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(56) Documents Cited:
GB 2519626 A **EP 2602443 A1**
EP 2581584 A1 **EP 2559881 A2**
US 20110094231 A1 **US 20110094229 A1**

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INT CL **F01K, F02B, F02C**
Other: **WPI, EPODOC, TXTE**

(54) Title of the Invention: **A compressed air energy storage and recovery system**
Abstract Title: **Compressed air energy storage and recovery system**

(57) A compressed air energy storage (CAES) and recovery system is provided. The system comprises a plurality of compression stages 1, 37 each driven by an external supply of electrical power 31, 35 provided to compress air, a heat exchanger 5, 9 configured to remove heat from the compressed air, and a compressed air energy storage facility 12. During a storage phase the heat of compression is removed from the compressed air flow by two or more liquid media, the heat being stored in the liquid media used for heat transfer. The first liquid media is capable of thermal storage at temperatures above 350 Centigrade. The second liquid media is capable of thermal storage below 250 Celsius. During an energy recovery phase heat is returned to the air by the same liquid media, and same heat exchangers as those used in storage phase. The reheated compressed air is expanded in at least two separate stages of expansion in which electrical power is generated. Molten salt, or thermic oil may be used as the first liquid media, water may be used as the second liquid media.

Figure 5

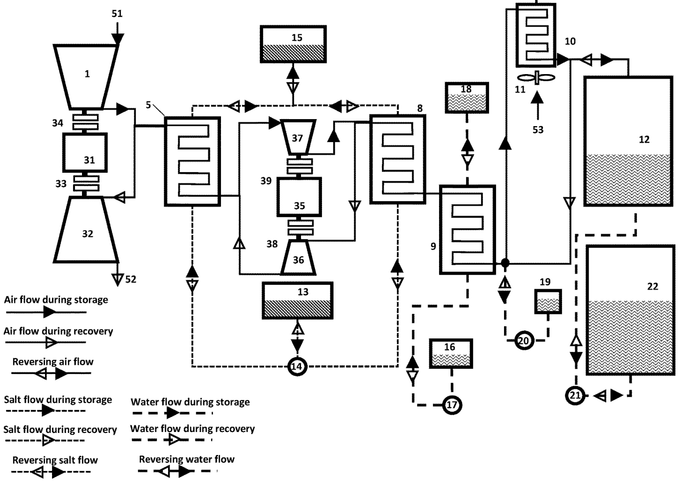
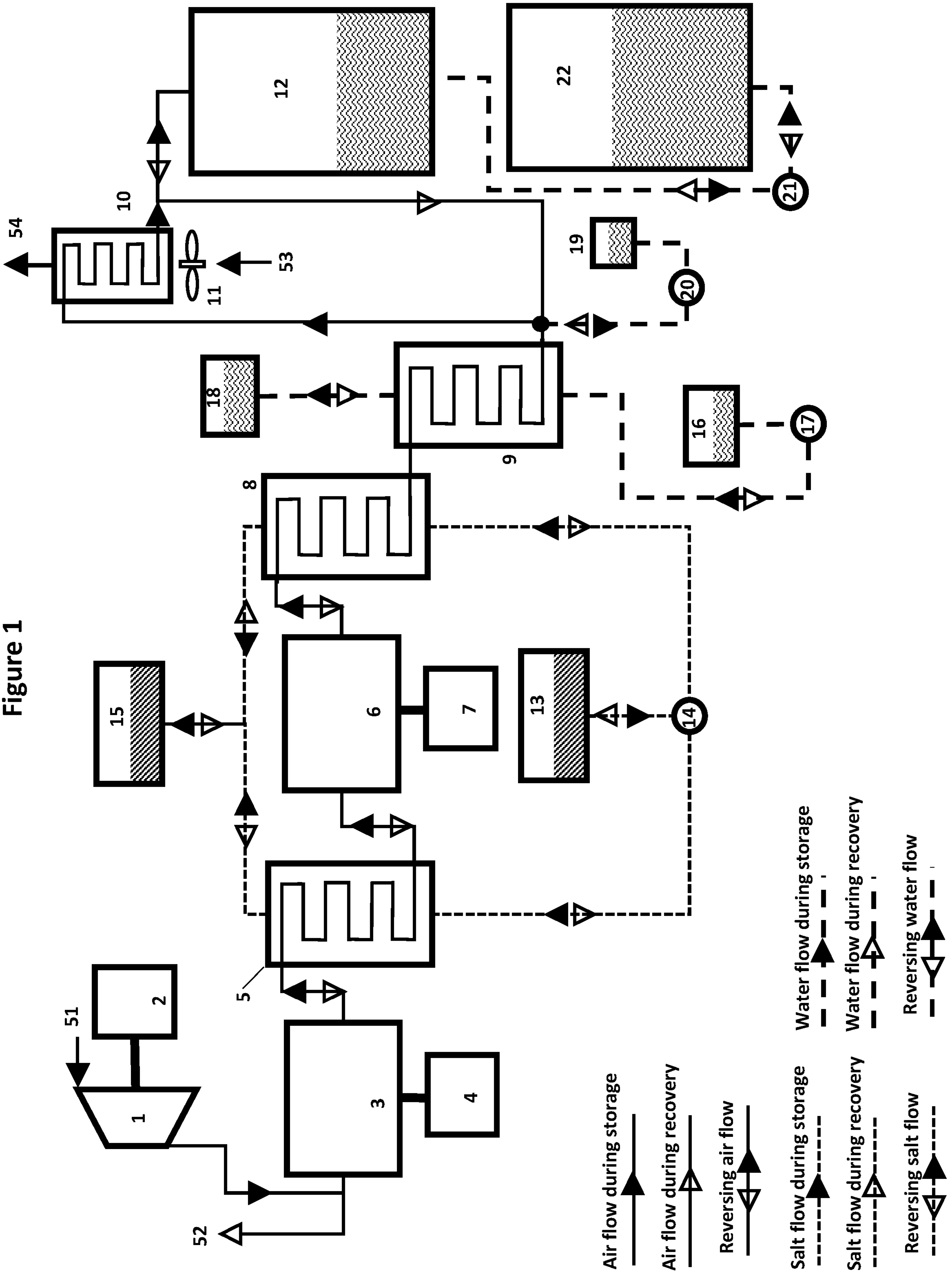


Figure 1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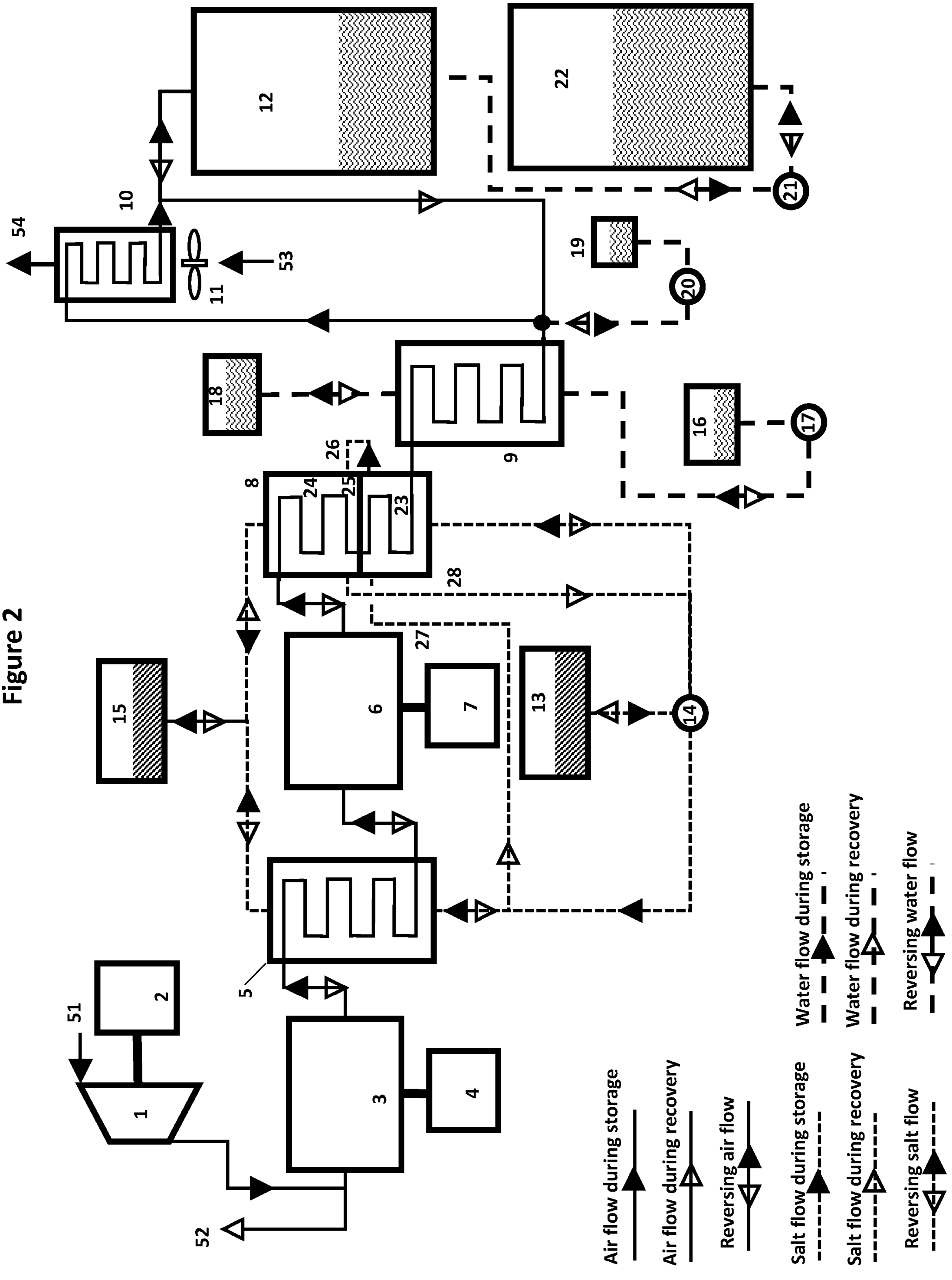
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow

Figure 2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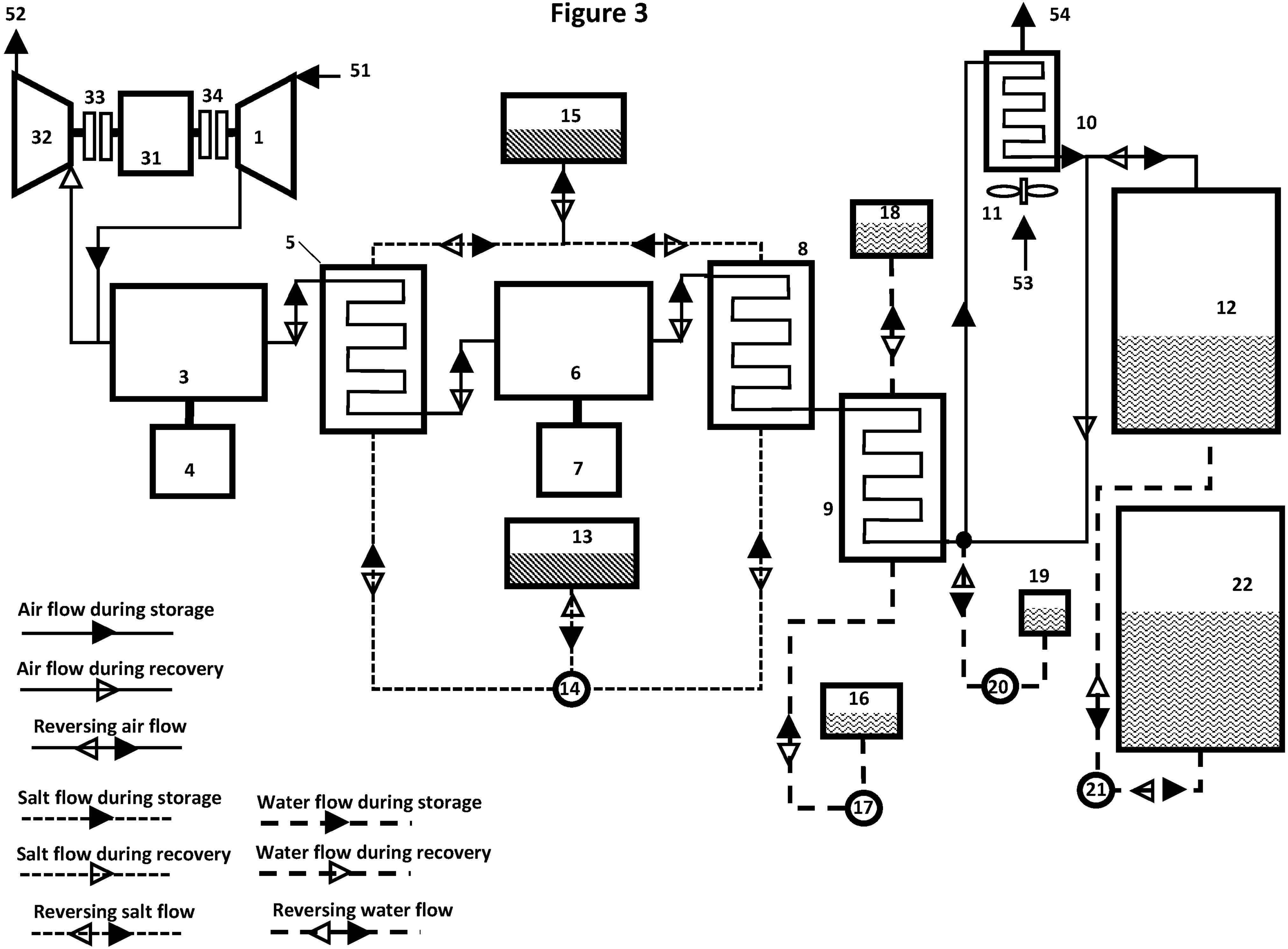
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow

Figure 3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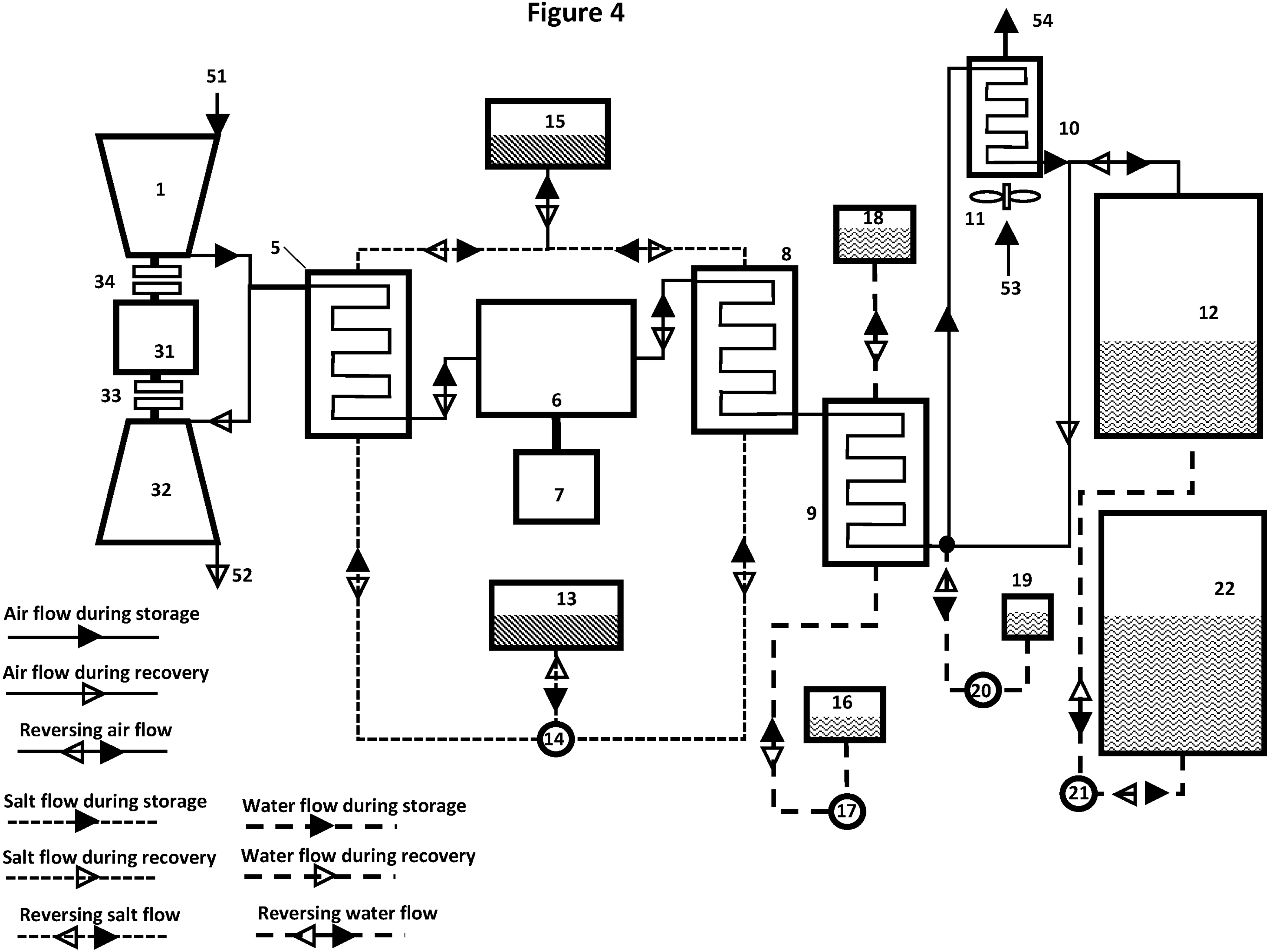
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow

Figure 4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Air flow during storage
Air flow during recovery
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Reversing air flow
14
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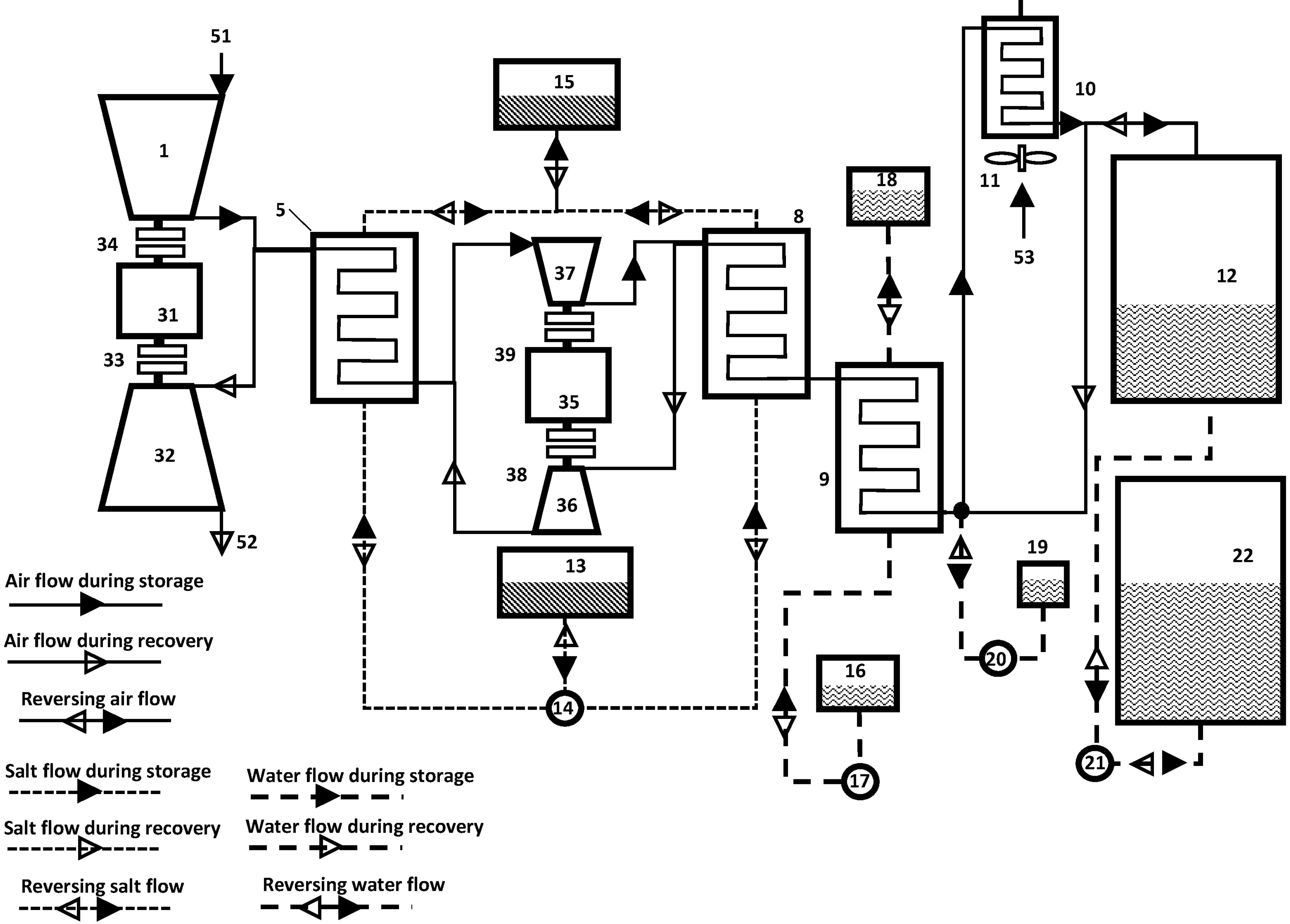
Salt flow during storage
Water flow during storage
17
Salt flow during recovery
Water flow during recovery
Reversing salt flow
Reversing water flow

Figure 5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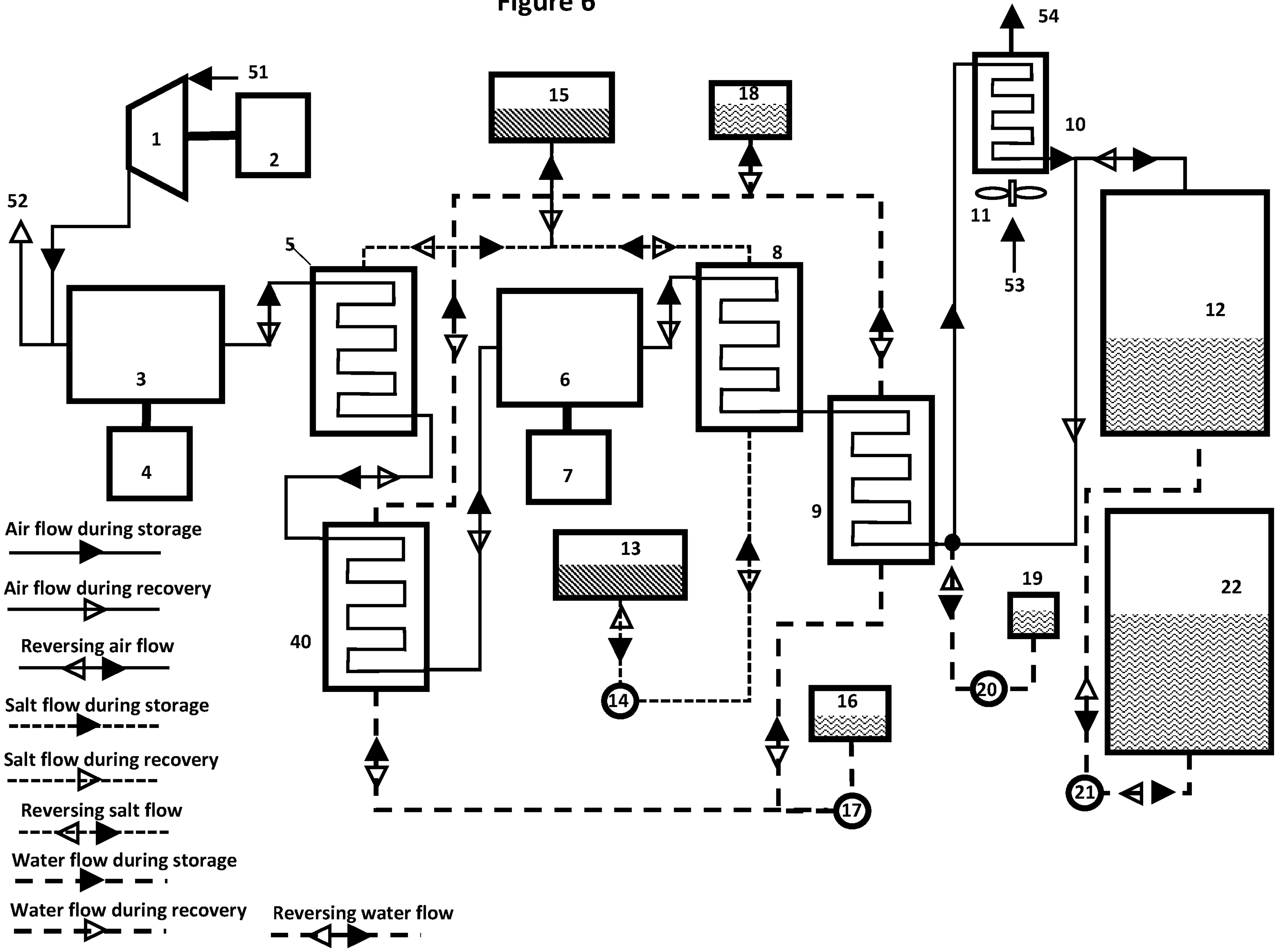
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow

Figure 6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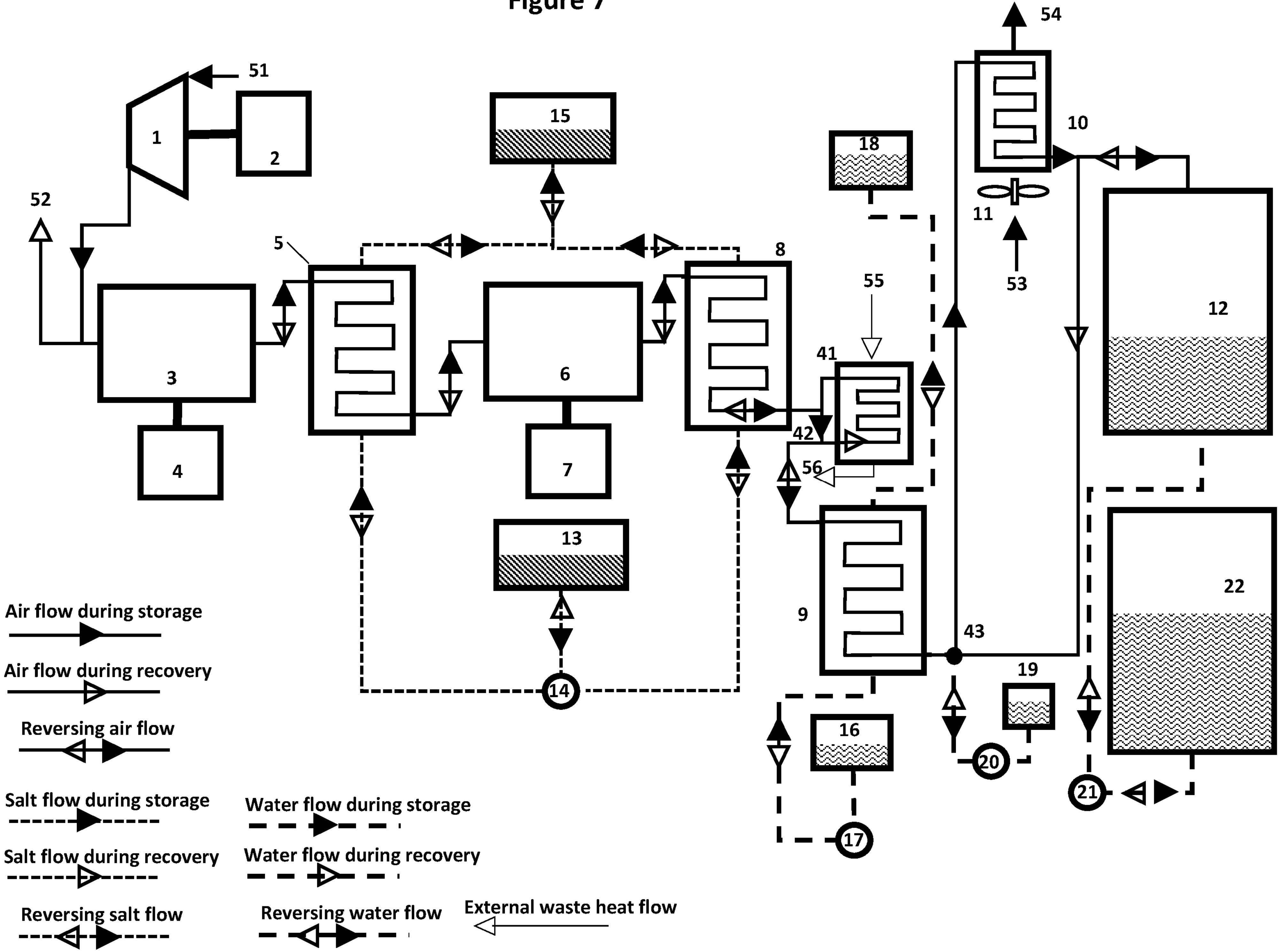
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow

Figure 7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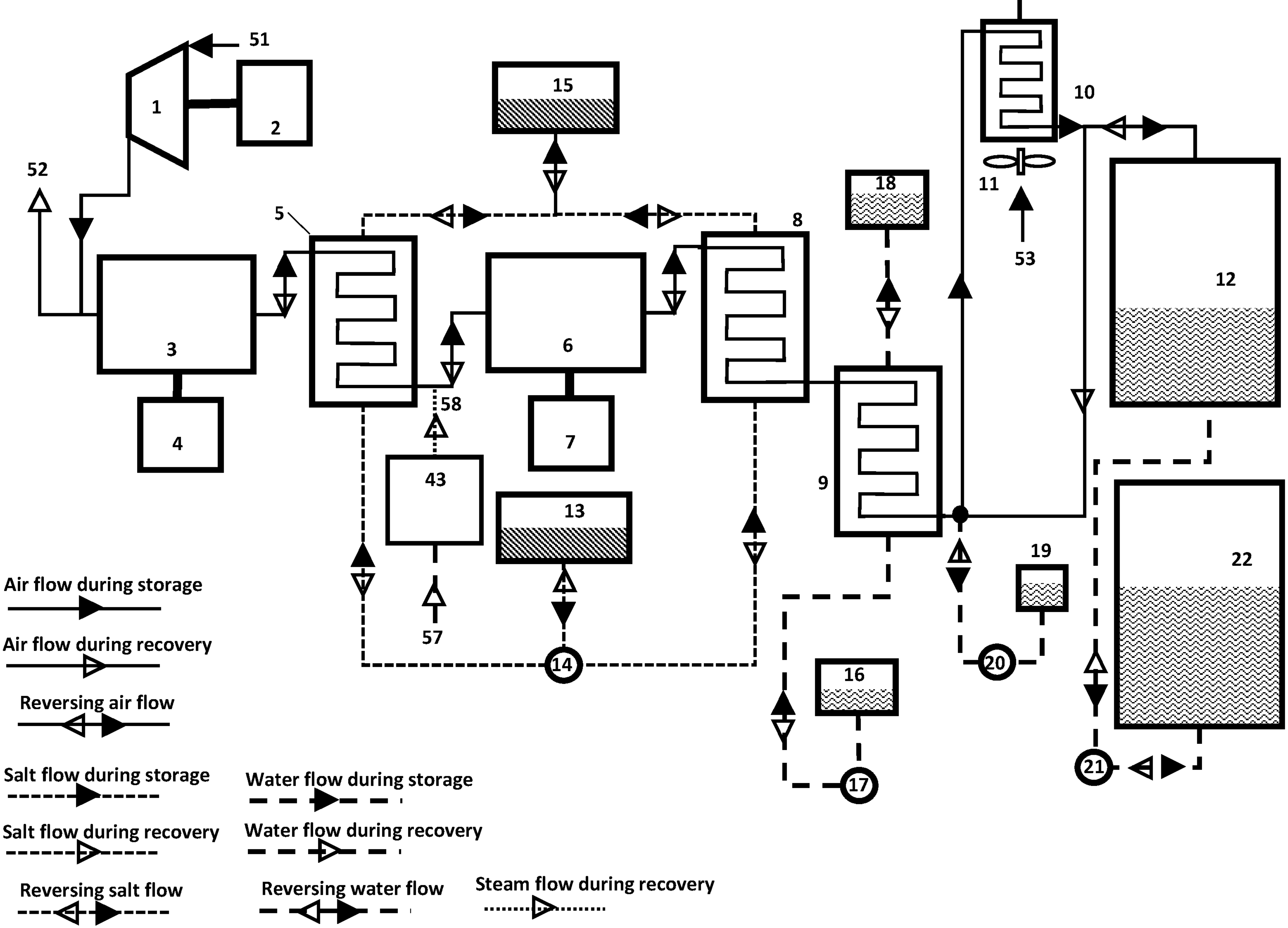
Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow
External waste heat flow

Figure 8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Air flow during storage
Air flow during recovery
Reversing air flow
Salt flow during storage
Salt flow during recovery
Reversing salt flow
Water flow during storage
Water flow during recovery
Reversing water flow
Steam flow during recovery

DESCRIPTION

BACKGROUND

[0001] It is well known that it is difficult and expensive to store large amounts of electrical energy, which means that most electric power must be generated at the same time that it is required by the customer. This is particularly inconvenient for most forms of renewable energy, such as solar and wind energy, since the output of these plants is dependent on natural phenomena, not on customer requirements.

[0002] A considerable amount of work has been and is still being done to try to develop better and cheaper methods of energy storage in order to try to overcome this limitation on the supply and use of electrical energy. Pumped storage of water is currently the main method of storage of electric energy in commercial operation, but this method is constrained by the need for geographic suitability. Batteries are of course also used commercially for storage of electric energy, but this technology generally becomes uneconomic for storage of large amounts of energy for periods of several hours.

[0003] Compressed air energy storage (CAES) is a possible option, but so far developments of this technology have met with limited success. Many of the developments of CAES are concerned with systems in which fuel is burned in a gas turbine and the exhaust heat of the turbine is used to heat the stored compressed air before it is expanded. In this case, the system is not a pure energy storage system, but is a hybrid between a power generating system and an energy storage system, which may not be suitable for some applications.

[0004] Other proposed methods of compressed air energy storage do not require the consumption of a fuel, but instead aim to return a large fraction of the energy which was stored, but they can of course never return 100% of the stored energy, because of inevitable inefficiencies of the system. For example, if we consider the case of a large pumped storage plant, we might expect that the hydraulic / mechanical efficiency of the large pump-turbine could be near 90% in both pumping and turbine mode. The electrical motor/generator could be 98% efficient in both directions. Combining these assumed efficiencies, we can therefore estimate the overall “round trip efficiency” at about 78%.

[0005] For the case of compressed air energy storage systems which do not involve the consumption of fuel, the achievement of a high round trip efficiency is more difficult than in the case of pumped storage because it not only involves at least one compressor and one expander, but it also involves the transfer of heat in some form both during the storage phase and during the recovery phase. Inefficiencies arise in the transfer and storage of heat which are additional to the inefficiencies in compression and expansion.

[0006] To some extent the inefficiencies of a CAES system can be reduced by operating at lower speeds or lower thermal loading so that the equipment becomes larger. This generally applies to components such as reciprocating machines and heat exchangers. There may also be other ways in which the inefficiencies may be reduced if the capital cost and size of the plant is allowed to increase.

[0007] It is widely recognized that there is potentially a very large benefit if a system of compressed air energy storage can be developed, which does not consume fuel and which can achieve a reasonable round trip efficiency at modest cost. To achieve this, the design of the system must be carefully chosen to minimize the cost and complexity of the system and to minimize efficiency losses. This is the purpose of the present invention.

BRIEF DESCRIPTION

[0008] A compressed air energy storage and recovery system involves at least two stages of adiabatic compression and expansion and at least two stages of heat removal and heat restoration by means of heat exchangers and suitable thermal fluids. Two different thermal fluids are used for heat transfer and storage at different temperatures. The air is stored at a high pressure of around 200 bar or greater but at near ambient temperature in above ground pressure vessels or in suitable underground cavities, which may be specially prepared for the purpose.

