

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
13 March 2003 (13.03.2003)

PCT

(10) International Publication Number
WO 03/021702 A1

(51) International Patent Classification⁷: **H01M 8/04**,
8/06, F02C 3/36, F01K 3/18, F02C 6/18

Hicham, Salah [LB/FR]; Air Liquide, 57 Avenue Carnot,
BP 313, F-94503 Champigny-sur-Marne Cedex (FR).

(21) International Application Number: PCT/GB02/03952

(74) Agents: **DRAPER, Martyn, John** et al.; Boulton Wade
Tennant, Verulam Gardens, 70 Gray's Inn Road, London
WC1X 8BT (GB).

(22) International Filing Date: 30 August 2002 (30.08.2002)

(25) Filing Language: English

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG,
SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ,
VC, VN, YU, ZA, ZM, ZW.

(26) Publication Language: English

(30) Priority Data:
0121191.1 31 August 2001 (31.08.2001) GB

(71) Applicant (*for all designated States except US*): **INNOGY
PLC** [GB/GB]; Windmill Hill Business Park, Whitehill
Way, Swindon, Wiltshire SN5 6PB (GB).

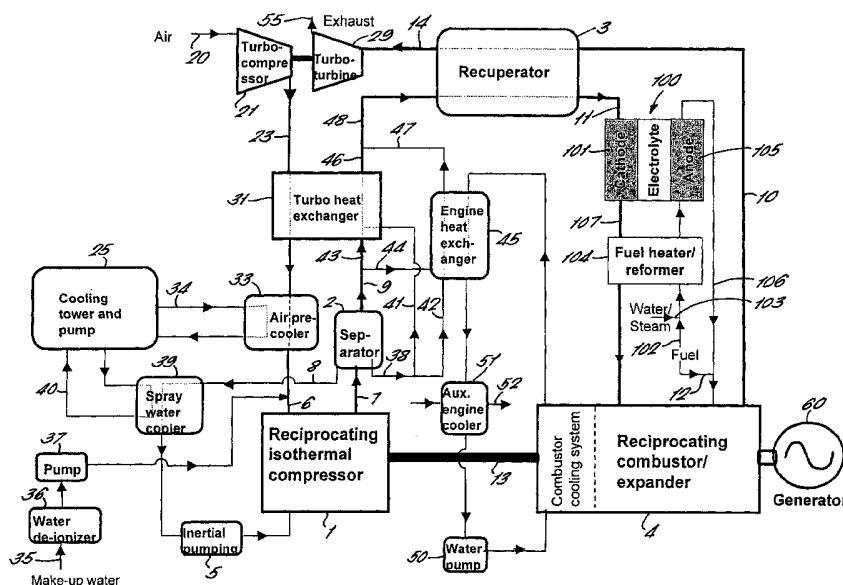
(84) Designated States (*regional*): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),
Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),
European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE,
ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK,
TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, ML, MR, NE, SN, TD, TG).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): **CONEY, Michael,
Willoughby, Essex** [GB/GB]; The Pinnocks, Broad
Town, Swindon, Wiltshire SN4 7RG (GB). **ABDALLAH,**

[Continued on next page]

(54) Title: A POWER GENERATION APPARATUS



(57) Abstract: A positive displacement compressor (1) compresses air while thermal energy is extracted from the air being compressed. A heat exchanger (3) heats the compressed air (9) from the compressor. A fuel cell (e.g. solid oxide or molten carbonate) has a cathode (101) supplied with heated compressed air from the heat exchanger and an anode (105) supplied with fuel. A positive displacement combustor (4) is fed with hot pressurised product gas from the fuel cell, and burns fuel (preferably unburned fuel in the anode product gas (106)) in the presence of the product gas and expands hot combustion gases to drive the compressor. The exhaust gas (10) is fed from the combustor (100) to the heat exchanger (3) to heat the compressed air.

**Declarations under Rule 4.17:**

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)

- of inventorship (Rule 4.17(iv)) for US only

Published:

- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

- 1 -

A POWER GENERATION APPARATUS

The present invention relates to a power generation apparatus. In particular, the invention relates to a power generation apparatus which combine a fuel cell cycle with a positive displacement cycle, and in which combustion and compression of air are carried out separately.

10 A power cycle combining a fuel cell and a gas turbine is known for example from US5413879 which describes the combination of a solid oxide fuel cell with a gas turbine.

15 The gas turbine drives a compressor which supplies compressed air to a heat exchanger in which the air is heated by the gas turbine exhaust. The hot compressed air from the heat exchanger is passed to the cathode of a pressurised solid oxide fuel cell. A compressed gaseous fuel such as natural gas, is also pre-heated by the gas turbine exhaust gases and is supplied to the anode of the fuel cell. The solid oxide fuel cell performs a conversion of most of the fuel gas to produce carbon dioxide and water vapour by an electrochemical process, which also produces electric power and heat. The quantity of compressed air, which is supplied to the fuel cell cathode, is considerably greater than that required for the electrochemical conversion process, because excess air is required to remove the heat produced in the cell. The anode product gas consists of carbon dioxide and water vapour, which are products of the conversion process, and a certain amount of unconsumed fuel and any water which was added to the fuel. The cathode product gas consists of air depleted by the removal of a certain fraction of the available oxygen. The two product gas streams are mixed and burned in the gas

- 2 -

turbine combustor together with some fresh fuel. The pressurised combustion products are then used to drive a high temperature turbine, which also drives a generator and the air compressor mentioned previously.

5

Natural gas is usually the preferred fuel, but in order to use this in a fuel cell, it must be converted to a hydrogen-rich gas, by means of the reformer reaction. This involves an endothermic chemical reaction between the natural gas and steam, to produce a mixture of carbon monoxide and hydrogen. The reformer reaction requires a high temperature, preferably above 800°C, and usually also a catalyst. The reaction is favoured by low pressures, but can be performed at high pressures if the temperature is high enough. The carbon monoxide can then be reacted with more steam to produce carbon dioxide and yet more hydrogen. This is the so-called water-gas shift reaction, which is exothermic and is favoured by more modest temperatures. The shift reaction is insensitive to pressure.

Alternatively other hydrocarbon fuels may be used, but these too must be reformed to a hydrogen rich gas.

In low temperature fuel cells, a separate reformer must be used so that the fuel is converted to a hydrogen rich gas before entering the fuel cell. This is known as "external reforming". In the solid oxide fuel cell, the operating temperature of the fuel cell is high enough that reforming can take place within the fuel cell, provided there is some water vapour present to start the process of conversion. It may also be necessary to add additional water or steam to the fuel to avoid deposition of carbon which can occur as a result of decomposition of carbon monoxide.

- 3 -

As the fuel cell reaction proceeds, oxygen ions combine with the hydrogen gas at the anode to produce more steam. The steam reacts with the hydrocarbons such as methane to produce more hydrogen and the process is self-sustaining until most of the fuel is consumed. This process, which is described as "internal reforming", is very advantageous, not only because it avoids the use of a separate reformer, which must be supplied with high temperature heat to support the endothermic reforming process, but also because it provides a sink for much of the waste heat produced in the fuel cell itself.

Another characteristic of high temperature fuel cells such as the solid oxide fuel cell, is that both hydrogen and carbon monoxide are consumed at the anode. Thus the solid oxide fuel cell is not limited by the efficiency of the shift reaction.

The advantages of combining a fuel cell and a gas turbine in the manner described in US5413879 are that:

- 1) the fuel cell converts some of the fuel electrochemically rather than via combustion, which therefore partially avoids the thermodynamic limitations on efficiency, known as the Carnot limit
- 2) the pressurised fuel cell has a higher efficiency and power density (per electrode surface area) than a non-pressurised fuel cell, which reduces the size and cost of the fuel cell
- 3) the energy of the unburned fuel from the fuel cell is released in the gas turbine combustor, and is recovered in the turbine and in the heat exchanger
- 4) the waste heat from the fuel cell (which is

- 4 -

normally contained in the fuel cell exhaust gases) is at a high temperature and pressure and can therefore also be recovered and converted to useful power in the turbine

- 5 5) the exhaust heat from the gas turbine is used productively to pre-heat the air and the fuel before they enter the fuel cell, thus improving efficiency.

