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(54) **Title:** HYBRID CYCLE SOFC - INVERTED GAS TURBINE WITH CO2 SEPARATION

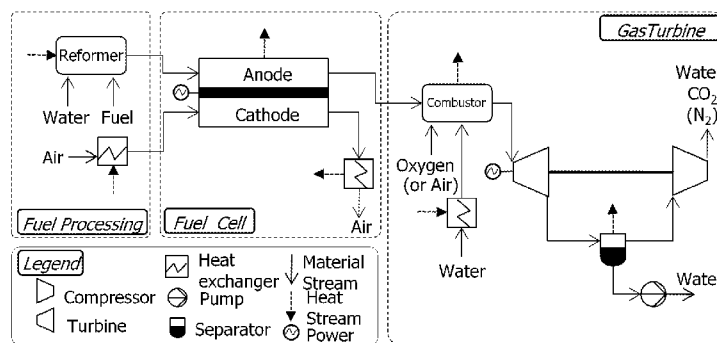


Figure 5: Schematic drawing of a fuel cell-gas turbine hybrid cycle in accordance with the invention

(57) **Abstract:** A new gas turbine-fuel cell Hybrid Cycle is proposed. The fuel cell advantageously operates close or under atmospheric pressure and is fully integrated with the gas turbine that is based on an Inverted Brayton-Joule Cycle. The idea of the invention is to capitalize on the intrinsic oxygen-nitrogen separation characteristic of the fuel cell electrolyte by sending to the Inverted Brayton-Joule Cycle only the anodic flow, which is the one free of nitrogen. In this way the flow that expands in the turbine consists only in steam and carbon dioxide. After the expansion the steam can be easily condensed, separated and pumped up. Therefore the compressor has mainly only to compress the separated carbon dioxide. This effect generates a substantial advantage in term of efficiency and enables separating the carbon dioxide. The new proposed Hybrid Cycle enables to: substantially increase the system efficiency compared to the known gas turbine-fuel cell Hybrid Cycle, maintain the fuel cell operating under or close to atmospheric pressure and separate the carbon dioxide.

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## Hybrid cycle SOFC – Inverted Gas Turbine with CO<sub>2</sub> separation

### Field of invention

The present invention relates to power generation and cogeneration of heat and power.

5

### State of the Art

To face global warming and growing energy problems, concerted efforts are required. The rising demand for electrical power and the necessity to decrease fossil fuel consumption push for development of new power generating systems, with higher efficiencies and reduced environmental impacts.

10 An attractive way to reach a more rational energy conversion of fossil or bio fuels is the decentralized power generation and cogeneration of heat and power. Among major weaknesses of existing small systems at the building level, consisting mainly of internal combustion or Stirling engines, are low electrical efficiency, high maintenance costs, together with noise and vibration. Recently introduced mini gas turbines in the range of 40 to 120 kWel reduce the three latter problems but at an even lower efficiency.

15 Moreover they are not available in the smaller power range typical of many multi-family houses. Molten Carbon Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) are emerging as major candidates to alleviate all the above mentioned drawbacks.

However the fuel cannot be entirely converted electrochemically in the fuel cell alone and part of it is combusted downstream of the fuel cell with low energy efficiency. One existing approach suggests to

20 further improve the electrical efficiency by combining the fuel cell with a gas turbine in a hybrid system.

Both MCFC and SOFC are suitable partners for gas turbines, even though SOFC are considered to be the best candidates for these applications because of their higher working temperature (around 950 °C).

The first applications and simulations show a potential of efficiency of the order of 60% or higher which

25 would make decentralized generation as or more efficient than large combined cycle power plants.

In spite of the advantages of this hybrid technology, many technical barriers have to be overcome to develop a highly efficient system. Fuel cell and gas turbines are rather different power generation systems: the operational mode of a standalone gas turbine is dynamic, whereas the fuel cell is static. The matching between the two systems is crucial. It is essential to guarantee a safe and stable operation point for the fuel

cell, to avoid structural or physical stack damages. Fuel cell pressurization represents one of the greatest challenges.

5 Considering the SOFC, two different classes are nowadays available: the tubular and planar geometry. Planar geometry is today the most efficient and compact of the two and object of much research, however it is the more problematic under pressurized conditions.

The Hybrid Cycle can be classified into two classes with respect to the integration level between the gas turbine and the fuel cell [1].

