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(54) **ELECTRO-THERMAL ENERGY STORAGE SYSTEM AND METHOD FOR STORING  
ELECTRO-THERMAL ENERGY**

ELEKTROTHERMISCHES ENERGIESPEICHERSYSTEM UND VERFAHREN ZUR SPEICHERUNG  
ELEKTROTHERMISCHER ENERGIE

SYSTÈME DE STOCKAGE D'ÉNERGIE ÉLECTROTHERMIQUE ET PROCÉDÉ POUR STOCKER  
DE L'ÉNERGIE ÉLECTROTHERMIQUE

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(56) References cited:

**EP-A1- 2 390 473**

**WO-A1-2011/053411**

**WO-A2-2009/044139**

**US-A1- 2011 259 010**

- **None**

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**EP 2 909 451 B1**

## Description

### FIELD OF THE INVENTION

**[0001]** The present invention relates generally to electrothermal energy storage. It relates in particular to a system and method for storing thermal energy according to the preamble of the independent patent claims.

### BACKGROUND OF THE INVENTION

**[0002]** Electro-thermal energy storage (ETES) systems, sometimes also referred to as thermoelectric energy storage (TEES) systems, and methods for electro-thermal (sometimes also named thermoelectric) energy storage play an ever increasing role for production and distribution of energy, in particular electric energy. The basic principles of electro-thermal energy storage are described e.g. in EP 1 577 548 A1 and EP 2 157 317 A2. The ETES system described in EP 2157317 A2 converts excess electricity to heat in a charging mode, stores the heat, and converts the heat back to electricity in a discharging mode when required. Such an energy storage system is robust, compact, and suited to the storage of electrical energy in large amounts. Thermal energy can be stored by one or more thermal storage media in the form of sensible heat via a change in temperature or in the form of latent heat via a change of phase or a combination of both. The storage medium for the sensible heat may be a solid, liquid, or a gas. The storage medium for the latent heat may involve any of these phases or a combination of them in series or in parallel.

**[0003]** In general, an electro-thermal energy storage system comprises at least one hot thermal storage arrangement, comprising a first thermal storage medium, and at least one cold thermal storage arrangement, comprising a second thermal storage medium. The charging mode of the ETES system is generally realized by operating a heat pump between the cold thermal storage arrangement and the hot thermal storage arrangement, whereas the discharging mode is realized by operating a heat engine between the hot thermal storage arrangement and the cold thermal storage arrangement. Heat pump and heat engine may be individual thermodynamic machines with separate working fluid circuits, possibly containing different working fluids, and without common parts. Preferably, however, a single thermodynamic machine with a single working fluid circuit may be configured to alternatively act as a heat pump or a heat engine by reverting a flow direction of the single working fluid, i.e. by switching between a heat pump cycle and a heat engine cycle.

**[0004]** In the ETES concept, heat needs to be transferred from hot working fluid to the first thermal storage medium during the heat pump cycle and back from the first thermal storage medium to working fluid during the heat engine cycle. A heat pump requires work to move thermal energy from a thermal energy source on a cold

side, e.g. the second thermal storage medium of the cold thermal storage arrangement, to a (warmer) thermal energy sink on a hot side, e.g. to the first thermal storage medium of the hot thermal storage arrangement. Since the amount of energy deposited at the hot side is greater than the work required by an amount equal to the energy taken from the cold side, a heat pump will "multiply" the heat as compared to resistive heat generation. The ratio of heat output to work input is called coefficient of performance, and it is a value larger than one. In this way, the use of a heat pump will increase the round-trip efficiency of a ETES system.

**[0005]** EP 2 390 473 A1 relates to a thermoelectric energy storage system having an improved round-trip efficiency. This may be achieved by an intercooler provided between two compression stages for intercooling a working fluid. The intercooling may be carried out by flashing a portion of the working fluid exiting the first compression stage in a flash intercooler and/or by heating a secondary thermal storage with working fluid exiting the first compression stage in an additional heat exchanger.

**[0006]** ETES systems are preferably installed in a so called site independent arrangement, where the ETES would ideally be a closed system without any thermal interaction with its environment. For such site independent ETES system installations, ice storage is preferably foreseen as part of the cold thermal storage arrangement to form the cold end of the charging and discharging cycles of the system; i.e. ice would be produced in charging mode, while ice would be consumed when the ETES is in discharging mode. CO<sub>2</sub> may preferably be used as working fluid; and is preferably evaporated to produce ice when the ETES system is in charging mode, and condensed to melt ice in discharge mode.

**[0007]** However, principally, losses of charging and discharging operations of the ETES system would gradually modify thermal energy sources and sinks (e.g. ice storage on the cold side, and hot water storage on the hot side) leading to gradual warming up and - ultimately - dysfunction of the ETES system. Therefore, in principle, the ETES system has to interact with an environment in some way in order to compensate for the losses of the involved processes, i.e. release the losses to the environment.

**[0008]** One of the ways suggested previously is to use an auxiliary heat pump, which would generate additional cold by interaction with the environment. The cold would be used to cool the second thermal storage medium of the cold thermal storage arrangement, in order to compensate for the losses of the whole system. For example, an additional ammonia chiller could be used to produce additional ice, in particular in the charging mode. Thus, the charging and discharging cycles of the system would not need to be modified by this measure. The auxiliary heat pump would supply cold to compensate for the losses in order to enable the periodic charging and discharging operation to work repeatedly. However, when producing additional cold to compensate for the losses, this

cold needs to be stored, which leads to an increase in size and cost of the cold storage, and thus to an increased cost and footprint of the ETES system.

**[0009]** WO 2011103306 A1 describes a method of keeping energy balance in an electro-thermal energy storage system based on a Rankine cycle. The document discloses a "storage refrigerant circuit that receives input electric power and converts the electric power to stored thermal energy" with "a second condenser in fluid communication with the first condenser, wherein the second condenser releases heat sufficient to balance the energy around the hot sink". In other words, the method uses cooling on the hot side after the compressor to balance the electro-thermal energy storage.

**[0010]** On a hot side of a ETES cycle, a temperature difference between the thermal storage medium and the working fluid may be reduced using intermediate thermal storage tanks as described in the applicant's earlier patent application EP 2275649. Such factors would also enable the ETES system to have a higher round-trip efficiency.

#### DESCRIPTION OF THE INVENTION

**[0011]** It is an objective of the invention to provide a method for balancing of energy in electro-thermal energy storage system that allows for an improved round-trip efficiency. This objective is achieved by an electro-thermal energy storage system according to claim 1 and a method according to claim 10. Preferred embodiments are evident from the dependent claims.

**[0012]** An electro-thermal energy storage system according to the invention comprises: a hot thermal storage arrangement comprising a hot storage heat exchanger; a cold thermal storage arrangement comprising a cold storage heat exchanger; a thermodynamic cycle unit configured to transfer thermal energy from the cold storage arrangement to the hot storage arrangement in a charging mode, and to convert thermal energy from the hot storage arrangement into work and, preferably, subsequently into electric energy in a discharging mode, wherein the thermodynamic cycle unit comprises a fluid circuit for circulating a working fluid through the hot storage heat exchanger as well as through the cold storage heat exchanger, wherein the fluid circuit further comprises a pump for maintaining a circulation of working fluid in the discharging mode and a first turbine for expanding working fluid in the discharging mode; and wherein the thermodynamic cycle unit comprises a second turbine for expanding working fluid in the discharging mode, said second turbine being connected in series with the first turbine so that working fluid may flow from the first to the second turbine in the discharging mode, and an intercooling heat exchanger located in the fluid circuit between the first and the second turbine, said intercooling heat exchanger configured to cool working fluid in the discharging mode by exchanging heat with an environment of the electro-thermal energy storage system.

**[0013]** Preferably, for exchanging heat with the environment of the electro-thermal energy storage system, intercooling heat exchanger is configured to exchange heat with, in particular to transfer heat to, ambient air. Alternatively, intercooling heat exchanger is configured to exchange heat with, in particular to transfer heat to, ambient water, in particular river water, lake or sea water, or ground water; preferably from a neighborhood of a location of the ETES system

**[0014]** To allow for optimum heat exchange with the environment, intercooling heat exchanger preferably has one or more of the following properties:

- intercooling heat exchanger is a counter flow and/or cross flow heat exchanger;
- intercooling heat exchanger is adapted for heat exchange between two fluids, each of which either in liquid or gaseous form;
- intercooling heat exchanger is adapted for heat exchange between two fluids without occurrence of any mixture and/or direct contact of the two fluids, in particular, intercooling heat exchanger is not a direct contact heat exchanger;
- intercooling heat exchanger is adapted for heat exchange between two fluids without occurrence of any phase transition, in particular, intercooling heat exchanger is not a phase change heat exchanger.

