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(54) **ENERGY CONVERSION METHOD, PARTICULARLY OF THE HYBRID THERMODYNAMIC CYCLE TYPE, AND THERMODYNAMIC MACHINE**

(57) An energy conversion method, particularly of the hybrid thermodynamic cycle type, characterized in that it comprises the following steps:
- isothermal compression of a thermodynamic fluid, from a first pressure "p1" to a second pressure "p2";
- adiabatic compression of the thermodynamic fluid from the second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- isobaric thermal regeneration of the thermodynamic fluid with increase of the temperature from the second temperature "T2" to a third temperature "T3";
- isobaric heating of the thermodynamic fluid from the third temperature "T3" to a fourth temperature "T4";
- isothermal expansion of the thermodynamic fluid from the third pressure "p3" to a fourth pressure "p4";
- adiabatic expansion of the thermodynamic fluid from the fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from the fourth temperature "T4" to a fifth temperature "T5";
- thermal regeneration of the thermodynamic fluid with reduction of the temperature from the fifth temperature "T5" to a sixth temperature "T6".

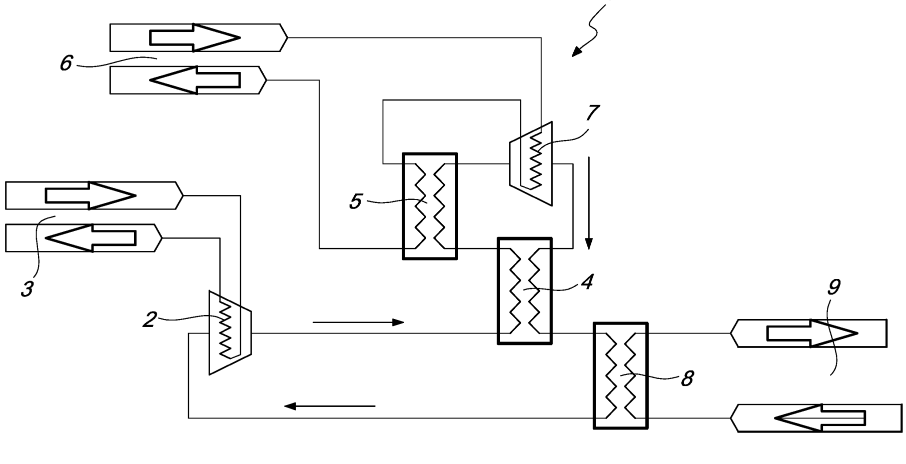

Fig. 1

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Description

[0001] The present invention relates to an energy conversion method, particularly of the hybrid thermodynamic cycle type, and a thermodynamic machine that is adapted to carry out such method.

[0002] In more detail, in the present invention reference will be made to a hybrid thermodynamic cycle and to a hybrid thermodynamic machine that are capable of best exploiting the characteristics of the traditional Stirling and Brayton thermodynamic cycles.

[0003] In the energy conversion sector, in particular in the conversion of the chemical/physical energy of a thermodynamic fluid to heat energy, different thermodynamic cycles are known including the Stirling cycle and the Brayton cycle.

[0004] As is known, such cycles have yields that depend on the thermal inertias of real components which, unfortunately, differ from those of the components of theoretical machines.

[0005] The aim of the present invention consists of developing an energy conversion method and of providing a thermodynamic machine, both capable of best exploiting the characteristics of the traditional Stirling and Brayton cycles, by providing an alternative technical solution.

[0006] Within this aim, an object of the present invention consists of developing an energy conversion method and of providing a thermodynamic machine, both free from thermodynamic phenomena that imply the alternation of hot-cold-hot, thus overcoming the drawbacks deriving from the thermal inertia of real components with respect to the components of theoretical machines.

[0007] Another object of the present invention consists of providing a thermodynamic machine that is adapted to be installed in plant engineering implementations of industrial type, in any case static, which have variable sizes in a range of powers, which depends on the type of construction technologies adopted.