10 The result of these factors is that the overall efficiency and power output of the combined gas turbine fuel cell cycle is significantly higher than could be achieved by the fuel cell on its own, whether this is pressurised or not.

15 The main limitation of the gas turbine/fuel cell system is that high pressure operation of the system means that the temperature of the air, which is supplied by the compressor is also high. Consequently, relatively little additional heat is required to heat the air to the required entry temperature of the fuel cell. Thus there is little scope for the economic utilisation of the exhaust heat from the gas turbine, unless this is used to raise steam and drive a
20 separate steam turbine, resulting in greater complexity and cost. In practice, the increased compressor work at high pressures and the inability to make use of all the heat sources within the cycle means that the turbine/fuel cell system is limited to
25 low pressure ratios.
30

 An attempt to overcome this limitation has been made by the development of the above concept, to include two or more stages of air compression
35 separated by one or more intercooling stages. For example, a gas turbine/solid oxide fuel cell cycle with a two stage intercooled compressor has been

- 5 -

described in a paper "Solid oxide fuel cells in future gas turbine combined cycle plants" by Kent B. Johansson, Martin H. Bafalt and Jens Paisson, published in the proceedings of the CIMAC congress, Copenhagen 1998. The intercooling reduces the work of compression at higher pressure ratios. Also the final temperature of the compressed air is lowered, so that there is more scope to use the gas turbine exhaust heat. With this modification, an increased pressure ratio brings some improvement in power output and efficiency. However, as the pressure ratio is increased, the exhaust temperature of the gas turbine falls to the point where the exhaust gases are no longer hot enough to pre-heat the air required by the fuel cell. This limit occurs because a high pressure ratio implies a relatively high absolute temperature ratio. There is a metallurgical limit on the inlet temperature to the turbine, so the outlet temperature must fall.

One possible way of avoiding this problem is to use a reheat gas turbine, with two combustion stages separated by a turbine, but this an expensive and difficult development and no such turbine is commercially available except at very large sizes.

One of the disadvantages of the gas turbine/solid oxide fuel cell combined cycle is that excess air is needed to cool the gas turbine combustor, transition section, stationary blades and moving blades. This is in addition to the excess air needed to maintain the fuel cell at the right temperature. Thus the overall air demand is high in relation to the amount of oxygen which is actually needed for the fuel cell or for the gas turbine combustion process. The need to supply a large quantity of compressed air has a negative effect on the overall cycle efficiency.

- 6 -

Although the example given above relates to the integration of a solid oxide fuel cell with a gas turbine combined cycle, there are also schemes involving the use of molten carbonate fuel cells with gas turbines. The molten carbonate fuel cell is another type of fuel cell, which also operates at high temperature. Typically a molten carbonate fuel cell operates at about 600°C, whereas a solid oxide fuel cell may operate between 800° to 1000°C. Research is also on-going into the possibility of solid oxide fuel cells operating at lower temperatures.

The molten carbonate fuel cell is also capable of having internal reforming as opposed to a separate external reformer. However, as the temperature is not as high as in the solid oxide fuel cell, a catalyst is more likely to be needed.

There is an important difference between the solid oxide and the molten carbonate fuel cell, apart from the difference in operating temperature, which must be taken into account in the design of a combined cycle. In the solid oxide fuel cell, negative oxide ions are formed at the cathode and move through a solid ceramic electrolyte to the anode, where they react with hydrogen or carbon monoxide. In the molten carbonate fuel cell, negative carbonate ions are formed at the cathode and move through a liquid electrolyte to the anode, where they also can react with either hydrogen or carbon monoxide. In the solid oxide fuel cell, the process only requires the presence of oxygen at the cathode, but in the molten carbonate fuel cell, a plentiful supply of both carbon dioxide and oxygen is needed in the gas supplied to the cathode. Either the solid oxide fuel cell or the molten carbonate fuel cell can be used in the invention described here, albeit with certain

- 7 -

modifications to accommodate their different requirements.

According to the present invention there is
5 provided a power generation apparatus comprising a
positive displacement compressor for compressing air;
means for extracting thermal energy from the air being
compressed; a primary heat exchanger for heating the
10 compressed air from the compressor; a fuel cell having
a cathode supplied with heated compressed air from the
primary heat exchanger and an anode supplied with
fuel; a positive displacement combustor fed with hot
pressurised product gas from the fuel cell, the
15 combustor being arranged to burn fuel in the presence
of the product gas and to expand hot combustion gases
to drive the compressor; and means to feed exhaust gas
from the combustor to the primary heat exchanger to
heat the compressed air from the compressor.

20 The present invention takes a different approach
to that of all the known prior art. Instead of using a
gas turbine to burn the residual fuel and to provide
the means to pre-heat the air for the fuel cell, a
combined cycle of a fuel cell with a particular form
25 of positive displacement engine is proposed. This has
substantial advantages in terms of efficiency and
capital cost per unit output of the combined system,
as will be explained.

30 Most types of positive displacement engine are
entirely unsuitable for a combined cycle of this type
because the air is conventionally compressed,
combusted with fuel and expanded in a rapid sequence
within the cylinder. Therefore the compressed air
35 cannot be used for any external purpose. To overcome
this problem, a form of positive displacement engine
in which air is compressed externally is proposed
instead.

- 8 -

Various forms of reciprocating engine involving external air compression have been proposed, such as those of GB1,120,248, US4,300,486 or WO94/12785. A recent development of this type of engine, involving internal recovery of heat, is described in UK patent application 0007923.6.

The advantages of this fuel cell cycle relative to the gas turbine-fuel cell cycle are:

1. The present system is suitable for operation at higher pressures than the gas turbine based system, which increases the efficiency and power density of the fuel cell and allows more expansion of the cathode product gas, which allows more fuel to be burned thus increasing power output, and reducing cost per unit output.
2. The temperature of the combustion gas at the start of expansion can be higher than in a gas turbine, which is limited by temperature constraints on the turbine blades.
3. Heat can be released during expansion in the combustor, unlike in a gas turbine combustor (unless it has reheat stages).
4. The exhaust heat can be utilised more efficiently than in the gas turbine cycle, in which the compressed air is already relatively hot.
5. The need for additional compressed cooling air for the cooling of components can be avoided (as opposed to air cooling of the gas turbine combustion chamber, transition duct and both the moving and stationary blades of the turbine).

The overall benefit of the invention is that a

- 9 -

higher overall efficiency and a lower capital cost per unit of power output is obtainable than for a combined cycle involving a fuel cell and a gas turbine.

5 The fuel burned in the combustor may be unburned fuel in the anode product gas as this supply of fuel is conveniently available. However, it is not necessary to use the unburned fuel in the anode product gas in this way as it can be used for some
10 other purpose in the cycle, such as in a supplementary burner to further heat the compressed air from the primary heat exchanger. Thus, alternatively or additionally the fuel burned in the combustor may be from a source other than the fuel cell.

15 In order to minimise temperature differences and achieve efficient utilisation of heat, a heater is preferably provided to heat the gas supplied to the anode. If necessary, this heater can be arranged to
20 operate as a reformer. The heater may be a secondary heat exchanger which can recover heat from some other part of the cycle. In particular, the secondary heat exchanger may receive heat from the exhaust gas or the heated compressed air from the primary heat exchanger.

25 Water and/or steam may be added to the anode fuel in order to avoid deposition of carbon which can occur as a result of decomposition of carbon monoxide.

30 The fuel cell is preferably either a solid oxide fuel cell, or a molten carbonate fuel cell, in which case, carbon dioxide is fed to the cathode together with the compressed air. One way of providing this carbon dioxide to the fuel cell is to provide a burner
35 between the primary heat exchanger and the cathode to generate gas rich in oxygen and carbon dioxide. The burner may be supplied with an external supply of

- 10 -

fuel, or may be supplied with the anode product gas. The burner may be any type of burner with a means of reliably consuming the remaining fuel in the anode product gas, such as a burner which uses a separate
5 pilot fuel. However, it is currently believed to be more efficient to use a catalytic burner as this does not require pilot fuel.

