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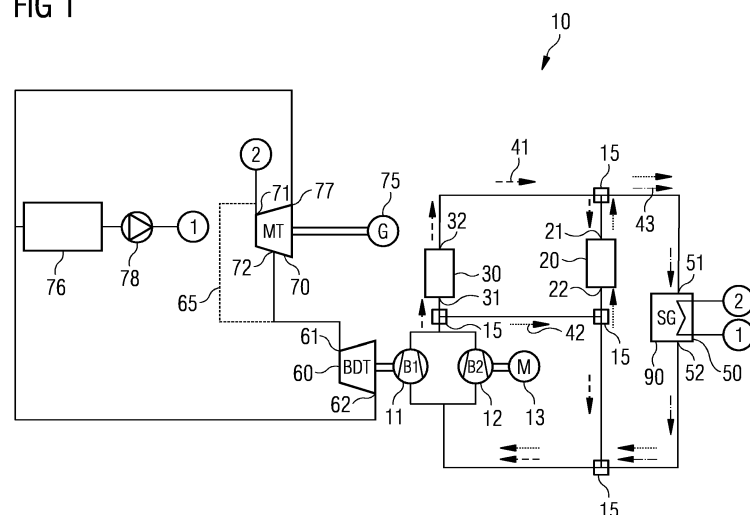
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(54) **THERMAL ENERGY STORAGE SYSTEM**

(57) A thermal energy storage system is provided. The system comprises an energy storage device (20) configured to store thermal energy, a charging flow path (41) configured to guide a heat transfer medium from a heat source (30) to the energy storage device (20) in order to transfer thermal energy from the heat source (30) to the energy storage device (20), and a discharging flow path (42) configured to guide the heat transfer medium from the energy storage device (20) to a heat consumer (50) in order to transfer thermal energy from the energy storage device (20) to the heat consumer (50). A blower (11) of the system (10) is configured to convey the heat transfer medium in the charging flow path (41) and/or the discharging flow path (42). The thermal energy storage system (10) further comprises a blower driving turbine (60) a rotational output of which is coupled to the blower (11) to provide rotational mechanical energy to the blower (11) so as to drive the blower (11).

sumer (50) in order to transfer thermal energy from the energy storage device (20) to the heat consumer (50). A blower (11) of the system (10) is configured to convey the heat transfer medium in the charging flow path (41) and/or the discharging flow path (42). The thermal energy storage system (10) further comprises a blower driving turbine (60) a rotational output of which is coupled to the blower (11) to provide rotational mechanical energy to the blower (11) so as to drive the blower (11).

FIG 1



Description

FIELD OF THE INVENTION

[0001] The present invention relates to a thermal energy storage system that includes an energy storage device storing thermal energy and to a method of operating such thermal energy storage system.

BACKGROUND

[0002] As the amount of energy that is produced from renewable sources is increasing, situations may occur in which the energy output from such energy sources is higher than the demand. Excess energy may be stored, for example in a storage device that is charged by thermal energy converted from electrical energy. Such thermal energy storage device may also store residual or waste heat from a conventional heat cycle, for example waste heat from an industrial process or the like. Thermal storage devices are known that employ a storage material in the form of sand, rocks or the like. At a desired point in time, the stored thermal energy is converted back into electrical energy, which can be fed into the utility grid during periods of high demand. An example of such thermal energy storage device is for example described in the document EP 3 102 796 A1.

[0003] A heat transfer medium, which may also be termed "working medium" and which is a fluid, in particular a gas, is passed through the storage material of the storage device to deposit heat in the storage device (i.e. to charge the storage device) or to extract heat from a storage device (i.e. to discharge the storage device). In particular for storing and withdrawing larger amounts of thermal energy, significant amounts of heat transfer medium need to be transported through the storage device and through the remaining components of the system. The medium can be conveyed through the system by means of a blower that is driven by an electric motor. The motor can be powered with electricity from a power grid or it may be powered by electricity obtained by converting thermal energy of the storage device into electrical energy. During the discharging of the storage device, the power required to drive the blower is thus part of a parasitic load, which reduces the net electric power output of the respective storage system.

[0004] It is desirable to operate such thermal energy storage system more efficiently. In particular, it is desirable to increase the net electrical power output of such thermal storage system.

SUMMARY

[0005] Accordingly, there is a need to mitigate at least some of the drawbacks mentioned above and in particular to provide a more efficient thermal energy storage system.

[0006] This need is met by the features of the inde-

pendent claims. The dependent claims describe embodiments of the invention.

[0007] According to an embodiment of the invention, a thermal energy storage system comprising an energy storage device configured to store thermal energy is provided. The system includes a charging flow path configured to guide a heat transfer medium from a heat source to the energy storage device in order to transfer thermal energy from the heat source to the energy storage device and a discharging flow path configured to guide the heat transfer medium from the energy storage device to the heat consumer in order to transfer thermal energy from the energy storage device to the heat consumer. The system further comprises a blower configured to convey the heat transfer medium in the charging flow path and/or the discharging flow path. The system further comprises a blower driving turbine (BDT) having a rotational output that is coupled to the blower to provide rotational mechanical energy to the blower so as to drive the blower.

[0008] During the operation of such system, no additional electrical energy may be required for driving the blower as the blower is driven by the blower driving turbine (BDT). Thus, no electrical energy needs to be drawn from a power grid, and electrical energy that is generated during the discharging of the energy storage device does not need to be employed for powering the blower.

[0009] In particular, the thermal energy storage system may be configured to operate the blower driving turbine by a working fluid that is energized using thermal energy from the heat source and/or from the energy storage device (for example, steam may be generated or supercritical CO₂ may be heated). Although the BDT may constitute an additional component that requires a supply with energized working fluid, e.g. steam, operation may be more energy-efficient since the energy comprised in the working fluid does not first need to be converted to electrical energy and then converted back to rotational energy by an electrical motor. In particular, by operating the components of the thermal energy storage system at ideal operating points, the use of the energized working fluid to power the blower is more efficient than the use of electric power. The net power output of the thermal energy storage system may thus be increased. The energy storage system may for example comprise a respective heat exchanger, e.g. a steam generator, that energizes the working fluid using the thermal energy, and may further comprise a respective flow line that provides the energized working fluid (directly or indirectly) to the BDT. As explained in more detail below, such heat exchanger may be a dedicated steam generator or other heat exchanger for the BDT or may be a main heat exchanger (e.g. steam generator) providing energized working fluid for driving a main turbine that generates electricity via a generator, such as a steam turbine or a turbine expanding a gas or supercritical fluid, such as supercritical CO₂ (sCO₂).

[0010] In an embodiment, the heat consumer is or comprises a heat exchanger (e.g. a main steam generator) that is configured to energize the working fluid by means

of thermal energy received from the energy storage device or from the heat source. The main heat exchanger is further configured to provide the energized working fluid (e.g. steam or heated sCO₂) to a main turbine (e.g. a main steam turbine). Main turbine means that the turbine is a major consumer of the thermal energy provided by the storage system, it may for example consume more thermal energy than the BDT (if the BDT and the main turbine are provided as separate turbines). As a non-limiting example, the main turbine may consume more than 30% or 50% of the thermal energy provided during discharging from the storage device, it may for example have a rated output power of at least 1 MW. The main turbine may generate electrical power from the received energized working fluid, e.g. steam, for example by means of a generator coupled to the rotational output of the main turbine. The thermal energy storage system may comprise the heat consumer, i.e. the main heat exchanger; it may further comprise the main turbine and the generator.

[0011] The BDT may be a blower driving steam turbine and the main turbine may be a main steam turbine. The BDT may be configured to receive steam from an intermediate stage of the main steam turbine. The BDT may accordingly receive the steam from the main steam generator (SG) via the main steam turbine. The system may for example include a flow line for steam from the intermediate stage of the main steam turbine (MT) to a steam inlet of the blower driving steam turbine. A control valve may be provided in the flow line upstream of such steam inlet in order to control the flow of steam and thus the operating power of the blower. Withdrawing steam from such intermediate stage of the MT may only insignificantly reduce the power output of the MT, thus having only little effect on the generated net electrical power.

[0012] In an example, the thermal energy storage system may comprise at least a first flow line from a first steam extraction point of the main steam turbine to a steam inlet of the BDT and a second flow line from a second steam extraction point of the main steam turbine to the steam inlet. The first and second flow lines may each comprise a control valve to control the flow of steam from the respective extraction point to the steam inlet. The extraction points may be provided at an intermediate stage of the steam turbine and may provide steam at different pressures and/or temperatures. Such arrangement allows the control of the output power of the blower over a wide operating range by controlling the parameters of the steam provided to the BDT. The valves can for example be controlled to provide higher pressure steam or a larger amount of steam to the BDT to increase the output power of the blower and thus the mass flow of the heat transfer medium in the thermal energy storage system.

[0013] The charging flow path may provide a fraction of the heat transfer medium exiting the heat source to the main steam generator to generate steam when operating in a charging mode. The generated steam may

then be provided directly to the BDT, e.g. by a flow connection for the steam from the main steam generator to the BDT which bypasses the main steam turbine. Such bypass may be opened/closed via a respective valve; it may be closed when operating the system in a discharging mode in which the main steam turbine is powered by steam from the main steam generator.

[0014] Likewise, the main turbine can be implemented as a turbine that expands a gas or supercritical fluid, such as sCO₂, and such turbine may also have multiple stages (high pressure stage and low pressure stage). The BDT may then receive energized working fluid from an intermediate stage, i.e. from a position between such stages. The above explanations apply correspondingly.

[0015] The system may comprise a gearbox between the BDT and the blower. The gearbox may be configured to provide a desired rotational speed of the blower at a nominal rotational speed of the BDT. The rotational speed of the blower may thus be set to a desired value.

[0016] In a further embodiment, the blower driving turbine serves as a main turbine configured to generate electrical energy from the thermal energy supplied from the energy storage device, the main turbine may in particular from part of the heat consumer. In such configuration in which the blower is directly driven by the main turbine, a clutch may be provided between the main turbine and the blower in order to control the operation of the blower and to be able to disconnect the blower from the main turbine.

[0017] In such configuration, a gearbox may be provided between the main turbine and the blower to adjust the rotational speed of the blower to the desired value.

[0018] In an embodiment, the thermal energy storage system further comprises an auxiliary heat exchanger, e.g. an auxiliary steam generator, arranged in the charging and/or discharging flow path so as to receive thermal energy via the heat transfer medium. The thermal energy storage system comprises a flow connection from the auxiliary heat exchanger to an inlet, such as a steam inlet, of the BDT to provide the working fluid energized by the auxiliary heat exchanger to the BDT (e.g. generated steam).

[0019] In some implementations, the auxiliary heat exchanger is provided as an auxiliary steam generator that may be the only steam generator in the storage system, for example if the heat consumer directly uses the thermal energy without steam generation, such as an industrial process that is directly supplied with the heat transfer medium. In other implementations, the auxiliary steam generator is provided in addition to a main steam generator constituting the heat consumer.

[0020] The auxiliary heat exchanger (e.g. the auxiliary steam generator) is in particular not the main heat consumer, i.e. it consumes (significantly) less than 50%, e.g. less than 10% of the thermal energy extracted from the storage device during normal operation. By means of such auxiliary heat exchanger, an independent supply of energized working medium, such as steam, for the BDT

can be ensured, so that operation thereof can be decoupled from an operation of a main turbine and associated main heat exchanger.

[0021] The auxiliary heat exchanger is preferably arranged in the charging flow path downstream of the energy storage device, so that it receives heat transfer medium that leaves the energy storage device, and is arranged in the discharging flow path downstream of the heat consumer so that it receives heat transfer medium that leaves the heat consumer (i.e. that is exhausted or given out by the heat consumer). Such arrangement of the auxiliary heat exchanger has the advantage that both during charging and discharging modes of the storage system, heat transfer medium passes through the auxiliary heat exchanger so that a continuous energization of working fluid (e.g. steam generation or heating of sCO_2) may be achieved. It is in particular not necessary to divert any heat transfer medium towards a main heat exchanger during the charging cycle to provide continuous energization of working fluid.

[0022] For example, the auxiliary heat exchanger may be arranged upstream of the blower both in the charging flow path and the discharging flow path. Alternatively, it may be arranged downstream of the blower in the discharging flow path (i.e. between the blower and the energy storage device), and upstream of the blower in the charging flow path (i.e. between the energy storage device and the blower). In the former case, the heat transfer medium passes in the same direction through the auxiliary heat exchanger both during charging and discharging, whereas the latter case, the heat transfer medium passes in opposite directions through the auxiliary heat exchanger during charging and discharging.

[0023] 'Downstream' means 'in flow direction behind' with respect to the flow direction of the heat transfer medium in the respective flow path. 'Upstream' means 'in flow direction before' with respect to the flow direction of the heat transfer medium in the respective flow path.