[0008] This aim and these and other objects which will become better apparent hereinafter are achieved by an energy conversion method, characterized in that it comprises the following steps:

- isothermally compressing a thermodynamic fluid, from a first pressure "p1" to a second pressure "p2";
- adiabatically compressing the thermodynamic fluid from said second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- isobarically thermally regenerating said thermodynamic fluid with increase of the temperature from said second temperature "T2" to a third temperature "T3";
- isobarically heating said thermodynamic fluid from said third temperature "T3" to a fourth temperature "T4";
- isothermally expanding said thermodynamic fluid from said third pressure "p3" to a fourth pressure "p4";
- adiabatically expanding said thermodynamic fluid from said fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from said fourth temperature "T4" to a fifth temperature "T5";
- thermally regenerating said thermodynamic fluid with reduction of the temperature from said fifth temperature "T5" to a sixth temperature "T6".

[0009] Moreover, this aim and these and other objects which will become better apparent hereinafter are achieved by a thermodynamic machine, characterized in that it comprises:

- a compressor which is functionally connected to an external cooling source for the isothermal compression of a thermodynamic fluid from a first pressure "p1" to a second pressure "p2", and for the adiabatic compression of said thermodynamic fluid, from said second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- a heat regenerator which is functionally connected downstream of said compressor for the isobaric thermal regeneration of said thermodynamic fluid with increase of the temperature from said second temperature "T2" to a third temperature "T3";
- a heat exchange device which is functionally connected downstream of said heat regenerator and to an external heat source for the isobaric heating of said thermodynamic fluid from said third temperature "T3" to a fourth temperature "T4";
- an expansion motor which is functionally connected downstream of said heat exchange device and functionally connected to said external heat source for the isothermal expansion of said thermodynamic fluid from said third pressure "p3" to a fourth pressure "p4", and for the adiabatic expansion of said thermodynamic fluid from said fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from said fourth temperature "T4" to a fifth temperature "T5";
- a heat recovery device which is functionally connected downstream of said heat regenerator and functionally connected to external user devices for the cooling of said thermodynamic fluid at the end of the cycle;
- a control device for regulating the power level of said compressor as a function of the state variables of said thermodynamic fluid;

said heat regenerator being adapted for the thermal regeneration of said thermodynamic fluid with reduction of the temperature from said fifth temperature "T5" to said sixth temperature "T6".

[0010] Further characteristics and advantages of the invention will become better apparent from the detailed description of a preferred, but not exclusive, embodiment of an energy conversion method, particularly of the hybrid thermodynamic cycle type, and of a thermodynamic machine, illustrated by way of non-limiting example with the aid of the accompanying drawings wherein:

- Figure 1 is a schematic view of the thermodynamic machine according to the present invention;
- Figure 2 is the diagram of the thermodynamic cycle of the machine shown in Figure 1;
- Figure 3 is a graph showing the progression of the physical variables of the thermodynamic fluid of the machine shown in Figure 1.

[0011] With reference to the above figures, the thermodynamic machine, generally designated by the reference numeral 1, comprises the following components:

- a compressor 2 which is functionally connected to an external cooling source 3 for the isothermal compression of a thermodynamic fluid from a first pressure "p1" to a second pressure "p2", and for the adiabatic compression of said thermodynamic fluid, from said second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- a heat regenerator 4 which is functionally connected downstream of the compressor 2 for the isobaric thermal regeneration of the thermodynamic fluid with increase of the temperature from the second temperature "T2" to a third temperature "T3";
- a heat exchange device 5 which is functionally connected downstream of the heat regenerator 4 and to an external heat source 6 for the isobaric heating of the thermodynamic fluid from the third temperature "T3" to a fourth temperature "T4";
- an expansion motor 7 which is functionally connected downstream of the heat exchange device 5 and functionally connected to the external heat source 6 for the isothermal expansion of the thermodynamic fluid from the third pressure "p3" to a fourth pressure "p4", and for the adiabatic expansion of the thermodynamic fluid from the fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from the fourth temperature "T4" to a fifth temperature "T5";
- a heat recovery device 8 which is functionally connected downstream of the heat regenerator 5 and functionally connected to external user devices for the cooling of the thermodynamic fluid at the end of the cycle;
- a control device, not shown for the sake of graphic simplicity, for regulating the power level of the compressor 2 as a function of the state variables of the thermodynamic fluid.