10 An alternative way of supplying carbon dioxide to the molten carbonate fuel cell is to provide means to extract carbon dioxide from the exhaust gas downstream of the primary heat exchanger. Alternatively, means may be provided to extract carbon dioxide from the product gas from the anode.

15 The compressor may be a positive displacement compressor such as a sliding vane compressor. However, the compressor is most preferably a reciprocating compressor. In this case, the coupling
20 to drive the compressor from the combustor is preferably a crankshaft coupled to the combustor and the reciprocating compressor.

25 The positive displacement compressor may consist of a number of adiabatic compression stages with intercooling providing the means for extracting thermal energy from the air being compressed. However, the current preference is for the compressor to be arranged to compress the air substantially
30 isothermally.

35 One preferred way of carrying out the isothermal compression is to provide a spray of water into the air being compressed and to provide a separator for receiving the compressed air and water from the compressor and substantially separating this into compressed air and water streams. Such an arrangement

- 11 -

is disclosed in WO 94/12785.

The exhaust gas which has passed through the primary heat exchanger still retains some useful heat which may be used, for example, for space or water heating. Preferably, however, a turbo-turbine is arranged to be driven by the exhaust gas from the primary heat exchanger. This turbo-turbine can provide power output externally of the cycle, for example, to a generator. However, preferably, the apparatus further comprises a turbo-compressor driven by the turbo-turbine and arranged to compress air upstream of the positive displacement compressor. This increases the overall compression ratio of the cycle, and hence improves the efficiency of the apparatus.

A further improvement in the cycle efficiency can be provided by a means for recovering the heat from part of the cycle into the compressed air upstream of the primary heat exchanger. The heat may be recovered, for example, from air compressed by the turbo-turbine, or from a cooling system provided to cool the combustor.

Examples of apparatus constructed in accordance with the present invention will now be described with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram showing the inter-relationship of the various components of a first apparatus;

Fig. 2 is a schematic diagram showing the inter-relationship of the various components of a second apparatus;

- 12 -

Fig. 3 is a schematic diagram showing the inter-relationship of the various components of a third apparatus;

5 Fig. 4 is a schematic diagram showing the inter-relationship of the various components of a fourth apparatus;

10 Fig. 5 is a schematic diagram showing the inter-relationship of the various components of a fifth apparatus;

15 The basic elements of the engine to which the invention is applied are shown in Fig. 1. The engine consists of five basic components, namely an isothermal compressor 1, a separator 2, a recuperator 3, a combustor 4 and a fuel cell 100.

20 The interaction of these basic elements will now be described.

25 The isothermal compressor 1 is a reciprocating isothermal compressor comprising a single cylinder in which a piston reciprocates. A spray of water into the cylinder is provided by a spray pump 5. Suitable inlet and outlet valves are provided on the cylinder, such that on the downward stroke of the piston, air is drawn into the isothermal compressor through air inlet 6, and upon the return stroke, the air is compressed, while the spray of liquid is controlled so as to maintain the compression as near as possible to isothermal compression. The cold compressed air with the water entrained is forced out through isothermal compressor outlet 7 at the end of the compression stroke.

30 35

The isothermal compressor is described in WO

- 13 -

94/12785. Further details of the compressor, and in particular the arrangement of the nozzles used for the water spray are given in WO 98/16741.

5 The separator 2 separates the incoming stream into a water stream 8 and a cold compressed air stream 9. The cold compressed air stream 9 is then fed to the recuperator 3 where it is heated by the exhaust stream 10 from the combustor 4. This heated
10 compressed air leaves the recuperator 3 as hot compressed air stream 11 which is fed to a cathode 101 of fuel cell 100. The cathode product gas 107 is then fed to combustor 4.

15 In the combustor 4, the cathode product gas is mixed with fuel provided from fuel inlet 12 and is combusted to generate power. The combustor is a reciprocating internal combustor, in this case comprising three cylinders. A crankshaft 13 driven by
20 the combustor 4 is connected to the isothermal compressor 1, such that the isothermal compressor is driven directly by the combustor.

25 The exhaust gas which has given up heat to the cold compressed air leaves the recuperator as cooled exhaust stream 14 which may be either released to the atmosphere at this point, or used as described below.

30 The example shown in Fig. 1 will now be described in greater detail.

35 Air enters the air charge system through ambient air inlet 20 and is initially compressed in a turbo compressor 21 driven by a turbo-turbine 29 which is driven by exhaust gas as described below.

Typically the turbo compressor 21 is set up so as

- 14 -

to provide a 4:1 compression ratio for the incoming air.

5 The air leaving the turbo compressor 21 is discharged along turbo compressor discharge line 23 to turbo heat exchanger 31 where it gives up some of its heat to another part of the cycle as will be described below.

10 The air leaving the turbo heat exchanger 31 along turbo heat exchanger cold discharge line 32 passes through air pre-cooler 33 which cools the air down close to the lowest available temperature dumping the rejected heat to cooling tower 25 along first cooling
15 tower line 34. This maximises the air mass intake to the compressor. The average temperature of the rejected heat is very low, so that there is little or no adverse effect on efficiency.

20 On leaving the air pre-cooler, the cold partially compressed air enters the isothermal compressor 1, and is compressed as previously described.

25 Water is injected into the air, both just upstream of the isothermal compressor 1, and into the isothermal compressor 1 during compression as previously described. The water system shown has a make-up water supply line 35 to replace water lost from the water supply system during operation. The
30 water from the make-up water supply line is supplied via a deioniser 36 and is pumped by pump 37 so as to enter the air inlet 6 through an atomising nozzle located just upstream of the isothermal compressor 1. This provides additional cooling to the air at this
35 point thus maximising the mass of air that is compressed at each stroke. A further advantage of adding make-up water at this point is that the make-up

- 15 -

pump 37 need only pump the water to the isothermal compressor inlet pressure.

5 Water and compressed air leave the isothermal compressor 1 via isothermal compressor outlet 7 and are fed to separator 2. The separator separates the water from the compressed air, the water being discharged as first water stream 8 and second water stream 38.

10

The first water stream 8 gives up its heat in spray water cooler 39 to cooling tower 25 via second cooling tower line 40. The cooled water is then pumped from the spray water cooler 39 into the
15 isothermal compressor by spray pump 5 as previously described. The spray pump is preferably an inertial pumping system as described in PCT/GB01/01457.

20 While the bulk of the liquid is returned via first water stream 8, a bleed flow of liquid is provided as second water stream 38. This is split into two flows as turbo heat exchanger water stream 41 and engine heat exchanger stream 42. Similarly, the air stream 9 leaving the separator is split into a
25 turbo heat exchanger air stream 43 and an engine heat exchanger air stream 44.

The two turbo heat exchanger streams 41, 43 are then recombined in turbo heat exchanger 31 where they
30 receive heat from the flow discharge from the turbo compressor 21. Similarly, the two engine heat exchange streams 42, 44 are combined in an engine heat exchanger 45 so as to receive heat from the engine cooling system as will be described below.

35

The water added to the turbo heat exchanger 31 and engine heat exchanger 45 approximately equalises

- 16 -

the thermal capacity on both sides of each heat exchanger. The humidification of air in this way allows most, if not all of the available heat to be utilised within the cycle to improve efficiency and power output. The mass of liquid added should be sufficiently small that all of the liquid is evaporated within the heat exchanger to which the liquid is added. The reason why the air and liquid are separated and then recombined within the heat exchangers is that it is difficult to control the distribution within the heat exchanger of a two-phase mixture. The recombination of the two flows therefore only occurs within the individual elements of the heat exchanger, thereby allowing precise control of the phase composition.

The control of the air flow split and of the water injection is described in detail in co-pending application No. PCT/GB01/01456.

20

A turbo heat exchanger hot discharge stream 46 and an engine heat exchanger discharge stream 47 are combined into combined discharge stream 48 which is fed to the recuperator 3 where it receives heat from the engine exhaust stream 10.