[0024] When implemented as a steam cycle, the thermal energy storage system may further comprise a feedwater pump arranged in the steam cycle upstream of the auxiliary steam generator, i.e. the feedwater pump may pump feedwater into the auxiliary steam generator. The feedwater pump may be controllable to control the amount of feedwater provided to the auxiliary steam generator. This way, the amount of steam supplied to the BDT may be controlled efficiently, thus providing a simple and effective means for adjusting the mass flow of the heat transfer medium provided by the blower.

[0025] In an embodiment in which the BDT is a blower driving steam turbine and the main turbine is a main steam turbine, the system may comprise a flow connection from a steam outlet of the BDT to a condenser of a main steam turbine. Such common condenser may comprise a first outlet for working medium of the steam cycle (in particular condensed steam) that is connected to an inlet of a main steam generator constituting the heat consumer, and further comprises a second outlet for the

working medium of the steam cycle connected to an inlet of the auxiliary steam generator. The MT and the BDT may accordingly use a common condenser that provides a return path for the working medium to the respective steam generators. Alternatively, a dedicated condenser may be provided for the BDT, which may accordingly comprise a flow connection to the steam outlet of the BDT and may furthermore provide the condensed working medium (water) to the inlet of the auxiliary steam generator using a respective flow connection (in which the above-mentioned feedwater pump may be provided). An efficient and independent operation of the BDT may thus be achieved.

[0026] In an embodiment, the thermal energy storage system further comprises an electric motor, which is coupled to the blower to drive the blower, or the thermal energy storage system may further comprise a second blower that is driven by the electric motor. The formerly mentioned blower may then be designated as first blower. Such electric motor is in particular beneficial for start-up operations during which the heat transfer medium has to be conveyed through the thermal energy storage system while steam for driving the BDT is not yet available. It may also be employed during the charging mode if no steam is available for the BDT. By coupling the electric motor to rotate the first blower, a simple configuration with only a single blower can be achieved. On the other hand, providing a second blower that is rotated by the electric motor has the advantage that redundancy is achieved. When the thermal energy storage system is operating, two independent blowers are available and may be used for conveying the heat transfer medium. Each of the blowers may accordingly be rated for the power required to convey the heat transfer medium during normal operation. When maintenance has to be carried on one of the blowers, the system can thus remain fully operable. Two blowers may also be used to boost the pressure/flow rate of the medium.

[0027] In particular by providing such electric motor and the BDT driven blower, the thermal energy storage system is capable of a black start, meaning that operation can be resumed without relying on power from an external electric power network, for example after a blackout. A backup electric power source that is independent of such power grid can be provided, such as a Diesel generator or a battery. As such backup power source only needs to operate the electric motor during a start-up period of the storage system, until sufficient energized working medium is available for driving the BDT, the size, rating and capacity of such backup electric power source can be kept small. This is a significant advantage over conventional systems in which the blower is electrically driven, since such system requires for a black start full operation of the main turbine so that the main turbine generates electricity by which the blower can be powered. Conventional black start equipment thus requires a significantly larger power rating and capacity.

[0028] Preferably, the system comprises a second

blower coupled to the electric motor. The second blower may be connected in parallel to the first blower or may be connected in series with the first blower to convey the heat transfer medium in the respective flow path. When the first and second blowers are connected in series, they preferably comprise a fluid bypass around each blower so that only one blower can be operated while the other blower is bypassed by the heat transfer medium. Respective bypass flow lines may be provided with a valve to open and close the bypass. As outlined above, a redundant operation of the blowers may thus be achieved, wherein if the BDT driven blower fails or requires maintenance, operation can continue with the second electrically driven blower. Furthermore, both blowers may be operated simultaneously, thus increasing the flow rate of the heat transfer medium. Such operation may be termed "boost mode". Such boost mode may allow a steady charging/discharging rate with thermal energy towards the end of a full charging/discharging cycle. In particular, a pressure increase may be achieved by connecting the first and second blowers in series and operating both blowers in such boost mode.

[0029] It should be clear that the thermal energy storage system may comprise further blowers, which can be driven by respective BDTs. The reference to 'a blower' or 'the blower' encompasses configurations having multiple respective blowers. For example, the system may comprise one or more additional blowers, each driven by a respective BDT, that may be connected in parallel and/or in series with the above mentioned blower. By such parallel connection, an increased mass flow rate of the heat transfer medium may be achieved. By such series connection, the pressure of the heat transfer medium may be increased. Such additional blower(s) can be connected directly in series or parallel with the above-mentioned blower, or they may be connected at a different position in the charging and/or discharging flow path.

[0030] In an embodiment, the thermal energy transfer system further comprises a control unit configured to control the electric motor. Upon start-up of the thermal energy storage system, the control unit operates the electric motor to convey the heat transfer medium such that at least part of the conveyed heat transfer medium passes through the heat source and transports thermal energy (directly or indirectly via the storage device) to a heat exchanger (main or auxiliary) of the thermal energy storage system to energize working fluid. The energized working fluid (e.g. generated steam or heated sCO₂) is then provided to the BDT so that the BDT is operated by the energized working fluid. For example, at start-up, the control unit may operate the thermal energy storage system such that heat transfer medium is conveyed along a start-up flow path that passes through the heat source and through the storage device, wherein a fraction of the heat transfer medium is diverted to pass through a main heat exchanger, e.g. a main steam generator. Alternatively, all of the heat transfer medium, after passing through the heat source, may be provided to the main

heat exchanger. Thereby, energization of the working fluid and thus start-up of the BDT may be accelerated. In configurations comprising an auxiliary heat exchanger, heat transfer medium discharged from the energy storage device during startup is led through the auxiliary heat exchanger to energize working fluid (e.g. generate steam) for the BDT.

[0031] When implemented as a steam cycle, the thermal energy storage system may in particular be configured to provide the steam generated during start-up to the BDT, either directly via a respective flow line from the respective steam generator, or for example via a bypass flow line that bypasses the main steam turbine (e.g. if the steam is generated by a main steam generator of the main steam turbine). The control unit may be configured to control the flow through the respective flow lines, for example by respective control valves. It may for example open the bypass around the main steam turbine during start-up and may close such bypass line after sufficient steam is available for operating the main steam turbine. Also, in a series connection of the first and second blowers, the control unit may open the bypass line around the first blower during start-up when operating the motor, and may thereafter close this bypass and open the bypass line around the second blower when the BDT receives a sufficient amount of steam for driving the first blower. In any case, after operation of the BDT and thus of the first blower has started, the operation of the electric motor may be stopped by the control unit.

[0032] The heat transfer medium is preferably a gaseous medium, in particular air or nitrogen.

[0033] Preferably, the charging flow path is configured to guide the heat transfer medium through the energy storage in a first flow direction, and the discharging flow path is configured to guide the heat transfer medium through the energy storage device in a second flow direction that is opposite to the first flow direction. The charging and discharging flow paths are configured such that the heat transfer medium at least partially flows through the same passage in the energy storage device. A simple configuration of the energy storage device and thus of the thermal energy storage system may thereby be achieved, in particular as no separation between the charging and discharging flow paths is necessary.

[0034] It is further preferred that the blower is configured to convey the heat transfer medium both in the charging flow path and the discharging flow path, wherein the flow direction of the heat transfer medium through the blower is the same for the charging flow path and for the discharging flow path. It is thus not necessary to reverse the operation of the blower when changing from charging to discharging. An efficient blower operation thus becomes possible, and the blower can be optimized for conveying the medium in one flow direction. If a second blower is provided, it preferably conveys the medium in the same flow direction as the first blower.

[0035] The thermal energy storage system may be configured to store thermal energy in the energy storage

device at a temperature between 300 °C and 1000 °C, preferably between 500 °C and 1000 °C, more preferably between 600°C and 900°C. For example, the temperature in the energy storage device may be kept between 650 and 800°C. In the discharging flow path, the temperature of the heat transfer medium leaving the energy storage device may lie within the range of about 600°C to 800°C. The pressure of the heat transfer medium in the charging flow path and in the discharging flow path may be lower than 2 bar, it may be close to atmospheric pressure, e.g. between 0.8 bar and 1.2 bar.

[0036] In an embodiment, the energy storage device comprises an insulated storage chamber and a heat storage material disposed in the insulated storage chamber, wherein flow channels are provided in the heat storage material and/or the heat storage material has open pores through which the heat transfer medium can flow. Flow channels (or heat exchange channels) can be built into the heat storage material, or such channels may form due to the structure of the material, e.g. by interspaces or gaps in the heat storage material, e.g. between rocks/stones. Preferably, the heat storage material comprises a mesh of heat exchange channels through which the heat transfer medium passes, both along the charging and the discharging flow paths.

[0037] The heat storage material may comprise or consist of rocks, bricks, stone, lava stone, granite, basalt and/or ceramics provided as bulk material (which may be configured as pebble bed). Preferably, the heat storage material comprises or consists of sand and/or stones, in particular gravel, rubble and/or grit. The stones can be natural stones or artificial stones (e.g. containers filled with material, such as clinkers or ceramics). The heat storage device can thus be provided cost efficiently while being capable of storing large amounts of thermal energy.

[0038] The energy storage device may be a horizontal storage device wherein a main flow direction of the heat transfer medium through the storage device is in horizontal direction (i.e. substantially parallel to the earth's surface). A horizontally oriented direction of the heat exchange flow may be achieved by providing inlet/outlet ports laterally, e.g. in side walls/boundaries of the storage chamber. In other embodiments, the energy storage device may be a vertical storage device wherein a main flow direction of the heat transfer medium through the storage device is in vertical direction (i.e. substantially perpendicular to the earth's surface). The inlet/outlet ports may then be provided in upper/lower walls/boundaries of the storage chamber, or one port may be provided in an upper part and the other in a lower part of side walls/boundaries of the storage chamber.

[0039] In some implementations, the energy storage device may comprise a diffuser section for evenly distributing the heat transfer medium into the storage and for reducing the flow speed of the medium. The diffuser may be provided at either port of the storage device. The diffuser may comprise a convection reducing structure, for

example by providing a vertical layer of convection reducing elements within the diffuser of the respective port.

[0040] The storage chamber may be a space, a cavity, an excavation or a housing in which the heat storage material is located. The energy storage device may further comprise a nozzle section provided between the storage chamber and the respective port. The nozzle section may for example include a tapered portion leading from the storage chamber to the respective port. Flow speed and pressure of the heat transfer medium entering/leaving the energy storage device through the respective port may be adjusted by providing such nozzle section.

[0041] In an embodiment, the energy distribution system is configured to alternately operate in a charging mode in which the heat transfer medium is transported/conveyed along the charging flow path (e.g. by the above mentioned blower) and a discharging mode in which the heat transfer medium is transported/conveyed along the discharging flow path (by this blower). Accordingly, the system may cause alternating flows in opposite directions or in the same direction through the energy storage device to charge/discharge the energy storage device.

[0042] In the charging mode, heat transfer medium that has been heated by the heat source passes through the energy storage device and thereby heats the heat storage material, a cooler medium being exhausted from the energy storage device. After the charging is completed, the storage device may be left in a standstill period of hours or even days until the stored thermal energy is needed. In the discharging mode, the flow direction is reversed, so that colder heat transfer medium (e.g. air) is introduced into the port that acted as outlet in the charging mode. The heat storage material transfers heat to the heat transfer medium, which leaves the energy storage device at the other (hot) end through the port that acted as inlet in the previous charging mode. The storage device may thus have a hot port (inlet for charging and outlet for discharging) and a cold port (inlet for discharging and outlet for charging). For a modified distribution of the medium within the storage, the energy storage device may include a plurality of hot ports and/or a plurality of cold ports.

[0043] The heat storage material may be separated into a layered thermal energy storage structure by dividing elements, such as steel plates or metal sheets. The sheets or plates may comprise any suitable heat resistant material, such as metal, synthetic fabric or the like, that are substantially impermeable for the working fluid. The dividing elements may prevent a change in the temperature distribution within the thermal energy storage structure due to natural convection during the standstill period, i.e. prevent that hot fluid surrounding heat storage material in the lower part of the chamber flows to the upper part of the chamber.

[0044] In some configurations, the energy storage device may include several storage chambers placed in se-

ries and/or parallel with valves and piping in between, including bypass-lines. This may allow an adaptation of the size of the active storage chamber to the present needs. For example, during charging, the flow of the heat transfer medium and thus the heating may be stopped for one chamber if the specific chamber has been fully charged. This allows the maintaining of a desired temperature gradient within each of the storage chambers.