[0012] Conveniently, the heat regenerator 5 is adapted for the thermal regeneration of the thermodynamic fluid with reduction of the temperature from the fifth temperature "T5" to the sixth temperature "T6".

[0013] Advantageously, the compressor 2 and the expansion motor 7 are mechanically mutually independent.

[0014] In this way, the thermodynamic machine 1 can operate with greater flexibility in terms of temperatures and operating pressures, by virtue of the possibility to optimize the flow rate of the thermodynamic fluid and the operating pressure of the circuit as a function of the minimum and maximum temperatures available.

[0015] Considering the thermodynamic fluid, this is of the compressible type and consists of any gas or mixture of gases adapted to operate in the thermodynamic machine 1 without chemical alterations or changes in state.

[0016] For example, if the thermodynamic fluid is air, the thermodynamic machine 1 is capable of operating in a simplified, open-cycle configuration, without requiring the section for cooling the thermodynamic fluid at the end of the expansion cycle and the step, if present, of regeneration via heat exchange.

[0017] Conversely, if the thermodynamic fluid is a gas that cannot be discharged into the environment, or it has particular physical/chemical characteristics, the thermodynamic machine 1 would be capable of operating in a closed-cycle configuration, availing of the section for cooling the thermodynamic fluid at the end of the expansion cycle and the step, if present, of regeneration via heat exchange.

[0018] The energy conversion method and the thermodynamic cycle with which the thermodynamic machine 1 operates comprises the following steps:

- isothermally compressing the thermodynamic fluid, from a first pressure "p1" to a second pressure "p2";
- adiabatically compressing the thermodynamic fluid from the second pressure "p2" to the third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from the first temperature "T1" to the second temperature "T2";
- isobarically thermally regenerating the thermodynamic fluid with increase of the temperature from the second temperature "T2" to the third temperature "T3";
- isobarically heating the thermodynamic fluid from the third temperature "T3" to the fourth temperature "T4";
- isothermally expanding the thermodynamic fluid from the third pressure "p3" to the fourth pressure "p4";
- adiabatically expanding the thermodynamic fluid from the fourth pressure "p4" to the fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from the fourth temperature "T4" to the fifth temperature "T5";
- thermally regenerating the thermodynamic fluid with reduction of the temperature from the fifth temperature "T5" to the sixth temperature "T6".

[0019] According to the necessity to have an open cycle or a closed cycle, the method can selectively and respectively comprise a step of expulsion or step of cooling the thermodynamic fluid at the end of the cycle, by way of the heat recovery device 8 for sending heat to external user devices 9.

[0020] Advantageously, as mentioned previously, the step of isothermal compression of the thermodynamic fluid occurs by way of the high-efficiency compressor 2, which is cooled by way of the external cooling source 3, which is mechanically independent of the expansion motor 7.

[0021] Moreover, the step of isothermal compression of the thermodynamic fluid comprises the recovery of heat intended for external user devices 9 and, in the step of isobaric thermal regeneration of the thermodynamic fluid the residual heat is recovered at the end of the step of adiabatic expansion, with a consequent increase of the temperature from the second temperature "T2" to a third temperature "T3".

[0022] Furthermore, the step of isobaric heating of the thermodynamic fluid occurs by way of the heat exchange device 5 which is functionally connected to the external heat source 6, and the step of isothermal expansion of the thermodynamic fluid occurs by way of the expansion motor 7 heated by the external heat source 6.

[0023] Finally, the step of thermal regeneration of the thermodynamic fluid occurs by way of the heat recovery device 8 for the recovery of the heat of the thermodynamic fluid at the end of the step of adiabatic expansion, with consequent reduction of the temperature, from the fifth temperature "T5" to the sixth temperature "T6".

[0024] In practice it has been found that the energy conversion method, particularly of the hybrid thermodynamic cycle type, and the thermodynamic machine adapted to carry out such method, according to the present invention, achieve the intended aim and objects in that they offer an alternative technical solution to traditional thermodynamic cycles characterized by the use of external heat sources.

[0025] In fact, the thermodynamic machine according to the present invention is capable of best exploiting the characteristics of the traditional Stirling and Brayton cycles, by way of a configuration that makes it possible to eliminate the problems associated with the thermal inertias of the regeneration system that characterizes machines that operate according to the Stirling cycle, which is known for being theoretically the most efficient, being based on the thermodynamic conversions that are characteristic of the ideal Carnot cycle.