25

An engine cooling circuit 49 is provided to cool the engine and convey the recovered heat to the engine heat exchanger 45 where it is transferred to the engine heat exchanger water and air streams 42, 44. Water is used as the engine coolant fluid which is pumped round the circuit by water pump 50. An auxiliary engine cooler 51 is available if needed to provide additional cooling of the water downstream of the engine heat exchanger 45. The low grade heat removed in the auxiliary engine cooler 51 is dumped to cooling tower 25 along third cooling tower line 52.

30
35

- 17 -

The cooled exhaust stream 14 leaving the recuperator is fed to turbo turbine 29, where it is expanded to drive the turbo compressor 21. The expanded exhaust gas from which most, if not all
5 useful energy has now been extracted, is discharged through turbo turbine discharge line 55.

Much of the above cycle is disclosed in our co-pending PCT/GB01/01456. This earlier application
10 discloses various alternative examples, any of which may be used in conjunction with the present invention.

The operation of the fuel cell within the engine of Fig. 1 will now be described in greater detail.
15

The cycle shown in Fig. 1 is particularly applicable to a solid oxide fuel cell.

The compressed humidified hot air stream 11
20 leaving the recuperator 3 is fed to the cathode 101 of the solid oxide fuel cell. A fuel 102, such as compressed natural gas, is combined with a supply of water or steam 103 and heated in a fuel gas heat exchanger 104 as will be described. This heated
25 mixture is supplied to an anode 105 of the solid oxide fuel cell.

Additional fuel 12 is supplied to the anode product gas 106 as it leaves the fuel cell 100 and the
30 mixed gases are supplied to the combustion cylinders of the combustor 4. The cathode product gas 107 passes first to the exchanger 104 to heat the fuel 102 and water 103 mixture, and is then supplied to the combustor cylinders.

35

The anode product gas 106 with additional fuel 12 and the cathode product gases 107 are introduced into

- 18 -

each cylinder of the combustor after the piston in that particular cylinder reaches top dead centre and are then combusted at high pressure within the cylinders. The pistons expand the combustion gases to produce power. Exhaust valves in the combustor 4 open shortly before bottom dead centre and some of the gases blow down into the exhaust system. As the piston rises it forces out most of the remaining exhaust gas through the valves. The exhaust valves close shortly before top dead centre, trapping a fraction of the exhaust gas. A small fraction of fuel is injected at this point to provide the ignition for the next cycle, which begins again at top dead centre. This is described in detail in our co-pending PCT/GB01/01471.

Some of the power is used to drive the reciprocating compressor via crankshaft 13, but most of it is used to drive a generator 60.

The arrangement shown in Fig. 1 can alternatively be used with a solid oxide fuel cell, which has external reforming. In this case the heater which supplies heated fuel to the anode of the fuel cell would be a reformer 104, normally containing a suitable catalyst. The amount of water or steam, which would be added to the fuel, would have to be much greater in the case of external reforming, and it would be desirable to evaporate the water to steam prior to entry to the reformer.

Alternative arrangements for the heating of the fuel and water/steam would also be possible, both for internal and external reforming. For example, instead of taking heat from the cathode product gas, it would be possible to take heat from the combustion gases leaving the combustor cylinders, prior to their entry to the recuperator 3. A further possibility would be

- 19 -

to extract heat from the compressed air leaving the recuperator 3 before entry to the cathode 101 of the fuel cell. Clearly the issue of whether the reforming is internal or external is important in making this decision, since the required temperature is higher and the amount of heat required is much greater in the case of external reforming.

The advantage of the arrangement for fuel heating or reforming shown in Fig. 1 is that the temperature of the cathode product gases leaving a solid oxide fuel cell is probably around 1000°C, which is rather high for the pipework and valves controlling entry into the reciprocating combustor cylinder. Although this difficulty can be overcome by cooling of the pipes and valves etc. a lower temperature would be easier to deal with. The alternative of using heat from the combustor exhaust gases implies an increase in the temperature of the gases passing through the combustor exhaust valves, if the temperature at the inlet to the main heat exchanger is maintained. The option of using heat from the compressed air leaving the main heat exchanger has the disadvantage that this temperature would be rather low for reforming and that the temperature of the air entering the cathode of the fuel cell may also be rather low.

Fig. 2 shows an alternative scheme for a solid oxide fuel cell. This arrangement is broadly the same as Fig. 1 and the same reference numerals have been used to designate the same components. Only the differences between the two systems are described below.

In this case there is no turbocharger and all the compression is performed by the isothermal compressor 1. It is not possible to achieve such a high pressure

- 20 -

in this arrangement as in the case of Fig. 1. On the other hand, certain inefficiencies in the turbo compressor 21 and turbine 29 are eliminated. The choice between the two schemes would be determined by
5 calculations to determine the best way to optimise performance and cost. Fig. 2 shows that atmospheric air is drawn directly into the inlet of the isothermal compressor 1 through ambient air inlet 20. The air/water mixture discharged from the compressor is
10 separated into air and water streams as in Fig. 1. The compressed air is split into two streams as in Fig. 1, but since there is no heat available from the air compressed by the turbo-compressor heat is recovered instead from the exhaust gases leaving the main heat
15 exchanger in exhaust gas heat exchanger 31 to produce an exhaust gas heat exchange discharge stream 46'. This is fed into combined discharge stream 48 as before. Heat is recovered from the combustor cooling system as before.

20

The use of humidification, i.e. the addition of water to the compressed air streams upstream of the first stage of heat exchangers 31, 31', 45, as described in connection with Figures 1 and 2 enhances
25 the utilisation of heat internally within the cycle in order to maximise the efficiency. However, the humidification is not essential to the process. In some circumstances, it may be beneficial for economic reasons to dispense with this feature if for example,
30 the plant is built in a dry region where water is expensive. There is also a saving in terms of capital costs, if humidification is not implemented.

Also if the heat is needed for some external
35 purpose, such as an industrial process or for space or water heating, then again it may be advantageous not to implement humidification.

- 21 -

Without humidification, there would probably be no need for both a turbo-heat exchanger 31 and an engine heat exchanger, which are shown in Fig. 1. One of these would become unnecessary. Similarly in Fig. 2, it would probably not be necessary to have both the exhaust gas heat exchanger and the engine heat exchanger.

Fig. 3 shows a scheme applied to a molten carbonate fuel cell, involving an isothermal compressor 1 with the inlet air boosted by a turbo compressor 21. Fig. 3 has many common feature with Fig. 1 and the same reference numerals have been used to designate the same components. Only the differences between Figs. 1 and 3 are described below.

The differences between Fig. 3 and Fig. 1 are associated with the flow streams to and from the fuel cell 100 itself. The configuration shown in Fig. 3 is designed so that carbon dioxide and oxygen are fed to the cathode 101. The configuration is also arranged to be more suitable for the lower temperatures of operation of the molten carbonate fuel cell.

Compressed fuel 102 with added water or steam 103 is heated in a heat exchanger 104 and then fed to the anode 105 of the fuel cell. The anode product gas 106, which contains carbon dioxide and some unconsumed fuel is then passed to a catalytic burner 110, into which compressed air from the recuperator 3 also flows. The anode product gas 106 is burned with an excess of compressed air, to consume all remaining fuel, and produce a hot compressed gas stream 111, which is rich in both oxygen and carbon dioxide. This gas supplies the heat required by the fuel heater/reformer 104 and is then fed to the fuel cell cathode 101. The cathode

- 22 -

product gas 107 from the fuel cell 100 is fed to the combustor cylinders, into which additional fuel 12 is also injected. The fuel is burned and the hot combustion gases are expanded to produce power to drive the compressor 1 and the generator 60.

In Fig. 3, the heat for the fuel heater or fuel reformer 104 is taken from the exhaust gas from the catalytic burner 110. This is convenient because otherwise the exhaust gas from the burner may be too hot for the molten carbonate fuel cell 100. In principle, heat for the fuel heater/reformer could be taken from elsewhere, but this might not provide such a good match to the various requirements as the arrangement, which is shown in Fig. 3. For example, the temperature of the compressed air provided by the recuperator is not really hot enough for reforming, although the exhaust gases from the combustor 4 could be hot enough for this purpose.