[0045] In particular, the system may be configured such that during the charging cycle of a storage chamber, a temperature front travels through the heat storage material from the hot end to the cold end of the chamber. The temperature front is a zone of strong temperature gradient in the heat storage material, which separates the hot and the cold zones in the chamber. The charging of the respective storage chamber will preferably be stopped when the temperature at the cold end begins to rise above a predetermined temperature threshold. By using a plurality of chambers interconnected in series via valves and bypass-lines, during idling operations, i.e. between charging and discharging phases, the chambers can be disconnected from each other to prevent a mass flow between them initiated by natural convection. A valve may thus be provided for isolating a charged storage chamber from its neighboring storage chamber(s). Thus, mass flow caused by convection inside a heat storage chamber, which contains the temperature gradient, is limited to this single storage chamber.

[0046] The thermal energy storage system may comprise a control unit configured to operate the thermal energy storage system alternately in the charging mode and the discharging mode. The control unit may in particular control respective control valves that are opened and closed so that the heat transfer medium is conveyed along the respective flow path and in the respective flow direction. The control unit may be the same as the control unit that controls the above-mentioned electric motor, or separate control units may be provided.

[0047] In an embodiment, when implemented as a steam cycle, the thermal energy storage system further comprises a steam conditioning station arranged upstream of the BDT, said station being configured to control one or more parameters of steam provided to the BDT. For example, the pressure, flow rate and/or temperature of the steam provided to the BDT may be controlled. The power output of the blower and thus the mass flow of the heat transfer medium through the storage system may thereby be controlled efficiently.

[0048] The thermal energy storage system may comprise flow connections, in particular conduits, pipes and the like that provide the respective flow paths. It may further include the respective control valves for controlling the flow through these flow connections.

[0049] The system may implement a steam cycle, which means that the BDT is a blower driving steam turbine and the working fluid is steam. The main and auxiliary heat exchangers may be main and auxiliary steam generators, respectively. The main turbine may be a main

steam turbine. The cycle may in particular be a Rankine cycle.

[0050] In other implementations, the working fluid may be a supercritical fluid or a gas, preferably supercritical carbon dioxide (sCO_2). The system is then configured to expand the supercritical fluid or gas in the blower driving turbine in order to drive the blower. The cycle may for example correspond a Brayton cycle. Likewise the cycle of the main turbine may employ a supercritical fluid or a gas, preferably supercritical carbon dioxide (sCO_2) as a working fluid, and the main turbine may be configured to expand such working fluid.

[0051] It should be clear that the cycle of the BDT and of the main turbine may be separate, and may accordingly employ different working fluids (e.g. one may employ steam and the other sCO_2). If the cycles are combined (e.g. when feeding the BDT from an intermediate stage of the main turbine), the cycles employ the same working fluid.

[0052] According to a further embodiment of the invention, a method of operating a thermal energy storage system is provided. The method comprises guiding a heat transfer medium from a heat source to an energy storage device along a charging flow path in order to transfer thermal energy from the heat source to the energy storage device, guiding the heat transfer medium from the energy storage device to a heat consumer along a discharging flow path in order to transfer thermal energy from the energy storage device to the heat consumer, and conveying the heat transfer medium in the charging flow path and/or the discharging flow path by means of a blower. The thermal energy storage system comprises a blower driving turbine (BDT) the rotational output of which is mechanically coupled to the blower, e.g. via a respective shaft.

[0053] Rotational mechanical energy is provided from the blower driving turbine to the blower so as to drive the blower. By such method, advantages similar to the ones outlined further above may be achieved.

[0054] In an embodiment, the method further comprises receiving energized working fluid from a heat exchanger (e.g. steam generator) of the thermal energy storage system at the blower driving turbine, e.g. at a respective inlet, and operating the blower driving turbine with the received energized working fluid. The heat exchanger may be a main heat exchanger providing energized working fluid for a main turbine, or may be an auxiliary heat exchanger, as outlined above. As indicated above, the BDT may operate with steam as a working fluid or may likewise operate with a different working fluid, such as sCO_2 .

[0055] The method may further comprise, upon start-up of the thermal energy storage system, operating an electric motor to drive the blower or to drive a second blower to convey the heat transfer medium along a start-up flow path, wherein the start-up flow path provides heat transfer medium from the heat source to a heat exchanger of the thermal energy storage system; providing work-

ing fluid energized by the heat exchanger to the blower driving turbine to operate the blower driving turbine using the received working fluid; and, after the operation of the blower driving turbine has started, stopping or reducing the operation of the electric motor. An efficient start-up of the thermal energy storage system can thus be achieved. Part of the medium heated by the heat source or the entire heated medium may be provided to the heat exchanger. The medium may be provided directly or indirectly to the heat exchanger, e.g. via the energy storage device.

[0056] It should be clear that the method may be performed by the thermal energy storage system in any of the configurations described herein. Furthermore, any of the methods steps described herein with respect to the thermal energy storage system may form part of embodiments of the method.

[0057] It is to be understood that the features mentioned above and those yet to be explained below can be used not only in the respective combinations indicated, but also in other combinations or in isolation, without leaving the scope of the present invention. In particular, the features of the different aspects and embodiments of the invention can be combined with each other unless noted to the contrary.

BRIEF DESCRIPTION OF THE DRAWINGS

[0058] The forgoing and other features and advantages of the invention will become further apparent from the following detailed description read in conjunction with the accompanying drawings. In the drawings, like reference numerals refer to like elements.

Fig. 1 is a schematic drawing showing a thermal energy storage system according to an embodiment of the invention.

Fig. 2 is a schematic drawing showing the providing of steam from a main steam turbine to a blower driving steam turbine according to an embodiment of the invention.

Fig. 3 is a schematic drawing showing a thermal energy storage system with two series connected blowers according to an embodiment of the invention.

Fig. 4 is a schematic drawing showing a thermal energy storage system with an auxiliary steam generator according to an embodiment of the invention.

Fig. 5 is a schematic drawing showing a thermal energy storage system with an auxiliary steam generator according to an embodiment of the invention.

Fig. 6 is a schematic drawing showing a thermal energy storage system with an auxiliary steam generator and an independent steam cycle according to

an embodiment of the invention.

Fig. 7 is a schematic drawing showing a thermal energy storage system with a single blower according to an embodiment of the invention.

Fig. 8 is a schematic drawing showing a thermal energy storage system with a single blower driven by a main steam turbine according to an embodiment of the invention.

Fig. 9 is a schematic drawing showing a energy storage device according to an embodiment of the invention.

Fig. 10 is a schematic flow diagram illustrating a method according to an embodiment of the invention.

DETAILED DESCRIPTION

[0059] In the following, embodiments of the invention will be described in detail with reference to the accompanying drawings. It is to be understood that the following description of the embodiments is given only for the purpose of illustration and is not to be taken in a limiting sense. It should be noted that the drawings are to be regarded as being schematic representations only, and elements in the drawings are not necessarily to scale with each other. Rather, the representation of the various elements is chosen such that their function and general purpose become apparent to a person skilled in the art. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted.

[0060] For the sake of a concise presentation, the detailed description provided below is given with respect to a steam cycle, wherein the BDT is implemented as a steam turbine and the working fluid is steam. The main heat exchanger and the auxiliary heat exchanger are implemented as a main steam generator and an auxiliary steam generator, and the main turbine is implemented as a main steam turbine. It should be clear that the description and explanations are likewise applicable to embodiments that do not implement a steam cycle, but that use a different working fluid, such as a gas or a supercritical fluid, such as sCO₂. The BDT may then be configured to expand the respective working fluid. The main turbine may work with the same working fluid, e.g. sCO₂, or may employ a different working fluid, if the cycle of the BDT and the main turbine are separate. The embodiments described below may accordingly be varied to implement such cycle(s), and may in particular implement a sCO₂ cycle, for the BDT, for the main turbine or for both.

[0061] Fig. 1 schematically shows a thermal energy

storage system 10 that includes an energy storage device 20 which stores thermal energy, i.e. energy in the form of heat (which may thus also be termed "thermal energy storage device" or short "storage device"). The thermal energy storage system 10 includes a charging flow path 41 indicated by dashed arrows in Fig. 1. It further includes a discharging flow path 42 indicated by dotted arrows in Fig. 1. A heat transfer medium, which is preferably a gaseous medium, such as air, flows along the respective flow path to transport thermal energy. The flow paths are thus provided by respective conduits or piping, for example by thermally insulated pipes.

[0062] The system 10 includes a heat source 30 arranged in the charging flow path 41, which transfers thermal energy to the heat transfer medium. Heat source 30 includes an electrical heater that receives electrical energy, for example from a renewable source, from an electrical power grid, or from another source of electric energy, and that converts the received electrical energy into thermal energy, i.e. heat. As another example, it may include a heat exchanger that receives heat from a power plant, industrial plant or the like, for example waste heat, heat from exhaust gases, or from other sources. Another possible implementation of the heat source 30 is a heat pump. Preferably, the heat source 30 receives energy from a renewable power source, such as electrical energy from a wind power plant, or thermal or electrical energy from a solar power plant, or electrical energy from a hydro power plant. The heat transfer medium flows through the heat source 30, whereby thermal energy is transferred from the heat source 30 to the heat transfer medium. The temperature of the heat transfer medium is thus increased. Heat source 30 includes an inlet port 31 where the heat transfer medium is received and an outlet port 32 through which the heated/energized heat transfer medium is discharged.

[0063] Along the charging flow path, the outlet 32 of heat source 30 is in flow connection with a first port 21 of the energy storage device 20, the first port 21 acting as an inlet. The energized heat transfer medium flows through the energy storage device 20 and deposits thermal energy in the energy storage device 20. The heat transfer medium is thereby cooled down and leaves the energy storage device 20 through a second port 22, thus acting as an outlet port along the charging flow path. The heat transfer medium is then returned via a blower 11 arranged downstream of the energy storage device 20 to the heat source 30, as indicated by the dashed arrows in Fig. 1. The charging flow path is thus completed. As can be seen, the charging flow path implements a closed cycle in which thermal energy is transported from the heat source 30 to the energy storage device 20 where it is deposited, the blower 11 conveying the heat transfer medium in the charging flow path 41.

[0064] Blower 11 likewise conveys the heat transfer medium in the discharging flow path 42. An outlet of blower 11 can thus be brought into flow communication both with the inlet 31 of the heat source 30 and the second

port 22 of the energy storage device 20. In the discharging flow path, the heat transfer medium is conveyed by blower 11 through port 22 into the energy storage device 20, where it takes up thermal energy, i.e. increases its temperature. The heated/energized heat transfer medium is discharged from the energy storage device 20 through the first port 21 (thus acting as an outlet). A flow connection is provided from the first port 21 to an inlet 51 of a heat consumer 50, which is preferably a steam generator, in particular a main steam generator 90. The energized heat transfer medium is thus conveyed from the storage device 20 to the heat consumer 50 and thus transfers thermal energy to the heat consumer 50. In the heat consumer 50, the thermal energy may be used to heat a working fluid of a steam cycle, such as water. The heat transfer medium thus passes on the thermal energy and is thereby cooled down, and the cooled heat transfer medium leaves the heat consumer 50 through an outlet 52, which is in flow communication with an inlet of the blower 11, thus completing the discharging flow path. In the example of Fig. 1, the discharging flow path is a closed cycle in which the heat transfer medium is returned to the blower 11.

[0065] The thermal energy storage system 10 is configured to operate alternately in a charging mode in which the blower 11 conveys the heat transfer medium along the charging flow path 41 and a discharging mode in which blower 11 conveys the heat transfer medium along the discharging flow path 42. A respective control unit may be provided that controls the operation of a system 10, for example in dependence on a charging state of the thermal energy storage device 20 and a heat demand of the heat consumer 50. For example, when no heat demand exists, the storage device 20 may be charged until it reaches a full state, upon which system 10 may enter an idle mode. Upon receiving a demand for thermal energy, system 10 may be operated in the discharge mode until no further heat demand is present, or until storage device 20 is depleted to such extent that recharging becomes necessary.

[0066] As can be seen, the heat transfer medium flows through the storage device 20 along the charging flow path in a first direction from port 21 to port 22, and along the discharging flow path in a second direction from port 22 to port 21 that is opposite to the first direction. The heat transfer medium thereby preferably flows along the same flow passages through the device 20, i.e. through the same channels or pores of a heat storage material in the storage device 20. Details of the storage device 20 are provided further below with respect to Fig. 9.

[0067] System 10 furthermore comprises control valves 15, such as controllable three-way valves or on/off valves that are for example controlled by the control unit such that the heat transfer medium flows along the desired flow path. A valve 15 may for example be controlled to direct the flow out of blower 11 either into the heat source 30 (charging flow path) or into the storage device 20 (discharging flow path). At other positions, valves may

simply be implemented by directional flow valves (check valves), possibly in combination with on/off valves (for example when combining the flow from port 22 to the blower 11 in the charging flow path and the flow from port 52 to blower 11 in the discharging flow path).