[0026] This is by virtue of the substantial difference, with respect to traditional machines based on the Stirling cycle, which consists of the absence of thermodynamic phenomena that imply the alternation of hot-cold-hot and the consequent problems deriving from the thermal inertia of real components with respect to the components of theoretical machines.

[0027] In more detail, the fundamental elements that differentiate the thermodynamic machine, according to the present invention, from machines of the conventional type based on the Stirling cycle, are the following:

- continuity of flow in the thermodynamic circuit, characterized by the absence of alternating cycles imposed by synchronized motion necessary in order to ensure the cold compression and hot expansion of the fluid;
- the mechanical independence between the compression unit and the expansion drive unit, giving the machine the capacity to operate with greater flexibility in terms of temperatures and operating pressures, by virtue of the possibility to optimize the flow rate of the thermodynamic fluid and the operating pressure of the circuit as a function of the minimum and maximum temperatures available;
- the compressor, mechanically independent of the motor, is regulated on the basis of the state variables of the thermodynamic fluid which has to flow uniformly from the compression unit to the drive unit, expanding by virtue of the supply of heat;
- in the closed-cycle configuration, the cycle is completed with the cooling of the fluid by way of a dissipative heat exchange unit or optionally by sending heat to user devices.

[0028] In other words, the thermodynamic machine, according to the present invention, makes it possible to compensate for the dynamic shortcomings of traditional Stirling motors, which are subject to thermal inertias that are such as to considerably alter the real thermodynamic cycle from the theoretical cycle; furthermore it makes it possible to improve the efficiency of the Brayton cycle by virtue of the steps of isothermal compression and expansion and of the consequent capacity to recover a greater share of residual heat, despite the lower temperature of the fluid exiting from the compressor and the higher temperature of the fluid exiting from the motor.

[0029] Finally, it should be noted that the theoretical yield of the thermodynamic cycle with heat recovery tends to reach the values that characterize the Stirling cycle for the same operating temperatures; the thermal regeneration system, not being subject to the cyclic dynamics that characterize Stirling-configuration motors, makes it possible to recover greater amounts of heat energy.

[0030] The energy conversion method, particularly of the hybrid thermodynamic cycle type, and thermodynamic machine adapted to carry out such method, thus conceived, are susceptible of numerous modifications and variations all of which are within the scope of the appended claims.

[0031] Moreover, all the details may be substituted by other, technically equivalent elements.

[0032] In practice the materials employed, provided they are compatible with the specific use, and the contingent dimensions and shapes, may be any according to requirements.

[0033] The disclosures in Italian Patent Application No. 102020000026245 from which this application claims priority are incorporated herein by reference.

[0034] Where technical features mentioned in any claim are followed by reference signs, those reference signs have been included for the sole purpose of increasing the intelligibility of the claims and accordingly, such reference signs do not have any limiting effect on the interpretation of each element identified by way of example by such reference signs

Claims

1. An energy conversion method, **characterized in that** it comprises the following steps:

- isothermally compressing a thermodynamic fluid, from a first pressure "p1" to a second pressure "p2";
- adiabatically compressing said thermodynamic fluid from said second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- isobarically thermally regenerating said thermodynamic fluid with increase of the temperature from said second temperature "T2" to a third temperature "T3";
- isobarically heating said thermodynamic fluid from said third temperature "T3" to a fourth temperature "T4";
- isothermally expanding said thermodynamic fluid from said third pressure "p3" to a fourth pressure "p4";
- adiabatically expanding said thermodynamic fluid from said fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from said fourth temperature "T4" to a fifth temperature "T5";
- thermally regenerating said thermodynamic fluid with reduction of the temperature from said fifth temperature "T5" to a sixth temperature "T6".

2. The method according to claim 1, **characterized in that** it comprises selectively a step of expulsion or a step of cooling of said thermodynamic fluid at the end of the cycle.

3. The method according to claim 2, **characterized in that** said step of cooling said thermodynamic fluid occurs by way of a heat recovery device (8) for sending heat to external user devices (9).