The catalytic burner 110 shown in Fig. 3 could possibly be replaced by another type of burner with another means of reliably consuming the remaining fuel in the anode product gas, such as combustion using a separate pilot fuel. This may be cheaper in terms of the capital cost, but it may not be the cheapest option when the cost of the pilot fuel is taken into account.

A variation of Fig. 3 involving a molten carbonate fuel cell 100, but with no turbocharger is another possibility. In this case the air inlet and arrangements to the isothermal compressor would be as shown in Fig. 2, but the fuel cell layout would be according to Fig. 3.

An alternative method of providing carbon dioxide

- 23 -

to the air supplied to the cathode of a molten carbonate fuel cell is to separate it from the exhaust gas leaving the system as shown in Fig. 4. Fig. 4 has many common feature with Fig. 2 and the same reference numerals have been used to designate the same components. Only the differences between Figs. 2 and 4 are described below.

The separation process can for example be pressure swing adsorption. In this scheme, the exhaust gas is cooled first in the recuperator 3 and secondly in an exhaust gas heat exchanger 31' as shown in Fig. 4. After separation in separation unit 120, the carbon dioxide is recompressed in a carbon dioxide compressor 121 and restored to the main circuit downstream of the separator 2. It is not feasible to mix the carbon dioxide with atmospheric air at the inlet of the isothermal compressor 1 because carbon dioxide would dissolve in the compressor spray water.

In the case of Fig. 4, the heat required for reforming or pre-heating the fuel is taken from the exhaust gas from the combustor 4, since this is probably at the most appropriate temperature for reforming. If the heat is needed for pre-heating only then a lower temperature source could be used.

The recovery of carbon dioxide from the exhaust gas can also be applied to a turbocharged molten carbonate fuel cell cycle. In this case the carbon dioxide separation unit 120 would treat the exhaust gas downstream of the turbocharger turbine.

An alternative configuration, which does not require the separate compression of carbon dioxide, is shown in Fig. 5. Fig. 5 has many common feature with Fig. 4 and the same reference numerals have been used

- 24 -

to designate the same components. Only the differences between Figs. 4 and 5 are described below.

5 In this case carbon dioxide is separated from the anode product gas 106 at high pressure in carbon dioxide separation unit 120. This produces a CO₂ rich stream. Since the anode product gas is very hot it is probably necessary to cool this gas down before separation and then to reheat the separated gases. The
10 most convenient way of achieving is to use rotary regenerators, which are very suitable for exchanging heat between two streams, which are at about the same pressure. These are not shown in Fig. 5, since they can be considered to be part of the CO₂ separation
15 unit. For example, the hot anode product gases can be split into two flows, which are supplied to the primary sides of two rotary regenerators arranged in parallel. The two flows are cooled by the regenerators and then re-mixed before entry to the CO₂ separator.
20 Following separation, the CO₂ is supplied to the secondary side of one of the regenerators, and the residual gases are supplied to the secondary side of the other regenerator. The flow split on the primary side of the two rotary regenerators would be arranged
25 to match the different thermal capacities of the two separated gas streams on the secondary sides. Finally, the re-heated separated carbon dioxide is supplied to the inlet of the cathode and the remaining gases to the inlet of the reciprocating combustor.

30

The arrangement shown in Fig. 5 can also be adapted for use with a turbocharger.

35 As in the case of the solid oxide fuel cell, the use of humidification with a molten carbonate fuel cell is optional.

- 25 -

As an alternative to the isothermal compressor 1 shown in Figs. 1 to 5, it would also be possible to use a conventional multistage reciprocating compressor, with intercooling stages. No separator would be required in this case. Conventional reciprocating compressors have a pressure ratio of less than 4:1 in each stage. For example three stages would be needed to achieve an overall compression ratio of 50:1. In this case an intercooler would be needed between the first and second compressor stage and between the second and third stage. This would be less efficient and more expensive than the isothermal compressor described above, but the scheme may still be preferable to the gas turbine/fuel cell cycle in terms of efficiency and cost.

Any of the schemes shown in Figs. 1 to 5, would be capable of being used for combined heat and power applications, using the exhaust heat and heat recovered from the spray water cooler. Also it would be possible to store the cold compressed air provided by the compressor at times of low power demand, in order that the power output of the system can be increased at times of high demand, by consuming the stored air.

- 26 -

CLAIMS

1. A power generation apparatus comprising a positive displacement compressor for compressing air;
5 means for extracting thermal energy from the air being compressed; a primary heat exchanger for heating the compressed air from the compressor; a fuel cell having a cathode supplied with heated compressed air from the primary heat exchanger and an anode supplied with
10 fuel; a positive displacement combustor fed with hot pressurised product gas from the fuel cell, the combustor being arranged to burn fuel in the presence of the product gas and to expand hot combustion gases to drive the compressor; and means to feed exhaust gas
15 from the combustor to the primary heat exchanger to heat the compressed air from the compressor.
2. An apparatus according to claim 1, wherein the fuel is unburned fuel in the anode product gas.
20
3. An apparatus according to claim 1 or claim 2, wherein fuel is from a source other than the fuel cell.
- 25 4. An apparatus according to any one of the preceding claims, further comprising a heater to heat the gas supplied to the anode.
5. An apparatus according to claim 4, wherein the
30 heater is a reformer.
6. An apparatus according to claim 4 or claim 5, wherein the heater is a secondary heat exchanger.
- 35 7. An apparatus according to claim 6, wherein the heat exchanger receives heat from the exhaust gas or the heated compressed air from the primary heat

- 27 -

exchanger.

8. An apparatus according to any one of the preceding claims, further comprising a source of water or steam connected to the fuel supply to the anode.

9. An apparatus according to any one of the preceding claims, wherein the fuel cell is a solid oxide fuel cell.

10. An apparatus according to any one of claims 1 to 8, wherein the fuel cell is a molten carbonate fuel cell in which carbon dioxide is fed to the cathode together with the compressed air.

11. An apparatus according to claim 10, further comprising a burner between the primary heat exchanger and the cathode to generate a gas rich in oxygen and carbon dioxide.

12. An apparatus according to claim 11, wherein product gas from the anode is combusted in the burner.

13. An apparatus according to claim 11 or claim 12, wherein the burner is a catalytic burner.

14. An apparatus according to claim 10, wherein carbon dioxide is extracted from the exhaust gas downstream of the primary heat exchanger.

15. An apparatus according to claim 10, wherein carbon dioxide is extracted from the product gas from the anode.

16. An apparatus according to any one of the preceding claims, wherein the positive displacement compressor is a reciprocating compressor.

- 28 -

17. An apparatus according to any one of the preceding claims, wherein the positive displacement combustor is a reciprocating combustor.
- 5 18. An apparatus according to claim 16, wherein the combustor is coupled to the compressor via a crankshaft.
- 10 19. An apparatus according to any one of the preceding claims, wherein the compressor is arranged to compress the gas substantially isothermally.
- 15 20. An apparatus according to claim 19, further comprising a water spray arranged to spray water into the air being compressed, and a separator for receiving the compressed air and water from the compressor and substantially separating this into compressed air and water streams.
- 20 21. An apparatus according to any one of the preceding claims, further comprising a turbo-turbine arranged to be driven by the exhaust gas from the primary heat exchanger.
- 25 22. An apparatus according to claim 20, further comprising a turbo compressor driven by the turbo-turbine to compress air upstream of the compressor.
- 30 23. An apparatus according to any one of the preceding claims, further comprising means for recovering heat from part of the cycle into the compressed air upstream of the primary heat exchanger.
- 35 24. An apparatus according to any one of the preceding claims, wherein the fuel cell has an operating temperature of at least 300°C, preferably at least 500°C and more preferably at least 700°C.

- 29 -

25. An apparatus according to any one of the preceding claims, wherein the fuel cell has an operating pressure of at least 10 bar, preferably at least 30 bar and more preferably at least 90 bar.