[0009] The minimum air storage which is envisaged for this invention is 150 bar. This pressure is much higher than the figure of 80 bar, which is normally considered appropriate for an underground salt cavern.

[00010] Underground storage is still a possible option if for example the cavity is drilled out of rock and is at a sufficient depth which can support the high pressure. The rock may need to be lined with a suitable liner in order to seal it.

[00011] Above ground pressure vessels can be made from steel, but a more cost-effective option is to use pressure vessels made from carbon fibre.

[00012] Typically one of the thermal fluids used in the present invention is a molten salt suitable for heat transfer and storage at temperatures between 150-230^{0}C and 530^{0}C. The other thermal fluid is typically pressurized water which is used for heat transfer and storage in the temperature range from ambient up to 250^{0}C.

[00013] A thermal fluid other than molten salt may be used for the high temperature fluid but it is envisaged that the temperature of storage of the hot fluid would be at least 350^{0} C.

[00014] The compression and expansion are typically performed either by turbo-machinery or by adiabatic reciprocating compressor/expanders, but other types of compressor/expander, such as screw-type or rotary vane machines may be used.

[00015] In the case of reciprocating compressors/expanders it is expected that the same machines will be used for both compression and expansion, but with different valve timing in each case. The reciprocating compressor/expanders may be modified commercial diesel engines.

[00016] The pressure of the air storage system may be maintained at a constant level by means of a hydraulic pump-turbine which pumps water at high pressure into the air storage system during the energy recovery phase and releases the water in the opposite direction through the pump-turbine during the energy storage phase.

[00017] Water injection may be used during the energy recovery phase in order to re-inject water which condenses out of the atmospheric air during the energy storage phase. Additional water may also be injected during the energy recovery phase to make use of all the available stored heat and thereby enhance the overall efficiency of the system.

[00018] If some additional waste heat at a suitable temperature is available from some external source, this may also be used to provide additional heating to the energy recovery system. This allows more water to be injected into the compressed air during the energy recovery phase, so that more energy can be produced.

PRIOR ART

[00019] US patent application 12/609,449 by Freund et al describes an adiabatic compressed air energy system with liquid thermal energy storage. This system involves at least two stages of compression and expansion using rotary compressors and turbines and two stages of heat removal using a liquid heat transfer medium such as molten salt. The same liquid is also used as a thermal storage medium. The patent application refers to storage of the air in a cavern, which is intended by the authors to include salt and rock caverns and above ground pressure vessels. There is no disclosure relating to the storage pressure of the air and no reference to high air storage pressures above 150 bar or any other pressure. The patent application refers to alternative liquids such as mineral oil, synthetic oil and molten salt, which can be used for heat transfer and storage. There is no disclosure of using more than one liquid in the same system and there is no disclosure of using water as a low temperature liquid medium for heat transfer and storage in the system. It is also stated by Freund et al that the liquid thermal medium is unpressurised, which would of course preclude the use of water at any temperature above 100°C.

[00020] European patent application EP 2687702 by Guidati describes a compressed air energy storage system in which the inlet temperature of the first stage of compression is raised to 300°C by a recuperator. The heat supplied to the recuperator comes from within the system as described below. The first stage compressor increases the pressure from atmospheric pressure at the inlet to about 4 bar at the outlet, such that the outlet temperature of the air is 550°C. This heat is transferred to a thermal storage medium which may be molten salt and the air is cooled to 300°C. This air at 4 bar and 300°C may then be compressed in a second compressor such that the outlet condition becomes 16 bar and 550°C and again the heat of compression is transferred to a thermal storage medium which may be molten salt. This process can be repeated a third and a fourth time so that the pressure reaches 64 bar and a temperature of 300°C. The air is then returned to the recuperator for the purpose of heating the atmospheric air before the first stage of compression. The compressed air leaving the recuperator is therefore at 64 bar but the temperature is near atmospheric temperature. The final stage of compression to the storage pressure, which may be about 100 bar, is performed by an intercooled compressor, in which the heat of compression is apparently dissipated to the environment. Energy recovery is a reversal of the energy storage process, except that the initial expansion from the storage pressure to 64 bar is performed by a simple throttling process, in which no energy is recovered.

[00021] EP 2687702 discloses multiple stages of heat transfer to a thermal storage medium which can be molten salt, but the storage medium is the same in each case. The invention described in EP 2687702 has no need for a separate low temperature thermal storage medium because the air temperature is increased to 300°C by means of a recuperator.

[00022] Other prior art relating to compressed air energy storage can be found in which fuel is combusted in order to generate energy in excess of that which is stored. Typically this is done using a gas turbine and indeed two energy storage plants of this type have been built. This type of energy storage plant involves a fundamentally different principle, which is not relevant to the present application.

[00023] A further type of compressed air energy storage system involves the quasi-isothermal compression of air by using water sprays or a liquid foam to cool the air during the actual compression process. Unlike the present application this type of compression is by definition non-adiabatic. These quasi-isothermal systems may store the heat transfer fluid, but the storage is at a low temperature well below the 350°C considered to be the minimum storage temperature for the present invention. Accordingly there is no need for a high temperature thermal storage fluid such as molten salt or thermic oil.

DETAILED DESCRIPTION

[00024] There are a number of possible embodiments of the invention which will be described below, but the present detailed description focuses on a particular preferred system which is shown in Figure 1. This shows the components and the direction of flow of air, molten salt and water both during energy storage and during energy recovery.

[00025] The description includes typical values of pressure and temperature in different parts of the system. These values are simply indicative and the invention is not limited to these particular values.

[00026] During the energy storage phase, ambient air entering at 51 is compressed in a turbo or screw compressor 1 which is driven by an electric motor 2. Typically the pressure ratio of the turbo/screw compressor would be between 1.5 and 4. The discharged air is fed directly to an intermediate pressure (IP) reciprocating compressor/expander 3, which is driven by an electric motor-generator 4.

[00027] The air from the compressor/expander, which is typically at a temperature of about 525°C, is fed to an intermediate pressure (IP) air-salt heat-exchanger 5 which transfers heat to a flow of molten salt, such as the commercially available Hitec HTS. The hot air is thereby cooled to a temperature of about 180°C and is then fed to a high pressure (HP) reciprocating compressor/expander 6, which produces hot compressed air at a pressure over 200 bar and a temperature of about 525°C. The HP compressor/expander 6 is driven by a motor/generator 7.

[00028] The hot compressed air flows to a high pressure (HP) air-salt heat exchanger 8 where it again transfers heat to molten salt and is again cooled to about 180°C. Next, the compressed air flows to an air/water heat exchanger 9 in which further heat is transferred to a flow of pressurized water. This cools the air further to a temperature of about 70°C. The high pressure air then flows to an air cooler 10, in which a final stage of cooling takes place, which brings the high pressure air down to a temperature of about 35°C.

[00029] The atmospheric air which is used in this system contains water vapour. The amount of water vapour depends on the atmospheric temperature and the relative humidity of the air. When the atmospheric air is compressed to a high pressure and then cooled down to near atmospheric pressure, most of the atmospheric water vapour condenses. This condensate is separated from the compressed air at the air outlet of the air/water heat exchanger 9 and is stored in a condensate tank 19.

[00030] The heat removed in the air cooler can be dissipated to the atmosphere by means of a fan 11 blowing air, which enters the cooler at 53 and leaves at 54. Alternatively the compressed air can be cooled by water from a lake, river or from the sea. Finally the air flows to the constant high pressure storage vessel 12.

[00031] The molten salt required by the two air/salt heat exchangers is pumped from a cool molten salt storage tank 13, which is used to contain molten salt at a temperature of about 150°C. A molten salt pump 14 is used for this purpose. After passing through the two molten salt heat exchangers 5 and 8, the hot molten salt flows to a hot molten salt storage tank 15, which contains molten salt at about 500°C. The molten salt tanks are unpressurised.

[00032] Molten salts used as thermal fluids for heat transfer and storage are typically mixtures of different salts. "Solar Salt", which is used in some thermal solar power plants, consists of a 60/40 mixture of sodium nitrate and potassium nitrate. This has a freezing point of 220°C and is stable up to a maximum operating temperature of 550°C. Hitec HTS consists of a eutectic mixture of sodium nitrate, potassium nitrate and sodium nitrite. This has a melting point of 142°C and maximum operating temperature of 538°C according to the supplier's literature. There is a slow decomposition of the sodium nitrite at the highest temperatures, which can be controlled by blanketing with nitrogen. Other salts are available commercially with lower melting temperatures than 142°C. Some of these may also be subject to some degradation at the highest temperatures.

[00033] The pressurised water required by the air/water heat exchanger 9 is pumped from a pressurised cold water storage tank 16 at near atmospheric temperature using a water pump 17. After passing the air/water heat exchanger 9, the hot pressurised water flows to a pressurised hot water storage tank 18 at a temperature of about 160°C. A pressure of about 10 bar is sufficient to prevent boiling of the hot water in the pressurised water system.