**[0015]** A method in accordance with the invention for storing and retrieving energy in an electro-thermal energy storage system comprises the steps of: in a charging mode, transferring thermal energy from a cold thermal storage arrangement to a hot thermal storage arrangement by means of a first thermodynamic cycle configured to convert work into thermal energy; in a discharging mode, transferring thermal energy from the hot thermal storage arrangement to the cold thermal storage arrangement by means of a second thermodynamic cycle configured to convert thermal energy into work, wherein the second thermodynamic cycle process comprises the steps of generating work by expanding a working fluid of the second thermodynamic cycle (process) in a first turbine, and (2) generating work by further expanding the working fluid in a second turbine, and cooling the working fluid between steps (1) and (2) by exchanging heat with an environment.

**[0016]** In a preferred variant of the method in accordance with the invention, working fluid is cooled between steps (1) and (2) through transfer of heat to ambient air and/or to ambient water, in particular river water, lake or sea water, or ground water; preferably from a neighborhood of a location of the ETES system.

**[0017]** To allow for optimum heat exchange with the environment, an intercooling heat exchanger is preferably provided in a flow path for the working fluid between the first turbine and the second turbine, said intercooling heat exchanger preferably having one or more of the following properties:

- intercooling heat exchanger is a counter flow and/or cross flow heat exchanger;
- intercooling heat exchanger is adapted for heat exchange between two fluids, each of which either in liquid or gaseous form;
- intercooling heat exchanger is adapted for heat exchange between two fluids without occurrence of any mixture and/or direct contact of the two fluids, in particular, intercooling heat exchanger is not a direct contact heat exchanger;
- intercooling heat exchanger is adapted for heat exchange between two fluids without occurrence of any phase transition, in particular, intercooling heat exchanger is not a phase change heat exchanger.

**[0018]** Carbon dioxide ( $\text{CO}_2$ ) is preferably used as working fluid. The working fluid may also comprise ammonia ( $\text{NH}_3$ ) and/or an organic fluid (such as methane, propane or butane) and/or a refrigerant fluid (such as R 134a (1,1,1,2-Tetrafluoroethane), R245 fa (1,1,1,3,3-Pentafluoropropane)).

**[0019]** If technically possible but not explicitly mentioned, also combinations of embodiments of the invention described in the above and in the following may be embodiments of the method and the system. These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0020]** The subject matter of the invention will be explained in more detail in the following text with reference to preferred exemplary embodiments, which are illustrated in the attached drawings, in which:

Figure 1 shows a simplified schematic diagram of an electro-thermal energy storage system in accordance with the present invention;

Figure 2 shows the electro-thermal energy storage from Fig. 1 in a charging mode;

Figure 3 shows the electro-thermal energy storage from Fig. 1 in a discharging mode;

Figure 4 shows a simplified schematic diagram of another preferred embodiment of an electro-thermal energy storage system in accordance with the present invention;

Figure 5 shows T-s-diagrams of exemplary thermodynamic cycles; and

Figure 6 shows a simplified schematic diagram of another preferred embodiment of an electro-thermal energy storage system in accordance with the present invention.

**[0021]** For consistency, the same reference numerals are used to denote similar elements illustrated throughout the figures.

#### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

**[0022]** Figure 1 shows a simplified schematic diagram of a preferred embodiment of an electro-thermal energy storage system in accordance with the present invention.

**[0023]** The system comprises a hot thermal storage arrangement 1, which in turn comprises a hot storage heat exchanger 11, a first storage tank 121 for a first thermal storage medium, in particular for storing first thermal storage medium at a low temperature  $T_{1,l}$  and a second storage tank 122 for the first thermal storage medium, in particular for storing first thermal storage medium at a high temperature  $T_{1,h} > T_{1,l}$ . In particular, water may be used as first thermal storage medium.

**[0024]** The system further comprises a cold thermal storage arrangement 2, which in turn comprises a cold storage heat exchanger 21, and a third storage tank 223 for a second thermal storage medium, preferably also water.

**[0025]** The electro-thermal energy storage system shown in Fig. 1 further comprises a thermodynamic cycle unit which, when in operation, executes one of a plurality of thermodynamic cycles. The thermodynamic cycle unit comprises a plurality of fluid conduits for circulating a working fluid through the hot storage heat exchanger 11 and the cold storage heat exchanger 21. A plurality of valves 30a, 30b, 30c, 30d, 30e and 30f allow to switch between different working fluid paths, in particular for switching between a charging and a discharging mode of the electro-thermal energy storage system.

**[0026]** Figure 2 shows the electro-thermal energy storage system from Fig. 1 in a charging mode. A compressor unit comprises a low pressure compressor block 322' as a first compressor and a high pressure compressor block 321' as a second compressor and is configured to compress a working fluid, in particular  $\text{CO}_2$ , under consumption of work  $W_{in,1}$  and  $W_{in,2}$ , with  $W_{in} = W_{in,1} + W_{in,2}$ , wherein the work may preferentially be provided by a motor through conversion from electric energy. Due to the compression, which may preferentially be at least approximately isentropic, a pressure and temperature of the working fluid is increased and pressurized working fluid is forced into hot storage heat exchanger 11. In the hot storage heat exchanger 11, thermal energy is transferred from the working fluid to a first thermal storage medium, in particular water, which flows from the first storage tank 121 of the hot thermal storage arrangement 1 to the second storage tank 122 of the hot thermal storage arrangement 1, e.g. under influence of a pump. After exiting the hot storage heat exchanger 11, the working fluid enters a work recovering expander 31' where its pressure is reduced under recovery of work  $W_{out,0}$ , which may preferentially be used to drive a generator for generat-

ing electric energy, or may be used to provide at least part of the work  $W_{in}$ , in particular  $W_{in,2}$ , by means of mechanical coupling, e.g. to the low pressure compressor block 322'. After the work recovering expander 31', the working fluid enters the cold storage heat exchanger 21, where thermal energy is transferred from the second thermal storage medium to the working fluid, preferably causing the second thermal storage medium to solidify. This way, cold may be stored in latent form in cold thermal storage arrangement 2.

**[0027]** Preferably, an evaporative ice storage arrangement as described in European patent application EP11169311, is used as cold thermal storage arrangement 2. Alternatively, ice may be stored on coils as e.g. in commercially available ice storage systems which are as such known to a person skilled in the art.

**[0028]** Alternatively, cold may be stored in sensible form, in particular by providing a fourth storage tank for storing second thermal storage medium at a high temperature  $T_{2,h} > T_{2,l}$ , where  $T_{2,l}$  is a low temperature of second thermal storage medium in the third storage tank 223, and  $T_{1,h} > T_{2,l}$ , so that second thermal storage medium may flow through cold storage heat exchanger 21 from the fourth storage tank to the third storage tank 223 in charging mode, and vice versa in discharging mode, which will be described below.

**[0029]** Figure 3 shows the electro-thermal energy storage system from Fig. 1 in discharging mode. A working fluid pump 31 pumps condensed working fluid into hot storage heat exchanger 11. In the hot storage heat exchanger 11, thermal energy is transferred from the first thermal storage medium - which in discharging mode flows from the second storage tank 122 of the hot thermal storage arrangement to the first storage tank 121 of the hot thermal storage arrangement 1 - to the working fluid, so that the working fluid is vaporized. The vaporized working fluid then enters a turbine unit. The turbine unit comprises a high pressure turbine block 321 as a first turbine and a low pressure turbine block 322 as a second turbine and is configured to expand the working fluid under recovery of work  $W_{out,1}$  and  $W_{out,2}$ , with  $W_{out} = W_{out,1} + W_{out,2}$ . Due to the expansion, which is preferably at least approximately isentropic, a pressure and temperature of the working fluid is decreased. Subsequently, the working fluid enters cold storage heat exchanger 21, where thermal energy is transferred from the working fluid to the second thermal storage medium, thus causing the working fluid to condense and preferably the second thermal storage medium to melt.

**[0030]** Each of the turbine blocks 321, 322 and compressor blocks 321', 322' may have a single or multiple stages, and may be of either radial or axial type. The turbine blocks 321, 322 may be separate, individual turbines, but may also be parts of an integrated two-block turbine with integrated air cooler. The same applies to compressor blocks 321', 322'.