[0068] A respective control unit configured to control such control valves 15 may include a microprocessor and memory, which stores control instructions which are executed by the processor and which alternately operate the system 10 in the charging mode and the discharging mode and possibly in an idle mode. Such processor may for example be a digital signal processor, an application specific integrated circuit (ASIC), a microprocessor or the like. The memory may include flash-memory, a hard disk drive, RAM, ROM, and other types of volatile and non-volatile memory. Such control unit may furthermore include input and output interfaces for controlling the control valves and for receiving sensor signals. As a non-limiting example, the temperature in the energy storage device 20 may be monitored to determine when operation in the charging mode is necessary or when the maximum amount of energy is stored. Likewise, it may determine the heat demand of heat consumer 50 and operate the system 10 accordingly in the discharging mode to supply the respective thermal energy.

[0069] In the example of Fig. 1, the heat consumer 50 is a steam generator of a main steam turbine 70. In other examples, the heat may directly be provided to a consumer, and the discharging flow path may implement an open cycle in which the heat transfer medium is not returned. Examples of such consumers are industrial processes that make use of the energized heat transfer medium. Heat transfer medium may then be replaced from the environmental air by means of a respective fresh air inlet (not shown).

[0070] In conventional systems, the blower 11 that conveys the heat transfer medium through the thermal energy storage system 10 is driven by an electric motor, for example with electric power received from a power grid. In contrast, in the embodiment of Fig. 1, blower 11 is driven by a blower driving steam turbine (BDT) 60. BDT 60 provides rotational mechanical energy via a rotational output shaft, which is coupled to the blower 11 and thereby rotates the blower, thus conveying the heat transfer medium along the charging/discharging flow paths (which pass in the same direction through blower 11). Accordingly, in such system, no additional electric power is required for driving the blower 11, so that a net electric power output of the storage system 10 can be increased.

[0071] The energy storage system 10 may for example include a main steam generator (SG) 90 that constitutes a main thermal consumer 50, i.e. that consumes the largest amount of thermal energy provided along the discharging flow path from storage device 20. The SG 90 produces steam, which constitutes a working fluid of the steam cycle and which is provided to a steam inlet 71 of the main steam turbine 70. The main steam turbine 70 can be any conventional steam turbine and is thus not

described in greater detail here. Expanded and cooled down steam is discharged through the outlet 77 and provided to a condenser 76 of the steam turbine, and the condensed working fluid is conveyed via a feedwater pump 78 back into the SG 90. It is noted that in Fig. 1, there is a flow connection between the circles designated with "1", and a flow connection between the circles designated with "2". The rotational output of the main steam turbine 70 is coupled to a generator 75 that generates electricity. Accordingly, system 10 provides a storage for energy that can be provided as electrical energy to the heat source 30, and that can at a later time be released as electrical energy from the generator 75. Thermal energy storage system 10 thus provides an efficient buffer for electrical and/or thermal energy and is thus particularly useful for renewable energy sources which may at times have a higher power output than a current power demand.

[0072] In the embodiment of Fig. 1, the BDT 60 is supplied with steam from an intermediate stage of the main steam turbine (MT) 70. An extraction point 72 of MT 70 is flow-connected to a steam inlet 61 of BDT 60. As the power required for driving blower 11 is only limited, it is sufficient if the BDT is powered by steam extracted from such intermediate stage of MT 70. The steam is then discharged through an outlet 62 of BDT 60 and is provided to condenser 76, where it is condensed and conveyed back to the SG 90 by means of the feedwater pump 78. BDT 60 is thus effectively driven by steam generated by means of the main steam generator 90, although it receives the steam indirectly via the MT 70.

[0073] At start-up of the system 10, no steam may yet be available from the SG. System 10 thus comprises a second blower 12 that is driven by an electric motor 13, and that can accordingly be operated irrespective of the availability of steam, for example by electricity from a power grid or from a backup electric power source, such as diesel generator or a battery. System 10 may be configured to operate in a start-up mode in which the heat transfer medium is conveyed along a start-up flow path 43. This flow path passes the heat transfer medium through the heat source 30 and then passes at least a fraction of the heated medium through the SG 90 (thin dot dashed arrows). Accordingly, the SG 90 starts to generate steam, which can be provided directly to BDT 60 via a bypass line 65 that bypasses the main steam turbine 70. BDT 60 thus becomes operational and starts to drive the first blower 11. Operation of the electric motor 13 and thus of blower 12 can be shut down thereafter. In some embodiments, only a small fraction of the energized heat transfer medium may be conveyed through the SG 90. In other embodiments, the majority or all of the energized heat transfer medium may be conveyed through the SG 90 in order to accelerate the steam generation and thus the operation of the first blower 11. Once the BDT 60 and the blower 11 are operating, the fraction of energized heat transfer medium directed through the SG 90 can be reduced and the majority of the heat transfer medium is

directed through the energy storage device 20, thereby transitioning operation from a startup mode to the charging mode.

[0074] Likewise, during normal operation in the charging mode, the heat transfer medium may be conveyed by blower 11 driven by BDT 60, and a fraction of the heat transfer medium heated up by heat source 30 may be passed through the SG 90 in order to provide steam (in particular via the bypass 65) to the BDT 60. In other embodiments, the charging flow path 41 may not include the passing of such fraction of the medium through the SG 90, but all of the medium may be passed through the storage device 20. In this case, the medium may be conveyed only by the second blower 12 by operation of the electric motor 13. In the discharging mode, all the energized medium passes through the SG, so that the BDT is operated by the steam received from the intermediate stage of the main turbine 70 and the bypass 65 is closed. It is also possible to keep the bypass 65 partially or fully open so that the BDT is fully operated with steam from the bypass 65, or is operated with a combination of steam received via bypass 65 and from the intermediate stage of main turbine 70.

[0075] The second blower 12 may only be provided for starting-up of the system 10. Blower 12 may then be configured to have a relatively small power or mass flow output compared to the first blower 11, since it only needs to provide the mass flow of heat transfer medium required to produce enough steam in the SG 90 for operating the BDT 60. The electric motor 13 may then have a simple design, e.g. be a fixed speed motor. A simple design may thus be achieved, while not requiring any electric power for conveying the medium during normal operation.

[0076] In other embodiments, both blowers 11, 12 may have the same or a similar power rating, blower 12 may for example have a power rating of 50% or more of blower 11. This may allow the operation of the thermal energy storage system 10 with the electrically driven blower 12 alone, which provides redundancy and thus protection against outages of blower 11, and furthermore allows continued operation of system 10 during maintenance of the first blower 11. A full redundancy is achieved if both blowers 11, 12 are configured to provide the full required mass flow of the heat transfer medium along the flow paths of system 10. An additional electric motor may be provided for the first blower 11 to drive blower 11 in case of failure of the BDT 60, thus further improving the redundancy and protection against outages of BDT 60.

[0077] Fig. 2 shows a possible implementation of how the steam may be provided from an intermediate stage of the main turbine 70 to the BDT 60 of Fig. 1. Two or more, for example three or four extraction points 72, 73, 74 may be provided at the main steam turbine 70 from which steam can be extracted at different temperature and/or pressure. Flow connections are provided from each extraction point 72, 73, 74 to the steam inlet 61 of the BDT 60. Upstream of the inlet 61, a control valve 63 is provided to control the flow of steam into the BDT 60,

for example the pressure and flow rate. Such valve 63 may also be provided if only a single extraction point is present. Furthermore, in each of the extraction pipes, a further control valve 64 is provided to control the flow of steam. Accordingly, by opening and closing valves 64, it can be selected from which extraction point steam is provided to the BDT 60, or steam from different extraction points may be mixed to achieve the desired pressure and/or temperature of the steam.

[0078] The mass flow of the working fluid through the storage system 10 is regulated by blower 11. The power setting of the blower 11 depends on the amount of steam entering the BDT 60. Accordingly, by regulating the amount of steam using the valve 63 and/or the valves 64, the output power of the BDT and thus the power of the blower 11 can be adjusted.

[0079] Additionally or alternatively, a steam conditioning station may be provided upstream of the BDT 60, i.e. in the flow path that leads the steam into the inlet 61. By means of such steam conditioning station, the pressure/amount of steam entering the BDT 60 may be adjusted to efficiently control the power setting of blower 11.

[0080] It should be clear that the different extraction points are optional, and the power output of the BDT 60 may likewise be controlled by passing the steam through the bypass 65 and through such steam conditioning station.

[0081] Fig. 3 illustrates an embodiment that is a modification of the embodiment of Fig. 1, so that the above explanations are equally applicable and only differences will be explained. In the embodiment of Fig. 1, the blowers 11 and 12 are connected in parallel, so that either blower may independently convey the heat transfer medium through the system. In Fig. 3, blowers 11, 12 are connected in series. To allow an independent operation of the blowers, a bypass line 16 bypassing the first blower 11 and a bypass line 17 bypassing the second blower 12 are further provided. For example, when the heat transfer medium is to be conveyed by means of the second blower 12, e.g. during a start-up mode or during a charging mode of operation, the bypass 17 is closed and the bypass 16 is opened, so that the heat transfer medium bypasses blower 11. An additional valve can be provided directly adjacent to each blower (e.g. directly upstream of the blower and downstream of the branching point at which the bypass around the blower branches off) so that the flow of heat transfer medium through the bypassed blower can be shut off. After steam is available in the charging mode, or in a discharging mode of operation, the bypass line 16 is closed and the bypass 17 is opened, and only blower 11 conveys the heat transfer medium.

[0082] In either embodiment, both blowers 11, 12 can be operated simultaneously, for example to increase the mass flow of the heat transfer medium through the system. This is particularly beneficial towards the end of a full charging or discharging cycle in order to maintain a steady or constant charging/discharging rate. Such boost mode of operation can in particular be implemented with

the series connection of the blowers, since a pressure increase of the heat transfer medium is easier to achieve when the blowers are series-connected compared to a parallel connection.

[0083] Fig. 4 illustrates a further embodiment that is a modification of the embodiment of Fig. 1, so that the above explanations and the modification of Fig. 3 are also applicable to the embodiment of Fig. 4. The thermal energy storage system 10 of Fig. 4 comprises an additional steam generator 80, which is an auxiliary steam generator, i.e. it does not constitute a main heat consumer and only consumes a relatively small fraction of the thermal energy compared to the remaining heat consumer(s) 50. The auxiliary steam generator 80 is dedicated to generating steam for the BDT 60, i.e. the generated steam is provided only to the BDT 60 via a respective flow connection. In Fig. 4 and in the further Figs. 5 and 6, the circle indicated with "3" at the SG 80 is connected to the circle "3" at BDT 60 via a respective flow connection, and the circle designated with "4" at the SG 80 is connected to the circle "4" downstream of the feedwater pump 68 by a respective flow connection.

[0084] The auxiliary SG 80 is in the charging flow path 41 located downstream of the storage device 20 and thus receives the heat transfer medium leaving the storage device 20. In the discharging flow path 42, the auxiliary SG 80 is located downstream of the main heat consumer 50, i.e. downstream of the main steam generator 90, and thus receives heat transfer medium leaving the main steam generator (either indirectly via the blower as shown in Fig. 4, or directly as shown in Fig. 5). It thus receives the heat transfer medium at a lower temperature, which is however sufficient for generating steam for operating BDT 60. In the example of Fig. 4 the auxiliary SG 80 is connected in the charging flow path downstream of storage device 20 and upstream of blower 11, 12. In the discharging flow path, it is connected downstream of the blower 11, 12 and upstream of the storage device 20. Accordingly, in operation, the heat transfer medium passes in different directions through the SG 80 during the charging mode and the discharging mode. Fig. 5 shows a different placement of the auxiliary steam generator 80, wherein in the discharging flow path, the auxiliary SG 80 is arranged downstream of the heat consumer 50 and upstream of the blower 11, 12. By such placement, the heat transfer medium passes through the auxiliary SG 80 in the same direction both during the charging and the discharging modes of operation.

[0085] Accordingly, for both placements shown in Figs. 4 and 5, heat transfer medium is passed through the auxiliary SG 80 in both charging and discharging modes of operation so that steam is continuously produced and available for powering the BDT 60. Also, it is not necessary during start-up or during the charging mode of operation to divert a fraction of the heat transfer medium to the main SG 90, so that the entire medium can pass through the storage device 20, thus accelerating the charging process. The placement of the auxiliary SG 80

as shown in Figs. 4 and 5 is furthermore beneficial, as it is not exposed to the high temperatures of the medium that are present downstream of the heat source 30 or, in the discharging mode, downstream of the storage device 20.

[0086] In the exemplary configuration of Figs. 4 and 5, the steam outlet 62 of BDT 60 is again flow-connected to the common condenser 76, which thus provides condensation of the working fluid both for the main turbine 70 and for the blower driving steam turbine 60. An additional feed pump 68 may furthermore be provided for conveying the working fluid of the steam cycle, i.e. the condensed water, through the auxiliary steam generator 80.