[00034] During the energy recovery phase, the directions of flow of the air, the water and the molten salt through the pipework are reversed and the direction of heat transfer in the heat exchangers 5, 8 and 9 is also reversed, with heat being transferred from the liquid thermal storage media to the compressed air. The water pump 17 and the molten salt pump 14 are either capable of reversing their flow direction or are connected by valves which can be operated to reverse the flow direction through the system. Hot molten salt flows from the hot molten salt storage tank 15 via the air-salt heat exchangers 5 and 8 and returns to the cold molten salt storage tank 13. Hot water flows from the pressurised hot water storage tank 18 via the air-water heat exchanger 9 and returns to the pressurised cold water storage tank 16.

[00035] Also during energy recovery, the cold compressed air flows from the compressed air energy store 12 to the same air/water heat exchanger 9 as used during energy storage. The condensate that was removed during energy storage is re-injected using the pump 20. The air is pre-heated in the air/water heat exchanger 9 and most but not necessarily all the re-injected condensate is evaporated. The air then passes into the HP air/salt heat exchanger 8 and is heated further by hot molten salt to about 490°C. All the remaining water vapour is evaporated in this heat exchanger. The very hot compressed air is then fed to the HP compressor/expander 6, which operates as an expander during energy recovery. This cools the air to a temperature of about 140°C. The partially expanded air is then reheated in the IP air-salt heat exchanger 5 to achieve a temperature 490°C once again. Finally the partially expanded reheated air is expanded further in the IP compressor/expander 3, so that the air is released to the atmosphere at near atmospheric pressure.

[00036] The expansion taking place in the HP and IP compressor/ expanders 8 and 5 may include an element of blow-down at the end of the power stroke. This refers to a residual depressurisation of the cylinder when the exhaust valve opens, which is a feature of most if not all reciprocating engines. This achieves some additional thermodynamic expansion without increasing the stroke of the piston, which can result in additional frictional loss outweighing the benefit of a more complete mechanical expansion.

[00037] The IP compressor/expander 3 and the HP compressor/expander 6 are equipped with valves, the timing of which may be adjusted so that they can operate as compressors during energy storage and as expanders during energy recovery. The motor/generators 4 and 7 operate as motors during energy storage and as generators during energy recovery. The drive shafts of the compressor/expanders may be connected together so that a single motor-generator may be used, instead of separate motor/generators as shown in Figure 1.

[00038] The reciprocating compressor/expanders may be modified commercial multi-cylinder diesel or spark-ignited engines which retain the original crankshafts and crankcases. Some or all of the original cylinders, pistons and piston rods may also be retained, or they may be changed. The cylinder heads and valves assemblies would almost certainly be changed, but some parts of the original valve assemblies may be retained. Of course, the fuel and ignition systems of such modified commercial engines would be removed.

[00039] Such modified multi-cylinder commercial engines may include both high pressure and intermediate pressure compressor/expanders in the same block and be driving/driven by the same crankshaft. In this case, different bore sizes may be used for the high pressure and intermediate pressure cylinders.

[00040] Alternatively the reciprocating units operating at different pressures may be based on different commercial engines.

[00041] A feature of this preferred embodiment of the invention is that a hydraulic system is employed to maintain the air storage vessel at approximately constant pressure. This is achieved by pumping water from a reservoir at atmospheric pressure 22 into the high pressure air storage vessel 12 during the energy recovery phase. It is proposed that a hydraulic pump-turbine 21 is used for this purpose in a similar way to the pump-turbines used in pumped storage plant. These hydraulic machines can work efficiently both as a pump and as a turbine. Therefore the same machine may be used as a turbine during the energy storage mode in order to extract power from the water as it flows out of the air storage vessel.

[00042] The hydraulic pump-turbine 21 may be used as a fast response system to modify the input or output of the energy storage system as a short-term temporary measure. This may be useful as a means of stabilising a grid supply in a similar way to that which may be done with hydraulic pumped storage systems. The hydraulic pump-turbine could be adjusted to run at a lower or higher flow rate or it could be stopped altogether. Over a longer period of time the pressure of the air reservoir may drift from its normal setting, but the fast response of the hydraulic pump-turbine could give valuable time for other generating plant to be run up or run down as necessary. The drift of pressure in the air storage system can then be corrected.

[00043] The hydraulic system consumes or generates power in opposition to the air storage system, which means that the power rating and performance of the overall

system at a fixed pressure condition is degraded relative to that which could be obtained without such a hydraulic system. Without the hydraulic system however, it is not possible to realize a system that could operate continuously at a fixed pressure, unless the air storage volume was effectively infinite, or the air was stored deep underwater at a fixed hydrostatic pressure. In practice the pressure of a finite air storage volume would vary over a wide range, for example from a maximum of 200 bar down to about 50 bar.

[00044] The system includes measures to control the temperatures of molten salt and of water, in order that the molten salt does not overheat or freeze and that the pressurised water does not boil or freeze. The molten salt storage tanks will be very well insulated to avoid heat losses during storage. The salt storage tanks and the pipelines require heating systems which can be automatically activated if the temperature drops too much. There may also be a need to provide cooling for the salt and the water, which can also be automatically activated if either of these fluids become too hot. These systems are not shown in Figure 1.

METHODS OF CONTROLLING THE POWER INPUT AND OUTPUT

[00045] In addition to the flexibility to switch from energy storage mode to energy recovery mode and vice versa, the compressor/expanders may have the flexibility to vary the power input and the power output according to the requirements of the operator or the customer.

[00046] Any method which adjusts the power input or output will preferably do this by adjusting the air mass flow into or out of the system. If this is not the case, the system is likely to be inefficient when operated at lower power.

[00047] One method of reducing the mass flow rate is to isolate individual cylinders of the compressor/expander with valves so that no air flows between the inactive cylinders and the compressed air storage system. When this is done, it is important to minimise the parasitic load of the inactive cylinders. Some loss due to friction of the piston in the cylinder will still occur, but the pressure load on the piston can be minimised by maintaining the low pressure valve (ie. the intake valve in compression and the exhaust valve in expansion) in the open position throughout the entire 360^0 of each revolution. Thus the piston remains continuously exposed to the low pressure side of the respective compressor/expander. Some energy is lost through dissipation of the air passing into and out of the cylinder, but this should be small.

[00048] Another option is to keep the low pressure valves of the inactive cylinders closed but to keep the high pressure valves open so that the piston is continuously exposed to the high pressure. Although the high pressure air is denser than low pressure air, it may be that this effect is compensated by a larger flow area for the high pressure valves. Alternatively it could simply be mechanically more convenient to keep the high pressure valves open.

[00049] A further option may be to keep both the low and high pressure valves closed throughout each 360^0 revolution. However, this option could potentially suffer from unacceptably high pressures in the cylinder. Also the piston friction is likely to increase substantially as more pressure difference is applied to the piston seals.

[00050] A possible way of adjusting the air mass flow and hence the power input in the energy storage mode is to vary the operating conditions of the LP compressor. If the LP compressor is a turbo-compressor, then it would be possible to use inlet guide

vanes and/or a motor with a variable frequency drive to control the mass flow. A rotary screw machine could also be adjusted with a variable frequency drive.

[00051] Adjustable valve timing on the low pressure valves of the reciprocating units during compression allows the volume and mass of intake air to be varied. If the low pressure valves can be made to close either before or after bottom dead centre then the air mass flow is reduced.

[00052] Adjustable timing of the high pressure valves of the reciprocating units during compression allows the pressure ratio to be varied during the energy storage mode. This flexibility would be particularly useful if the system does not have a hydraulic pressure compensating system as shown in Figure 1, but instead operates with a variable air storage pressure. Even if a hydraulic pressure compensating system is used, the flexibility to adjust the timing of the high pressure valves is useful to accommodate changes in pressure ratio of an LP turbo-compressor.

[00053] Adjustable valve timing of the high pressure valves of the reciprocating compressor/expanders during operation as expanders allows the air mass flow to be varied. The mechanical expansion ratio is also changed, but this may not mean that the thermodynamic pressure ratio is changed, since there can be different amounts of blow-down when the exhaust valve opens.

[00054] Adjustable timing of the closing of the low pressure valves of the reciprocating units during expansion can change the mass of air which is retained in the cylinder after each exhaust stroke. This affects the intake mass of air in the next stroke, which in turn affects the mass flow.

[00055] A further method of controlling the power input/output and the mass flow of the system is to vary the speed of the reciprocating units by means of a variable frequency drive.

ALTERNATIVE EMBODIMENTS OF THE INVENTION

[00056] An alternative embodiment of the invention is to use an air pressure store without a hydraulic pressure compensating system. For example, the pressure in the air storage system might be allowed to vary from a maximum of 200 bar down to about 50 bar, such that the system pressure varies by a factor of 4. In this case, it is necessary to have much more flexibility in the individual components and in the complete system to cope with the varying pressure, particularly if it is desired to maintain a constant power input during energy storage and a constant power output during energy recovery. This implies that the air mass flow should actually increase as the pressure falls and decrease as the pressure rises.

[00057] The need for flexibility in the individual components can be reduced by reducing the variation in the system pressure. For example the system pressure may be allowed to vary between 200 bar and 100 bar. The disadvantage is that a significantly larger air storage volume is required for the same amount of stored energy.

[00058] The methods of controlling the power input/output which were described in the previous section may be applied to the case where the air storage pressure is allowed to vary over a range.