**[0031]** An air cooler 33 is provided in a working fluid path between low pressure turbine block 322 and high

pressure turbine block 321. Working fluid passing through the air cooler 33 may transfer thermal energy to an environment of the ETES system, in particular to ambient air surrounding the ETES system. Removing heat from the working fluid in this manner allows to balance the overall losses of the ETES system. To achieve optimum balancing, a control of the air cooler 33, and/or the turbine blocks 321 and 322, and/or the compressor blocks, needs to allow for variations in an ambient temperature, e.g. by adjusting the cooling performance of the air cooler 33, e.g. through a rotation speed of its fans.

**[0032]** Valves 30e and 30f from Fig. 1 are not shown in Figs. 2 and 3 to improve readability. However, the invention could also be realized with fixed working fluid paths as shown in Figs. 2 and 3. In particular, a single compressor could be used in this case rather than the two compressor blocks 321', 322'.

**[0033]** Figure 4 shows a simplified schematic diagram of another preferred embodiment of an electro-thermal energy storage system in accordance with the present invention. Instead of the compressor unit and the turbine unit of the embodiment shown in Figs. 1-3, the system comprises a reversible thermodynamic machine unit comprising a first thermodynamic machine block 321" and a second thermodynamic machine block 322", which function as second and first compressor in charging mode, and as first and second turbine in discharging mode. Air cooler 33' is again provided in a working fluid path between first thermodynamic machine block 321" and second thermodynamic machine block 322". Preferably, cooling performance of air cooler 33' can be individually adjusted for charging mode and discharging mode, and air cooler 33' may be completely switched off for each mode.

**[0034]** Similarly, instead of working fluid pump 31 and work recovering expander 31', an auxiliary reversible thermodynamic machine may be foreseen in any of the embodiments described above or below, which is capable of providing a functionality of both working fluid pump 31 and work recovering expander 31' by reverting a direction of rotation of the auxiliary reversible thermodynamic machine.

**[0035]** Figure 5 shows T-s-diagrams of exemplary thermodynamic cycles that working fluid in the above described embodiments may be subjected to.

**[0036]** Fig. 5a shows a T-s-diagram of a first thermodynamic cycle which the working fluid undergoes in charging mode. At point c40, the working fluid enters the cold storage heat exchanger 21 of the cold storage arrangement 2, where it absorbs solidification energy from the second thermal storage medium, leading to an increase in the working fluid's entropy s. At point c10, working fluid enters the low pressure compressor block 322', at point c12 the high pressure compressor block 321', where it is compressed to a maximum pressure of 14 MPa. At point c20, working fluid enters the hot storage heat exchanger 11 of the hot storage arrangement 1, where it transfers heat to the first thermal storage medium

and is in return cooled down to approximately 10°C. At point c30, working fluid enters the work recovering expander 31', where it is at least approximately isentropically expanded and returned to point c40.

**[0037]** Fig. 5b shows a T-s-diagram of a second thermodynamic cycle which the working fluid undergoes in discharging mode. At point d20, the working fluid enters the cold storage heat exchanger 21 of the cold storage arrangement 2, where it melts solidified second thermal storage medium, leading to an decrease in the working fluid's entropy  $s$ . At point d30, working fluid enters the working fluid pump 31, by which it is pumped into the hot storage heat exchanger 11 of the hot storage arrangement 1, which it enters at point d30. In the hot storage heat exchanger 11, working fluid is heated to approximately 120°C by heat exchange with the second thermal storage medium, raising its pressure to the maximum value of 14 Mpa. At point d10, working fluid enters the high pressure turbine 321, where it is expanded under recovery of work  $W_{out,1}$  as described above, and thus is cooled to around 45°C. At point d12, working fluid enters the air cooler 33, where it is cooled to around 35°C at an at least approximately constant pressure of around 6 Mpa. At point d14, working fluid enters the low pressure turbine 322, where it is further expanded under recovery of work  $W_{out,2}$  as also described above, and returned to point d20.

**[0038]** Figure 6 shows a simplified schematic diagram of another preferred embodiment of an electro-thermal energy storage system in accordance with the present invention. The embodiment shown in Fig. 6 is similar to the one from Fig. 1, but comprises an additional hot thermal storage arrangement 1'. An additional air cooler 33" is located between the hot thermal storage arrangement 1 and the additional hot thermal storage arrangement 1'. Valves 30g allow to selectively direct a part or all of the working fluid flowing between the hot thermal storage arrangement 1 and the additional hot thermal storage arrangement 1' through the additional air cooler 33", or to bypass the latter completely. The additional air cooler 33" may be employed to remove thermal energy from the system in addition or alternatively to the air cooler 33, in particular in charging mode. Preferably, a fluid connection - including a control valve and possibly a pump - for thermal storage medium is provided between second storage tank 122 of hot thermal storage arrangement 1 and a first storage tank 121' of the additional hot thermal storage arrangement 1' to allow for balancing respective levels of thermal storage medium (not shown in Fig. 6). One or more further additional hot thermal storage arrangements may advantageously be provided adjacent to the additional hot thermal storage arrangement 1', preferably in series with further additional air coolers, in particular to allow for split streams and/or varying flow rates of working fluids between parts of a split stream heat exchanger and/or individual heat exchangers, as e.g. described in EP 2 275 649 A1 or EP 2 182 179 A1.

**[0039]** It could be shown by means of computer simu-

lations that by balancing irreversibilities through cooling of working fluid (in particular CO<sub>2</sub>) at certain locations in the fluid circuit, in particular as described above, higher overall efficiency may be achieved than by generating additional cold with an auxiliary heat pump due to lower parasitic losses of air coolers when compared to compressor work required for the auxiliary heat pump.

**[0040]** Ideal locations for cooling were found to be between first and second turbines in discharging mode, or between hot thermal storage arrangement 1 and the additional hot thermal storage arrangement 1' in charging mode.

**[0041]** While an efficiency gain of the latter approach is limited, it may be of interest due to substantially reduced system complexity and possible reduction of tank dimensions and heat exchanger dimensions due to increased mean temperature differences in the heat exchangers. In addition, a maximum temperature of thermal storage medium in the hot thermal storage arrangements is reduced, allowing for an improved match between temperature profiles of thermal storage medium and working fluid, in particular for water and CO<sub>2</sub>.

**[0042]** In addition to the various approaches for balancing energy in an ETES system according to the invention as described above, direct control of the thermal energy stored in the hot thermal storage arrangement, in particular of temperatures  $T_{1,h}$  and/or  $T_{1,l}$  of the first thermal storage medium, may advantageously also be foreseen or provided, in particular during a start-up phase of an operation of the ETES system or method. This, may be, e.g., be achieved by supplying additional heat to the first thermal storage medium, in particular by an electric heater provided in any of the storage tanks for the first thermal storage medium, or a supplementary heat pump configured to heat first thermal storage medium in any of the storage tanks. Alternatively, first thermal storage medium may be cooled by releasing some thermal energy to the ambient, in particular in a supplementary heat exchanger.

**[0043]** While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art and practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims.

**[0044]** In the description above and in the patent claims below, the term "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. Any reference signs in the patent claims should not be construed as limiting the scope.