[0087] To control the power output of the BDT 60, the amount of working fluid conveyed by the feedwater pump 68 may be controlled. This may occur in addition or alternatively to the control of the steam provided into the BDT 60 via inlet 61 using, e.g., the control valve 63 that can be provided between the auxiliary SG 80 and the BDT 60 or the steam conditioning station.

[0088] In these embodiments comprising an auxiliary steam generator 80, start-up may again occur by operating the second blower 12 during the start-up phase until sufficient steam is generated by the auxiliary steam generator 80 for operation of the first blower 11. In these embodiments, the system 10 can thereafter be fully operated by the blower 11, since steam is continuously produced by the auxiliary SG 80. Furthermore, the heat consumed by SG 80 has only minimal effect on the charging cycle and the discharging cycle, as the SG 80 only receives the cooled down heat transfer medium discharged from storage device 20 or from the heat consumer 50, respectively.

[0089] The embodiments of Figs. 4 and 5 may be further modified as illustrated in Fig. 6 by providing an entirely separate steam cycle for the BDT and the auxiliary steam generator 80. In the embodiment of Fig. 6, an additional condenser 66 is thus provided and connected to the outlet 62 of BDT 60. The working fluid discharged by condenser 66 is then conveyed by the feedwater pump 68 of the auxiliary steam cycle to the auxiliary steam generator 80. As outlined above, the steam generated by auxiliary SG 80 is received via a respective flow connection at the inlet 61 of the BDT 60, thus completing the water-steam cycle for the auxiliary SG 80. This has the advantage that the operation of the main steam turbine 70 and of the BDT 60 are entirely decoupled.

[0090] In all of the above embodiments, two blowers 11, 12 are provided. However, each of these embodiments can also be implemented with only a single blower 11. Such modification is shown in Figs. 7 and 8. The above explanations and modifications are therefore equally applicable to the embodiments of Figs. 7 and 8, and only differences are explained.

[0091] In the embodiment of Fig. 7, the electric motor 13 is directly coupled to the blower 11, for example via a respective rotational shaft. As the BDT 60 and the motor

13 may have different operational speeds, a clutch may be coupled between motor 13 and blower 11, and/or between BDT 60 and blower 11. Accordingly, during start-up, motor 13 may drive the blower 11 until sufficient steam for BDT 60 is available. During the charging mode of operation, motor 13 may be operated if no auxiliary SG 80 is present, and if no fraction of the heated heat transfer medium is directed through the SG 90 to provide steam for BDT 60. Otherwise, motor 13 may only be operated during the start-up phase. Such modification may be made to any of the embodiments of Figs. 1 to 6. Further, it should be clear that a respective electric motor for the first blower 11 may be provided in any of the embodiments of Figs. 1 to 6, so that two electric motors are present in these embodiments.

[0092] As outlined above, further redundancy may thus be provided and the probability of an outage of system 10 may be reduced.

[0093] In the embodiment of Fig. 8, the blower driving steam turbine is the main steam turbine 70, i.e. the main steam turbine 70 drives the blower 11. Due to the different operating points of the main steam turbine 70 and the blower 11, a clutch 18 is provided between the rotational output of the steam turbine and the blower 11. Although such configuration has the benefit that no additional steam turbine is needed, it requires a relatively large amount of time prior to being capable of operating the blower 11 by means of the steam turbine 70, as the main steam turbine 70 first needs to be heated-up and become operational.

[0094] Similar to Fig. 7, the motor 13 is coupled to the first blower 11 in the embodiment of Fig. 8. However, it should be clear that the embodiment of Fig. 8 may likewise be provided with a second blower 12 connected in series or in parallel to the first motor 11, and driven by the electric motor 13.

[0095] The blower 11, 12 may for example comprise or consist of a shaft with a rotor, the rotor comprising rotor blades for conveying the heat transfer medium, such as air. The blower can thus be simple without any own driving means. The shaft is mechanically coupled to the rotational output of the BDT 60 (directly or via gears) and/or the respective electric motor 13. Blowers 11, 12 may thus have a very simple configuration.

[0096] Fig. 9 illustrates an embodiment of the energy storage device 20 that may be used with any of the embodiments of the thermal energy storage system 10 described herein. It comprises a storage chamber 23 in which a heat storage material 24 is disposed. The storage chamber 23 may be formed by a housing with walls, yet it may also be formed by simply an excavation that is covered. The heat storage material may be a material that is capable of storing heat at higher temperature and that may be simple and cost-efficiently to obtain. Examples are rocks or stones, sand, bricks, granite, basalt, ceramics or the like. It should be clear that it may also include a mixture of such materials. The energy storage device 20 includes a first port 21, which acts as an inlet

during the charging mode (receiving hot air from the heater, as indicated by arrows) and acts as an outlet during the discharging mode (exhausting hot transfer medium heated up by material 24). It further comprises a second port 22, which acts as an outlet during the charging mode (exhausting cooled-down heat transfer medium) or as an inlet during the discharging mode (receiving cold heat transfer medium). In both modes, the heat transfer medium passes through the same passages formed in the material 24 (e.g. pores, crevices or other flow channels), although in opposite directions.

[0097] The energy storage device 20 further includes nozzle sections 25 adjacent to the respective ports 21, 22, which have a tapered shape. The energy storage device 20 may be configured as described further above, and may in particular be configured as disclosed in the document EP3102796A1.

[0098] Fig. 10 illustrates a flow diagram of a method according to an embodiment. During a start-up phase of system 10, the electrical motor 13 is operated to drive either the first blower 11 coupled to the BDT 60, or to drive the second blower 12 if present (step S1). The heat transfer medium is then conveyed by operation of the respective blower through the heat source 30 and through the energy storage device 20 in accordance with the charging flow path or a start-up flow path. At least part of the heat transfer medium is thereby conveyed through a steam generator (step S2). As indicated above, a fraction of the heated medium may be conveyed to the main steam generator 90, all of a medium may be conveyed through the main steam generator 90, or medium discharged from the storage device 20 may be conveyed through the auxiliary SG 80.

[0099] The respective steam generator then generates steam, which is provided to the BDT 60 to operate the BDT 60 (step S3). Once the BDT is operational, the start-up phase ends, and the system may continue operation in the regular charging mode (step S4), in which the heat transfer medium is conveyed along the charging flow path by operating the blower 11 driven by the BDT 60. Accordingly, no electrical energy is used for operating system 10 during the charging phase. As indicated above, steam for operating the BDT during the charging phase may either be received by guiding a fraction of the heat transfer medium through the main steam generator 90, or by generating the steam in the auxiliary SG 80. Alternatively, the charging mode may employ the electric motor 13 for driving the respective blower.

[0100] Upon receiving a demand for thermal energy (or for electrical energy) or after the storage device 20 is fully charged, the thermal energy storage system is operated in a discharging mode (step S5) in which the heat transfer medium is conveyed along the discharging flow path 42 by means of the blower 11 driven by the BDT 60. Accordingly, also during discharging, no electrical energy is required for driving the blower. Operation in the discharging mode may then continue until no further heat/electricity demand is present, or until the tempera-

ture in the energy storage device has dropped below a respective threshold, i.e. the energy storage device 20 is fully discharged (step S6). Operation may then switch back into the charging mode of step S4. Otherwise, operation in the discharging mode continues. It should be clear that if no demand is present and the storage device is fully charged, operation may transition into an idle mode. Also, it should be clear that the charging mode of operation may end prior to the energy storage device reaching a fully charged state (e.g. 100% charged), but may stop at a predetermined charging level or for other reasons, such as the cost of energy used for charging or manual intervention. Likewise, discharging may not stop at a charging state of 0%, but may stop at a predetermined discharging level or for other reasons, such as the availability of energy at a certain cost for charging or manual intervention.

[0101] It should be clear that steps S4, S5 and S6 may continuously be performed during operation of system 10 and until operation of system 10 is ended, for example by operator intervention. Steps S1 to S3 may only be performed once during start-up of the system 10.

[0102] The above embodiments result in a reduction of the electric power needed for the operation of the storage system 10, since the blower 11 is powered during most of its operation by the BDT. Although there is an additional steam supply required for the BDT, using steam to power the blower is advantageous over the use of electric power, in particular since no conversion from steam power to electric power by a steam turbine is necessary. The parasitic load that a conventional blower constitutes for the production of electrical energy from stored thermal energy may thus be reduced significantly, so that the overall electric power output, i.e. the net power output of the thermal energy storage system 10 can be improved.

[0103] As outlined above, embodiments furthermore provide a high degree of redundancy in particular with respect to the operation of the blower. Maintenance of the blowers is facilitated, and the storage can remain fully operational during such maintenance. Also, the storage system is capable of a black start, for example after a blackout. It does not rely on external electric power received from a power network. Rather, a small backup electric power source is sufficient, such as a diesel generator or a battery, for starting-up of the thermal energy storage system. It is in particular not necessary to operate the system with electric power until the large main steam turbine is heated up and ready to generate electricity. The power and capacity of the required black start equipment can thus be reduced. Also, if the thermal energy storage system does not power a main steam turbine, but rather provides the heated heat transfer medium directly to the heat consumer which does not produce electric power, it is still possible to operate the storage system without requiring external electric power, both during charging and discharging.

[0104] Furthermore, the providing of two blowers im-

proves the operation of the storage system by allowing a constant charging and discharging rate with thermal energy by increasing the mass flow of the heat transfer medium towards the end of a full charging or discharging cycle, in particular by operating both blowers in parallel or preferably in a series-connection.

[0105] While specific embodiments are disclosed herein, various changes and modifications can be made without departing from the scope of the invention. The present embodiments are to be considered in all respects as illustrative and non-restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

Claims

1. A thermal energy storage system, comprising

- an energy storage device (20) configured to store thermal energy;
- a charging flow path (41) configured to guide a heat transfer medium from a heat source (30) to the energy storage device (20) in order to transfer thermal energy from the heat source (30) to the energy storage device (20) ;
- a discharging flow path (42) configured to guide the heat transfer medium from the energy storage device (20) to a heat consumer (50) in order to transfer thermal energy from the energy storage device (20) to the heat consumer (50); and
- a blower (11) configured to convey the heat transfer medium in the charging flow path (41) and/or the discharging flow path (42);

characterized in that the thermal energy storage system (10) further comprises

- a blower driving turbine (60) a rotational output of which is coupled to the blower (11) to provide rotational mechanical energy to the blower (11) so as to drive the blower (11).

2. The thermal energy storage system according to claim 1, wherein the thermal energy storage system (10) is configured to operate the blower driving turbine (60) by a working fluid that is energized using thermal energy from the heat source (30) and/or from the energy storage device (20).

3. The thermal energy storage system according to claim 1 or 2, wherein the heat consumer (50) is a main heat exchanger, preferably a main steam generator (90), wherein the main heat exchanger is configured to energize the working fluid by means of thermal energy received from the energy storage device (20) and/or from the heat source (30), and is further configured to provide the energized working

fluid, preferably steam, to a main turbine (70).

4. The thermal energy storage system according to claim 3, wherein the blower driving turbine (60) is configured to receive energized working fluid from an intermediate stage of the main turbine (70). 5
5. The thermal energy storage system according to claim 4, wherein the blower driving turbine is a blower driving steam turbine and the main turbine is a main steam turbine, wherein the thermal energy storage system (10) further comprises at least a first flow line from a first steam extraction point (72) of the main steam turbine (70) to a steam inlet (61) of the blower driving steam turbine (60) and a second flow line from a second steam extraction point (73, 74) of the main steam turbine (70) to the steam inlet (61), wherein preferably the first and second flow lines each comprise a control valve (64) to control the flow of steam from the respective extraction point (72, 73, 74) to the steam inlet (61). 10 15 20
6. The thermal energy storage system according to any of claims 1-3, wherein the thermal energy storage system (10) further comprises an auxiliary heat exchanger, preferably an auxiliary steam generator (80), arranged in the charging and/or discharging flow path (41, 42) so as to receive thermal energy via the heat transfer medium, the thermal energy storage system (10) comprising a flow connection from the auxiliary heat exchanger to a working fluid inlet (61) of the blower driving turbine (60) to provide energized working fluid to the blower driving turbine (60). 25 30
7. The thermal energy storage system according to claim 6, wherein the auxiliary heat exchanger (80) is arranged in the charging flow path (41) downstream of the energy storage device (20) to receive heat transfer medium that leaves the energy storage device, and is arranged in the discharging flow path (42) downstream of the heat consumer (50) to receive heat transfer medium that leaves the heat consumer (50). 35 40
8. The thermal energy storage system according to claim 6 or 7, wherein the auxiliary heat exchanger (80) is arranged upstream of the blower (11) both in the charging flow path (41) and the discharging flow path (42), or is arranged downstream of blower (11) in discharging flow path (42) and upstream of blower (11) in the charging flow path (41). 45 50
9. The thermal energy storage system according to any of the preceding claims, further comprising an electric motor (13), wherein the electric motor (13) is coupled to the blower (11) to drive the blower or wherein the thermal energy storage system (10) further com-

prises a second blower (12) driven by the electric motor (13).