10 The first and simplest Hybrid Cycle class consists in maintaining the two systems separate and uses a heat exchanger as interface. An example is shown in Figure 1. In this case the fuel cell exhaust heats the compressed air in the micro gas turbine recuperator whereas anode and cathode gases are preheated with the gas turbine exhaust gas and heat released from combustion of residual fuel contained in the fuel cell exhaust gas. This solution facilitates control of the entire system, and can allow the SOFC to work at atmospheric pressure. Inevitably, the drawbacks are high energy losses and therefore a low efficiency.

15 To increase the system efficiency it is necessary to fully integrate gas turbines and fuel cells. This is the direction taken in the second Hybrid Cycle class in which research efforts are more concentrated, and different design solutions have been developed. In the most common solution (Figure 2) the compressor supplies compressed air at the fuel cell cathode. Usually, for planar geometry, the differential pressure between the cathode and anode is hard to maintain; therefore the whole fuel cell is working under the same pressure. For tubular geometry differential pressure between the cathode and anode is easier to  
20 maintain. In each case pressurizing the fuel cells presents a challenge. After passing through the fuel cells, the anodic and cathodic flows are mixed and the mixture goes into a combustor into which the unconsumed fuel is fully oxidized. Following this, the hot gases including both the anodic and cathodic flows expand in the turbine and are ejected as waste gases. Usually air factors (ratio between real and stoichiometric air flow) are high because the gas flows are also there to take the extra heat due to  
25 irreversibility in the fuel cell, so that the produced steam is rather diluted in the exhaust and therefore difficult to condense.

The world's first SOFC/GT hybrid system, including a pressurized tubular SOFC module integrated with a micro turbine/generator, was delivered to Southern California Edison for operation at the Irvine's National Fuel Cell Research Center. This system was the first-ever demonstration of the SOFC/gas turbine hybrid  
30 concept and reached 53% electric efficiency for 220 kW [2].

Other experimental applications have been developed, but all are restricted to the tubular SOFC stacks. Only recently, Lim [3] operates for a few hours a pressurized Hybrid Cycle, according with the figure 3, with a 25 kW micro gas turbine and a 5 kW class planar SOFC, designed to work under atmospheric conditions.

5 Many studies have assessed the feasibility and operating condition of a variety of integrated high efficiency design alternatives. Palsonn [4] showed the possibility to reach, also with a low pressure ratio (typical of small to medium size dynamic turbomachinery), more than 65 % of efficiency. Massardo [5] analyzed pressurized and atmospheric systems with efficiency up to 75%.

10 Other approaches are related to the Hybrid System design with a thermo-economic analysis. Autissier [6] demonstrated the possibility to reach 70% efficiency for 6700 \$/kW with a 50 kW pressurized system.

A different way to fully integrate a gas turbine with fuel cells is proposed by Tsujikawa [7, 8, 9]. He proposed a Hybrid Cycle with the fuel cell operating at atmospheric pressure and the gas turbine driven in an Inverted Brayton-Joule Cycle (Figure 3).

15 The Inverted Brayton-Joule Cycle, which has been fully detailed by Wilson [10], is characterized by the expansion in the turbine before the compression. This technology is not in use today for power generation purposes due to the lower efficiency obtainable with respect to a traditional gas turbine because of the smaller power density. Inoue [11] and Tanaka [12] showed performance evaluations based on simulations and experimental measurements of a gas turbine based on Inverted Brayton-Joule Cycle.

20 The Tsujikawa system layout is shown in figure 4; he showed a 65% efficiency reachable either with a SOFC or a MCFC. It is important to stress that as in the most common pressurized fully integrated system (Figure 1), in the Tsujikawa system the anodic and cathodic flows are mixed and the mixture goes then into a combustor into which the unconsumed fuel is fully oxidized. Following this, the hot gases including both the anodic and cathodic flows expand in the turbine. In the Tsujikawa configuration, waste gases are ejected after being cooled and recompressed to atmospheric pressure with the compressor.

30 Summarizing, the research in the last years fully demonstrates the potential of the fuel cell-gas turbine hybrid system. However limits of this technology are also clear: to reach a high efficiency it is necessary to fully integrate the two power generation systems which is difficult as operating the fuel cell under pressurized conditions creates new technical difficulties.

The Inverted Brayton-Joule based proposals partially solve the problems. In fact with these systems it is possible to operate the fuel cell under atmospheric conditions and to fully integrate the gas turbine. However the limit of these solutions is a lower system efficiency with regard to a pressurized system.