## Claims

1. An electro-thermal energy storage system compris-

ing

- a) a hot thermal storage arrangement (1) comprising a hot storage heat exchanger (11),  
 b) a cold thermal storage arrangement (2) comprising a cold storage heat exchanger (21),  
 c) a thermodynamic cycle unit configured to transfer thermal energy from the cold storage arrangement (2) to the hot storage arrangement (1) in a charging mode, convert thermal energy from the hot storage arrangement (1) into work and, preferably, subsequently into electric energy in a discharging mode, wherein the thermodynamic cycle unit comprises a fluid circuit for circulating a working fluid through the hot storage heat exchanger as well as through the cold storage heat exchanger, 1 a pump (31) for maintaining a circulation of working fluid in the discharging mode, a first turbine (321) for expanding working fluid in the discharging mode, a second turbine (322) for expanding working fluid in the discharging mode, said second turbine being connected in series with the first turbine so that working fluid may flow from the first to the second turbine in the discharging mode, and an intercooling heat exchanger (33) located in the fluid circuit between the first turbine (321) and the second turbine (322), **characterized in that** said intercooling heat exchanger (33) is configured to cool working fluid by exchanging heat with an environment of the electro-thermal energy storage system, and **in that** the intercooling heat exchanger (33) is configured to cool working fluid flowing from the first turbine (321) to the second turbine (322) in the discharging mode.
2. The electro-thermal energy storage system of claim 1, wherein the intercooling heat exchanger (33) is configured to cool working fluid through transfer of heat to ambient air surrounding the electro-thermal energy storage system.
3. The electro-thermal energy storage system of claim 1, wherein the intercooling heat exchanger (33) is configured to cool working fluid through transfer of heat to ambient water, in particular river water, lake water, sea water or ground water.
4. The electro-thermal energy storage system of claim 1, 2 or 3, wherein the second turbine (322) is configured to be operated in reverse to act as a first compressor in the charging mode, and/or the first turbine is configured to be operated in reverse to act as a second compressor in the charging mode.
5. The electro-thermal energy storage system of claim 1, 2 or 3, wherein the intercooling heat exchanger (33) is configured to cool working fluid flowing from the first compressor to the second compressor in the charging mode.
6. The electro-thermal energy storage system of claim 1 or 2, wherein the intercooling heat exchanger (33) is an air cooler.
7. The electro-thermal energy storage system according to any preceding claim, wherein the system comprises CO<sub>2</sub> as working fluid.
8. The electro-thermal energy storage system according to any preceding claim, wherein the cold thermal storage arrangement (2) comprises water as a thermal storage medium.
9. The electro-thermal energy storage system according to any preceding claim, wherein the cold thermal storage arrangement (2) comprises a mixture of water and at least one further component as thermal storage medium.
10. The electro-thermal energy storage system according to any preceding claim, comprising one or more valves (30a, 30b, 30c, 30d, 30e, 30f) allowing for selective opening, closing and/or throttling one or more fluid connections.
11. A method for storing and retrieving energy in an electro-thermal energy storage system, the method comprising the steps of
- a) in a charging mode
- i) transferring thermal energy from a cold thermal storage arrangement (2) to a hot thermal storage arrangement (1)
- ii) by means of a first thermodynamic cycle
- iii) configured to convert work into thermal energy
- b) in a discharging mode
- i) transferring thermal energy from the hot thermal storage arrangement (1) to the cold thermal storage arrangement (2)
- ii) by means of a second thermodynamic cycle
- iii) configured to convert thermal energy into work

c) wherein

i) the second thermodynamic cycle comprises the steps of

- (1) generating work by expanding a working fluid of the second thermodynamic cycle in a first turbine (321),
- (2) generating work by further expanding the working fluid in a second turbine (322),
- (3) cooling the working fluid between steps (1) and (2) by exchanging heat with an environment.

12. The method according to claim 11, wherein step c)i)(3), working fluid is cooled by transfer of heat to ambient air surrounding the electro-thermal energy storage system, or by transfer of heat to ambient water, in particular river water, lake water, sea water or ground water.

13. The method according to claim 11 or 12, further comprising the steps of

i) in the first thermodynamic cycle

- (1) generating thermal energy by compressing a working fluid of the first thermodynamic cycle in a first compressor (322'),
- (2) generating thermal energy by further compressing the working fluid in a second compressor (321'),
- (3) cooling the working fluid between steps (1) and (2) by exchanging heat with an environment.

14. The method according to claim 11, 12 or 13, further comprising the steps of

a) reverting a working fluid flow direction in the electro-thermal energy storage system to switch between charging mode and discharging mode.

## Patentansprüche

1. Elektrothermisches Energiespeichersystem, umfassend

- a) eine Warm-Thermospeicheranordnung (1), die einen Warmspeicher-Wärmetauscher (11) umfasst,
- b) eine Kalt-Thermospeicheranordnung (2), die einen Kaltspeicher-Wärmetauscher (21) umfasst,
- c) eine thermodynamische Kreisprozesseinheit, die dazu ausgelegt ist,

thermische Energie von der Kaltspeichieranordnung (2) in einem Lademodus auf die Warmspeichieranordnung (1) zu übertragen,

thermische Energie aus der Warmspeichieranordnung (1) in Arbeit und vorzugsweise anschließend in einem Entlademodus in elektrische Energie umzuwandeln, wobei die thermodynamische Kreisprozesseinheit umfasst:

einen Fluidkreislauf zum Zirkulieren eines Arbeitsfluids durch den Warmspeicher-Wärmetauscher sowie durch den Kaltspeicher-Wärmetauscher, eine Pumpe (31) zum Aufrechterhalten einer Zirkulation des Arbeitsfluids im Entlademodus,

eine erste Turbine (321) zum Ausdehnen des Arbeitsfluids im Entlademodus,

eine zweite Turbine (322) zum Ausdehnen des Arbeitsfluids im Entlademodus,

wobei die zweite Turbine mit der ersten Turbine in Reihe verbunden ist, sodass das Arbeitsfluid im Entlademodus von der ersten zur zweiten Turbine fließen kann, und

einen Zwischenkühlungswärmetauscher (33), der im Fluidkreislauf zwischen der ersten Turbine (321) und der zweiten Turbine (322) angeordnet ist, **dadurch gekennzeichnet, dass**

der Zwischenkühlungswärmetauscher (33) dazu ausgelegt ist, Arbeitsfluid durch Austauschen von Wärme mit einer Umgebung des elektrothermischen Energiespeichersystems zu kühlen, und

dass der Zwischenkühlungswärmetauscher (33) dazu ausgelegt ist, das von der ersten Turbine (321) zur zweiten Turbine (322) fließende Arbeitsfluid im Entlademodus zu kühlen.

2. Elektrothermisches Energiespeichersystem gemäß Anspruch 1, wobei der Zwischenkühlungswärmetauscher (33) dazu ausgelegt ist, Arbeitsfluid durch Übertragung von Wärme an die Umgebungsluft, die das elektrothermische Energiespeichersystem umgibt, zu kühlen.

3. Elektrothermisches Energiespeichersystem gemäß Anspruch 1, wobei der Zwischenkühlungswärmetauscher (33) dazu ausgelegt ist, Arbeitsfluid durch Übertragung von Wärme auf Umgebungswasser, insbesondere Flusswasser, Seewasser, Meerwasser oder Grundwasser, zu kühlen.

4. Elektrothermisches Energiespeichersystem gemäß Anspruch 1, 2 oder 3, wobei die zweite Turbine (322) dazu ausgelegt ist,

- in umgekehrter Richtung betrieben zu werden, um als erster Kompressor im Lademodus zu arbeiten, und/oder die erste Turbine dazu ausgelegt ist, in umgekehrter Richtung betrieben zu werden, um als zweiter Kompressor im Lademodus zu arbeiten. 5
5. Elektrothermisches Energiespeichersystem gemäß Anspruch 1, 2 oder 3, wobei der Zwischenkühlungs-wärmetauscher (33) dazu ausgelegt ist, das vom ersten Kompressor zum zweiten Kompressor fließende Arbeitsfluid im Lademodus zu kühlen. 10
6. Elektrothermisches Energiespeichersystem gemäß Anspruch 1 oder 2, wobei der Zwischenkühlungs-wärmetauscher (33) ein Luftkühler ist. 15
7. Elektrothermisches Energiespeichersystem gemäß einem vorhergehenden Anspruch, wobei das System CO<sub>2</sub> als Arbeitsfluid umfasst. 20
8. Elektrothermisches Energiespeichersystem gemäß einem vorhergehenden Anspruch, wobei die Kalt-Thermospeicheranordnung (2) Wasser als thermisches Speichermedium umfasst. 25
9. Elektrothermisches Energiespeichersystem gemäß einem vorhergehenden Anspruch, wobei die Kalt-Thermospeicheranordnung (2) ein Gemisch aus Wasser und mindestens einer weiteren Komponente als thermisches Speichermedium umfasst. 30
10. Elektrothermisches Energiespeichersystem gemäß einem vorhergehenden Anspruch, umfassend ein oder mehrere Ventile (30a, 30b, 30c, 30d, 30e, 30f), die das selektive Öffnen, Schließen und/oder Drosseln einer oder mehrerer Fluidverbindungen ermöglichen. 35
11. Verfahren zum Speichern und Rückgewinnen von Energie in einem elektrothermischen Energiespeichersystem, wobei das Verfahren die folgenden Schritte umfasst:
- a) in einem Lademodus 45
- i) Übertragen von thermischer Energie von einer Kalt-Thermospeicheranordnung (2) zu einer Warm-Thermospeicheranordnung (1) 50
- ii) mittels eines ersten thermodynamischen Kreislaufs
- iii) dazu ausgelegt, Arbeit in Wärmeenergie umzuwandeln
- b) in einem Entlademodus 55
- i) Übertragen von thermischer Energie von der Warm-Thermospeicheranordnung (1)
- zur Kalt-Thermospeicheranordnung (2)
- ii) mittels eines zweiten thermodynamischen Kreislaufs
- iii) dazu ausgelegt, thermische Energie in Arbeit umzuwandeln
- c) wobei
- i) der zweite thermodynamische Kreislauf die folgenden Schritte umfasst:
- (1) Erzeugen von Arbeit durch Ausdehnen eines Arbeitsfluids des zweiten thermodynamischen Kreislafs in einer ersten Turbine (321),
- (2) Erzeugen von Arbeit durch weiteres Ausdehnen des Arbeitsfluids in einer zweiten Turbine (322),
- (3) Kühlen des Arbeitsfluids zwischen den Schritten (1) und (2) durch Austauschen von Wärme mit der Umgebung.
12. Verfahren gemäß Anspruch 11, wobei in Schritt c) i) (3) das Arbeitsfluid durch Übertragen von Wärme an die Umgebungsluft, die das elektrothermische Energiespeichersystem umgibt, oder durch Übertragen von Wärme an Umgebungswasser, insbesondere Flusswasser, Seewasser, Meerwasser oder Grundwasser, gekühlt wird.
13. Verfahren gemäß Anspruch 11 oder 12, ferner umfassend die folgenden Schritte:
- i) im ersten thermodynamischen Kreislauf
- (1) Erzeugen von thermischer Energie durch Verdichten eines Arbeitsfluids des ersten thermodynamischen Kreislafs in einem ersten Kompressor (322'),
- (2) Erzeugen von thermischer Energie durch weiteres Verdichten des Arbeitsfluids in einem zweiten Kompressor (321'),
- (3) Kühlen des Arbeitsfluids zwischen den Schritten (1) und (2) durch Austauschen von Wärme mit der Umgebung.
14. Verfahren gemäß Anspruch 11, 12 oder 13, ferner umfassend die folgenden Schritte:
- a) Umkehren der Flussrichtung eines Arbeitsfluids im elektrothermischen Energiespeichersystem, um zwischen Lade- und Entlademodus umzuschalten.