10. The thermal energy storage system according to claim 9, wherein the second blower (12) is connected in parallel to the blower (11) or is connected in series with the blower (11) to convey the heat transfer medium in the respective flow path (41, 42). 5
11. The thermal energy storage system according to claim 9 or 10, wherein the thermal energy storage system (10) further comprises a control unit to control the electric motor (13), the control unit being configured to perform the step of: 10 15
 - upon start-up of the thermal energy storage system (10), operating the electric motor (13) to convey the heat transfer medium such that at least part of the conveyed heat transfer medium passes through the heat source (30) and transports thermal energy to a heat exchanger (80, 90) of the thermal energy storage system (10) to energize working fluid, 20
- wherein the blower driving turbine (60) is operated by the energized working fluid. 25
12. The thermal energy storage system according to any of the preceding claims, wherein the charging flow path (41) is configured to guide the heat transfer medium through the energy storage device (20) in a first flow direction, and wherein the discharging flow path (42) is configured to guide the heat transfer medium through the energy storage device (20) in a second flow direction that is opposite to the first flow direction, wherein the charging and discharging flow paths (41, 42) are configured such that the heat transfer medium at least partly flows through the same passage in the energy storage device (20). 30 35 40
13. The thermal energy storage system according to any of the preceding claims, wherein the blower (11) is configured to convey the heat transfer medium both in the charging flow path (41) and the discharging flow path (42), wherein the thermal energy storage system (10) is configured such that the flow direction of heat transfer medium through the blower (11) is the same for the charging flow path (41) and for the discharging flow path (42). 45 50
14. The thermal energy storage system according to any of the preceding claims, wherein the blower driving turbine is a blower driving steam turbine, wherein the system further comprises a steam conditioning station arranged upstream of the blower driving steam turbine (60), wherein the steam conditioning station is configured to control one or more parameters of steam provided to the blower driving steam

turbine (60) to control the power of the blower (11).

15. The thermal energy storage system according to claim 2 or any of claims 3-4 and 6-13 when dependent on claim 2, wherein the working fluid is a supercritical fluid or a gas, preferably supercritical carbon dioxide, the blower driving turbine being configured to expand the supercritical fluid or gas in order to drive the blower.

16. A method of operating a thermal energy storage system, comprising:

- guiding a heat transfer medium from a heat source (30) to an energy storage device (20) along a charging flow path (41) in order to transfer thermal energy from the heat source (30) to the energy storage device (20);
- guiding the heat transfer medium from the energy storage device (20) to a heat consumer (50) along a discharging flow path (42) in order to transfer thermal energy from the energy storage device (20) to the heat consumer (50); and
- conveying the heat transfer medium in the charging flow path (41) and/or the discharging flow path (42) by means of a blower (11),

wherein the thermal energy storage system (10) comprises a blower driving turbine (60) a rotational output of which is coupled to the blower (11), the method further comprising:

- providing rotational mechanical energy from the blower driving turbine (60) to the blower (11) to drive the blower (11).