4. The method according to one or more of the preceding claims, **characterized in that** said step of isothermally compressing said thermodynamic fluid occurs by way of a high-efficiency compressor (2) which is cooled by way of an external cooling source (3).

5. The method according to claim 4, **characterized in that** said step of isothermally compressing said thermodynamic fluid comprises the recovery of heat intended for external user devices (9).

6. The method according to one or more of the preceding claims, **characterized in that** in said step of isobarically thermally regenerating said thermodynamic fluid the residual heat is recovered at the end of said step of adiabatic expansion, with a consequent increase of the temperature from said second temperature "T2" to a third temperature "T3".

7. The method according to one or more of the preceding claims, **characterized in that** said step of isobarically heating said thermodynamic fluid occurs by way of a heat exchange device (5) which is functionally connected to an external heat source (6).

8. The method according to one or more of the preceding claims, **characterized in that** said step of isothermally expanding said thermodynamic fluid occurs by way of an expansion motor (7) heated by said external heat source (6).

9. The method according to one or more of the preceding claims, **characterized in that** said step of thermally regenerating said thermodynamic fluid occurs by way of said heat recovery device (8) for the recovery of the heat of said thermodynamic fluid at the end of the step of adiabatic expansion, with consequent reduction of the temperature from said fifth temperature "T5" to said sixth temperature "T6".

10. A thermodynamic machine (1), **characterized in that** it comprises:

- a compressor (2) which is functionally connected to an external cooling source (3) for the isothermal compression of a thermodynamic fluid from a first pressure "p1" to a second pressure "p2", and for the adiabatic compression of said thermodynamic fluid, from said second pressure "p2" to a third pressure "p3", in the absence of heat exchange, with consequent increase of the temperature from a first temperature "T1" to a second temperature "T2";
- a heat regenerator (4) which is functionally connected downstream of said compressor (2) for the isobaric thermal regeneration of said thermodynamic fluid with increase of the tempera-

ture from said second temperature "T2" to a third temperature "T3";

- a heat exchange device (5) which is functionally connected downstream of said heat regenerator (4) and to an external heat source for the isobaric heating of said thermodynamic fluid from said third temperature "T3" to a fourth temperature "T4";
- an expansion motor (7) which is functionally connected downstream of said heat exchange device (5) and functionally connected to said external heat source (6) for the isothermal expansion of said thermodynamic fluid from said third pressure "p3" to a fourth pressure "p4", and for the adiabatic expansion of said thermodynamic fluid from said fourth pressure "p4" to a fifth pressure "p5", in the absence of heat exchange, with consequent reduction of the temperature from said fourth temperature "T4" to a fifth temperature "T5";
- a heat recovery device (8) which is functionally connected downstream of said heat regenerator (4) and functionally connected to external user devices (9) for the cooling of said thermodynamic fluid at the end of the cycle;
- a control device for regulating the power level of said compressor (2) as a function of the state variables of said thermodynamic fluid;

said heat regenerator (4) being adapted for the thermal regeneration of said thermodynamic fluid with reduction of the temperature from said fifth temperature "T5" to said sixth temperature "T6".

11. The thermodynamic machine (1) according to claim 10, **characterized in that** said compressor (2) and said expansion motor (7) are mechanically mutually independent.

12. The thermodynamic machine (1) according to claims 10 or 11, **characterized in that** said thermodynamic fluid is of the compressible type and consists of a gas or mixture of gases adapted to operate in said thermodynamic machine (1) without chemical alterations or changes in state.