## Invention Description

The present invention offers several advantages with respect to the state of the art, in particular: the system efficiency is substantially increased, the fuel cell operates close or under atmospheric conditions and the carbon dioxide is separated. One embodiment of the invention is presented in figure 5.

In Brayton-Joule Cycles (traditional or inverted), the compressor uses a large part of the turbine power (typically over the 60%). The new proposal Hybrid Cycle, based on a fuel cell operating at or close to atmospheric pressure coupled with a gas turbine driven in an Inverted Brayton-Joule Cycle, enables to reduce substantially the turbine power used by the compressor.

The idea is to capitalize on the intrinsic oxygen-nitrogen separation characteristic of the fuel cell electrolyte by sending to the Inverted Brayton-Joule Cycle only the flow from the anode, which is free of nitrogen. After the combustion, if the remaining fuel (not utilized in the fuel cell, typically 15 to 25 %) is oxidized using pure oxygen, the anodic flow consists only of carbon dioxide and water. The water can easily be condensed and separated in the cooling process between the turbine and the compressor. The latter mainly compresses carbon dioxide whereas the water is pumped up separately. As gas compression is much more demanding in terms of mechanic power than liquid pumping, the reduced gas flow leads to significant savings of power with respect to traditional systems.

To benefit as much as possible from this gain, supplementary water is preferably injected in the anodic flow either in the combustor and/or in the fuel processing unit and/or elsewhere before the turbine inlet. As a consequence, the anodic flow steam injection rate is optimized and usually increased compared to the standard hybrid fuel cell-gas turbine system.

An additional advantage of the present invention is that the carbon dioxide can be separated for other uses of storage and can be compressed to a compatible state for transportation and sequestration.

The advantages of the power savings and the carbon dioxide separation, although reduced, are maintained in case that the combustion is done with air instead of pure oxygen, as combustion concerns only a small part of the total fuel converted in the system.

All the heat exchangers required by the system can be organized in one or more heat exchange networks. The energy recovered by cooling down the cathodic flow, and/or the fuel cell, and/or the combustor, and/or the flow coming out the turbine before the compressor unit (compressor and pump), and/or the exhausted flows, and/or other units, and/or other complementary cycles, can be used to supply heat to the fuel processing unit, and/or to produce steam injected in the combustor, and/or to gasification units and/or to other complementary cycles (e.g. Rankine Cycle, ORC-ORC cycle), and/or for cogeneration purposes.

Summarizing, the main advantages related to the present invention are:

- ✓ Increased system efficiency, due to the fact that the steam expanded in the turbine is then condensed and recompressed by a pump and not by the compressor. Therefore the compressor's power is substantially decreased whereas the turbine's power remains constant.
- ✓ The system enables carbon dioxide separation.
- ✓ Possibility to operate the Fuel Cell at or close to atmospheric pressure.
- ✓ Higher combustion efficiency due to optimization of the Fuel – Oxygen ratio.
- ✓ Larger volume flow in small to medium size dynamic compressor and turbine that make easier high efficiency turbomachinery design.

5

Hereafter are presented some extensions at the above presented innovation.

#### **Extension 1**

15 A system according with the above described invention in which the supplementary steam injected in the anodic flow is generated at high pressure and is expanded in a turbine before to be injected in the anodic flow (Figure 6). The steam turbine represents an additional electric output.

#### **Extension 2**

20

A system according with the above described invention in which the flow coming out the fuel cell cathode is driven in a gas turbine based on an Inverted Brayton-Joule Cycle (Figure 7). The cathodic flow coming out the fuel cell cathode can exchange heat with the heat exchanger network before to expand in a turbine below the atmospheric pressure, then is cooled down and recompressed to the atmospheric pressure. The gas turbine represents an additional electric output.

25

The Extension 2 can be combined with the Extension 1.

**Extension 3**

A system according with the above described invention in which the cathodic flow coming out the fuel cell is expanded below the atmospheric pressure in a turbine, than it is cooled down and is mixed up with the anodic flow coming out the separator before the compressor inlet. The compressor compresses the mixture between cathodic and the anodic flow up to the atmospheric pressure. Both the anodic and the cathodic flows are driven into two gas turbines, based on an Inverted Brayton-Joule Cycle, that share the same compressor (Figure 8).

The compressor can be driven by the anodic turbine and/or by the cathodic turbine and/or by an electric motor.

The Extension 3 can be combined with the Extension 1, 2.

**Extension 4**

By extension the present invention can also be applied to a concept combining traditional Brayton-Joule Cycle and Inverted Brayton-Joule Cycle. The advantage of reducing compression power is then reduced but still more advantageous than the traditional design. However this configuration can make easier the system start up.