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FIG 1

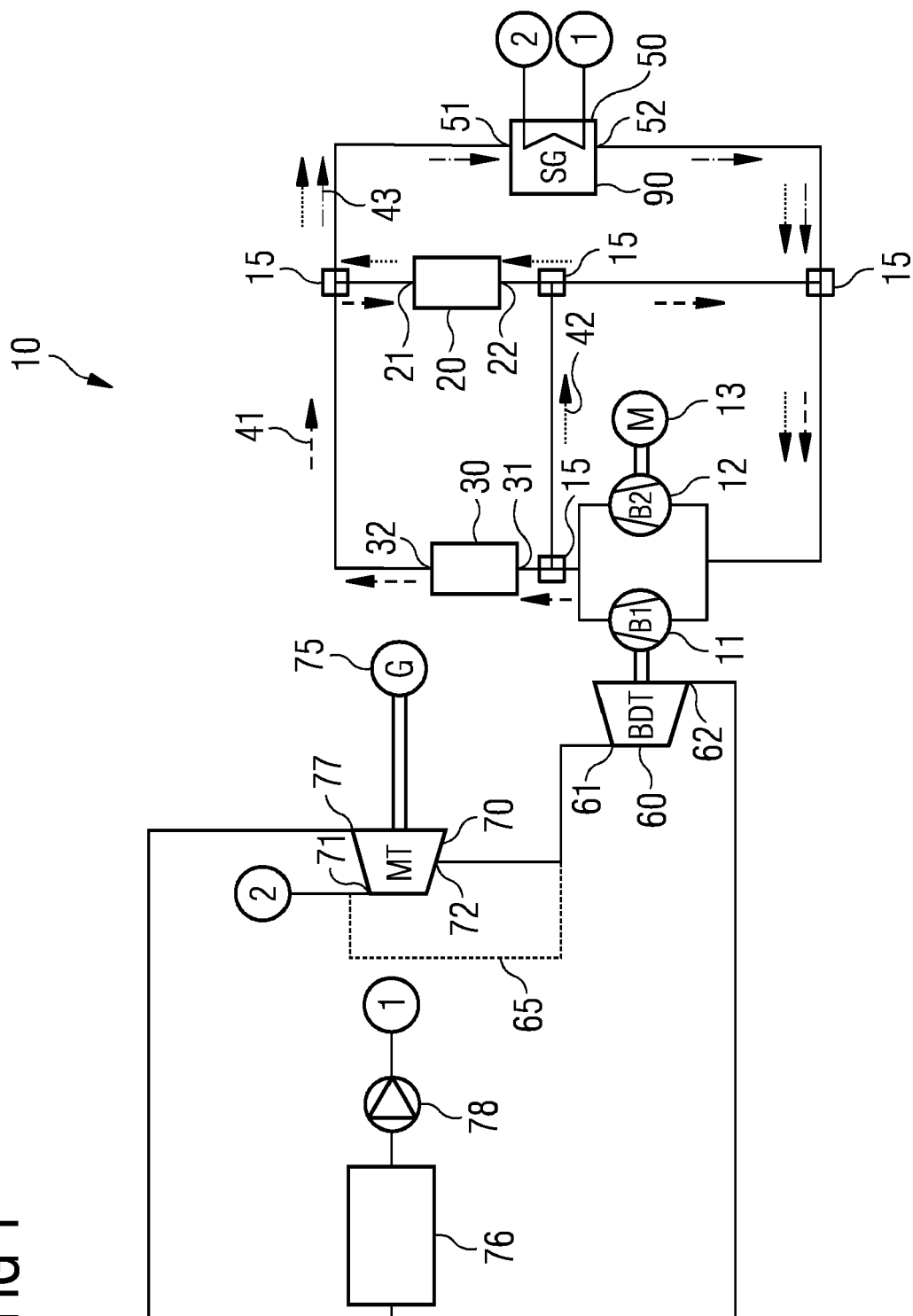


FIG 2

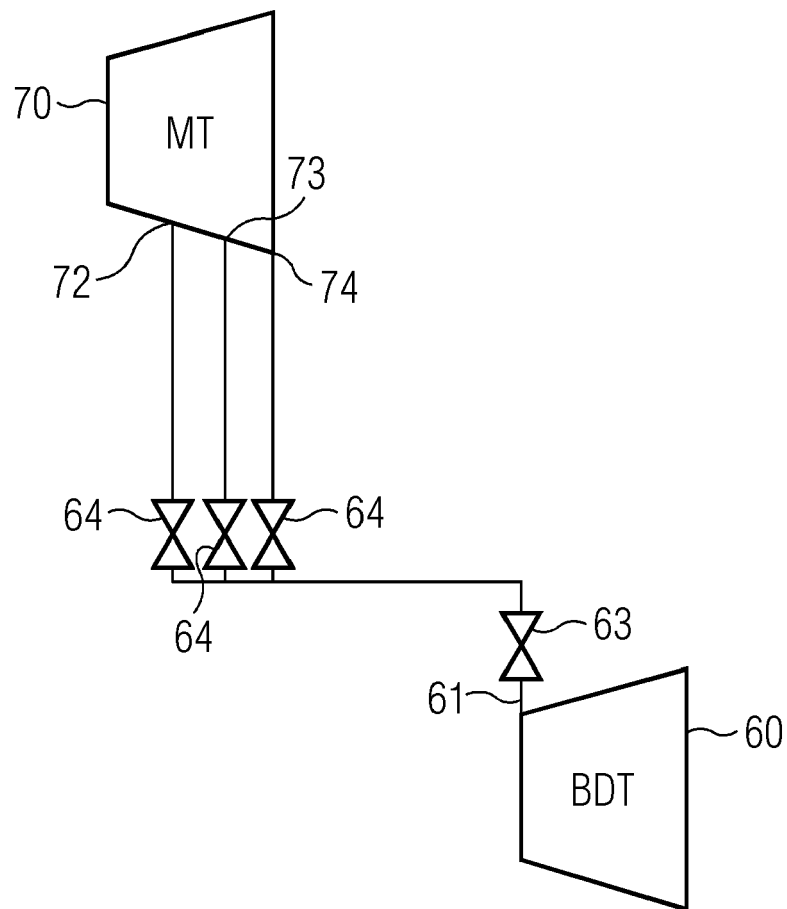


FIG 3

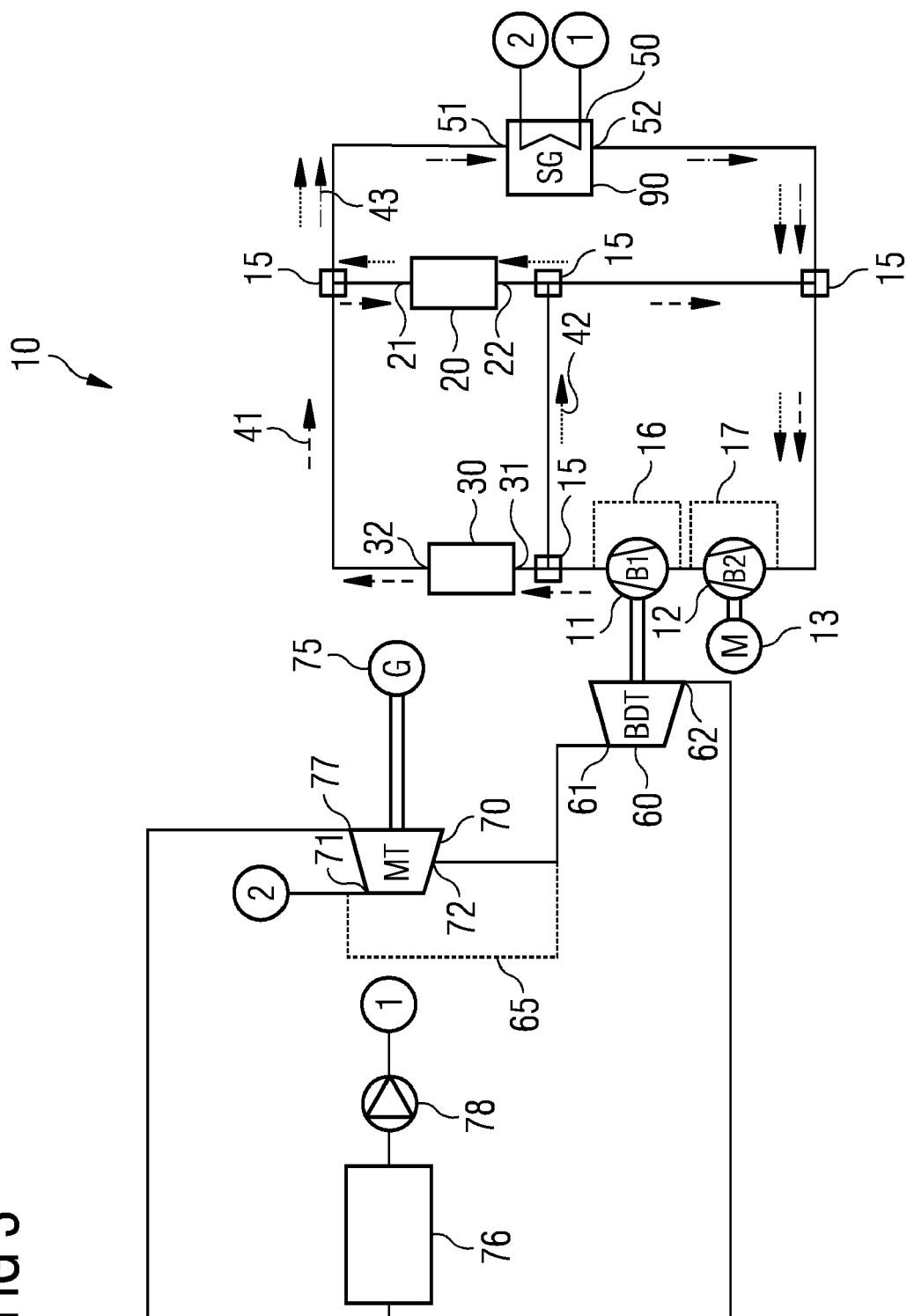


FIG 4

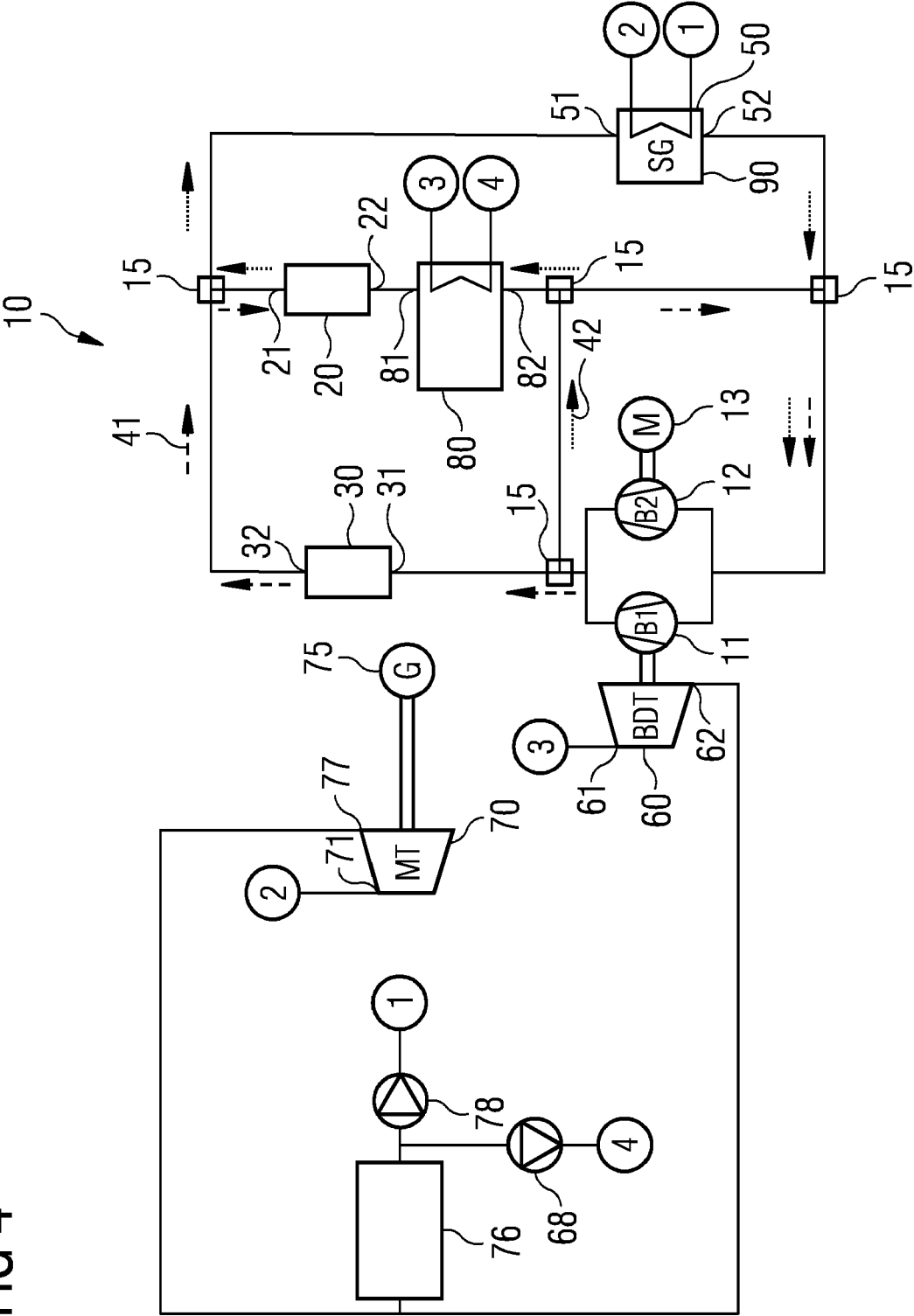


FIG 5

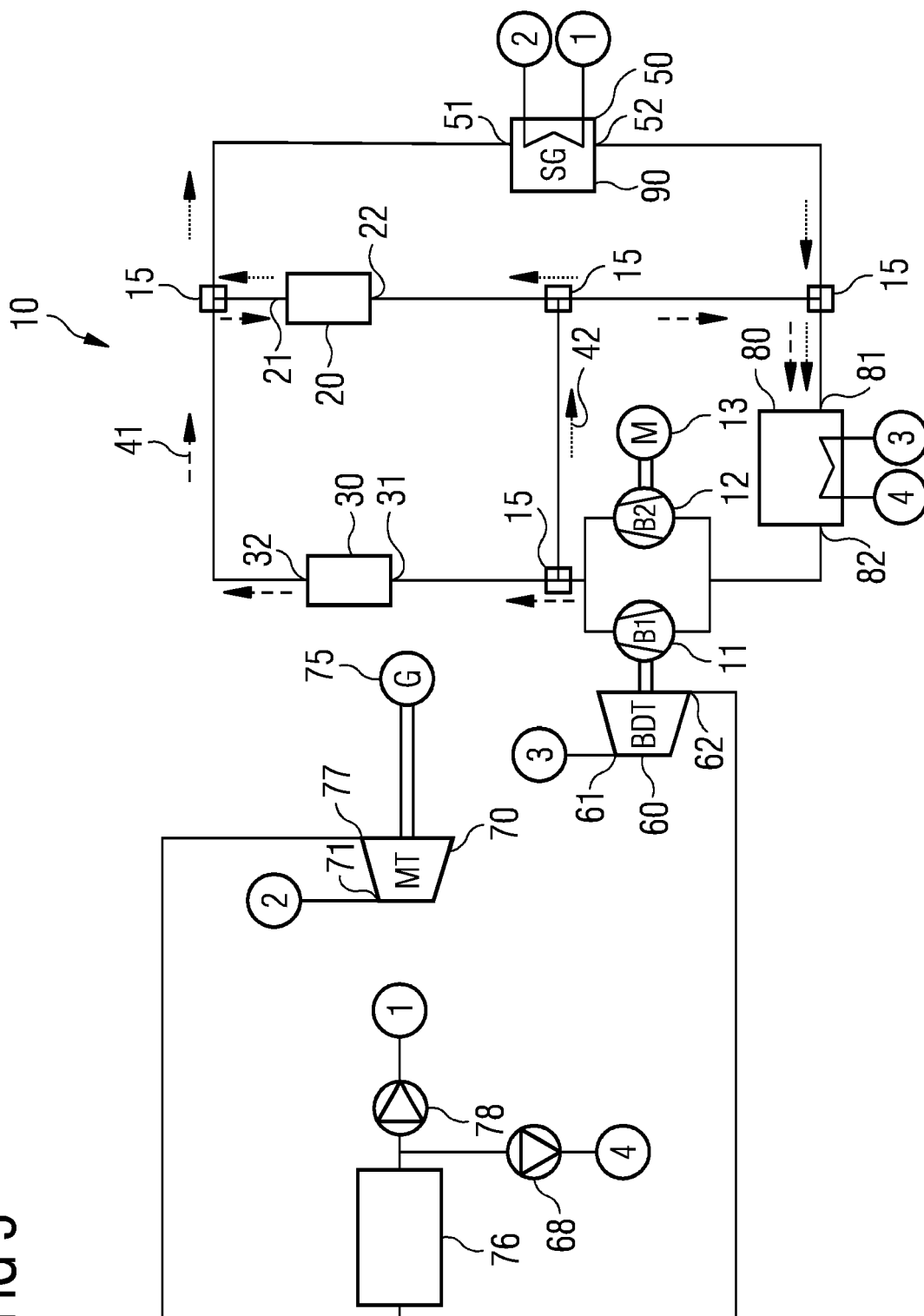


FIG 6

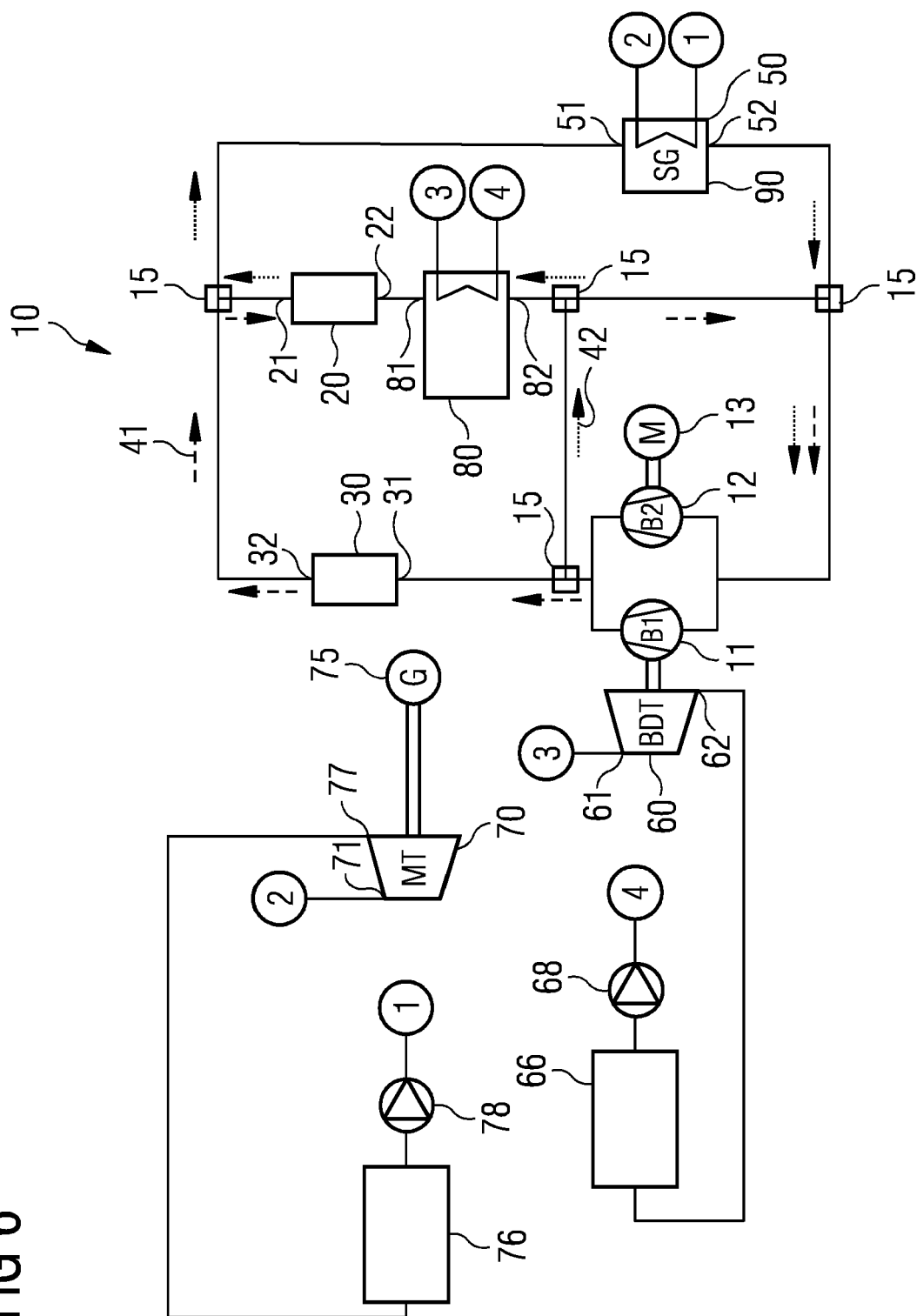


FIG 7

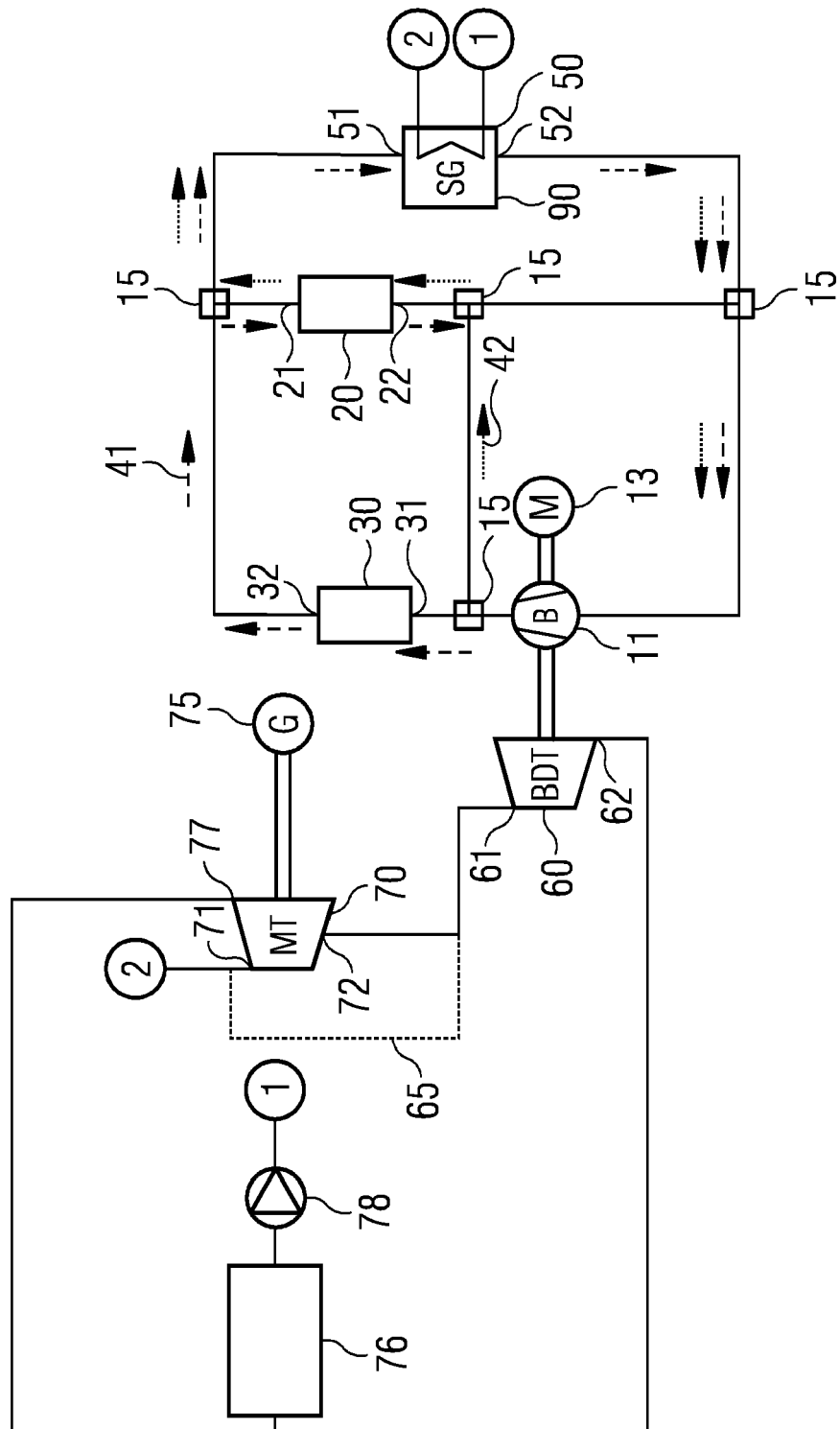


FIG 8

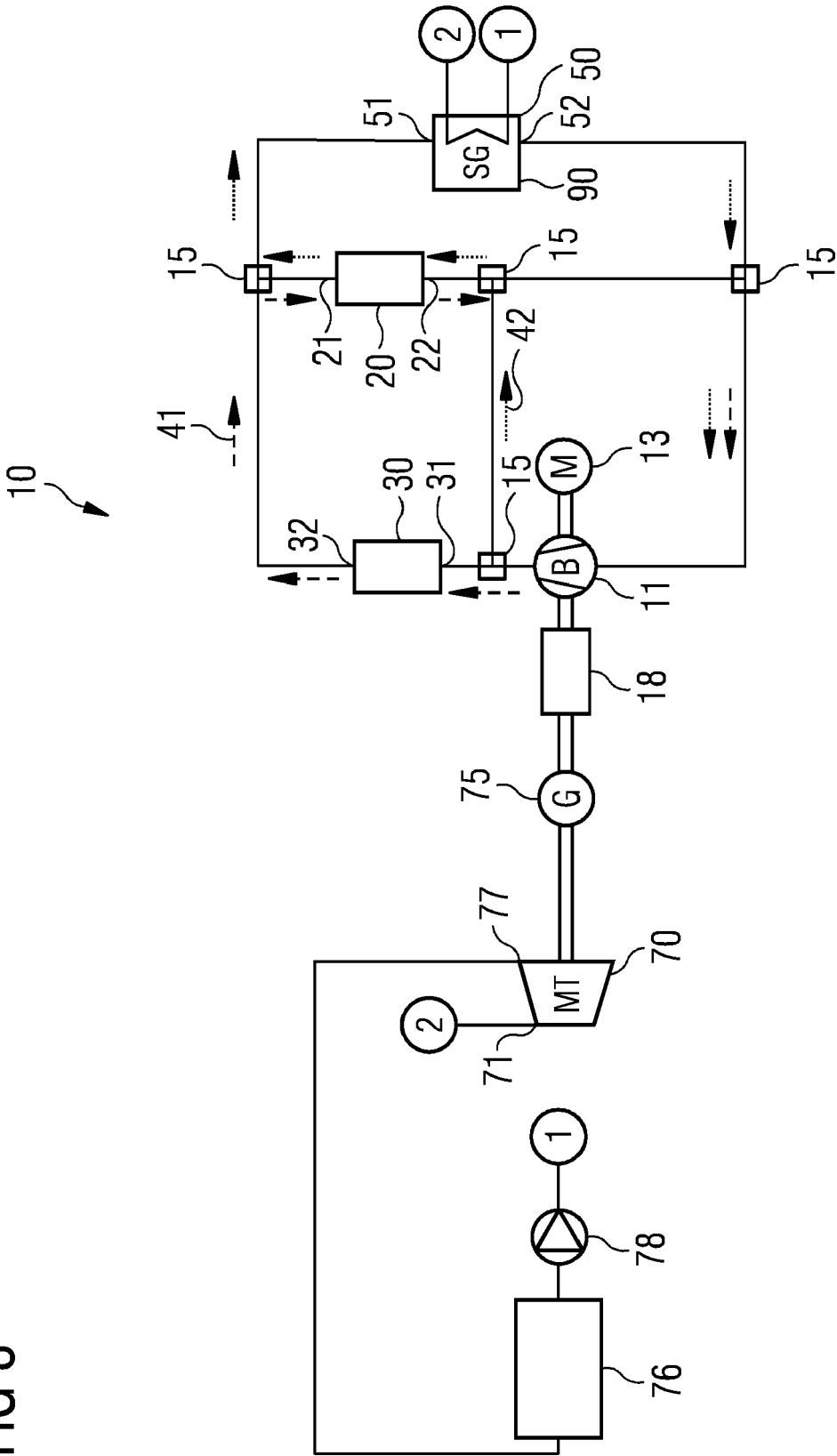


FIG 9