## Revendications

1. Système de stockage d'énergie électrothermique

comprenant

- a) un agencement de stockage thermique chaud (1) comprenant un échangeur de chaleur de stockage chaud (11),  
 b) un agencement de stockage thermique froid (2) comprenant un échangeur de chaleur de stockage froid (21),  
 c) une unité de cycle thermodynamique configurée pour transférer de l'énergie thermique de l'agencement de stockage froid (2) à l'agencement de stockage chaud (1) dans un mode de charge,  
 convertir l'énergie thermique provenant de l'agencement de stockage chaud (1) en travail et, de préférence, ensuite en énergie électrique dans un mode de décharge,  
 l'unité de cycle thermodynamique comprenant un circuit de fluide destiné à faire circuler un fluide de travail à travers l'échangeur de chaleur de stockage chaud ainsi qu'à travers l'échangeur de chaleur de stockage froid,  
 une pompe (31) destinée à maintenir une circulation de fluide de travail dans le mode de décharge,  
 une première turbine (321) destinée à détendre le fluide de travail dans le mode de décharge,  
 une deuxième turbine (322) destinée à détendre le fluide de travail dans le mode de décharge, ladite deuxième turbine étant raccordée en série à la première turbine de telle sorte que le fluide de travail peut s'écouler de la première à la deuxième turbine dans le mode de décharge, et un échangeur de chaleur de refroidissement intermédiaire (33) situé dans le circuit de fluide entre la première turbine (321) et la deuxième turbine (322), **caractérisé en ce que** ledit échangeur de chaleur de refroidissement intermédiaire (33) est configuré pour refroidir le fluide de travail en échangeant de la chaleur avec un environnement du système de stockage d'énergie électrothermique, et **en ce que** l'échangeur de chaleur de refroidissement intermédiaire (33) est configuré pour refroidir le fluide de travail s'écoulant de la première turbine (321) à la deuxième turbine (322) dans le mode de décharge.
2. Système de stockage d'énergie électrothermique de la revendication 1, dans lequel l'échangeur de chaleur de refroidissement intermédiaire (33) est configuré pour refroidir le fluide de travail par transfert de chaleur à de l'air ambiant entourant le système de stockage d'énergie électrothermique.
3. Système de stockage d'énergie électrothermique de la revendication 1, dans lequel l'échangeur de chaleur de refroidissement intermédiaire (33) est confi-

guré pour refroidir le fluide de travail par transfert de chaleur à de l'eau ambiante, en particulier de l'eau de rivière, de l'eau de lac, de l'eau de mer ou de l'eau souterraine.

4. Système de stockage d'énergie électrothermique de la revendication 1, 2 ou 3, dans lequel la deuxième turbine (322) est configurée pour fonctionner à l'envers pour agir comme un premier compresseur dans le mode de charge, et/ou la première turbine est configurée pour fonctionner à l'envers pour agir comme un deuxième compresseur dans le mode de charge.
5. Système de stockage d'énergie électrothermique de la revendication 1, 2 ou 3, dans lequel l'échangeur de chaleur de refroidissement intermédiaire (33) est configuré pour refroidir le fluide de travail s'écoulant du premier compresseur au deuxième compresseur dans le mode de charge.
6. Système de stockage d'énergie électrothermique de la revendication 1 ou 2, dans lequel l'échangeur de chaleur de refroidissement intermédiaire (33) est un refroidisseur d'air.
7. Système de stockage d'énergie électrothermique selon une quelconque revendication précédente, le système comprenant du CO<sub>2</sub> comme fluide de travail.
8. Système de stockage d'énergie électrothermique selon une quelconque revendication précédente, dans lequel l'agencement de stockage thermique froid (2) comprend de l'eau comme milieu de stockage thermique.
9. Système de stockage d'énergie électrothermique selon une quelconque revendication précédente, dans lequel l'agencement de stockage thermique froid (2) comprend un mélange d'eau et d'au moins un autre composant comme milieu de stockage thermique.
10. Système de stockage d'énergie électrothermique selon une quelconque revendication précédente, comprenant une ou plusieurs vannes (30a, 30b, 30c, 30d, 30e, 30f) permettant une ouverture, une fermeture et/ou un étranglement sélectifs d'un ou plusieurs raccords de fluide.
11. Procédé de stockage et récupération d'énergie dans un système de stockage d'énergie électrothermique, le procédé comprenant les étapes suivantes :
- a) dans un mode de charge,
- i) transfert d'énergie thermique d'un agencement de stockage thermique froid (2) à

- un agencement de stockage thermique chaud (1)  
 ii) au moyen d'un premier cycle thermodynamique  
 iii) configuré pour convertir un travail en énergie thermique, 5
- b) dans un mode de décharge,
- i) transfert d'énergie thermique de l'agencement de stockage thermique chaud (1) à l'agencement de stockage thermique froid (2) 10  
 ii) au moyen d'un deuxième cycle thermodynamique 15  
 iii) configuré pour convertir de l'énergie thermique en travail,
- c) dans lequel 20
- i) le deuxième cycle thermodynamique comprend les étapes suivantes :
- (1) production de travail par détente d'un fluide de travail du deuxième cycle thermodynamique dans une première turbine (321), 25  
 (2) production de travail par détente supplémentaire du fluide de travail dans une deuxième turbine (322), 30  
 (3) refroidissement du fluide de travail entre les étapes (1) et (2) par échange de chaleur avec un environnement.
- 12.** Procédé selon la revendication 11, dans lequel, à l'étape c) i) (3), le fluide de travail est refroidi par transfert de chaleur à de l'air ambiant entourant le système de stockage d'énergie électrothermique, ou par transfert de chaleur à de l'eau ambiante, en particulier de l'eau de rivière, de l'eau de lac, de l'eau de mer ou de l'eau souterraine. 35 40
- 13.** Procédé selon la revendication 11 ou 12, comprenant en outre les étapes suivantes : 45
- i) dans le premier cycle thermodynamique,
- (1) production d'énergie thermique par compression d'un fluide de travail du premier cycle thermodynamique dans un premier compresseur (322'), 50  
 (2) production d'énergie thermique par compression supplémentaire du fluide de travail dans un deuxième compresseur (321'), 55  
 (3) refroidissement du fluide de travail entre les étapes (1) et (2) par échange de chaleur avec un environnement.
- 14.** Procédé selon la revendication 11, 12 ou 13, comprenant en outre les étapes suivantes :
- a) inversion d'une direction d'écoulement de fluide de travail dans le système de stockage d'énergie électrothermique pour basculer entre le mode de charge et le mode de décharge.