[00059] Another embodiment of the invention, which may be used with or without a hydraulic pressure compensating system, is to have underground air storage at pressures of 200 bar or more, in which part of the pressure load is taken by the

surrounding rock or earth and part by a suitable liner. For example, a carbon fibre liner could be used. Preferably, the liner could be formed in situ within the cavity. This could enable suitable underground cavities to be made in earth or rock which is unable to bear the full pressure load of the stored air.

[00060] Figure 1 shows that separate storage tanks are used to store hot and cold molten salt. An alternative storage method is to use a single tank for molten salt but to keep the hot and cold salt separate from each other by thermal stratification and by including an insulating barrier which floats at the interface between the hot and cold fluids. The same method can be used to keep hot and cold water in the same tank. The advantage of this approach is that one or both of the fluids can be kept in the same tank, thus saving space and capital cost. The disadvantage is that the insulation between the two fluids will be less than perfect and that there may be some equalisation of temperatures over time, which will reduce the output and the efficiency of the system.

[00061] If the molten salt has a low freezing point which is near 100^{0}C then the water used as the low temperature thermal transfer and storage medium can be used at atmospheric pressure or at a pressure only slightly above atmospheric. This reduces the cost of storing the storing the water. In this situation, significantly more heat may be required from the molten salt for the purpose of heating the air leaving the air/water heat exchanger 9 than is required for reheating the air in the IP air/salt heat exchanger 5. In this case, it is possible to divert molten salt leaving the IP air/salt heat exchanger to perform some of the heating of the high pressure air. An arrangement and method of doing this is shown in Figure 2.

[00062] Figure 2 shows a variation of Figure 1 in which the HP air-salt heat exchanger 8 is split into two sections 24 and 23 by means of a baffle 25. The high pressure air flow passes continuously through both sections. However during the energy recovery phase, the molten salt flow in section 24 is taken from the hot molten salt tank 15 and then exits from the heat exchanger near the baffle 25 and passes via the pipe 28 to the molten salt pump 14. The second section 23 of the heat exchanger 8 is heated by molten salt taken from the outlet of the IP air/salt heat exchanger 5, passes along pipe 27 and enters the lower section 23 of the HP air/salt heat exchanger 8, just below the baffle 25. This salt exits the lower section 23 of the HP air-salt heat exchanger and also flows to the molten salt pump 14.

[00063] During energy storage, the molten salt flows from the cool molten salt tank 13 via the pump 14 into the section 23 of the air-salt heat exchanger 8. The molten salt bypasses the baffle by flowing through the pipe 26. Thus the baffle has essentially no effect in the energy storage mode, and the HP air-salt heat exchanger 8 behaves in essentially the same way as shown in Figure 1.

[00064] A variation of the above method of redistributing the heat stored in the molten salt is to have an additional HP air/salt heat exchanger, which is heated by molten salt coming from the salt outlet of the IP air/salt heat exchanger. In this case a baffle is not needed.

[00065] The method of redistributing the heat stored in the molten salt between the HP and IP salt/air heat exchangers may be used in other circumstances where there is an unequal demand for heat. A similar method can in principle also be applied in the energy storage mode if there is an unequal supply of heat for some reason.

[00066] In another embodiment the system shown in Figure 1 or Figure 2 is modified so that there is less expansion in the IP and HP expander and an LP expander is added to complete the expansion. This alternative embodiment is illustrated in Figure 3, which shows an LP compressor 1 and LP expander 24 connected via clutches 25 and 26 to a motor-generator 23. In this embodiment the clutch 25 is engaged during the energy storage phase and the compressor 1 is driven by the motor-generator 23, with clutch 26 disengaged.

[00067] During energy recovery clutch 25 is disengaged and clutch 26 is engaged so that the LP expander 24 drives the motor-generator 23 and generates power in addition to the produced by motor-generators 4 and 7.

[00068] An arrangement of this type may be achieved by adapting the compressor and turbine elements of one or more commercial turbochargers.

[00069] The advantage of the system shown in Figure 3 is that the size of the reciprocating components might be reduced relative to the system shown in Figure 1. It might also be possible to achieve a more efficient expansion. The disadvantage of the system shown in Figure 3 is the additional cost and complexity of including an LP expander together with the clutches 33 and 34.

[00070] Figure 4 shows another embodiment in which the low and intermediate pressure compressor/expanders are combined into one rotary compressor 1 and one rotary expander 32 connected via clutches 33 and 34 to a motor generator 31.

[00071] The compressor 1 shown in Figure 4 could potentially be a turbo or a screw compressor. The pressure ratio would probably be 20 or greater in order that the temperature of the air entering the IP air/salt heat exchanger is sufficiently high to allow an efficient thermal storage system using molten salt. A turbo-compressor would consist of multiple stages resembling the compressor of a gas turbine. Indeed an existing gas turbine compressor could be used for this purpose, assuming that it can be separated from the remainder of the gas turbine.

[00072] The expander could also be a turbine similar to a gas turbine expander, and the aerodynamics would be similar, but the temperatures in the present system would be very much lower and the density of the gas would be much higher. The low temperatures in the present system would avoid the need for expensive materials and elaborate cooling systems which are used in gas turbines.

[00073] It may be possible to adapt an existing turbine component of a gas turbine for the present purpose, but this may not be the most cost-effective approach.

[00074] Figure 5 shows a further embodiment in which a rotary compressor 37 and turbine 36 are used for the high pressure compression and expansion. The high pressure compressor would probably be a centrifugal compressor and the turbine could be an axial turbine or a radial inflow turbine. The compressor 37 and the turbine 36 are connected to a motor-generator 35 via clutches 38 and 39.

[00075] Figure 6 shows another embodiment of the invention in which there is an intermediate pressure air/water heat exchanger 40 in addition to a high pressure air/water heat exchanger 9. This arrangement could be applied in the case where a very high air storage pressure is used, for example a pressure in the range of 200-300 bars. In this case it may be desirable to cool the air which has already been compressed to the intermediate pressure of around 25 bar before beginning the high pressure compression. Figure 6 shows that the pressurised water used in the IP air/water heat exchanger 40 is pumped using the same water pump 17 and uses the

same cold water tank 16 and the same hot water tank 18 as that used for the HP air/water storage tank 9.

[00076] Figure 7 shows an embodiment of the invention in which available waste heat from an external source can be utilised to increase the power output in the energy recovery phase. For example there could be some waste heat available if the energy storage plant is near an industrial site or is sited near peaking power plant such as diesels or gas turbines.

[00077] Figure 7 shows a waste-heat heat exchanger 41 which is included the compressed air flow path between the air/water heat exchanger 9 and the HP air/salt heat exchanger 8. The waste heat flow, which could be exhaust gas from a diesel engine or gas turbine, enters at 55 and flows on the primary side of the heat exchanger 41 and exits at 56. The compressed air flows on the secondary side.

[00078] The waste heat may be absorbed by increasing the flow rate of water which is injected into the compressed air at the water injection point 43.

[00079] Figure 8 shows an embodiment of the invention in which external waste heat is utilised by raising steam in a waste heat boiler. During energy recovery, a supply of water 57 may be fed to the waste heat boiler 43 and the steam from the boiler may be injected into the partially expanded compressed air at a point 58 at the outlet of the HP compressor/expander 6. Depending on the temperature and pressure of the waste heat boiler, other possible locations could be chosen for the steam injection point. For example, if the waste heat boiler can operate at a pressure greater than the operating pressure of the compressed air plant, then steam from the waste heat boiler could be injected at the outlet of the HP air/water heat exchanger 9.

[00080] The effect of the added water or steam is to increase the mass flow and total enthalpy of the flow which increases the power output of the system. The moist air exits the system after the final expansion and passes into the atmosphere at 52.

[00081] In certain circumstances of shortage or high cost of water it may be worthwhile to recover some of the added water or steam by installing a condenser at the outlet of the final expansion. Such a condenser could need to have cooling provided so that the moist air could be cooled down to a temperature only slightly higher than ambient temperature. The condenser could be cooled by air or by seawater for example. The condensed water would then be re-used for injection as water or as steam.

[00082] Guide vanes may be used in any of the turbo compressors or turbines shown in Figures 1 to 8. The guide vanes can increase the operational flexibility of these components by altering the angle at which the air flow meets the rotating blades of the turbo-compressors or turbines. This allows the turbo-compressor to operate more efficiently over a wider range of flow conditions.

[00083] Variable frequency drives may also be used to increase the operational flexibility of turbo-compressors and of turbines used in the present invention.

[00084] Another possible embodiment of the invention is to do without the turbo- or screw compressor 1 and motor 2, which is shown in Figures 1 to 6, and instead perform the low pressure and intermediate pressure compression and expansions with one or two reciprocating machines, which can perform both compression during energy storage and expansion during energy recovery by changing the valve timing. Because of the high pressure ratio required before the air enters the IP air/salt heat exchanger, it is most likely that two stages of compression would be

needed for this purpose, in which case it may be convenient to have two stages of expansion also.

[00085] Other possible embodiments of the invention could use thermic oil as either the low temperature instead of water or as the high temperature thermal fluid instead of molten salt. A possible advantage of using thermic oil as the low temperature thermal fluid is that it could be used to higher temperatures than water without being pressurised, which would save the cost of pressure vessels. On the other hand thermic oil is many times more expensive than water and does not have as high a thermal capacity, so more thermic oil would be needed, again increasing cost.