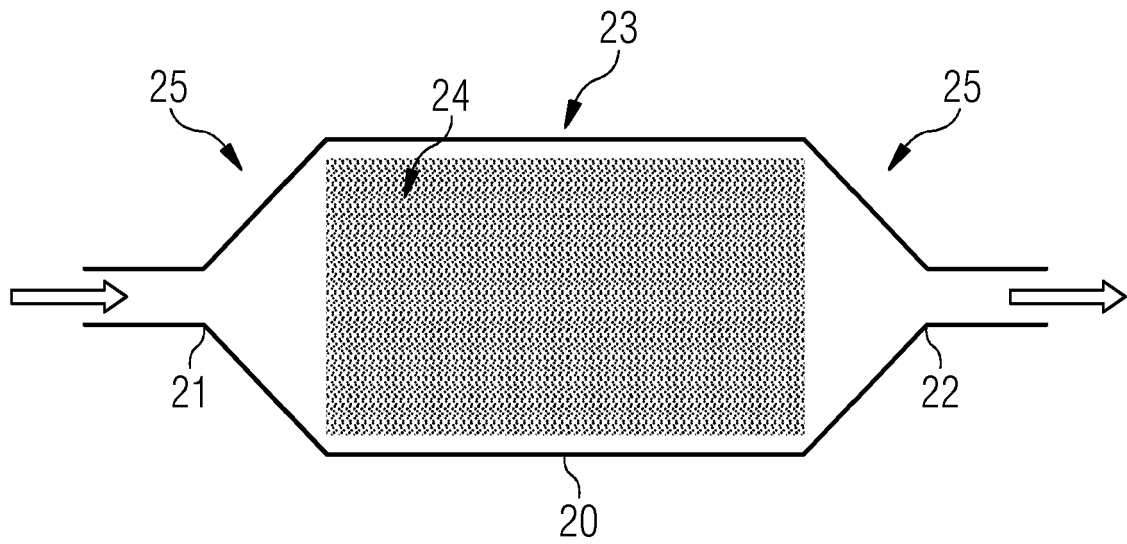
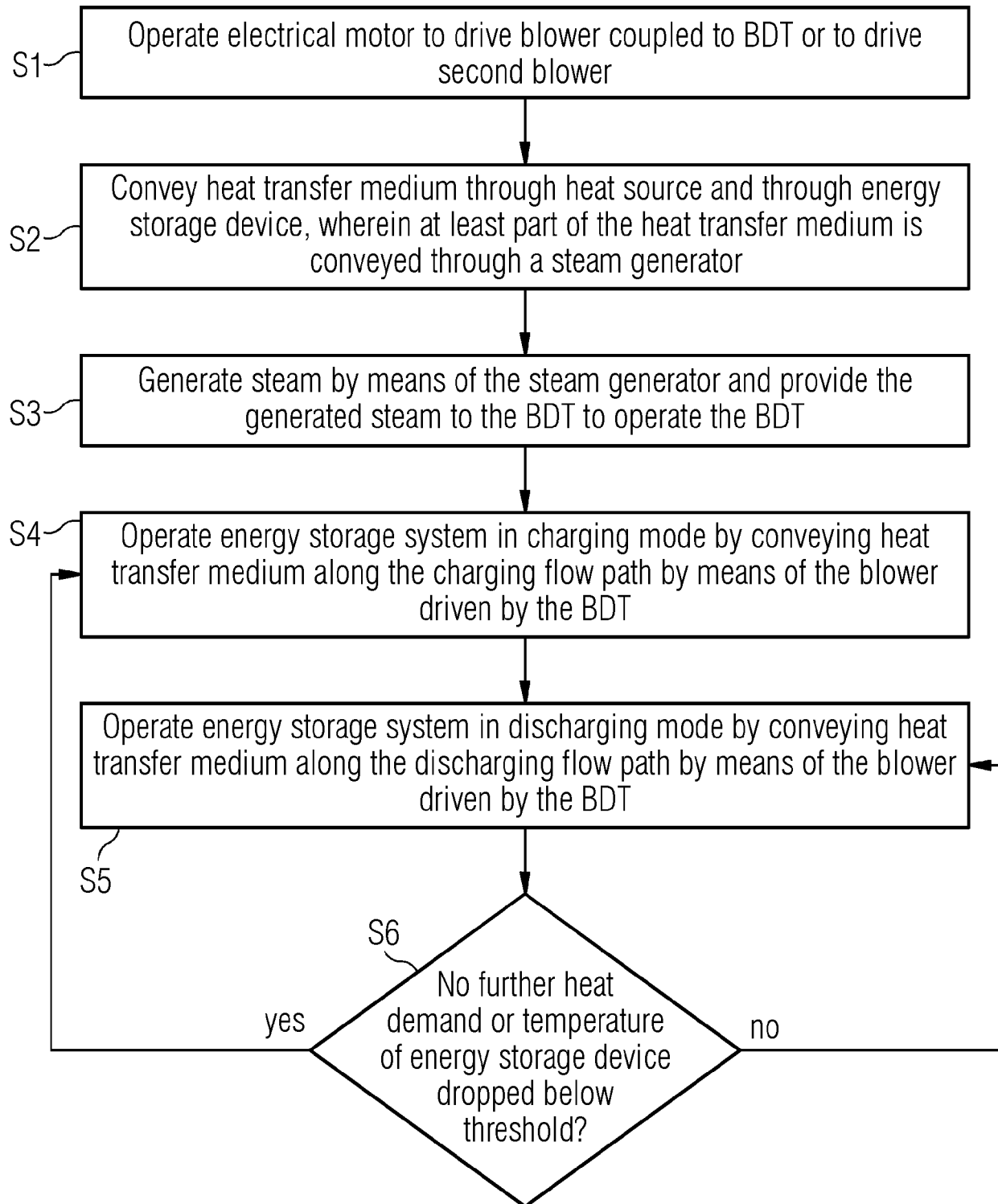


FIG 10





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Application Number
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A	* paragraphs [0134] - [0173]; figures 3a,9a *	6-8,10, 14	
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			F01K
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 2 December 2020	Examiner Röberg, Andreas
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