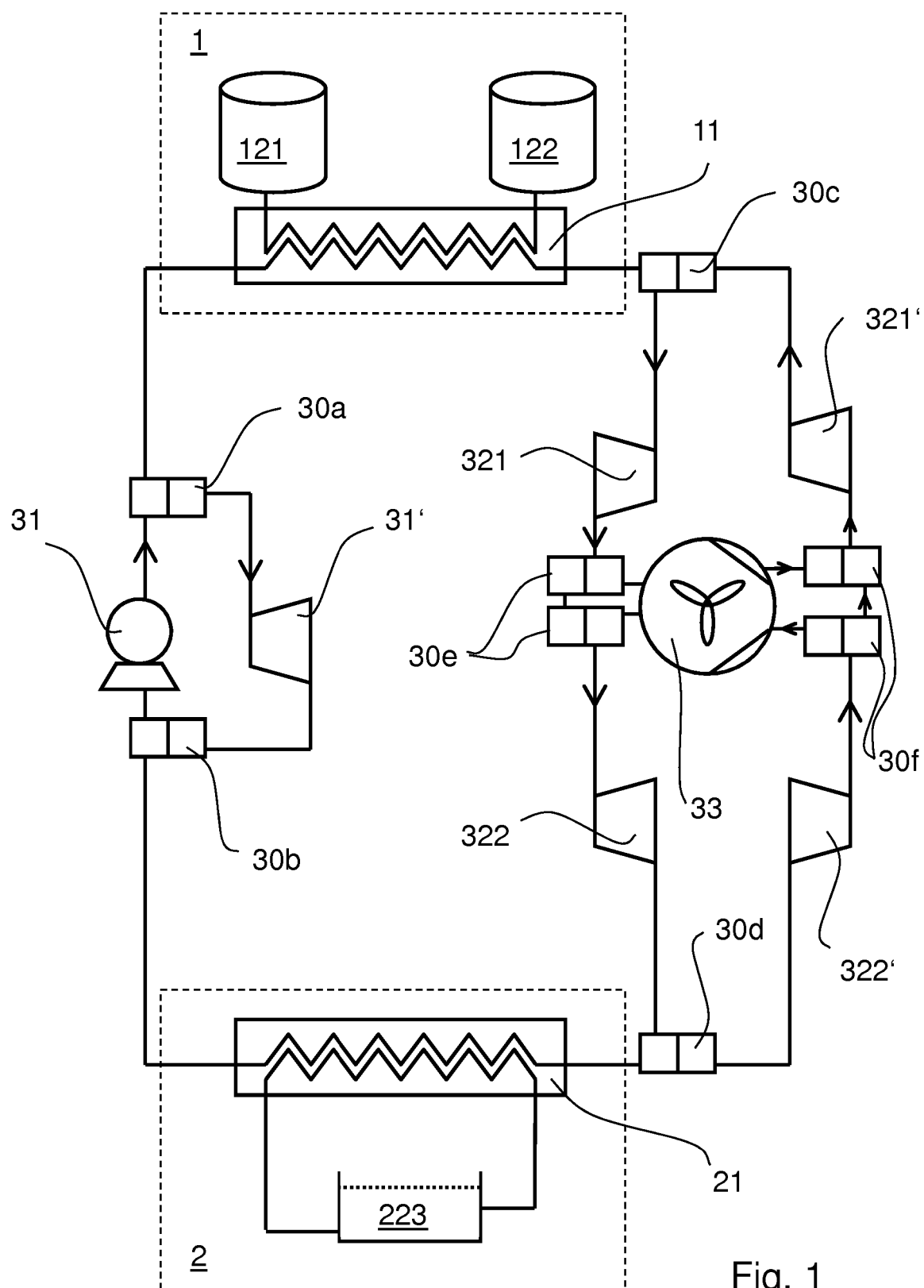


Fig. 1

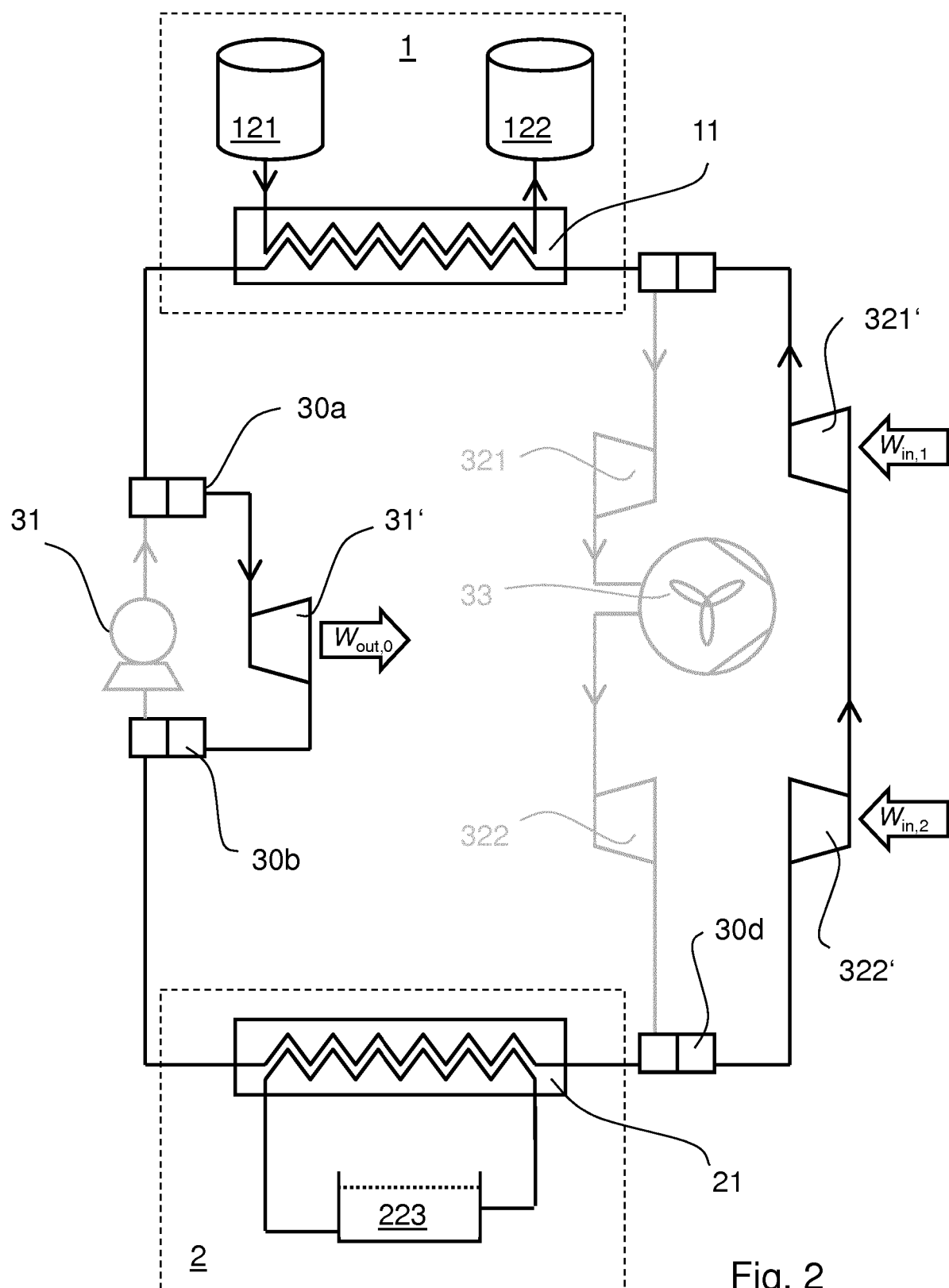


Fig. 2

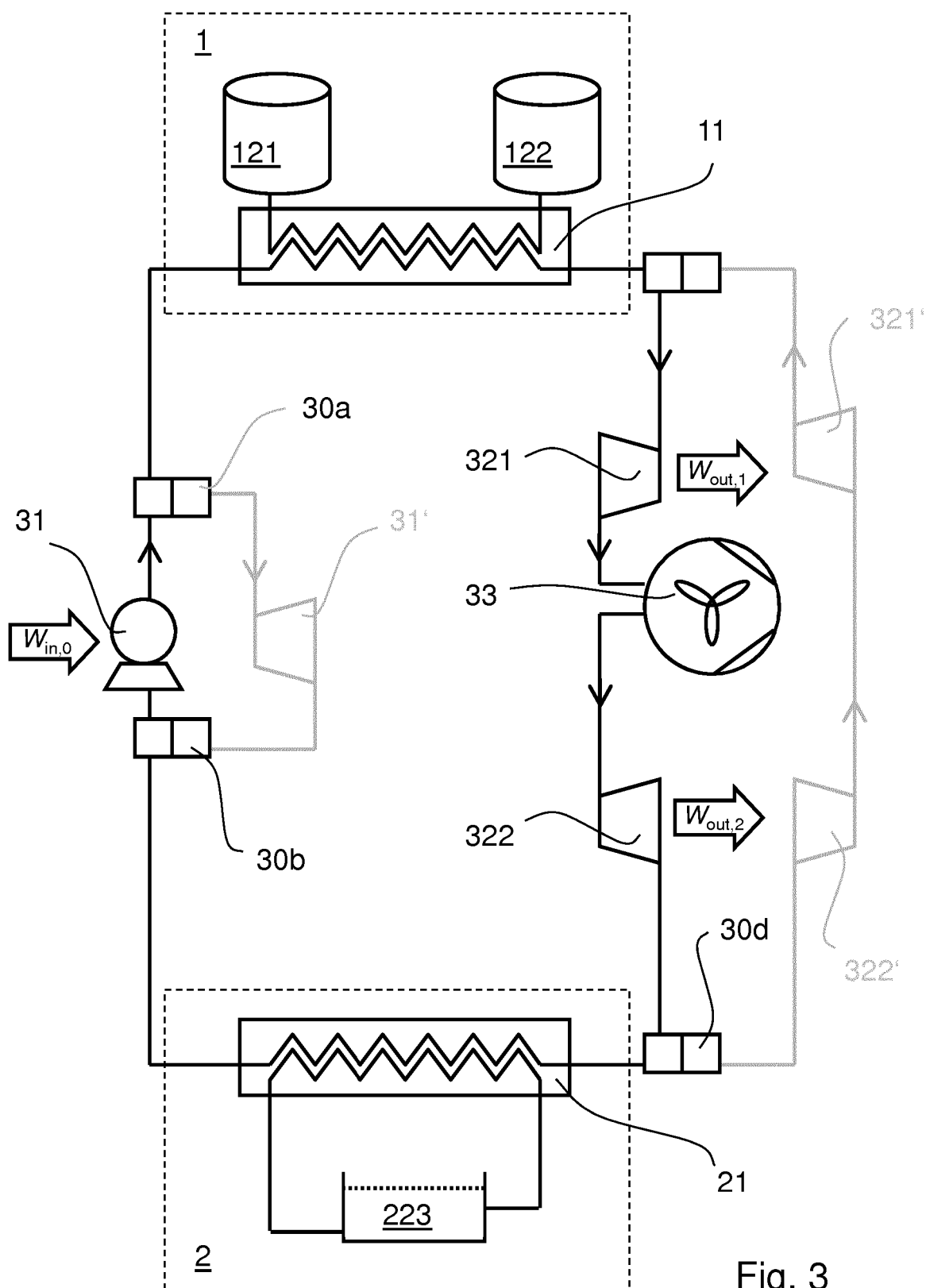