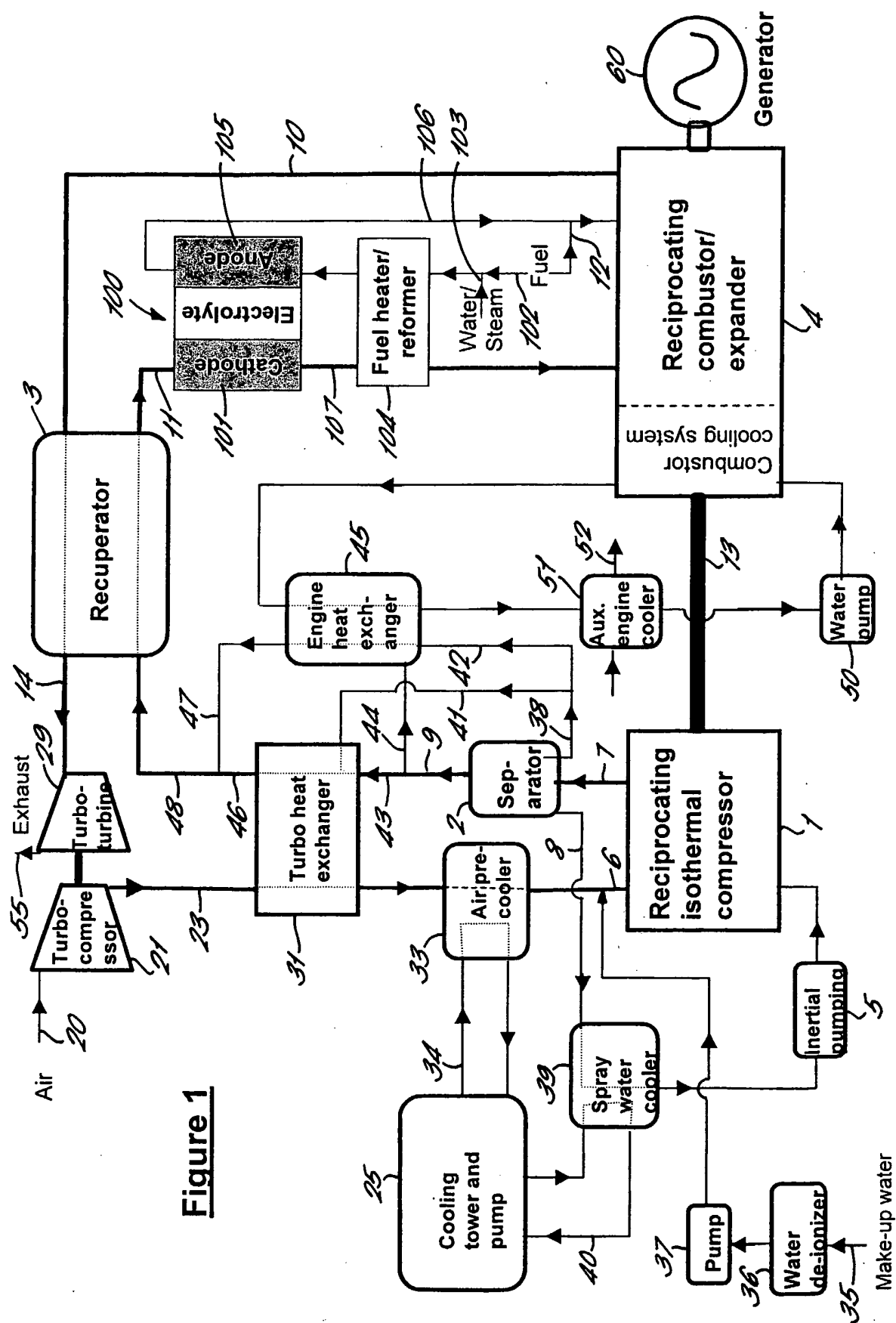
5

10

15

20

25



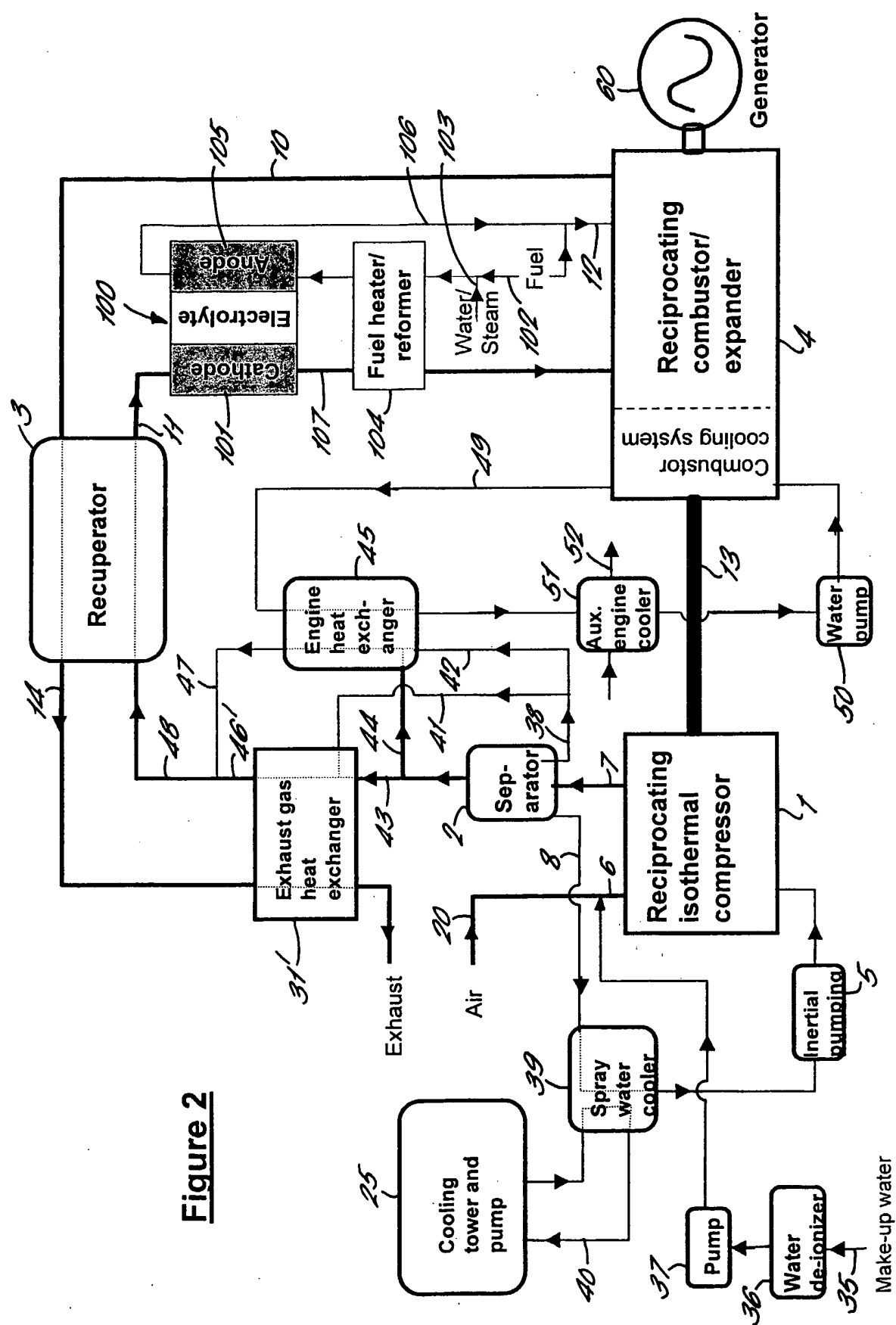


Figure 2

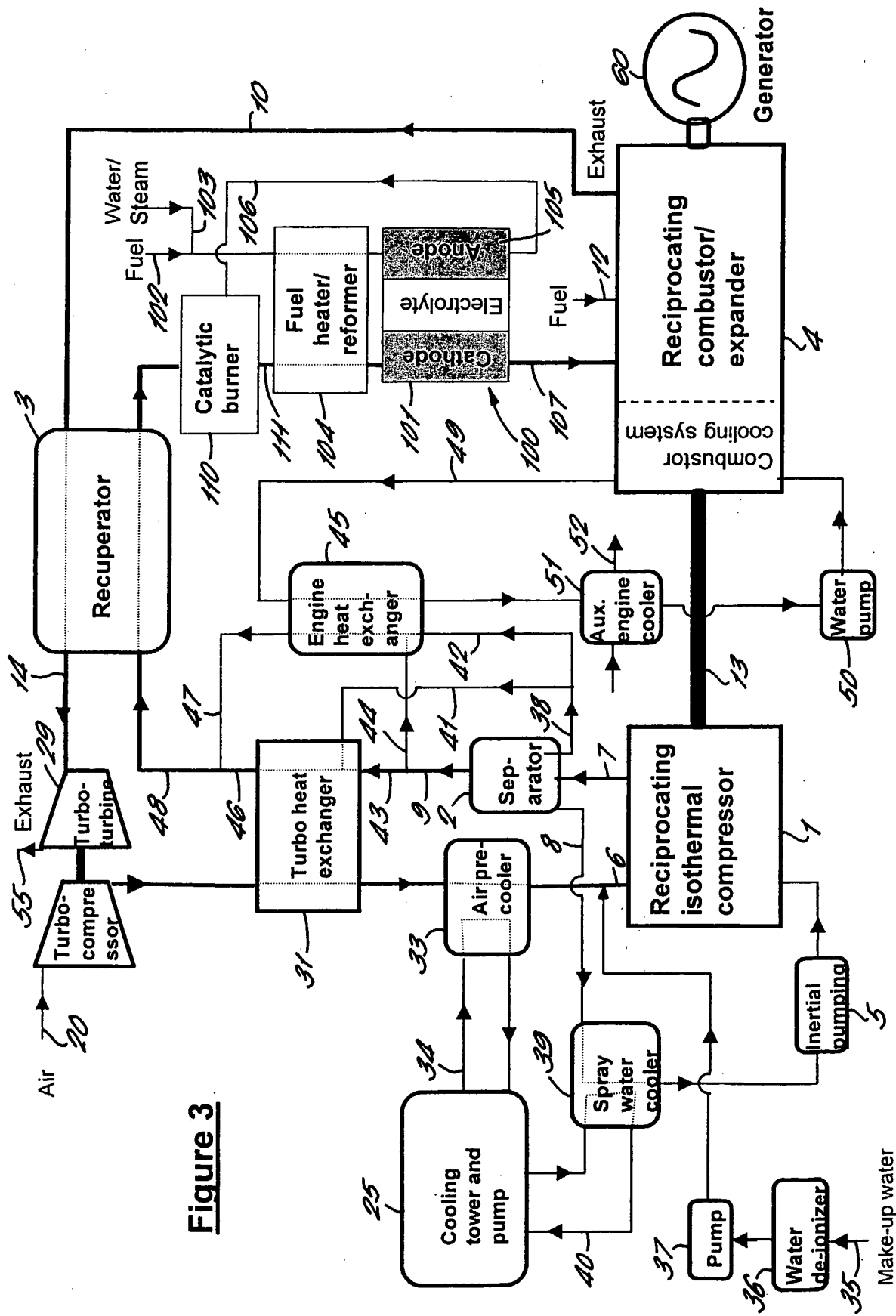


Figure 3

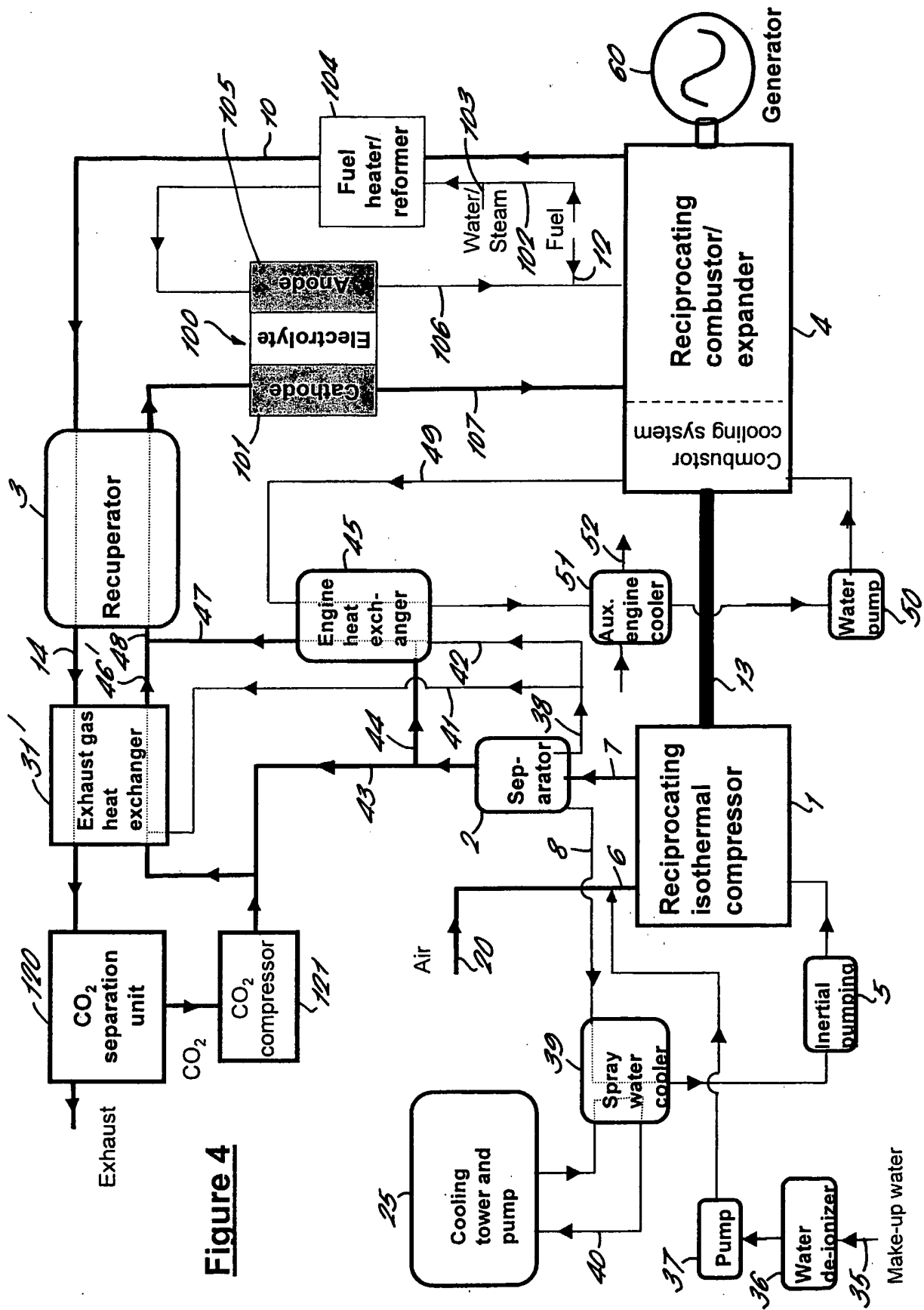


Figure 4

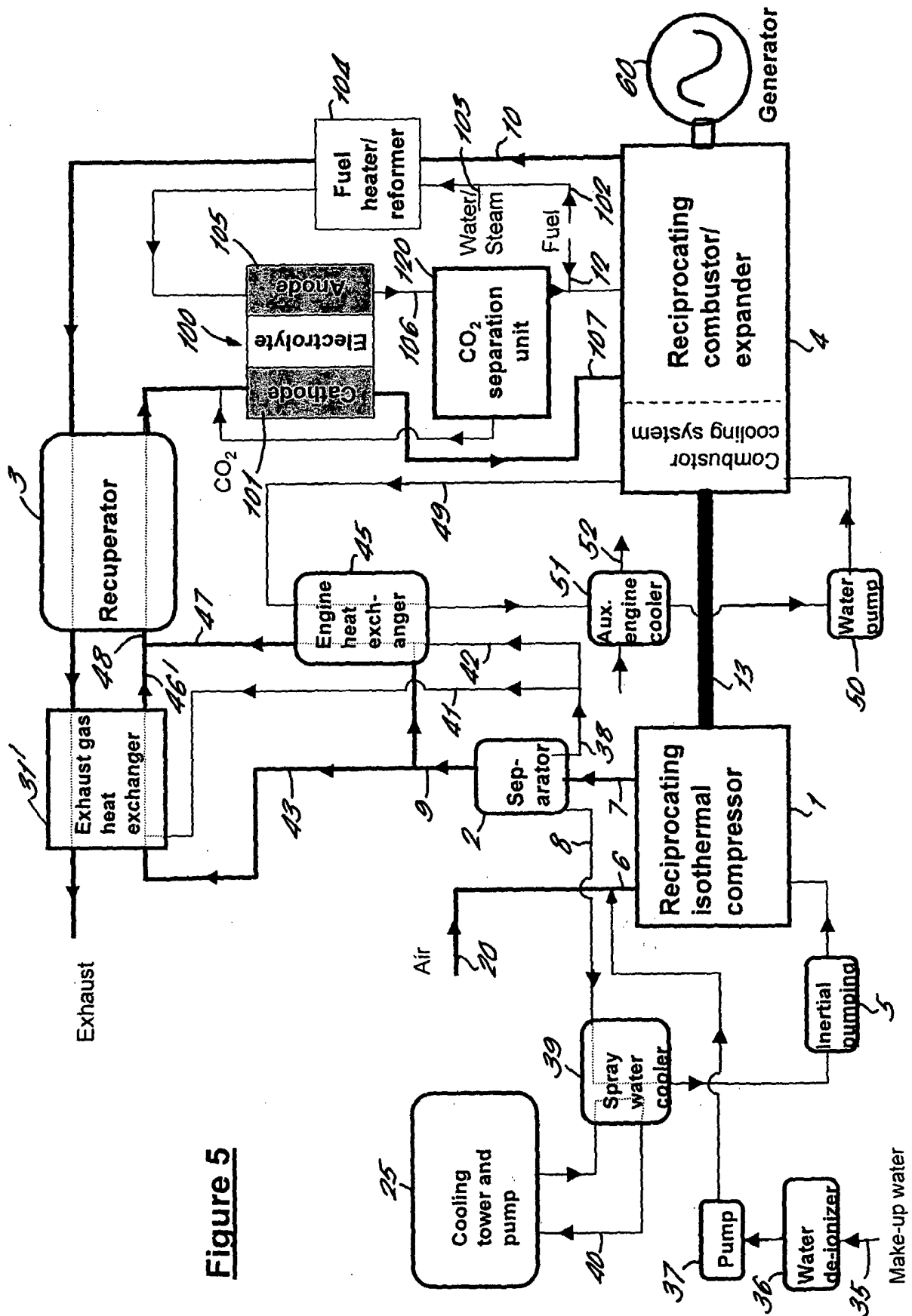


Figure 5

INTERNATIONAL SEARCH REPORT

PCT/GB 02/03952

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 H01M8/04 H01M8/06 F02C3/36 F01K3/18 F02C6/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 F02C H01M F01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 356 906 A (INT FUEL CELLS CORP) 7 March 1990 (1990-03-07) column 3 -column 4; figure 1 ---	1-25
X	US 5 693 201 A (HSU MICHAEL S ET AL) 2 December 1997 (1997-12-02) column 5 -column 6; figures 1-4 ---	1-25
A	US 5 449 568 A (MICHELI PAUL L ET AL) 12 September 1995 (1995-09-12) column 2, line 1-37 -column 5; figures 1-4,6 column 6 ---	1-25
A	US 5 319 925 A (ANKERSMIT HENDRIK JAN ET AL) 14 June 1994 (1994-06-14) column 4 -column 5; figures 1,3 ---	1-25
	--- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

A document defining the general state of the art which is not considered to be of particular relevance

E earlier document but published on or after the international filing date

L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

G document member of the same patent family

Date of the actual completion of the international search