The invention can be applied with advantage every time that in the gas turbine-fuel cell Hybrid Cycle there is one expansion before one compression. Therefore application of the discussed idea can be generalized also in the case in which the turbine expands from above atmospheric pressure (e.g. use of a pressurized fuel cell) or from below the atmospheric pressure.

In example figure 9 shows a cycle in which the turbine is expanding from above atmospheric pressure down to below atmospheric pressure. Also in this case the invention can be applied advantageously.

The Extension 4 can be combined with the Extension 1, 2, 3.

**Extension 5**

The present invention can be applied in a gas turbine-fuel cell hybrid cycle with any kind or size of Fuel Cell.

The Extension 5 can be combined with the Extension 1, 2, 3, 4.

**Extension 6**

5 The present invention can be applied independently to the class or size of the involved turbomachinery, including multi-stage compressions and expansions, intercooling between the compressions, re-heating between the expansions, mon shaft and/or multishaft configurations.

The Extension 6 can be combined with the Extension 1, 2, 3, 4, 5.

**Extension 7**

10

The present invention can be applied to convert any kind of fuel and can be integrated with any kind of fuel processing.

The Extension 7 can be combined with the Extension 1, 2, 3, 4, 5, 6.

15 **Extension 8**

The present invention can be applied to convert the syngas produced by any gasification process. In that case, the invention will allow for different integration with the gasification process:

- By heat integration with the gasification process, the fuel pretreatment or the gas treatment
- 20 • By the possible use in the gasification process of the gases processed in the invention
- By the direct or indirect integration of the burner in the gasification process.

The Extension 8 can be combined with the Extension 1, 2, 3, 4, 5, 6, 7.

**Extension 9**

25 A system according with the above described invention in which the oxygen necessary to oxidize the amount of fuel unconverted in the fuel cell can be added in the anodic flow either in the combustion chamber and/or in the fuel processing and/or elsewhere before the combustion chamber.

The alternatives to separate pure oxygen from air include:



- An oxygen separation membrane, in example to separate oxygen from the cathodic flow;
- A fuel cell used in reverse mode;
- Through water hydrolysis. The products of this process are oxygen and hydrogen. The hydrogen can be used as fuel for the fuel cell.

5 The Extension 9 can be combined with the Extension 1, 2, 3, 4, 5, 6, 7, 8.

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## Claims

1. A Hybrid Power Generation System comprising an anodic fluid line consisting of at least the following elements :
- 5
- a fuel cell,
  - a combustor,
  - an anodic turbine,
  - an anodic flow flowing from said fuel cell through said combustor and said anodic turbine;
- said System furthermore comprising a cathodic fluid line consisting of at least said fuel cell and a cathodic flow flowing from said fuel cell;
- 10
- characterized by the fact that said fluid lines are separated from each other between said fuel cell and the anodic turbine.
2. A Hybrid Power Generation System according to claim 1 wherein the anodic fluid line furthermore comprises a water inlet.
- 15
3. A Hybrid Power Generation System according to claim 2 wherein said water inlet is located on said combustor.
4. A Hybrid Power Generation System according to one of the previous claims wherein the cathodic fluid line comprises a cathodic turbine.
- 20
5. A Hybrid Power Generation System according to one of the previous claims wherein the cathodic fluid line comprises a cathodic compressor.
6. A Hybrid Power Generation System according to one of the claim 5 wherein said cathodic compressor is
- 25
- located downstream said cathodic turbine.
7. A Hybrid Power Generation System according to one of the previous claims wherein the anodic fluid line comprises an anodic compressor.
- 30
8. A Hybrid Power Generation System according to the claims 7 wherein said anodic compressor is located downstream the anodic turbine.