[00086] Thermic oil could be used as the high temperature fluid with water as the low temperature fluid. This would avoid the need for anti-freezing equipment which is necessary with molten salt. On the other hand, thermic oil is more expensive than molten salt and cannot be used above a temperature of 400^{o}C, so the cost of the system would be increased and the performance would be reduced.

CLAIMS

1. A system of compressed air energy storage and recovery in which
   - the compressed air is stored at pressures above 150 bar and at near ambient temperature in pressure vessels above ground or in underground cavities
   - the air is compressed in at least two separate stages of compression using compressors powered by an external supply of electrical power
   - heat is removed from the air after the multi-stage compression is completed and in at least one intermediate stage during the compression process
   - the heat of compression is removed from the air by a system of heat exchangers operating with two or more different liquid media and in each case the heat is stored in the same liquid medium as that used for heat transfer
   - the heat transfer and storage media include a first liquid which is capable of thermal storage at temperatures above 350 deg.C and a second liquid, which is capable of storing heat at temperatures below 250 deg.C
   - during energy recovery heat is restored to the air by the same liquid heat transfer media and the same heat exchangers as those used during storage
   - during energy recovery the reheated compressed air is expanded in at least two separate stages of expansion in which electrical power is generated.

2. A system of compressed air energy storage and recovery as in Claim 1, in which the stored air is maintained at approximately constant pressure during the storage and recovery cycle.

3. A system of compressed air energy storage and recovery as in Claim 1 in which condensed water is removed from the compressed air before storage and is re-injected into the compressed air during energy recovery.

4. A system of compressed air energy storage and recovery as in Claim 1 in which during energy recovery, thermal liquid which has already given up heat to compressed air in one heat exchanger operating at one air pressure flows to another heat exchanger operating with compressed air at a different air pressure, where it may give up some more heat.

5. A system of compressed air energy storage and recovery as in Claim 1 in which the compressed air is stored in a purpose-made underground cavity in a suitable rock formation.

6. A system of compressed air energy storage and recovery as in Claim 1 in which the purpose-made underground cavity is lined with a liner which provides gas tightness in situations where the cavity may not be gas tight.

7. A system of compressed air energy storage and recovery as in Claim 1 in which a gas tight pressure vessel is fitted inside the underground cavity and transfers some of the pressure load to the cavity around it, for the purpose of ensuring gas tightness or storing air at a higher pressure than the mechanical properties of the soil would allow, or for both purposes.

8. A system of compressed air energy storage and recovery as in Claim 1 in which the compressed air is stored above ground in pressure vessels.

9. A system of compressed air energy storage and recovery as in Claim 1 in which some or all of the compressors and expanders can be operated at variable speed by means of one or more electrical motor/generators with a variable frequency drive.

10. A system of compressed air energy storage and recovery as in Claim 1 in which some or all of the compressors and expanders consist of reciprocating machines.

11. A system of compressed air energy storage and recovery as in Claim 1 in which some or all of the compressors and expanders consist of turbo-machines.

12. A system of compressed air energy storage and recovery as in Claim 1 in which some or all of the compressors and expanders consist of screw or other rotary machines.

13. A system of compressed air energy storage and recovery as in Claim 1 in which at least some of the compressors are used as expanders during the energy recovery stage.

14. A system of compressed air energy storage and recovery as in Claim 1 in which the number of expansion stages is less than the number of compression stages.

15. A system of compressed air energy storage and recovery as in Claim 1 in which heat is transferred and stored by means of a molten salt.

16. A system of compressed air energy storage and recovery as in Claim 1 in which heat is transferred and stored by means of a thermic oil.

17. A system of compressed air energy storage and recovery as in Claim 1 in which the liquid used for low temperature storage is water, which may be pressurised or unpressurised.

18. A system of compressed air energy storage and recovery as in Claim 1 in which there are two or more consecutive compression stages with no heat removal between them.

19. A system of compressed air energy storage and recovery as in Claim 1 in which the first stage of heat removal to a high temperature liquid is followed by one or more additional stages of compression and then by a second stage of heat removal to a high temperature liquid, such as molten salt or thermic oil.

20. A system of compressed air energy storage and recovery as in Claim 1 in which the first stage of heat removal to and storage in a high temperature liquid such as molten salt or thermic oil is immediately followed by a further stage of heat removal to and storage in a low temperature liquid such as water.

21. A system of compressed air energy storage and recovery as in Claim 1 in which the second stage of heat removal to and storage in a high temperature liquid is immediately followed a stage of heat removal to and storage in a low temperature liquid such as water.

22. A system of compressed air energy storage and recovery as in Claim 1 in which the final stage of heat removal from the compressed air is performed by an air or water cooling system without storage of heat.

23. A system of compressed air energy storage and recovery as in Claim 2 in which the stored compressed air is maintained at constant pressure by means of a hydraulic pump and turbine, which pumps water into the air storage vessel(s) during energy recovery and extracts water via the turbine during the energy storage phase.

24. A system of compressed air energy storage and recovery as in Claim 23 in which the hydraulic pump-turbine is used as a fast response system for stabilising an electrical supply grid.

25. A system of compressed air energy storage and recovery as in Claim 1 in which the liquid used for low temperature thermal storage is used during the energy recovery phase to pre-heat the cold compressed air which is taken out of storage.

26. A system of compressed air energy storage and recovery as in Claim 25 in which the pre-heated compressed air is then heated by a high temperature liquid, such as molten salt or thermic oil and then expanded in a first stage expansion.

27. A system of compressed air energy storage and recovery as in Claim 26 in which partially expanded air is preheated with the low temperature thermal storage liquid prior to heating with the low temperature thermal storage liquid.

28. A system of compressed air energy storage and recovery as in Claim 26 in which the expanded air from the first stage expansion, which may or may not have been pre-heated, is then reheated by a high temperature thermal storage liquid prior to a second stage expansion.

29. A system of compressed air energy storage and recovery as in Claim 26 in which the expanded air from the second stage expansion is exhausted directly to the atmosphere.

30. A system of compressed air energy storage and recovery as in Claim 28 in which the air from the second stage expansion undergoes a third stage expansion to the atmosphere without reheating.

31. A system of compressed air energy storage and recovery as in Claim 3 in which water is added to the stored condensate and is injected into compressed air during energy recovery for the purpose of using all available heat to maximise the power output.

32. A system of compressed air energy storage and recovery as in Claim 31 in which waste heat from some external source is provided to the energy storage system during energy recovery by means of a heat exchanger.

33. A system of compressed air energy storage and recovery as in Claim 32 in which the heat exchanger provides heat to the compressed air at a location between two high pressure heat exchangers supplied by two different thermal storage liquids.

34. A system of compressed air energy storage and recovery as in Claim 1 in which waste heat from an external source is used in a boiler to produce steam which is injected into the compressed air at a suitable point before at least one stage of expansion.

35. A system of compressed air energy storage and recovery as in Claims 31 or 34 in which the added water or steam is condensed at the end of the expansion and recycled through the system.

36. A system of compressed air energy storage and recovery as in Claim 10 in which the reciprocating machines can be configured to operate either as compressors or as expanders, by means of changes to the operation of the valves.

37. A system of compressed air energy storage and recovery as in Claim 10 in which the reciprocating machines have adjustable timing on the intake valves and/or the discharge valves.

38. A system of compressed air energy storage and recovery as in Claim 10 in which the air flow to and from individual cylinders of the reciprocating machines can be switched off or on.

39. A system of compressed air energy storage and recovery as in Claim 38 in which the inlet or discharge valves of cylinders having no air flow can be operated to remain fully open to allow air to pass freely in and out of the cylinder during each stroke.

40. A system of compressed air energy storage and recovery as in Claim 11 in which some or all of the turbo-machines have variable inlet guide vanes.

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Claims searched:	1-40	**Date of search:**	19 June 2015

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 2, 5, 10- 12, 15, 16, 19, 20, 25-30, 40	US 2011/094229 A1 (FREUND) See abstract, figure 3 and paragraphs [0029]-[0036].
X	1, 2, 5, 10- 12, 15, 16, 19, 20, 25-30, 40	US 2011/094231 A1 (GENERAL ELECTRIC) See abstract, figure 1 and paragraph [0024].
Y	1, 2, 5, 10- 12, 15, 16, 19, 20, 25-30, 40	EP 2581584 A1 (ALSTOM TECHNOLOGY) See abstract, figures 1 and 2 and discussion thereof.
Y	1, 2, 5, 10- 12, 15, 16, 19, 20, 25-30, 40	EP 2602443 A1 (ALSTOM TECHNOLOGY) See abstract, figures and paragraph [0049].
A	-	EP 2559881 A2 (ALSTOM TECHNOLOGY) see figure 3 and description thereof. Note single heat storage facility.
A	-	GB 2519626 A (ISENTROPIC) See abstract, figures and discussion thereof. In particular see page 13 line 22 to page 14 line 25.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

F01K; F02B; F02C

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, TXTE

International Classification:

Subclass	Subgroup	Valid From
F02C	0006/16	01/01/2006
F02B	0021/00	01/01/2006