18 December 2002

Date of mailing of the international search report

03/01/2003

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer:

Chatziapostolou, A

INTERNATIONAL SEARCH REPORT

PCT/GF 02/03952

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 622 275 A (ARAKAWA TADAO ET AL) 11 November 1986 (1986-11-11) column 5 -column 6; figure 1 column 7 -----	1-25

INTERNATIONAL SEARCH REPORT

Information on patent family members

PCT/GB 02/03952

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 0356906	A	07-03-1990	US 4865926 A	12-09-1989
			CA 1309129 A1	20-10-1992
			DE 68907155 D1	22-07-1993
			DE 68907155 T2	27-01-1994
			DK 416389 A	25-02-1990
			EP 0356906 A1	07-03-1990
			ES 2042908 T3	16-12-1993
			JP 2119062 A	07-05-1990
US 5693201	A	02-12-1997	US 5501781 A	26-03-1996
			AT 184425 T	15-09-1999
			AU 688568 B2	12-03-1998
			AU 3269795 A	07-03-1996
			AU 704873 B2	06-05-1999
			AU 6197398 A	18-06-1998
			BR 9509065 A	23-12-1997
			CA 2196764 A1	22-02-1996
			CZ 9700358 A3	16-07-1997
			DE 69512075 D1	14-10-1999
			DE 69512075 T2	27-04-2000
			DK 776529 T3	03-04-2000
			EP 0776529 A1	04-06-1997
			ES 2136872 T3	01-12-1999
			GR 3031969 T3	31-03-2000
			HK 1014224 A1	05-05-2000
			HU 77148 A2	02-03-1998
			IL 115649 A	31-08-2000
			JP 11503860 T	30-03-1999
			JP 2000311698 A	07-11-2000
			KR 271096 B1	01-11-2000