9. A Hybrid Power Generation System according to one of the previous claims wherein the anodic fluid line comprises steam condensing means adapted to condensate the steam downstream the anodic turbine.
- 5 10. A Hybrid Power Generation System according to claim 9 wherein said fluid lines are separated from each other between said fuel cell and said steam condensing means.
11. A Hybrid Power Generation System according to claim 10 wherein said fluid lines are joined between said condensing means and said anodic compressor.
- 10 12. A Hybrid Power Generation System according to claim 10 wherein said fluid lines are joined between said condensing means and said cathodic compressor.
13. Use of a Hybrid Power Generation System as defined in one of the previous claims wherein compressor(s) and turbine(s) are operating on an Inverted Brayton Joule Cycle.
- 15 14. Use of a Hybrid Power Generation System as defined in one of the previous claims 1 to 12 wherein compressor(s) and turbine(s) are operating on a combination of Brayton-Joule Cycle and Inverted Brayton-Joule Cycle.
- 20 15. Use of a Hybrid Power Generation System as defined in one of the previous claims 1 to 12 characterized by the additional injection of water in the System.
16. Use of a Hybrid Power Generation System as defined in one of the previous claims 1 to 12 characterized by the carbon dioxide separation.
- 25 17. Use of syngas in a Hybrid Power Generation System as defined in one of the previous claims 1 to 12.
18. Use of a Hybrid Power Generation System as defined in one of the previous claims 1 to 12 for producing syngas.
- 30 19. Use of a Hybrid Power Generation System as defined in one of the previous claims 1 to 12 for converting syngas.