Fig. 3

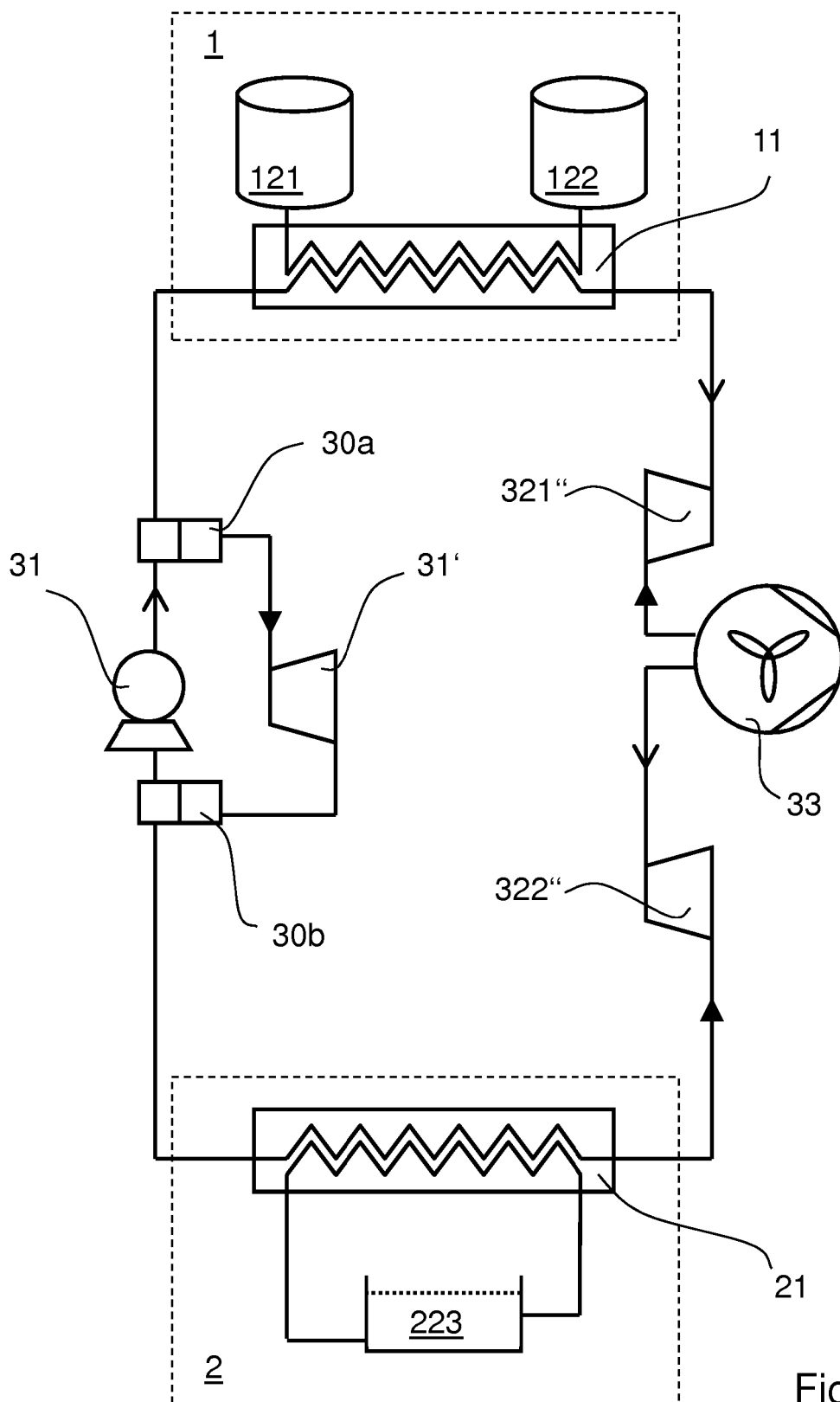
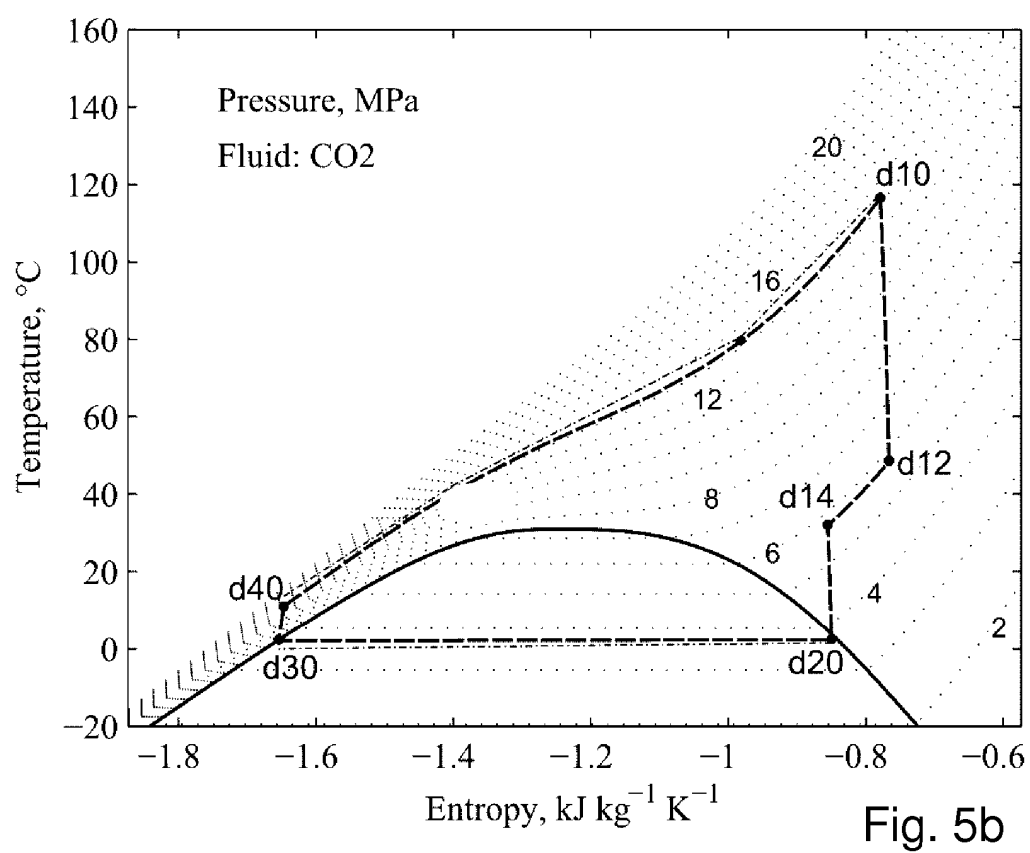
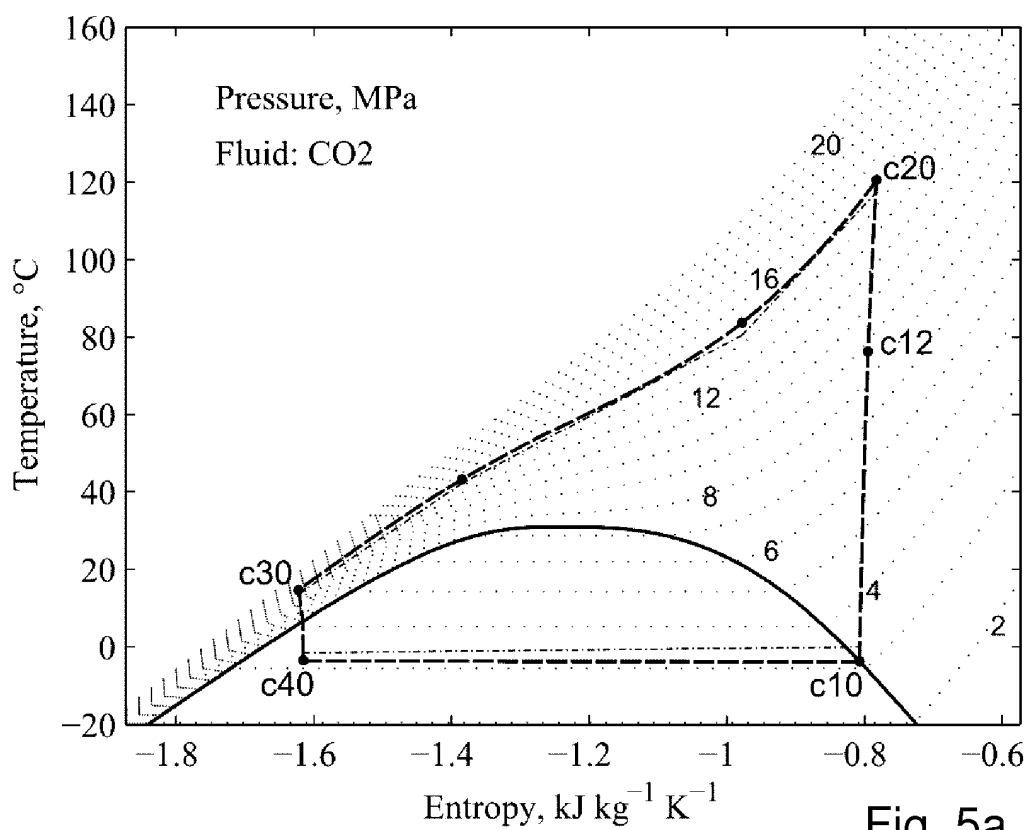