13. The thermodynamic machine (1) according to claim 12, **characterized in that** said thermodynamic fluid is air.

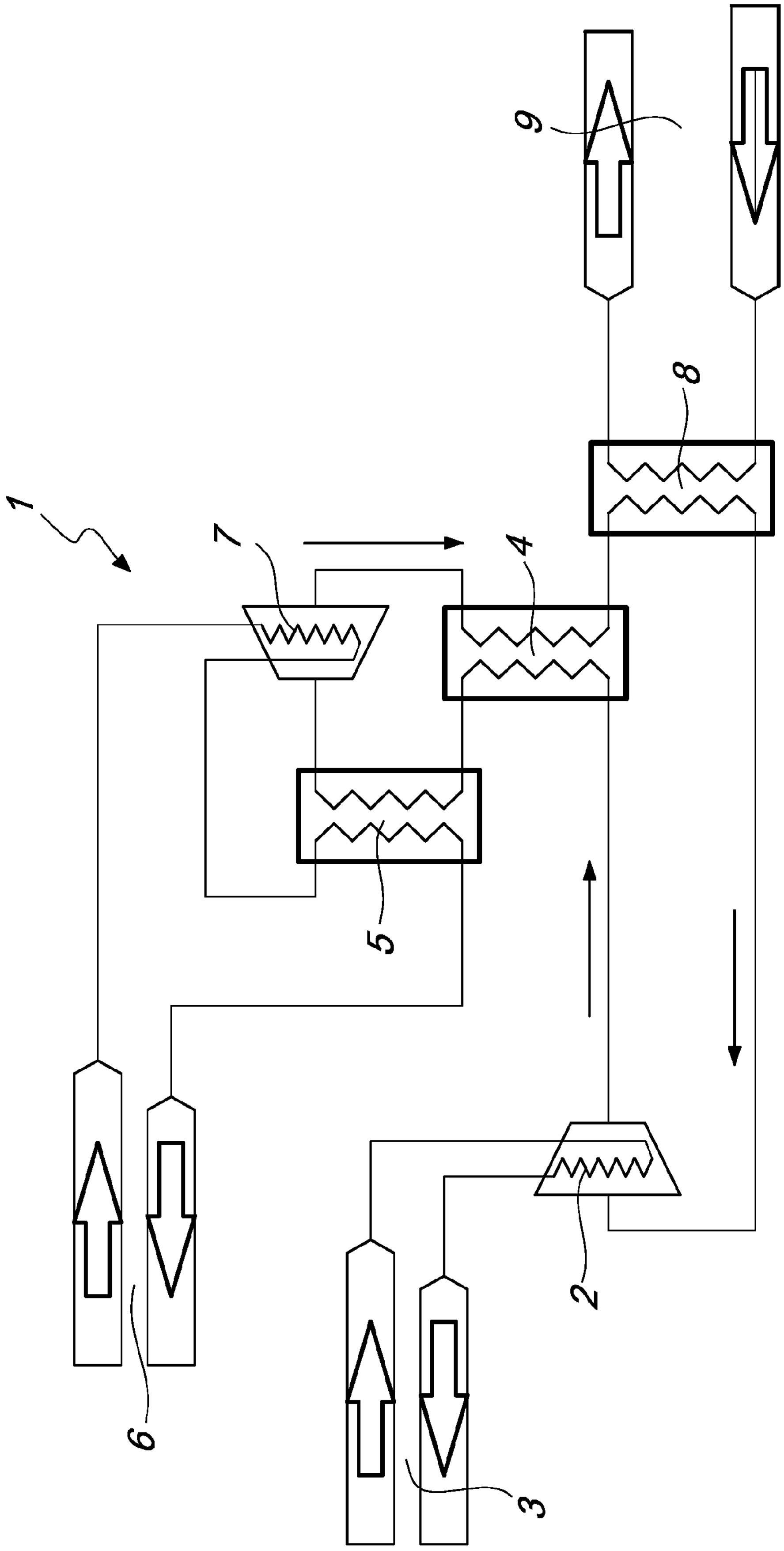


Fig. 1

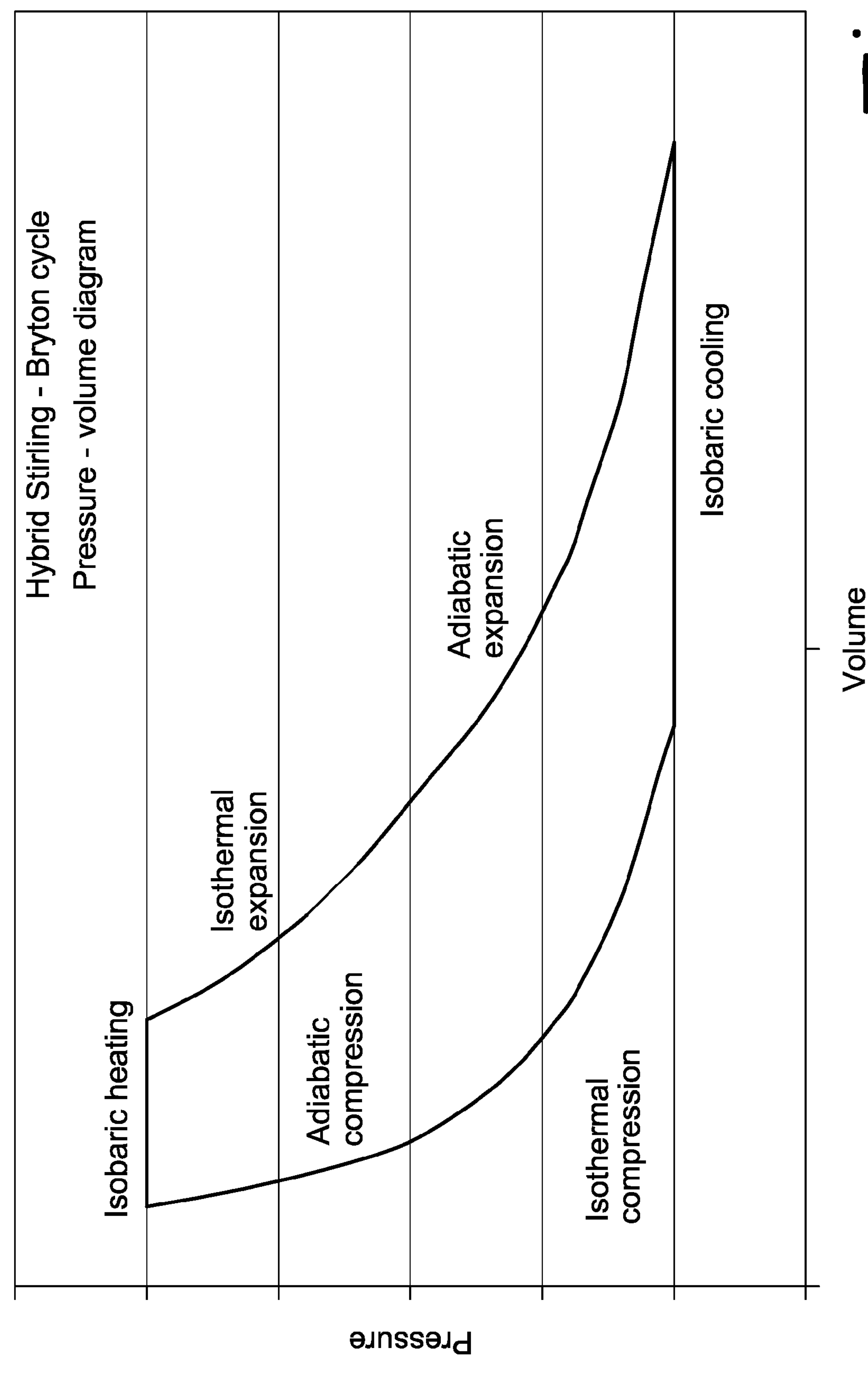
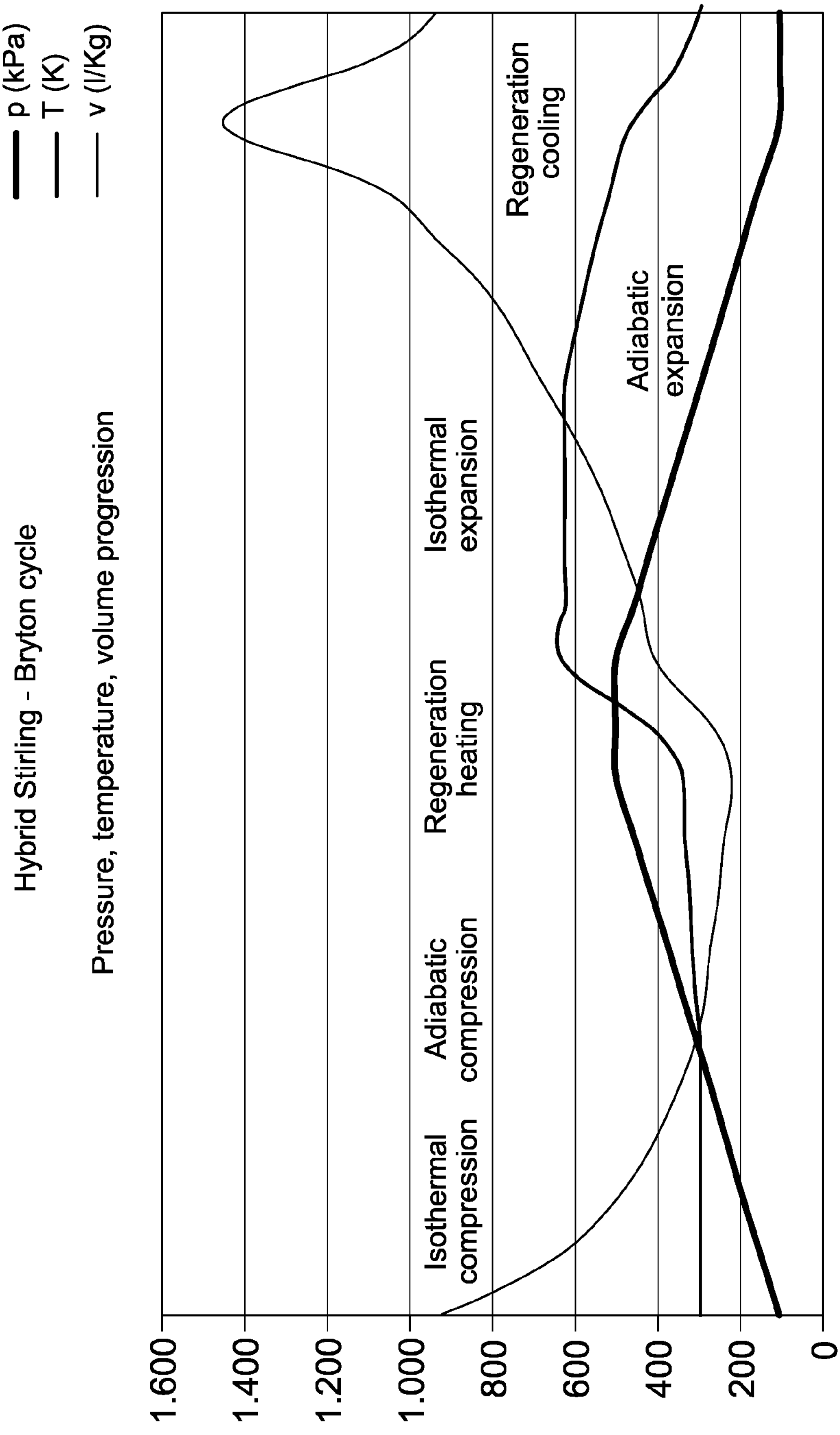