20. Use of a gasification process in a Hybrid Power Generation System as defined in one of the previous claims 1 to 12.

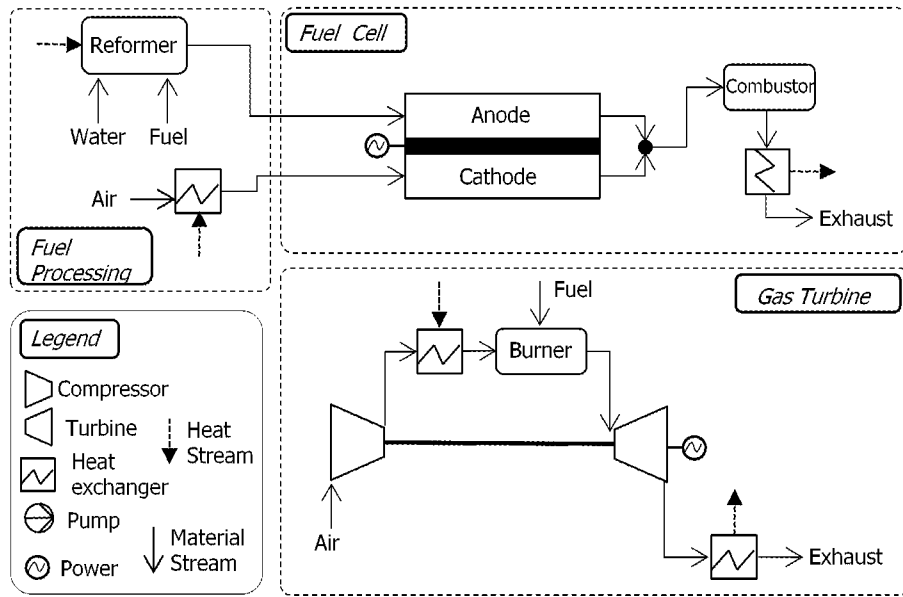


Figure 1: Hybrid Cycle integrated by heat exchanger

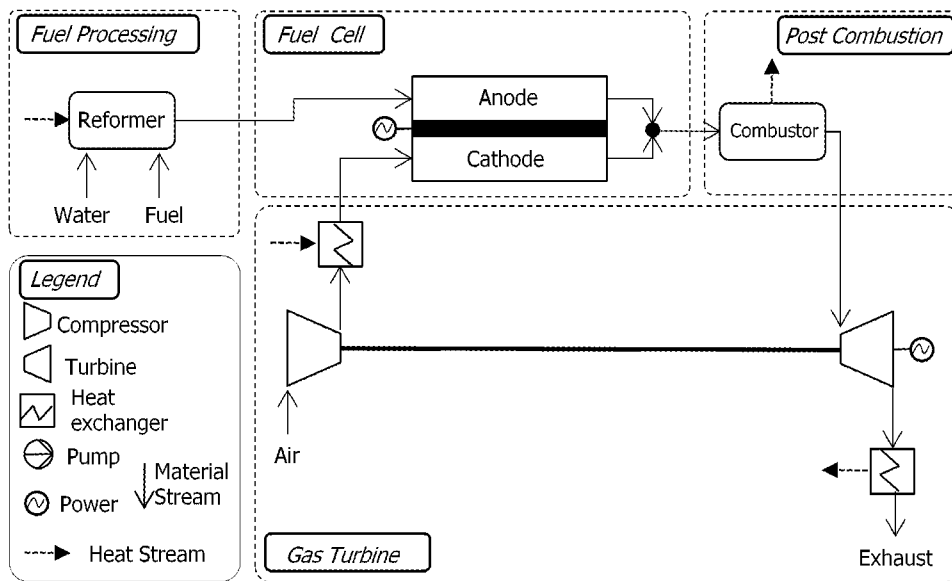


Figure 2: Directly coupled Hybrid Cycle

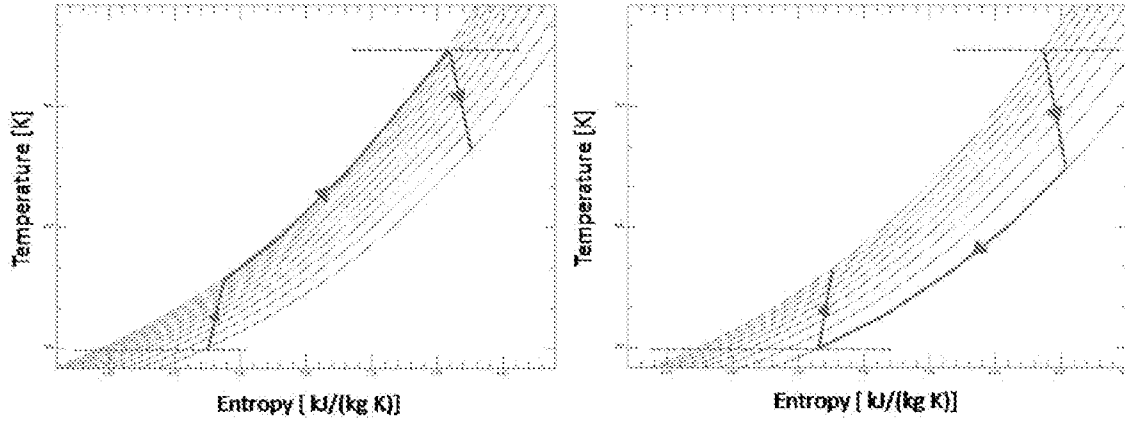


Figure 3: Representations in a Temperature-Entropy diagram of a traditional (left) and an Inverted (right) Brayton-Joule Cycle

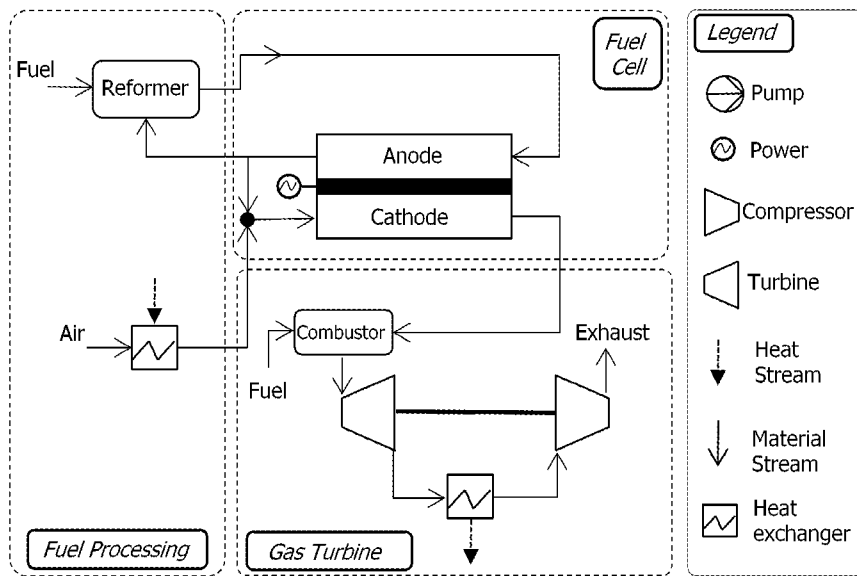


Figure 4: Hybrid Cycle, based on the Inverted Brayton-Joule Cycle, proposed by Tsujikawa