Fig. 4



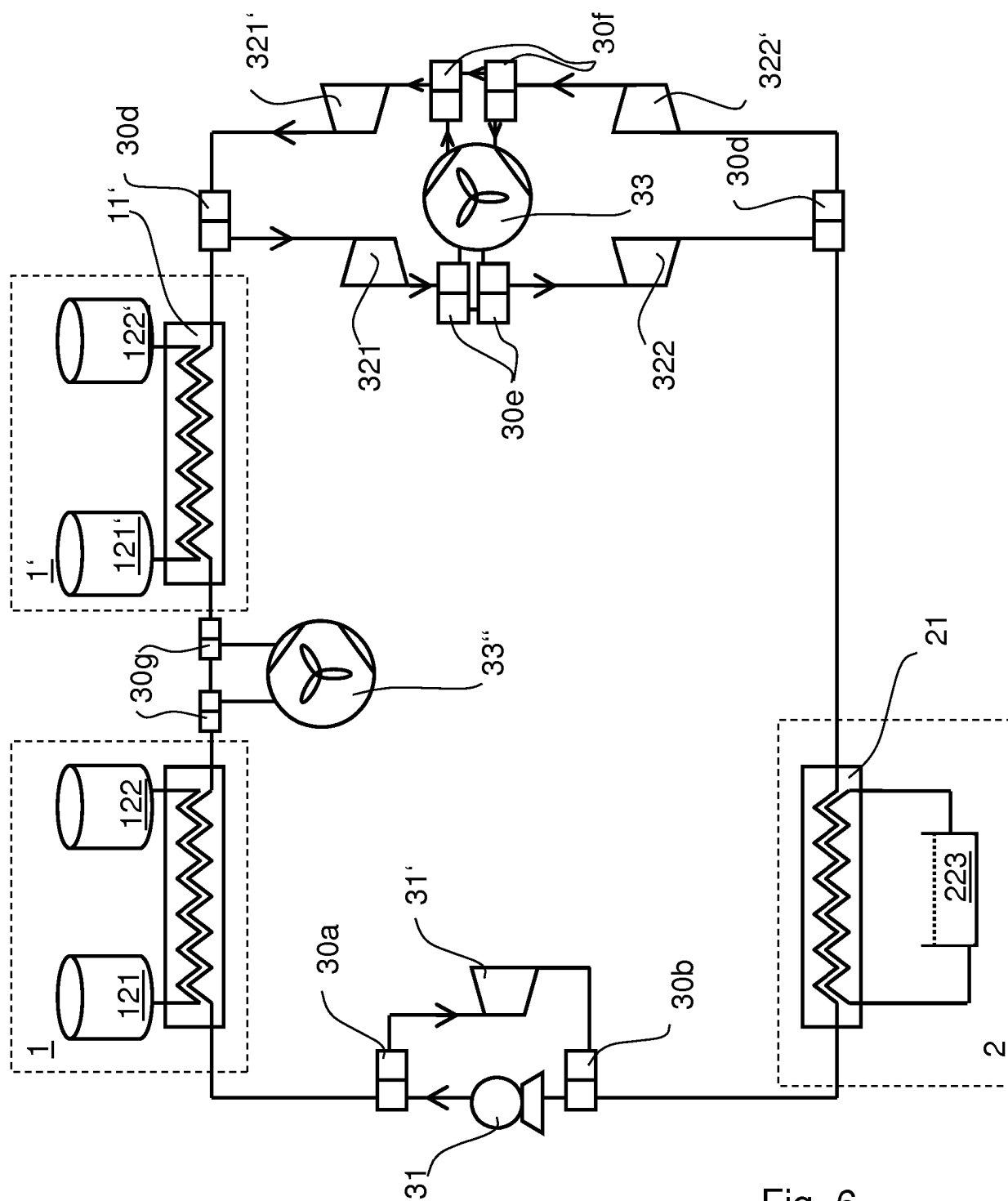


Fig. 6

**REFERENCES CITED IN THE DESCRIPTION**

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**Patent documents cited in the description**

- EP 1577548 A1 [0002]
- EP 2157317 A2 [0002]
- EP 2390473 A1 [0005]
- WO 2011103306 A1 [0009]
- EP 2275649 A [0010]
- EP 11169311 A [0027]
- EP 2275649 A1 [0038]
- EP 2182179 A1 [0038]