Hybrid Stirling - Bryton cycle
Pressure - volume diagram
Isobaric heating
Isothermal expansion
Adiabatic compression
Adiabatic expansion
Isothermal compression
Isobaric cooling
Volume
Pressure

Fig. 2



Graph showing the progression of the physical variables of the thermodynamic fluid

Fig. 3

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EUROPEAN SEARCH REPORT

Application Number
EP 21 19 7975

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 3 505 756 A1 (ITSUNLIMITED SYSTEMS ENG B V TRADING AS NGENI [NL]) 3 July 2019 (2019-07-03) * paragraph [0109]; figure 2 * -----	1-11	INV. F01K27/00 F25B9/14 F02G1/00 F25B49/02 F25B9/06 F25B9/00
A	CN 203 783 656 U (MENG NING) 20 August 2014 (2014-08-20) * abstract; figure 2 * -----	1-13	
A	US 9 574 502 B1 (FLUHLER HERBERT U [US]) 21 February 2017 (2017-02-21) * & associated description; figures 1A,9 * -----	1-13	

TECHNICAL FIELDS SEARCHED (IPC)

F25B
F01K
F22G
F02G

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	28 September 2021	Gasper, Ralf

CATEGORY OF CITED DOCUMENTS

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28-09-2021

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		EP 3732374 A1	04-11-2020
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US 9574502 B1	21-02-2017	US 8578695 B1	12-11-2013
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- IT 102020000026245 **[0033]**