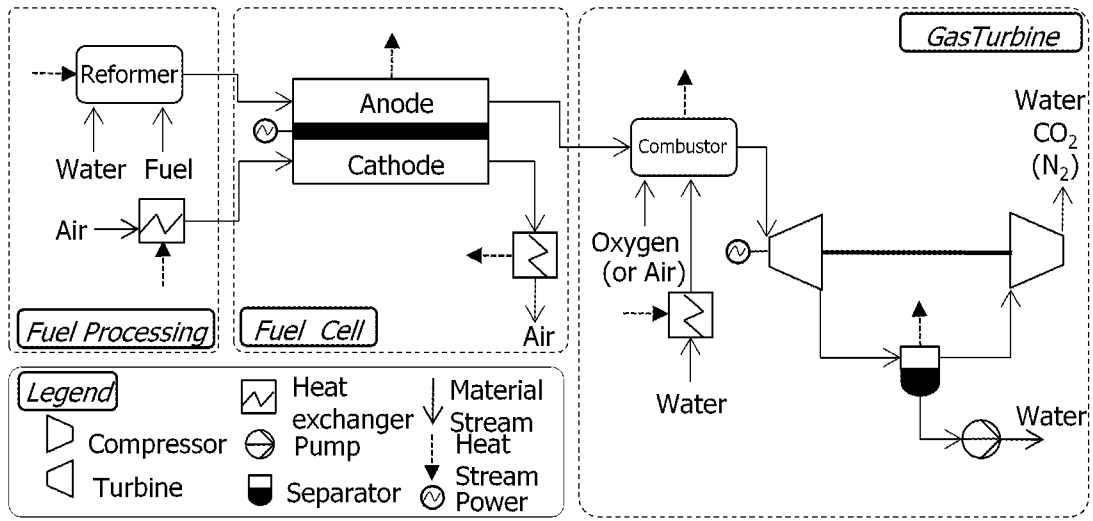


Figure 5: Schematic drawing of a fuel cell-gas turbine hybrid cycle in accordance with the invention

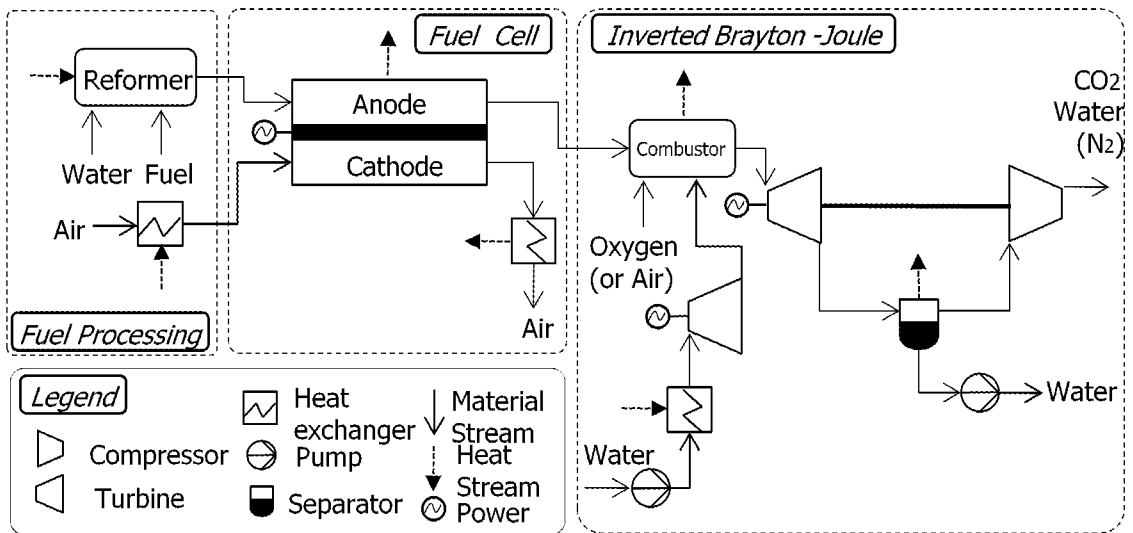


Figure 6: Schematic drawing of a fuel cell-gas turbine hybrid cycle in accordance with the Extension 1



