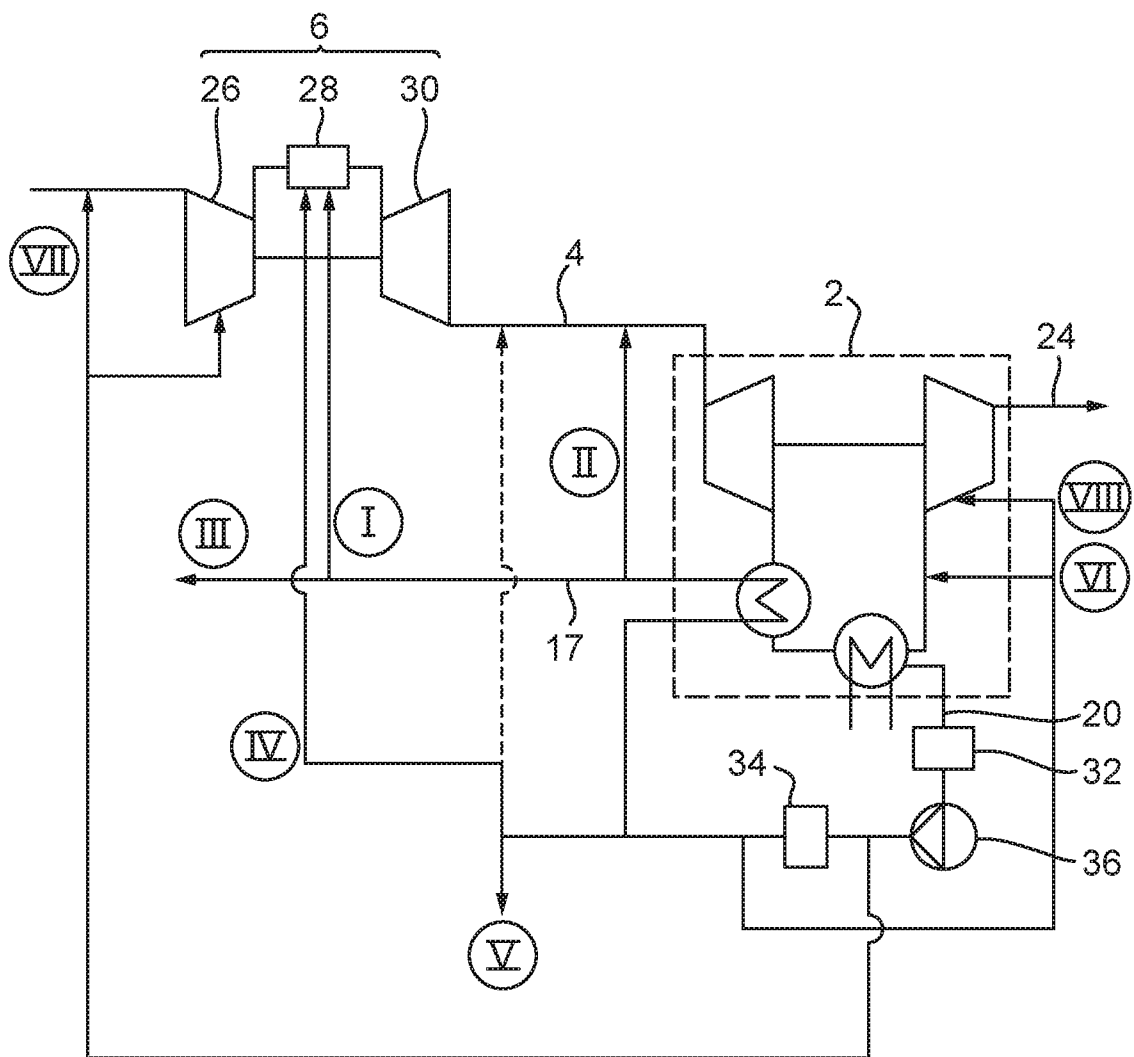


Fig. 2



## INTERNATIONAL SEARCH REPORT

International application No.

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| <b>A. CLASSIFICATION OF SUBJECT MATTER</b><br>B01D 53/00 (2006.01), B01D 53/26 (2006.01), F01N 3/02 (2006.01), F02B 37/00 (2006.01)<br>According to International Patent Classification (IPC) or to both national classification and IPC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                   |                                                                                            |
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| <b>B. FIELDS SEARCHED</b><br>Minimum documentation searched (classification system followed by classification symbols)<br>B01D, F02B, F01N                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                   |                                                                                            |
| Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched<br>DK, NO, SE, FI: Classes as above.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                   |                                                                                            |
| Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)<br>EPODOC, WPI, FULLTEXT: ENGLISH, GERMAN, FRENCH                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                   |                                                                                            |
| <b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                   |                                                                                            |
| Category*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Citation of document, with indication, where appropriate, of the relevant passages                                                | Relevant to claim No.                                                                      |
| Y                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | US 2014007590 A1 (HUNTINGTON, R. A. et al.) 2014.01.09.<br>Whole document, see especially figure 1.                               | 1-22                                                                                       |
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