			NO 970586 A	08-04-1997
			NZ 291537 A	28-01-1999
			NZ 332940 A	29-07-1999
			RO 116851 B1	29-06-2001
			WO 9605625 A2	22-02-1996
			US 6024859 A	15-02-2000
			US 6083636 A	04-07-2000
			US 6458477 B1	01-10-2002
			US 5948221 A	07-09-1999
			US 5976332 A	02-11-1999
			PL 318546 A1	23-06-1997
			PL 180962 B1	31-05-2001
			RU 2168806 C2	10-06-2001
US 5449568	A	12-09-1995	CA 2133809 A1	29-04-1995
			DE 4438624 A1	04-05-1995
			GB 2283284 A ,B	03-05-1995
			JP 7201349 A	04-08-1995
US 5319925	A	14-06-1994	NL 8901348 A	17-12-1990
			AT 134740 T	15-03-1996
			CA 2017072 A1	29-11-1990
			CN 1048911 A ,B	30-01-1991
			CZ 9002646 A3	11-06-1997
			DD 294759 A5	10-10-1991
			DE 69025496 D1	04-04-1996
			DE 69025496 T2	31-10-1996
			DK 400701 T3	08-07-1996

INTERNATIONAL SEARCH REPORT

Information on patent family members

PCT/GB 02/03952

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5319925	A	EP 0400701 A1	05-12-1990
		ES 2085882 T3	16-06-1996
		GR 3019482 T3	31-07-1996
		HU 53987 A2	28-12-1990
		JP 3018627 A	28-01-1991
		KR 175066 B1	20-03-1999
		NO 902355 A	30-11-1990
		PL 285382 A1	04-11-1991
		RO 114518 B1	30-04-1999
		SK 264690 A3	02-12-1998
		RU 2027046 C1	20-01-1995
		US 5083425 A	28-01-1992
US 4622275	A	11-11-1986	
		JP 1932162 C	26-05-1995
		JP 6022148 B	23-03-1994
		JP 61039459 A	25-02-1986
		DE 3573494 D1	09-11-1989
		EP 0170277 A2	05-02-1986