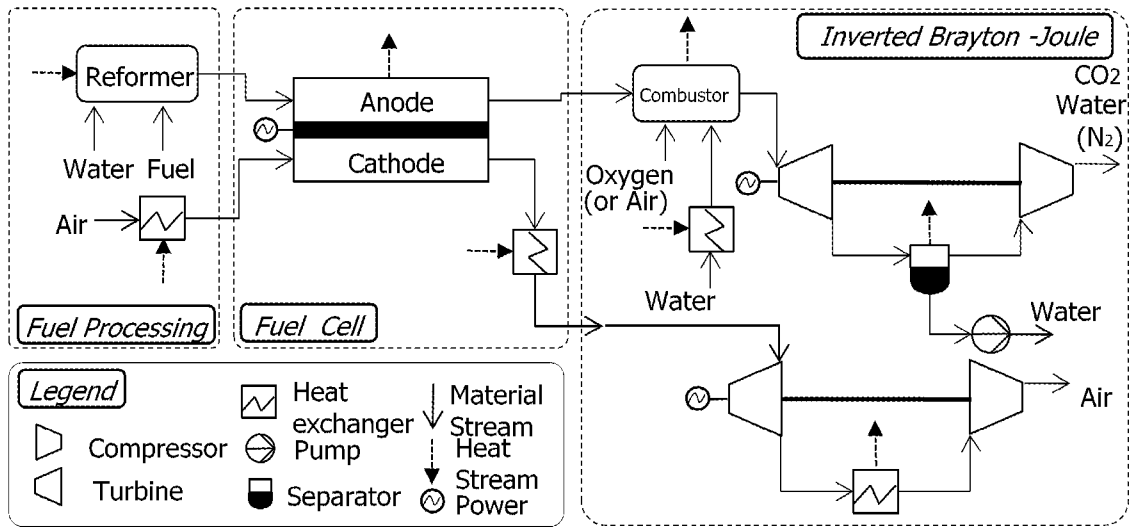


Figure 7: Schematic drawing of a fuel cell-gas turbine hybrid cycle in accordance with the Extension 2

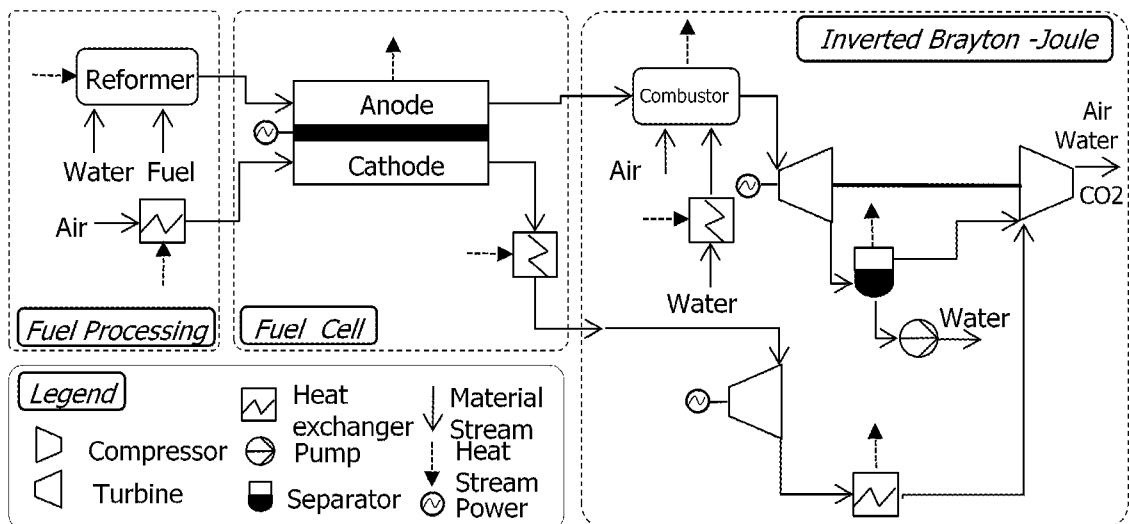


Figure 8: Schematic drawing of a fuel cell-gas turbine hybrid cycle in accordance with the Extension 3

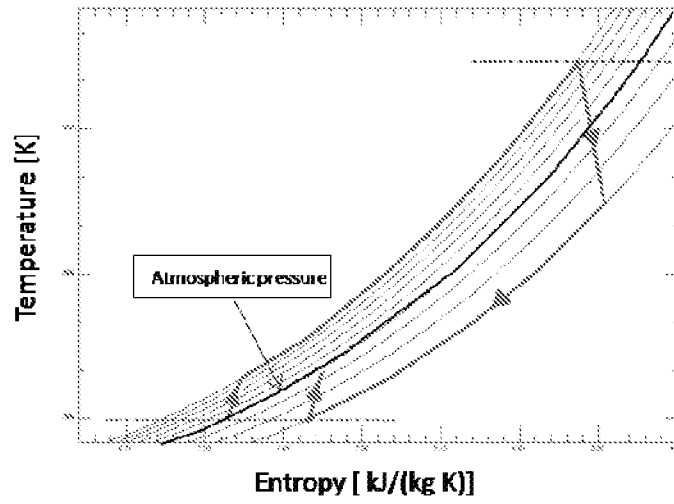


Figure 9: Representations in a Temperature-Entropy diagram of a Brayton-Joule Cycle crossing the atmospheric pressure level